Sustainability Assessment of Hydrogen Fuel Cell and Lithium-Ion Batteries in Residential Solar PV Systems

Masood Ul Hassan[1], Stephen Bremner[1], Chris Menictas[2] and Merlinde Kay[1]

[1]*School of Photovoltaic and Renewable Energy Engineering, UNSW Sydney, Australia*
[2]*School of Mechanical and Manufacturing Engineering, UNSW Sydney, Australia*

Photovoltaic (PV) systems provide an effective form of renewable energy that requires no substantial running cost and has a negligible impact on the environment [1]. The electrical energy generated by PV systems is intermittent in nature because of its dependency on solar irradiance, meaning it is unavailable during night-time. Also, the output from PV systems is impacted by weather conditions such as temperature, clouds, fog, rain, dust storms, etc. The variability caused by cloudy periods, in particular, introduces power regulatory issues and voltage fluctuations in the system [2]. In Figure 1, the daily PV generation profiles from a randomly selected normal, cloudy, and rainy day within all four Australian seasons (Spring, Summer, Autumn and Winter) are illustrated. The peak PV generation varies seasonally, and periods of cloud and rain can cause intermittency and high variability in PV output.

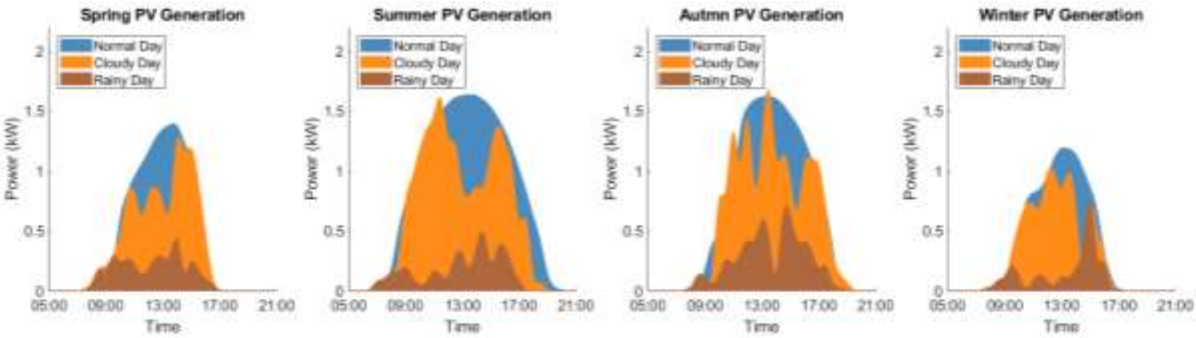

Figure 1: Weather based intermittency in electricity generation of a 3.7 kWp PV system.

To tackle the intermittent nature and best utilize the benefits of PV systems, energy storage devices are integrated with these PV systems [3]. The power generated from the PV system is stored in battery during off-peak electricity demand and peak solar times. The stored battery power is then utilized to serve the load during peak electricity demand and off-peak solar hours as shown in Figure 2. In this study, the peak (3pm−9pm), Shoulder (7am−3pm & 9pm−10pm) and Off Peak (10pm−7am) times from Australian Gas and Light (AGL) company are considered [4]. The integration of battery provides maximum utilization of solar energy and reduces the dependency on grid energy. This enhances the economic benefits associated with the PV systems [5].

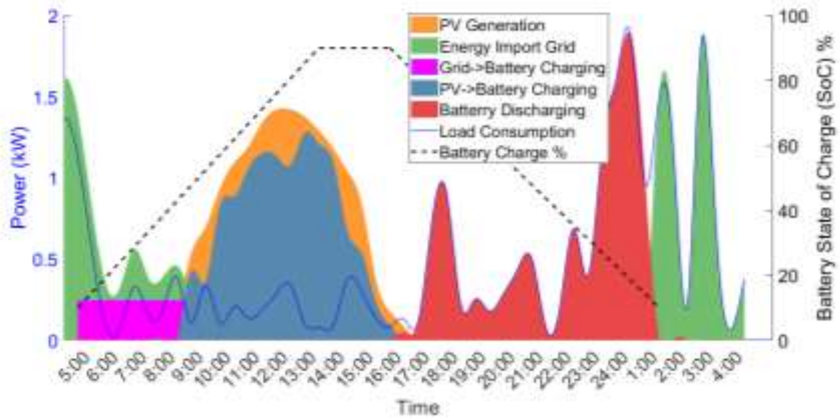

Figure 2: Battery arbitrage scheme operation in a 3.7 kWp PV system.

