www.ijarp.com ISSN 2456-9992 Page: 01-13

International Journal Advanced Research Publications

Research Article

Volume: 02
Issue: 09

INTELLIGENT HYBRID HYDROGEN-BATTERY ENERGY STORAGE SYSTEM FOR DC MICROGRID USING ARTIFICIAL NEURAL NETWORK-BASED ENERGY MANAGEMENT

[*1]Akash Patel, [2]Prof. Vaibhav Jha

[1]PG Scholar, [2]HOD

Electrical department SRIT Jabalpur.

Article Received: 13 August 2026, Article Revised: 03 September 2026, Published on: 23 September 2026

***Corresponding Author: Akash Patel**

PG Scholar, Electrical department SRIT Jabalpur.

Doi: https://doi-doi.org/101555/ijarp.5387

ABSTRACT

The increasing penetration of renewable energy sources such as solar and wind energy has created major challenges in maintaining voltage stability and reliable power delivery in DC microgrids due to their intermittent nature. Battery Energy Storage Systems (BESS) provide fast dynamic response but suffer from limited energy capacity and reduced lifespan under continuous stress. Hydrogen Energy Storage Systems (HESS), on the other hand, provide long-duration energy storage but exhibit slower response characteristics. This research proposes an intelligent hybrid hydrogen-battery energy storage system controlled using an Artificial Neural Network (ANN)-based energy management strategy for DC microgrid applications. The proposed system is modeled and analyzed using MATLAB scripting under varying renewable generation and dynamic load conditions. A comparative study between conventional rule-based control and ANN-based intelligent control is performed. The obtained results demonstrate that the ANN controller significantly improves DC bus voltage stability, enhances energy management efficiency, and ensures smoother power sharing between battery and hydrogen storage systems. The ANN-based controller reduced voltage deviation from 23.89 V to 7.61 V while improving overall system efficiency from 86.64% to 93.77%. The proposed intelligent hybrid storage system demonstrates improved reliability and suitability for future renewable energy-based smart microgrid applications.

KEYWORDS: DC Microgrid, Artificial Neural Network, Hydrogen Energy Storage System, Battery Energy Storage System, Renewable Energy, Energy Management System.

1 INTRODUCTION

The rapid growth of renewable energy sources such as solar photovoltaic and wind energy systems has significantly transformed modern power systems. Renewable energy provides clean and sustainable electricity generation; however, the intermittent and unpredictable nature of these sources introduces several operational challenges in microgrid systems. Variations in solar irradiance and wind speed cause fluctuations in generated power, leading to instability in DC bus voltage and degradation in power quality.

Energy storage systems play a crucial role in overcoming these challenges by balancing the mismatch between power generation and load demand. Among different storage technologies, Battery Energy Storage Systems (BESS) are widely used because of their fast response capability and high efficiency. However, batteries have limited energy density and experience performance degradation under frequent charging and discharging cycles.

Hydrogen Energy Storage Systems (HESS) have recently gained attention because of their capability to store large amounts of energy for long durations. In hydrogen storage systems, excess renewable power is converted into hydrogen using an electrolyzer and stored in hydrogen tanks. During power shortages, the stored hydrogen is converted back into electricity using fuel cells. Although hydrogen systems offer large energy storage capacity, their response time is relatively slow.

To utilize the advantages of both technologies, this research proposes a hybrid hydrogen-battery energy storage system for DC microgrids. In the proposed approach, the battery handles fast transient fluctuations while the hydrogen system provides long-term energy balancing. Furthermore, an Artificial Neural Network (ANN)-based intelligent energy management controller is implemented to improve system performance and adaptive power sharing.

2 Proposed System Architecture

The proposed DC microgrid consists of:

- Solar and wind renewable energy sources
- Battery Energy Storage System (BESS)
- Hydrogen Energy Storage System (HESS)
- Dynamic DC load
- ANN-based intelligent energy management controller

The ANN controller continuously monitors:

- Renewable power generation

- Load demand
- Battery State of Charge (SOC)
- Hydrogen storage level
- DC bus voltage

Based on these parameters, the controller intelligently determines the power contribution from the battery and hydrogen systems.

The battery system provides rapid compensation during sudden load variations, whereas the hydrogen system supplies long-duration backup power support.

3 METHODOLOGY

The complete hybrid energy storage system was developed using MATLAB scripting. Two different control strategies were implemented:

1. Conventional Rule-Based Energy Management System
2. ANN-Based Intelligent Energy Management System

The renewable generation profile was modeled using varying solar and wind generation patterns combined with random disturbances to emulate real-world operating conditions.

