Simulation of a Grid-Connected PV System for Electric Vehicle Charging with Energy Storage

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Abstract
This paper proposes a condition-based power management algorithm (PMA) for a multi-string photovoltaic (PV) based DC microgrid integrated with an electric vehicle (EV) battery and the utility grid. The main objective of the proposed system is to maintain DC bus voltage stability under varying solar irradiance and load conditions while ensuring efficient power distribution among the PV sources, battery storage, and the grid. The PMA continuously monitors key system parameters such as PV power generation, load demand, battery state of charge (SOC), and DC bus voltage to determine the appropriate operating mode of the microgrid. Based on these conditions, the algorithm dynamically manages the power flow between the PV arrays, EV battery, and grid to maintain power balance. During surplus PV generation, the battery is charged or excess power is exported to the grid, whereas during insufficient generation the battery or grid supports the load. The proposed strategy also incorporates limits on battery charging and discharging to prevent overuse and extend battery lifespan. Simulation results demonstrate that the proposed PMA effectively regulates DC bus voltage, ensures smooth power sharing among sources, and enhances the overall reliability and efficiency of the DC microgrid system.
Index Terms—DC microgrid, multi-string photovoltaic system, power management system, battery energy storage, converter control, DC bus voltage regulation.

I. Introduction

The increasing penetration of renewable energy sources and power-electronic-based loads has accelerated the transition from conventional AC distribution systems toward DC microgrids. Solar photovoltaic (PV) systems and battery energy storage inherently operate in DC form, while many modern loads such as electronic equipment, data centres, and electric vehicle chargers internally utilize DC power. Integrating these elements within a DC microgrid reduces unnecessary power conversion stages, improves overall efficiency, and enhances controllability.

Despite these advantages, DC microgrids face significant challenges arising from the intermittent nature of solar energy and the need for reliable voltage regulation under varying load conditions. Fluctuations in PV generation can directly affect the DC bus voltage, potentially leading to instability and degraded power quality. Energy storage systems, particularly battery energy storage systems (BESS), are therefore essential to buffer power variations and maintain stable operation.

As PV system capacities increase, multi-string PV architectures have become increasingly attractive due to their improved energy harvesting capability under partial shading and mismatch conditions. However, the integration of multiple PV strings into a DC microgrid introduces additional complexity in converter control, power coordination, and DC bus regulation. These challenges highlight the importance of an effective power management system (PMS) capable of coordinating multiple sources and storage units across different operating conditions.
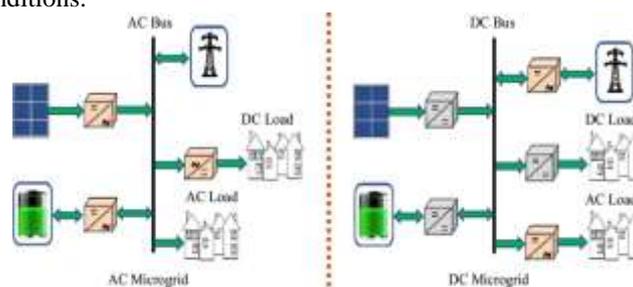

Figure 1: Comparison of AC distribution system and DC microgrid architecture

The figure 1 compares the structural differences between AC and DC microgrids. In the AC microgrid, renewable sources and battery storage generate DC power that must be converted to AC before being connected to the AC bus, while DC loads require an additional AC–DC conversion, resulting in multiple power conversion stages and increased losses. In contrast, the DC microgrid employs a DC bus that allows direct integration of photovoltaic sources, battery storage, and DC loads through DC–DC converters, significantly reducing conversion stages. AC loads and grid interaction are handled through a single interlinking inverter. This

architecture improves overall system efficiency, simplifies power management, and enhances compatibility with renewable energy sources and modern DC loads.

This paper presents a comprehensive DC microgrid architecture with a multi-string PV system and battery storage, along with a condition-based power management strategy and detailed converter control structures. Unlike result-oriented studies, this work focuses on system-level design, control coordination, and implementation readiness, providing a clear reference framework for researchers and practitioners.

II. DC Microgrid Architecture

The proposed DC microgrid architecture consists of a multi-string photovoltaic system, a battery energy storage system, DC loads, AC loads, and an interlinking converter connected through a common DC bus. The DC bus serves as the central power exchange node, enabling efficient integration of sources, storage, and loads.