Traditionally, Lithium Ion (Li-Ion) and Lead Acid batteries are utilised as an energy storage device to store and regulate energy in solar PV systems. However, with increasing environmental concerns, renewable technology shift and governmental regulations, hydrogen fuel cell (HFC) batteries are being promoted as potential energy storage systems [6]. The current research on HFC battery is largely based on theory and lab experiments [7] and limited research is performed on the practical application of HFC battery. This is because, no HFC battery was commercially available until recently in June 2021, LAVO began commercial distribution of the world first HFC battery to market with technology developed by researchers at University of New South Wales (UNSW), Australia with the collaboration of industry partners [8].

The aim of this research is to assess the technical and economic suitability of the commercially available HFC battery by modelling the performance alongside data from real-world systems. The results are compared in simulations run with Li-Ion counterparts. A number of scenarios are explored considering solar and arbitrage charge schemes [9] in conventional (No PV and Battery), On-Grid (With PV) and Hybrid (With PV & Battery) grid integrations. Two different battery capacities of HFC and Li-Ion batteries (13.5 kWh and 40 kWh) are analysed and compared.

PV generation and electricity demand data from actual residential houses are used in this study to analyse the HFC and Li-Ion batteries. The data is obtained from Ausgrid [10], which consists of 300 housholds and available for 3 years from 1 July 2010 to 30 June 2013. The data is validated by Ratnam et al. in [11]. Battery manufacturer specifications come from LAVO [8] and Tesla: Powerwall 2 [12] for HFC and Li-Ion batteries, respectively. The specifications of the batteries are listed in Table I. The Time of Use (ToU) electricity pricing tariff from Australian Gas and Light (AGL) are used to calculate the cost of electricity imported and exported (Solar Feed In - SFI) [4]. The water usage tariffs from Sydney Water Company (SWC) [13] are used to perform the water consumption analysis in this study.

TABLE I: Battery Manufacturer Specifications Data

Parameter	LAVO	Powerwall 2
Useable Capacity	40 kWh & 13.5 kWh	40 kWh & 13.5 kWh
Roundtrip Efficiency	50%	90%
End of Life Retained Capacity	80%[1]	70%
Useful Life	20,000 Cycles	3652 Cycles
Max Real Power	5 kW	5 kW
Depth of Discharge	100%[2]	100%
Cost of Purchase	A$ 34,750 & NA[3]	A$ 39,900 & A$ 13,300
Water Consumption	450 ml/kWh	N/A

1. The end of life retained capacity is not specified by the LAVO manufacturers, however based on the National Hydrogen Road Map by CSIRO Australia, end of life retained capacity of PEM based hydrogen energy storage is 80% [14].
2. 100% depth of discharge corresponds to the energy withdrawal equivalent to battery useable capacity of 40kWh.
3. The LAVO battery only comes in 40kWh size. Therefore, the cost of 13.5 kWh is not used in the calculations.

The criteria used to evaluate the HFC, and Li-Ion batteries is based on the following parameters:

- Technical evaluation: Energy Import, Energy Export, Battery Operational Age, Capacity Fading or Performance Degradation, Operational SoC Range and Water Consumption.
- Economic evaluation: Impact on Electricity Bill or Cost of electricity purchase, revenue generated through electricity sales, net income (profit/ loss), payback period and water utilisation cost.