Dynamic load variations and sudden load peaks were introduced to evaluate the robustness of the proposed controller under nonlinear operating conditions.

The ANN controller was trained using system operating data obtained from the rule-based energy management system as shown below

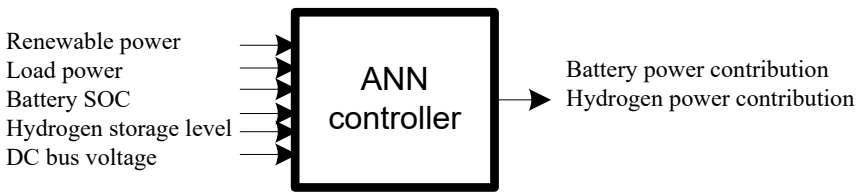


Figure 1 ANN controller inputs and outputs.

The ANN utilized:

- Renewable power
- Load power

- Battery SOC
- Hydrogen storage level
- DC bus voltage

as input parameters.

The ANN output determined:

- Battery power contribution
- Hydrogen power contribution

The system performance was analyzed based on:

- DC bus voltage deviation
- Average DC voltage
- Battery SOC variation
- System efficiency

4 Mathematical Modeling

A. DC Bus Voltage Dynamics

he DC bus voltage changes according to the power imbalance between generated power and load demand. The DC bus voltage equation is expressed as

$$V_{dc}(k+1) = V_{dc}(k) + \frac{\Delta P}{C_{dc}} dt$$

Where:

- V_{dc}= DC bus voltage
- ΔP = power imbalance
- C_{dc}= DC link capacitance

B. Battery State of Charge (SOC)

The battery State of Charge (SOC) represents the available energy stored in the battery. The SOC update equation is given by:

$$SOC(k+1) = SOC(k) - \frac{P_{bat}}{V_{bat} Q} * 100$$

Where:

- SOC: battery state of charge (%)
- P_{bat}=battery power
- V_{bat}: Battery voltage
- Q: Battery capacity in AH

C. Hydrogen Storage Dynamics

The hydrogen storage level changes according to electrolyzer and fuel cell operation:

$$H_2(k+1) = H_2(k) + \eta_{el}|P_{h2}|dt$$

Where:

- H_2: Hydrogen storage fuel
- η_{el}: electrolyser efficiency
- P_{h2}: hydrogen charging power

5 Simulation Parameters

The simulation parameters used in this research were selected to represent a practical DC microgrid operating environment. A nominal DC bus voltage of 400 V was maintained to ensure stable power delivery within the microgrid. The battery storage system was modeled using a 48 V battery with a capacity of 20 Ah to provide fast transient power support during sudden load variations and renewable power fluctuations. A DC link capacitance of 2 F was considered to stabilize the DC bus voltage during dynamic operating conditions. The complete simulation was carried out for 10000 seconds to evaluate the long-term performance and stability of the proposed energy management system under varying renewable generation and load conditions. Furthermore, the battery efficiency and hydrogen system efficiency were assumed as 92% and 80%, respectively, to represent realistic operational characteristics of practical energy storage systems.

Table 1 Simulation parameters.

Parameter	Value
DC Bus Voltage	400 V
Battery Voltage	48 V
Battery Capacity	20 Ah
DC Link Capacitance	2 F
Simulation Time	10000 s
Battery Efficiency	92%
Hydrogen System Efficiency	80%

6 RESULTS AND DISCUSSION

A comparative analysis between the conventional rule-based controller and the proposed ANN-based intelligent controller was carried out.

A. Performance Comparison

Parameter	Without ANN	With ANN
Voltage Deviation	23.89 V	7.61 V
Average Voltage	388.96 V	403.08 V
SOC Variation	0.22 %	0.34 %
Efficiency	86.64 %	93.77 %

The results indicate that the ANN-based controller significantly improves the performance of the DC microgrid.

The ANN controller successfully maintained the DC bus voltage close to the desired 400 V reference value even under renewable intermittency and load disturbances.

The voltage deviation was reduced from 23.89 V to 7.61 V, demonstrating improved voltage regulation capability.

The overall system efficiency improved from 86.64% to 93.77%, indicating better energy utilization and optimized power sharing between battery and hydrogen storage systems.

The ANN controller also provided smoother transient response and adaptive energy balancing compared to the conventional rule-based controller.