The PV system is interfaced with the DC bus through DC–DC boost converters, which regulate the PV output voltage and enable maximum power extraction. The battery energy storage system is connected via a bidirectional DC–DC converter that allows controlled charging and discharging of the battery based on system requirements. DC loads are directly supplied from the DC bus, minimizing conversion losses, while AC loads and the utility grid are interfaced through an interlinking inverter.

The architecture supports both grid-connected and islanded modes of operation. In grid-connected mode, the utility grid can absorb surplus renewable energy or supply power during deficit conditions. In islanded mode, the microgrid operates independently, relying on PV generation and battery storage to supply loads. The transition between these modes is governed by the power management system to ensure stable DC bus voltage and uninterrupted power delivery.
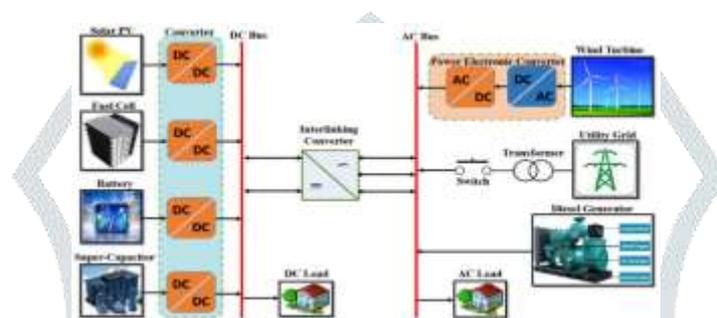

Figure 2: Typical DC microgrid with PV source, battery storage, and mixed loads

The figure 2 illustrates a hybrid AC–DC microgrid architecture integrating multiple distributed energy sources, energy storage systems, and loads through coordinated power electronic interfaces. DC sources such as solar photovoltaic modules, fuel cells, batteries, and supercapacitors are connected to a common DC bus via dedicated DC–DC converters, enabling efficient power regulation and direct supply to DC loads. An interlinking converter connects the DC bus to the AC bus, facilitating bidirectional power exchange and maintaining system stability. On the AC side, sources such as wind turbines and diesel generators are interfaced through appropriate AC–DC and DC–AC converters, while the utility grid is connected through a transformer and switching arrangement. This hybrid structure allows flexible integration of renewable and conventional sources, reduces unnecessary power conversion stages, and supports reliable operation under both grid-connected and islanded conditions.

III. Multi-String Photovoltaic System Configuration

In a multi-string PV configuration, several PV strings operate independently and are connected in parallel to a common DC bus through dedicated or shared DC–DC converters. Each PV string may experience different irradiance and temperature conditions, particularly under partial shading scenarios. Independent regulation of each string enables improved energy harvesting and reduces mismatch losses compared to single-string configurations.

The use of multiple PV strings enhances system reliability and fault tolerance, as reduced generation from one string does not necessarily affect the operation of others. However, the presence of multiple converters introduces challenges in current sharing, coordination, and DC bus voltage regulation. These challenges necessitate a coordinated control and power management approach to ensure stable and efficient operation of the microgrid.
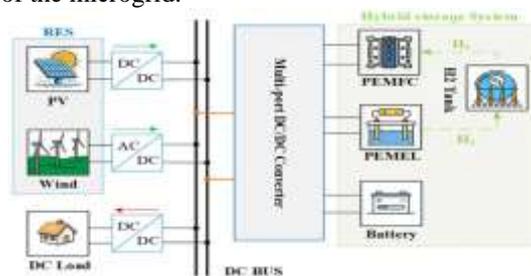

Figure 3: Multi-string PV system integrated into a DC microgrid Overall system architecture

The figure 3 illustrates a DC microgrid architecture that integrates renewable energy sources and a hybrid energy storage system through a common DC bus. Solar photovoltaic (PV) and wind energy sources are interfaced to the DC bus using appropriate DC–DC and AC–DC converters, allowing regulated power injection despite variations in irradiance and wind speed. A DC load is directly supplied from the DC bus, which reduces conversion stages and improves system efficiency. The DC bus acts as the central node for power exchange among sources, storage units, and loads.

