Abstract

This study presents a comprehensive techno-economic optimization framework for a standalone Hybrid Renewable Energy System (HRES) comprising solar photovoltaic (PV), wind turbine (WT), battery energy storage system (BESS), and an electric vehicle (EV) fleet with bidirectional Vehicle-to-Grid (V2G) functionality. The study hypothesizes that integrating probabilistic EV behaviour and V2G capability into the sizing stage can reduce system cost while maintaining the required reliability for off-grid rural electrification. To capture the stochastic behaviour of EVs with V2G capability, EV arrival/departure times and state of charge (SOC) were modelled using probability distribution functions, and EV participation was incorporated directly into the sizing stage to quantify its impact on the levelized cost of energy (LCoE). The framework employs three metaheuristic optimization techniques, namely particle swarm optimization (PSO), grey wolf optimizer (GWO), and whale optimization algorithm (WOA), to minimize net present cost (NPC) and LCoE subject to a 5% loss of power supply probability (LPSP) reliability constraint. Seven years of hourly time-series data, including load demand, global horizontal irradiance (GHI), wind speed, ambient temperature, and probabilistic EV arrival/departure patterns, were aggregated into a representative one-year dataset to capture realistic operating conditions. A case study was conducted for a rural load of 1,556 households. PSO achieved the best solution, with an NPC of $14.51 million, an LCoE of 0.083 $/kWh, and an LPSP of 5.00%. The optimal configuration consists of 2,500 kWp PV, 397.5 kW WT, 22,138 kWh BESS, and an EV fleet of 300 vehicles providing 1,020 kWh of V2G-enabled storage, with wind energy contributing more than 55% of the annual supply. A comparative assessment with previous studies confirms that the proposed framework achieves competitive techno-economic performance while explicitly incorporating both EV with V2G functionality, which are often absent or only partially considered in existing HRES studies. Sensitivity analysis further shows that battery cost is the dominant factor affecting LCoE and NPC, whereas wind speed, solar irradiance, EV V2G participation, and EV fleet size have comparatively smaller impacts within the investigated range. The proposed framework demonstrates the synergistic benefits of V2G integration in lowering system costs and enhancing reliability, offering a replicable model for sustainable rural and off-grid electrification.