6.1 ANN based power sharing

The ANN-based power sharing results demonstrate the effective coordination between renewable energy sources, battery storage, and hydrogen energy storage within the proposed DC microgrid system as shown in the figure below.

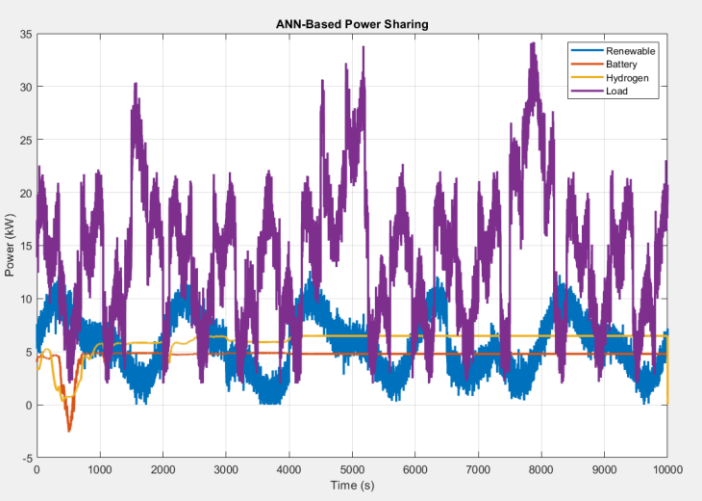


Figure 2 ANN based power sharing.

The renewable power generation exhibits continuous fluctuations due to varying solar and wind conditions, while the load demand changes dynamically with sudden peaks and disturbances. Under these operating conditions, the ANN controller intelligently allocates power between the battery and hydrogen storage systems to maintain stable microgrid operation. The battery storage system responds rapidly to transient load variations and renewable intermittency, whereas the hydrogen storage system provides smoother long-duration energy support. The obtained results clearly show that the proposed ANN-based controller successfully minimizes voltage fluctuations and improves overall system efficiency compared to the conventional rule-based controller. Furthermore, the coordinated hybrid operation enhances system reliability and ensures balanced power flow under varying renewable and load conditions, thereby validating the effectiveness of the proposed intelligent energy management strategy for DC microgrid applications.

6.2 Battery SOC comparison

The Battery State of Charge (SOC) comparison graph illustrates the charging and discharging behavior of the battery under both conventional rule-based control and ANN-based intelligent control strategies as shown in the figure below.

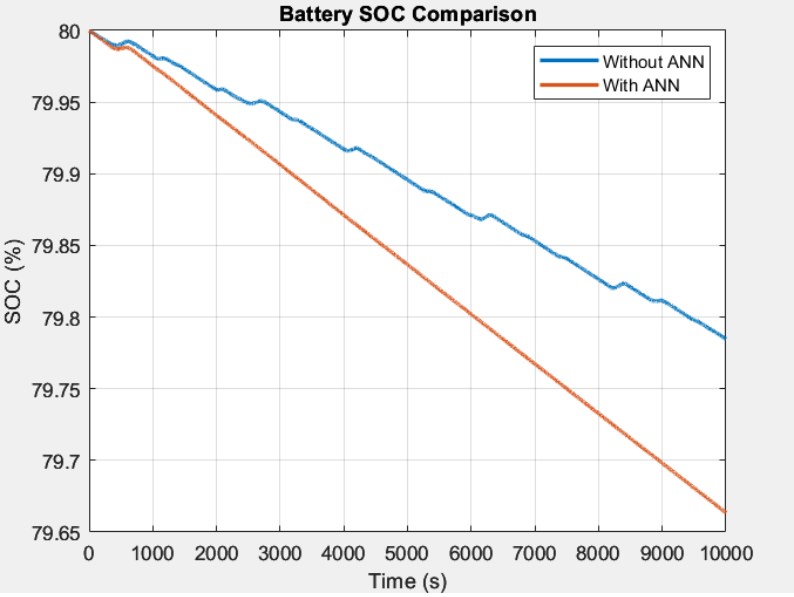


Figure 3 Battery SOC Comparison.

It can be observed that the SOC decreases gradually over the simulation period due to continuous power support provided by the battery to compensate for renewable power fluctuations and varying load demand. In the conventional control approach, the SOC

variation exhibits small irregular fluctuations due to less optimized power sharing and slower response to system disturbances. In contrast, the ANN-based controller demonstrates a smoother and more controlled SOC profile, indicating intelligent battery utilization and improved energy management. The ANN controller effectively balances the power contribution between the battery and hydrogen storage system, thereby preventing unnecessary battery stress and improving overall operational stability. The smoother SOC variation confirms that the ANN-based energy management strategy achieves more efficient battery utilization and coordinated hybrid storage operation within the proposed DC microgrid system.