The results suggest that the Li-ion battery outperforms the HFC battery overall in stationary energy storage applications in the residential domain. This is mainly due to the lower roundtrip efficiency of HFC battery (around 50%). Li-Ion batteries achieve their payback earlier with results indicating a net loss of 143% and 160% in arbitrage scheme and 27% and 29% in solar scheme for 13.5 kWh and 40kWh HFC batteries, respectively. Li-Ion batteries have better performance in terms of capacity utilisation, impact on grid import, net income and payback period in comparison with HFC battery. Moreover, Li-ion batteries does not consume water for its normal operation while HFC batteries in 3-year simulation run, require about 2.9kL (Kilo Litres) and 3.1kL in the solar scheme and 5.3kL and 15.7kL in the arbitrage scheme for 13.5kWh and 40kWh HFC batteries, respectively. For Off-Grid systems or remote areas where the maintenance and replacement of the batteries is challenging, the HFC battery could potentially achieve better utilisation because of its longer life as compared to the Li-ion batteries. The battery ageing and performance degradation analysis performed in this study show that HFC battery in comparison with Li-Ion battery in solar scheme can provide 18% and 12% more operational life for 13.5 kWh and 40 kWh battery capacities, respectively.

The future extension of this work can utilise the findings of this study in improving the tenacity of hydrogen fuel cell batteries in residential and small commercial applications. The methodology provided in this study can be replicated and further utilised to access the futuristic studies on the HFC technology. The results of this study can be employed to select the optimal battery systems. The water consumption analysis provided in this study can be utilised to study the impact of large scale HFC battery deployment on existing water facilities and assist researchers in planning the water supply and forecasted water demand in future for tariff regulations.

References

[1] M. U. Hassan, M. I. Nawaz, and J. Iqbal, "Towards autonomous cleaning of photovoltaic modules: Design and realization of a robotic cleaner," in *2017 First International Conference on Latest trends in Electrical Engineering and Computing Technologies (INTELLECT)*, 2017: IEEE, pp. 1-6.

[2] M. Hassan, S. Saha, and M. E. Haque, "A framework for the performance evaluation of household rooftop solar battery systems," *International Journal of Electrical Power & Energy Systems,* vol. 125, p. 106446, 2021.

[3] H. Zsiborács *et al.*, "Intermittent renewable energy sources: The role of energy storage in the european power system of 2040," *Electronics,* vol. 8, no. 7, p. 729, 2019.

[4] A. G. L. Comapny. "AGL-Residential Electricity Plan (Residential Solar Savers)." Australian Government. https://www.energymadeeasy.gov.au/plan?id=AGL15056MRE&postcode=2291 (accessed 30-Jun-2021, 2021).

[5] J. Linssen, P. Stenzel, and J. Fleer, "Techno-economic analysis of photovoltaic battery systems and the influence of different consumer load profiles," *Applied Energy,* vol. 185, pp. 2019-2025, 2017.

[6] F. Sorgulu and I. Dincer, "A renewable source based hydrogen energy system for residential applications," *International Journal of Hydrogen Energy,* vol. 43, no. 11, pp. 5842-5851, 2018.

[7] K. Ou, W.-W. Yuan, M. Choi, S. Yang, S. Jung, and Y.-B. Kim, "Optimized power management based on adaptive-PMP algorithm for a stationary PEM fuel cell/battery hybrid system," *International Journal of Hydrogen Energy,* vol. 43, no. 32, pp. 15433-15444, 2018.

[8] L. Systems. "TECHNICAL SPECS." LAVO Systems. https://lavo.com.au/#specs (accessed 2021).

[9] M. U. Hassan, S. Saha, and M. E. Haque, "PVAnalytX: A MATLAB toolkit for techno-economic analysis and performance evaluation of rooftop PV systems," *Energy,* vol. 223, p. 120074, 2021.

[10] Ausgrid. "Solar home electricity data." Ausgrid. https://www.ausgrid.com.au/Industry/Our-Research/Data-to-share/Solar-home-electricity-data (accessed 16-Apr, 2021).

[11] E. L. Ratnam, S. R. Weller, C. M. Kellett, and A. T. Murray, "Residential load and rooftop PV generation: an Australian distribution network dataset," *International Journal of Sustainable Energy,* vol. 36, no. 8, pp. 787-806, 2017.

[12] T. Powerwall. "Select Your Powerwall." Tesla. https://www.tesla.com/en_au/powerwall/design (accessed 26-Apr, 2021).

[13] S. Water. "Prices for your home." Sydney Water. https://www.sydneywater.com.au/sw/accounts-billing/understanding-your-bill/prices-for-your-home/index.htm (accessed 16-Apr, 2021).

[14] S. Bruce *et al.*, "National hydrogen roadmap," *Australia: CSIRO,* 2018.