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DEVELOPMENT OF AN OFF-GRID SOLAR POWER PLANT INTEGRATED WITH A HYDROGEN STORAGE SYSTEM

An off-grid photovoltaic power plant with integrated hydrogen storage is developed to ensure reliable and sustainable electricity in remote areas. A novel energy management algorithm optimally balances power distribution between Li-ion batteries and hydrogen storage, adapting to real-time conditions and both short- and long-term energy needs.

Keywords: photovoltaic power plant, hydrogen, storage system, Li-ion battery, fuel cell, electrolyzer, energy management.

Introduction. Energy is a cornerstone of socio-economic development, playing a pivotal role in enhancing productivity and fostering economic growth. This is especially critical in the context of the global shift toward clean energy sources. The production of economically efficient and environmentally sustainable electricity is fundamental to achieving long-term societal progress. However, despite significant advancements, energy access remains a pressing global challenge.

According to the International Energy Agency and the World Bank, approximately 675-680 million people worldwide lacked access to electricity in 2023. Furthermore, around 2.3 billion people, primarily in sub-Saharan Africa and Asia, still rely on traditional fuels such as wood, kerosene, and diesel for cooking [1, 2]. The World Health Organization estimates that exposure to the combustion products of these fuels results in approximately 3.2 million premature deaths annually. Without additional interventions, projections suggest that by 2030, 1.9 billion people will remain without access to clean cooking solutions, and 660 million will still lack electricity [3].

The challenge of energy access is particularly acute in rural and remote areas, where infrastructure development is complex and costly, and connection to centralized energy systems is often economically unviable [4]. In such contexts, solar energy emerges as a promising solution for off-grid power supply, especially in regions where extending traditional energy networks is impractical. However, the intermittent nature of solar energy-due to variations in solar radiation, reduced photovoltaic (PV) output on cloudy days, and no generation at night-necessitates the integration of reliable energy storage systems to address these fluctuations.

Battery storage systems, particularly lithium-ion (Li-ion) batteries, are currently the most widely used solution for short-term energy storage. While effective for daily cycles, their self-discharge makes them less suitable for long-term or seasonal energy storage [5]. This limitation underscores the need for alternative storage solutions capable of addressing both short-term and long-term energy imbalances.

Hydrogen has emerged as a promising candidate to enhance the flexibility and resilience of energy systems. Its unique properties enable the efficient storage of surplus energy over extended periods, from daily to seasonal scales, and facilitate its integration across multiple sectors, including industry, transportation, and residential applications. By leveraging hydrogen as an energy carrier, it is possible to address the challenges posed by the variability of renewable energy sources and ensure a stable and reliable energy supply.

The objective of this work is to design and develop an off-grid PV power plant integrated with a hydrogen storage system (H_2 – SS) for remote residential applications. A key focus is the development of an efficient energy management algorithm and mechanism to optimize energy production, storage, and consumption. This system aims to ensure stable and reliable operation under conditions of fluctuating energy generation and load, thereby contributing to the broader goal of sustainable energy access for all. For Armenia, the development of off-grid renewable energy systems, such as solar power plants integrated with hydrogen storage, is particularly relevant due to the country's mountainous terrain and the presence of remote communities with limited access to centralized energy infrastructure.

The system structure and operating principle. Fig. 1 presents a schematic diagram of the developed off-grid PV power plant with an H_2 – SS. The primary source of electricity in the system is the PV array (1), which generates direct current (DC). This DC power is converted by the hybrid inverter (HI) (2) into alternating current (AC) to supply residential loads (RL) (4). When electricity generation exceeds instantaneous demand, the surplus energy is initially stored in a Li-ion battery pack (5). This approach enables the rapid compensation of transient power deficits, such as those occurring during evening hours or sudden load fluctuations, ensuring a dynamic balance between energy supply and demand. Once the Li-ion battery pack reaches its maximum state of charge (SoC_{bat}), any additional surplus power is used to operate the electrolyzer (7). While electrolyzers inherently operate on DC, commercial models often include built-in AC/DC rectifiers to accommodate conventional AC power sources. Considering this, the electrolyzer is supplied with AC power via the inner electrical panel (IEP) (6), which is connected to the HI. The water required for the electrolysis process is drawn from a dedicated water tank (8).