6.3 DC Bus voltage comparison

The DC bus voltage comparison graph demonstrates the effectiveness of the proposed ANN-based energy management system in maintaining voltage stability within the DC microgrid as shown in the figure below.

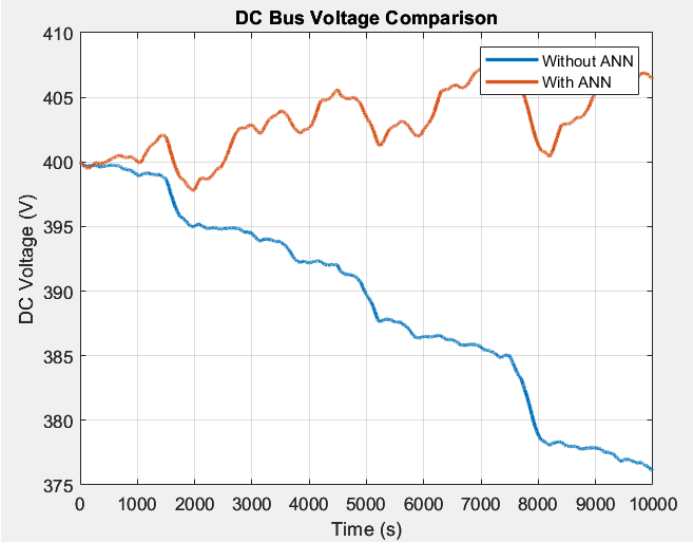


Figure 4 DC bus voltage comparison.

Under the conventional rule-based controller, the DC bus voltage gradually decreases over time due to inadequate compensation of renewable power fluctuations and dynamic load variations. Significant voltage drops can be observed during high load demand and low renewable generation conditions, indicating reduced system stability. In contrast, the ANN-based controller maintains the DC bus voltage close to the nominal 400 V reference value throughout the simulation period. The ANN controller intelligently coordinates the battery and hydrogen storage systems to provide adaptive power support during transient

disturbances and renewable intermittency. As a result, the voltage profile under ANN control remains significantly smoother with reduced fluctuations and improved regulation performance. The obtained results confirm that the proposed ANN-based hybrid energy management strategy effectively enhances DC microgrid stability, improves power balancing capability, and ensures reliable operation under varying operating conditions.

6.4 Error histogram

The ANN training error histogram illustrates the distribution of prediction errors obtained during the training, validation, and testing phases of the neural network model as shown in the figure below.

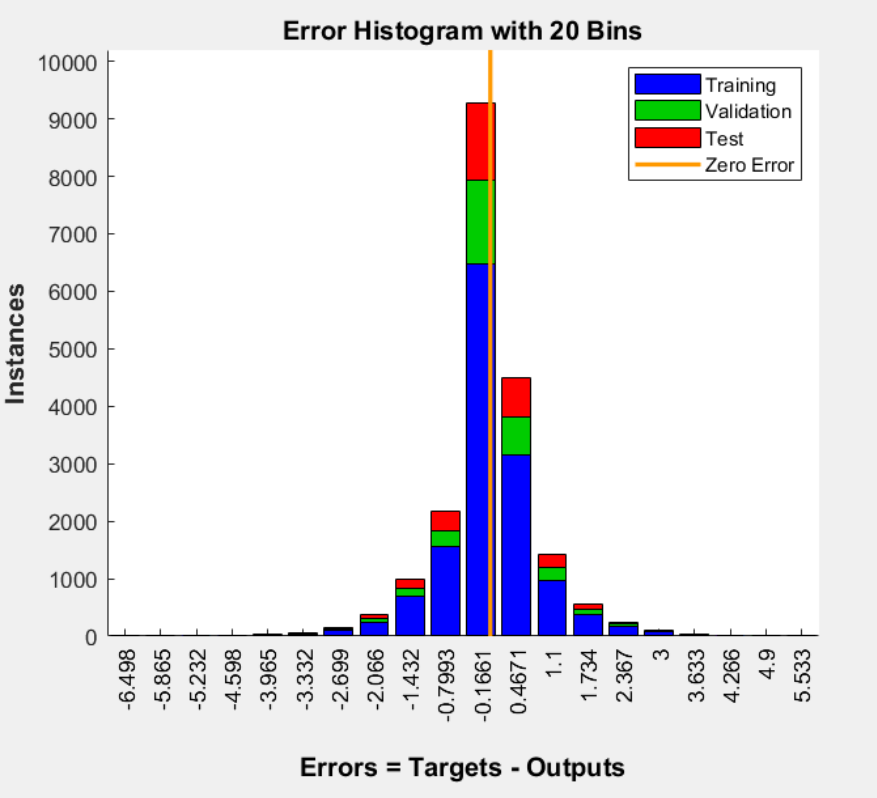


Figure 5 Error histogram.