Hybrid energy storage system and multi-port converter

A hybrid energy storage system is connected to the DC bus through a multi-port DC–DC converter, enabling coordinated control of different storage technologies. The system combines a battery, a proton exchange membrane fuel cell (PEMFC), and a proton exchange membrane electrolyzer (PEMEL) with a hydrogen storage tank. The multi-port converter allows bidirectional power flow,

supporting battery charging and discharging, hydrogen production through electrolysis during surplus power conditions, and fuel cell operation during power deficit conditions. This configuration enhances flexibility, improves energy utilization, and extends battery lifetime by distributing power among complementary storage devices.

Operating   principle   and   significance

During periods of excess renewable generation, surplus energy is directed to the battery and PEMEL to produce hydrogen, which is stored in the hydrogen tank for long-term energy storage. When renewable generation is insufficient, the battery and PEMFC supply power to maintain DC bus voltage and meet load demand. The coordinated operation enabled by the multi-port DC–DC converter ensures smooth power sharing, stable DC bus operation, and improved reliability of the microgrid. This architecture demonstrates an effective approach for integrating short-term and long-term energy storage within DC microgrids, supporting high renewable penetration and resilient operation

IV. Power Management Strategy

The power management system acts as the supervisory control layer of the DC microgrid. It continuously monitors key system variables, including PV power generation, load demand, battery state of charge, and grid availability. Based on these parameters, the PMS determines the operating mode of the microgrid and generates reference signals for the individual converter controllers.

The operating modes considered include sufficient power mode, deficit power mode, floating power mode, and PV-absent mode. In sufficient power mode, PV generation exceeds load demand, allowing loads to be supplied directly while surplus energy is directed toward battery charging or grid export. In deficit power mode, the battery and/or grid supply the required power to maintain load continuity. Floating power mode minimizes battery cycling when generation closely matches demand, while PV-absent mode ensures reliable operation during periods of negligible solar generation.

The condition-based nature of the PMS enables smooth transitions between operating modes while protecting the battery from overcharging and deep discharging. This approach improves system reliability and extends the operational lifetime of the energy storage system.
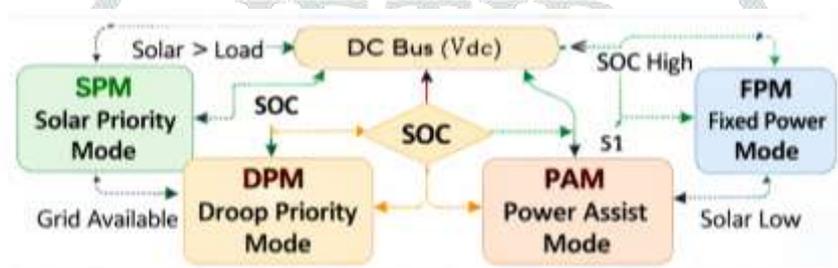

Figure:4 Over all Power Management System

The figure illustrates a **condition-based power management strategy** for a DC microgrid, where the operating mode is selected based on the balance between solar generation, load demand, battery state of charge (SOC), and grid availability. The DC bus voltage (Vdc) acts as the central control variable, while SOC information governs transitions between operating modes to ensure stable operation and protect the energy storage system.

When **solar generation exceeds load demand**, the system operates in **Solar Priority Mode (SPM)**, in which renewable energy is prioritized for supplying the loads and maintaining the DC bus voltage. Excess power may be used to charge the battery, provided the SOC remains within safe limits. This mode maximizes renewable energy utilization and minimizes dependence on auxiliary sources.

If solar power is insufficient, the control logic transitions to **Droop Priority Mode (DPM)** or **Power Assist Mode (PAM)** depending on grid availability and SOC. In DPM, the grid or auxiliary sources support the DC bus using droop-based power sharing, whereas in PAM the battery assists the system during low solar conditions. When the battery SOC is high and power balance is achieved, the system enters **Fixed Power Mode (FPM)** to limit unnecessary battery cycling. This coordinated mode selection ensures reliable power supply, smooth transitions, and extended battery lifetime.

V. Converter Control Design

A. PV Boost Converter Control

The PV boost converter is responsible for regulating the PV operating point and interfacing the PV strings with the DC bus. Under normal conditions, a maximum power point tracking algorithm determines the optimal PV operating voltage. A voltage control loop processes the error between the reference and actual PV voltage and generates the appropriate duty cycle for the converter switch.