The horizontal axis represents the error values calculated as the difference between the target outputs and the ANN predicted outputs, while the vertical axis represents the number of instances corresponding to each error range. It can be observed that the majority of the errors are concentrated very close to the zero-error line, indicating that the ANN model achieved accurate prediction and effective learning performance. The narrow distribution of errors around zero demonstrates good generalization capability and reduced prediction deviation during different operating conditions. Additionally, the training, validation, and testing

datasets exhibit similar error distributions, confirming that the ANN model is well-trained without significant overfitting or underfitting issues. The small prediction errors validate the effectiveness of the proposed ANN-based intelligent energy management system for optimal power sharing and stable DC microgrid operation.

7 CONCLUSION

This research presented an intelligent hybrid hydrogen-battery energy storage system for DC microgrids using an ANN-based energy management controller. The proposed system effectively combines the fast response capability of batteries with the large energy storage capacity of hydrogen systems.

MATLAB-based simulation results demonstrated that the ANN controller significantly improved DC bus voltage stability, enhanced overall system efficiency, and achieved better power management under varying renewable generation and dynamic load conditions.

The obtained results confirm that intelligent hybrid energy storage systems can play a vital role in future renewable energy-based smart microgrids.

Future work may include:

- Fuzzy logic control implementation
- Deep learning-based optimization
- Real-time hardware implementation
- Integration with electric vehicle charging systems

REFERENCES

1. R. Marks-Bielska, S. Bielski, K. Pik, K. Kurowska, The importance of renewable energy sources in Poland's energy mix, Energies 13 (18) (2020) 4624.
2. I. Dincer, Renewable energy and sustainable development: a crucial review, Renew. Sustain. Energy Rev. 4 (2) (2000) 157–175.
3. A. Garratt, I. Petrella, Y. Zhang, Asymmetry and interdependence when evaluating US energy information administration forecasts, Energy Econ. 121(2023), 106620.
4. Q. Hassan, A.Z. Sameen, H.M. Salman, M. Jaszczur, A.K. Al-Jiboory, Hydrogenenergy future: advancements in storage technologies and implications for sustainability, J. Energy Storage 72 (2023), 108404.
5. Q. Hassan, A.Z. Sameen, H.M. Salman, M. Jaszczur, A roadmap with strategicpolicy toward green hydrogen production: the case of Iraq, Sustainability 15 (6) (2023) 5258.

6. Q. Hassan, A.Z. Sameen, H.M. Salman, M. Jaszczur, Large-scale green hydrogen production using alkaline water electrolysis based on seasonal solar radiation, Energy Harvest. Syst. (2023).
7. Q. Hassan, M.K. Abbas, V.S. Tabar, S. Tohidi, M. Al-Hitmi, M. Jaszczur, H. M. Salman, Collective self-consumption of solar photovoltaic and batteries for a micro-grid energy system, Results Eng. 17 (2023), 100925.
8. N. Kannan, D. Vakeesan, Solar energy for future world:-A review, Renew. Sustain. Energy Rev. 62 (2016) 1092–1105.
9. X. Han, J. Garrison, G. Hug, Techno-economic analysis of PV-battery systems in Switzerland, Renew. Sustain. Energy Rev. 158 (2022), 112028.
10. Y. Wu, Z. Liu, J. Liu, H. Xiao, R. Liu, L. Zhang, Optimal battery capacity of gridconnected PV-battery systems considering battery degradation, Renew. Energy 181 (2022) 10–23.
11. R. Khezri, A. Mahmoudi, H. Aki, Optimal planning of solar photovoltaic and battery storage systems for grid-connected residential sector: review, challenges and new perspectives, Renew. Sustain. Energy Rev. 153 (2022), 111763.
12. Y. Zhang, T. Ma, P.E. Campana, Y. Yamaguchi, Y. Dai, A techno-economic sizing method for grid-connected household photovoltaic battery systems, Appl. Energy 269 (2020), 115106.
13. U.G.K. Mulleriyawage, W.X. Shen, Optimally sizing of battery energy storage capacity by operational optimization of residential PV-Battery systems: an Australian household case study, Renew. Energy 160 (2020) 852–864.
14. M.I. Hlal, V.K. Ramachandaramurthy, A. Sarhan, A. Pouryekta, U. Subramaniam, Optimum battery depth of discharge for off-grid solar PV/battery system, J. Energy Storage 26 (2019), 100999.
15. M.N. Ashtiani, A. Toopshekan, F.R. Astaraei, H. Yousefi, A. Maleki, Technoeconomic analysis of a grid-connected PV/battery system using the teachinglearning-based optimization algorithm, Sol. Energy 203 (2020) 69–82.
16. B. Zou, J. Peng, S. Li, Y. Li, J. Yan, H. Yang, Comparative study of the dynamic programming-based and rule-based operation strategies for grid-connected PVbattery systems of office buildings, Appl. Energy 305 (2022), 117875.
17. H. Rezk, M.A. Abdelkareem, C. Ghenai, Performance evaluation and optimal design of stand-alone solar PV-battery system for irrigation in isolated regions: acase study in Al Minya (Egypt), Sustain. Energy Technol. Assessments 36 (2019),100556.

18. M. Tostado-V´eliz, D. Icaza-Alvarez, F. Jurado, A novel methodology for optimal sizing photovoltaic-battery systems in smart homes considering grid outages and demand response, Renew. Energy 170 (2021) 884–896.
19. A. Chakir, M. Tabaa, F. Moutaouakkil, H. Medromi, M. Julien-Salame, A. Dandache, K. Alami, Optimal energy management for a grid connected PVbattery system, Energy Rep. 6 (2020) 218–231.
20. S. Bandyopadhyay, G.R.C. Mouli, Z. Qin, L.R. Elizondo, P. Bauer, Technoeconomical model based optimal sizing of PV-battery systems for microgrids, IEEE Trans. Sustain. Energy 11 (3) (2019) 1657–1668.
21. X. Ge, F.W. Ahmed, A. Rezvani, N. Aljojo, S. Samad, L.K. Foong, Implementation of a novel hybrid BAT-Fuzzy controller based MPPT for grid-connected PVbattery system, Control Eng. Pract. 98 (2020), 104380.
22. A. Mosavi, S.N. Qasem, M. Shokri, S.S. Band, A. Mohammadzadeh, Fractionalorder fuzzy control approach for photovoltaic/battery systems under unknown dynamics, variable irradiation and temperature, Electronics 9 (9) (2020) 1455. Q. Hassan et al.Results in Engineering 20 (2023) 10162122
23. A. Chaianong, A. Bangviwat, C. Menke, B. Breitschopf, W. Eichhammer, Customereconomics of residential PV–battery systems in Thailand, Renew. Energy 146 (2020) 297–308.
24. H.M. Ridha, C. Gomes, H. Hazim, M. Ahmadipour, Sizing and implementing offgrid stand-alone photovoltaic/battery systems based on multi-objectiveoptimization and techno-economic (MADE) analysis, Energy 207 (2020), 118163.
25. Q. Tian, G. Zhou, M. Leng, G. Xu, X. Fan, A nonisolated symmetric bipolar output four-port converter interfacing PV-battery system, IEEE Trans. Power Electron. 35 (11) (2020) 11731–11744.
26. B.A. Bhayo, H.H. Al-Kayiem, S.I. Gilani, Assessment of standalone solar PVBattery system for electricity generation and utilization of excess power for water pumping, Sol. Energy 194 (2019) 766–776.
27. M.J.M. Al Essa, Home energy management of thermostatically controlled loads and photovoltaic-battery systems, Energy 176 (2019) 742–752.
28. M.R. Al-Soeidat, H. Aljarajreh, H.A. Khawaldeh, D.D.C. Lu, J. Zhu, A reconfigurable three-port DC–DC converter for integrated PV-battery system, IEEE J. Emerg. Selected Topics in Power Electron. 8 (4) (2019) 3423–3433.

29. M. Aghamohamadi, A. Mahmoudi, M.H. Haque, Two-stage robust sizing and operation co-optimization for residential PV–battery systems considering the uncertainty of PV generation and load, IEEE Trans. Ind. Inf. 17 (2) (2020) 1005–1017.
30. X. Liu, P. Zhang, A. Pimm, D. Feng, M. Zheng, Optimal design and operation of PV-battery systems considering the interdependency of heat pumps, J. Energy Storage 23 (2019) 526–536.