During conditions such as battery fully charged or surplus power scenarios, the PV converter may operate in a voltage control mode to regulate the DC bus voltage and limit excessive power injection.
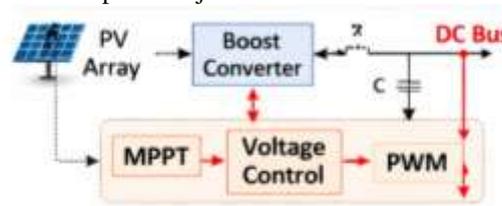

Figure 5: PV Boost Converter Control

B. Bidirectional Battery Converter Control

The bidirectional DC–DC converter enables controlled charging and discharging of the battery energy storage system. A dual-loop control structure is employed, consisting of an outer voltage loop and an inner current loop. The outer loop maintains DC bus voltage stability by generating a reference battery current, while the inner loop ensures accurate tracking of this current reference. The converter operates in buck mode during battery charging and in boost mode during discharging. The direction and magnitude of current flow are determined by the PMS based on system conditions and battery state of charge.
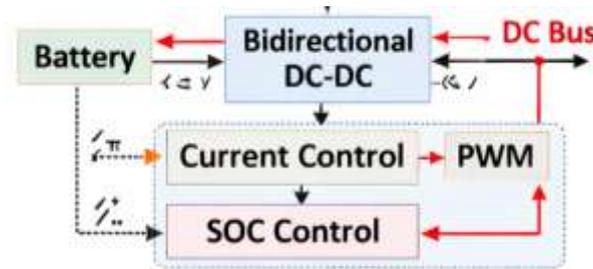

Figure-6: Bidirectional Battery Converter Control

C. Interlinking Converter Control

The interlinking converter facilitates power exchange between the DC microgrid and AC loads or the utility grid. A phase-locked loop synchronizes the inverter with the grid voltage, enabling the generation of a sinusoidal reference current. A current control strategy ensures low harmonic distortion, fast dynamic response, and unity power factor operation.
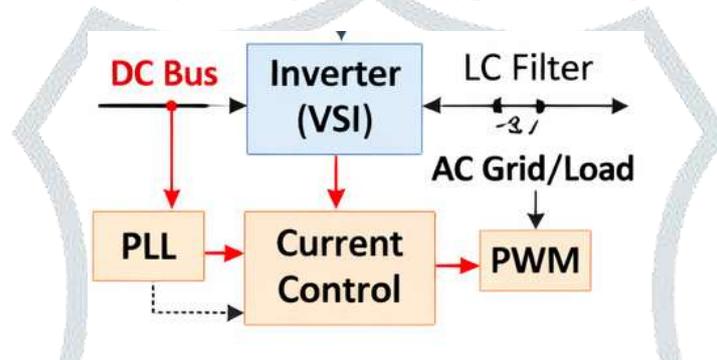

Figure:7 Interlinking Converter Control

VI. Results

The proposed photovoltaic-based EV charging system integrated with an energy storage unit was simulated in MATLAB/Simulink to analyze system performance under different operating conditions. The results demonstrate the effectiveness of the MPPT algorithm, the stability of the DC link, and the capability of the power management system to balance energy between the PV source, energy storage system (ESS), grid, and EV load.
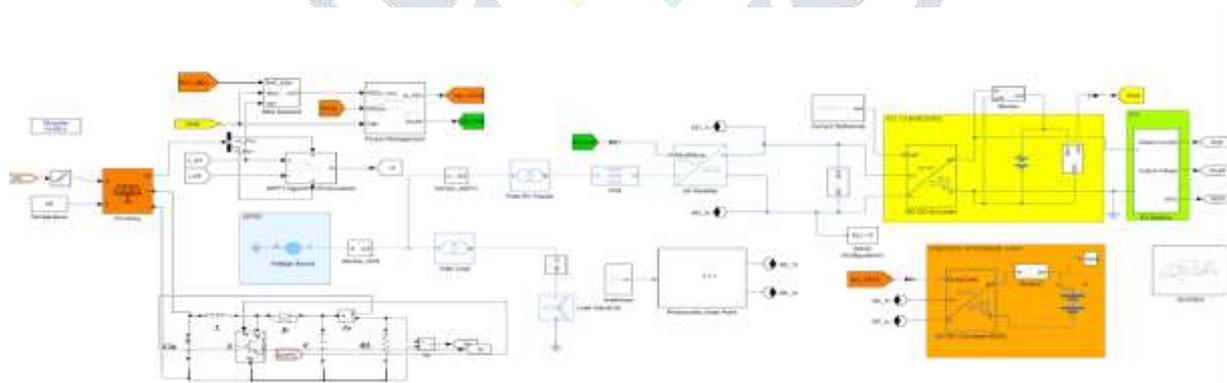

Fig: Simulink for Grid-Connected PV System for Electric Vehicle Charging with Energy Storage

The simulation results show that the **DC link voltage remains stable throughout the simulation period**, indicating proper operation of the DC–DC converters and voltage regulation mechanisms. After a short transient period at the beginning of the simulation, both the DC link voltage and the EV battery voltage settle to steady values. This confirms that the converter control strategy maintains a stable DC bus, which is essential for reliable EV charging.

Output Waveforms : The **grid current waveforms exhibit balanced three-phase sinusoidal characteristics** with approximately 120° phase displacement between phases. This indicates that the grid interface and rectifier operate effectively and maintain good power quality. The absence of distortion in the current waveform confirms that the system is properly synchronized with the grid and operates under stable conditions.

The EV demand power waveform shows an initial transient when the charging process begins, followed by a steady operating region. This behavior is typical for EV charging systems where the battery initially draws a higher current before stabilizing. The

simulation also demonstrates that the power required for EV charging is supplied through a coordinated combination of PV generation, the energy storage system, and the grid. When PV generation decreases or fluctuates, the ESS and grid compensate for the deficit to ensure continuous EV charging.
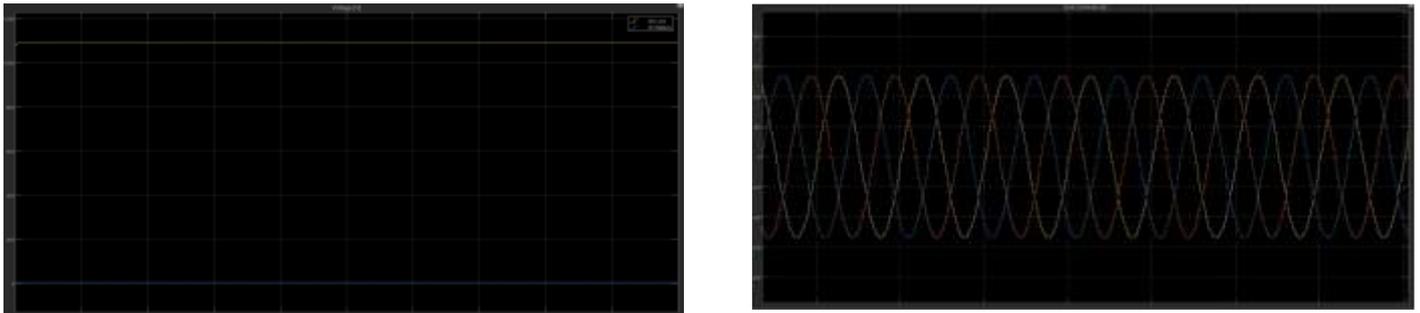

Fig: 8 Grid Current Waveforms

The power sharing results further highlight the effectiveness of the **power management strategy**. The photovoltaic source supplies a portion of the demand when solar energy is available, while the energy storage system provides additional support when PV output drops. In situations where both PV and ESS cannot fully satisfy the demand, the grid supplies the remaining power. This coordinated power sharing ensures uninterrupted EV charging and improves system reliability.

Fig: 9 Power Management

The results also show that the **battery charging current stabilizes quickly**, indicating smooth operation of the DC–DC converter used in the EV charging unit. The controlled charging current prevents excessive current spikes and protects the battery from stress, thereby improving battery life and system efficiency.

Fig:10 Output Waveforms for EV charging unit

Overall, the simulation results confirm that the proposed PV-based EV charging system with integrated energy storage and grid support operates efficiently. The MPPT controller successfully extracts maximum power from the PV array, the DC link voltage remains well regulated, and the power management system effectively distributes power among all components. These results

validate the capability of the proposed system to support sustainable EV charging while maintaining grid stability and energy efficiency.

VII. Conclusion

This paper presented a condition-based power management algorithm for a multi-string photovoltaic DC microgrid integrated with an electric vehicle battery and the utility grid. The proposed strategy effectively coordinates power flow among PV sources, the EV battery, and the grid to maintain stable DC bus voltage under varying solar irradiance and load conditions. By continuously monitoring system parameters such as PV generation, load demand, and battery state of charge, the algorithm determines appropriate operating modes to ensure balanced power distribution and reliable system operation. The implemented power management scheme also incorporates battery protection by limiting excessive charging and deep discharging, which helps improve battery lifespan and overall system efficiency. Simulation results confirm that the proposed approach successfully maintains DC bus voltage stability, enables smooth transitions between power sources, and ensures efficient utilization of available renewable energy.

Overall, the proposed power management algorithm enhances the reliability, stability, and operational efficiency of the DC microgrid. The strategy can serve as an effective solution for integrating renewable energy sources with energy storage and grid support in future smart microgrid applications.

VIII. References

[1] Y. Saeidinia, M. R. Arabshahi, S. Y. Mousazadeh Mousavi, and M. Biglari, "Autonomous control of DC microgrid based on a hybrid droop control scheme for total generation cost and transmission power loss reduction," *Electrical Engineering*, vol. 105, no. 1, pp. 267–283, Feb. 2023, doi: 10.1007/s00202-022-01662-w.

[2] A. A. Tavagnutti, S. Bertagna, M. D. Feste, M. Chiandone, D. Bosich, V. Bucci, and G. Sulligoi, "The coordinated power control of flexible DC microgrids in sustainably optimized yacht marinas," *Energies*, vol. 17, no. 2, p. 521, 2024, doi: 10.3390/en17020521.

[3] Y. Sun, Y. Hu, H. Zhang, H. Chen, and F.-Y. Wang, "A parallel emission regulatory framework for intelligent transportation systems and smart cities," *IEEE Transactions on Intelligent Vehicles*, vol. 8, no. 2, pp. 1017–1020, Feb. 2023, doi: 10.1109/TIV.2023.3246045.

[4] "Per capita greenhouse gas emissions by sector, India, 2021." Our World in Data. Accessed: Dec. 1, 2024. [Online]. Available: https://ourworldindata.org/grapher/per-capita-ghg-sector?country=IND

[5] P. Sharma and R. Chinnappa Naidu, "Optimization techniques for grid-connected PV with retired EV batteries in centralized charging station with challenges and future possibilities: A review," *Ain Shams Engineering Journal*, vol. 14, no. 7, Jul. 2023, Art. no. 101985, doi: 10.1016/j.asej.2022.101985.

[6] A. A. Rathod and B. Subramanian, "Scrutiny of hybrid renewable energy systems for control, power management, optimization and sizing: Challenges and future possibilities," *Sustainability*, vol. 14, no. 24, p. 16814, Dec. 2022, doi: 10.3390/su142416814.

[7] A. Bharatee, P. K. Ray, and A. Ghosh, "Hardware design for implementation of energy management in a solar-interfaced DC microgrid," *IEEE Transactions on Consumer Electronics*, vol. 69, no. 3, pp. 343–352, Aug. 2023, doi: 10.1109/TCE.2023.3243637.

[8] K. El Mezdi, A. El Magri, I. El Myasse, A. Watil, L. Bahatti, N. Elaadouli, and H. Ouabi, "Performance improvement through nonlinear control design and power management of a grid-connected wind-battery hybrid energy storage system," *Results in Engineering*, vol. 20, Dec. 2023, Art. no. 101491, doi: 10.1016/j.rineng.2023.101491.

[9] J. P. C. Silveira, P. J. dos Santos Neto, B. C. Moura, E. R. Filho, and T. A. D. S. Barros, "Power management with BMS to modified interlinking converter topology in hybrid AC/DC microgrid," *Energy Reports*, vol. 9, pp. 1743–1765, Dec. 2023, doi: 10.1016/j.egyr.2022.12.082.

[10] M. A. Mosa and A. A. Ali, "Energy management system of low voltage DC microgrid using mixed-integer nonlinear programming and a global optimization technique," *Electric Power Systems Research*, vol. 192, Mar. 2021, Art. no. 106971, doi: 10.1016/j.epsr.2020.106971.