For this study, a proton exchange membrane (PEM) electrolyzer was selected due to its high energy efficiency of 80–90% [6]. However, PEM electrolyzers require high-purity water to prevent the membrane degradation. To ensure the necessary water quality, most PEM electrolyzers incorporate built-in filtration and purification mechanisms.

Within the PEM electrolyzer, water is split into hydrogen and oxygen through electrolysis. The generated oxygen is safely vented from the system, as it has no immediate application in off-grid hydrogen-based power systems, and its storage involves complex and costly infrastructure. The hydrogen output pressure from a residential PEM electrolyzer typically ranges between 1 and 30 *bar* [7]. For long-term storage, hydrogen undergoes additional compression to reduce storage volume and enhance its usability.

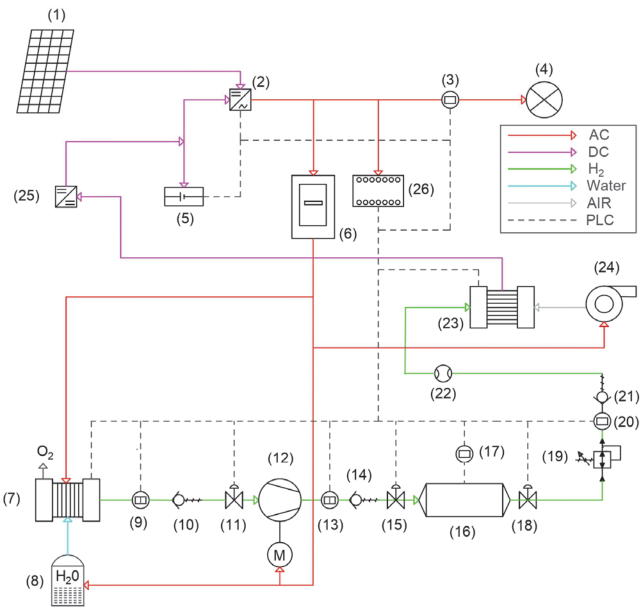

Fig. 1. A schematic diagram of an off-grid PV power plant with an H_2 - SS

The compression process is carried out by a hydrogen compressor (12), which is electrically powered via the IEP. Pressure transducers (PT) (9) and (13) continuously monitor the hydrogen pressure at the compressor's inlet and outlet, optimizing the compression process and preventing equipment overload. Check valves (CV) serve as essential safety components by preventing undesired backflow. Specifically, CV (10) blocks hydrogen recirculation into the electrolyzer, while CV (14) prevents backflow into the compressor.

The compressed hydrogen is then stored in a dedicated hydrogen storage unit (SU) (16), where PT (17) continuously monitors hydrogen pressure levels (PL_{H_2}) to ensure compliance with safety limits and prevent overpressure hazards. In case of prolonged insufficient renewable power supply, hydrogen is extracted from the SU and regulated by a pressure regulator (19) to achieve the optimal operating pressure required for the fuel cell (FC) (23). A mass flow meter (22) precisely controls the hydrogen flow, ensuring accurate measurement regardless of pressure and temperature variations. Additionally, PT (20) monitors the hydrogen inlet pressure to the FC, while CV (21) prevents uncontrolled backflow into the SU, eliminating unwanted gas recirculation.

To support the electrochemical reaction in the FC, oxygen is supplied via an air inlet (24), which is electrically powered via the IEP. This system captures ambient air and directs it to an integrated oxygen separation unit within the FC, extracting the necessary oxygen concentration for optimal fuel cell performance and efficiency.

The DC electricity generated by the FC is conditioned by a DC/DC converter (25) before being integrated into the power system. Finally, the HI converts the DC output into AC, making it compatible with the RL.

The developed power plant incorporates two energy storage systems: Li-ion batteries and a hydrogen storage system. Hydrogen, with its high energy density, is particularly suitable for long-term energy storage. However, the startup time of the FC is highly temperature-dependent. Hydrogen FCs, in particular, require several seconds or even minutes to reach full power output [8, 9]. This variability poses challenges in responding to sudden peak loads. In contrast, Li-ion batteries have rapid response times, typically within milliseconds to a few seconds, allowing them to efficiently manage sudden power surges and daily energy fluctuations.

Development of energy management system. To ensure effective energy management (EM) and optimize the performance of the PV power plant with H_2 – SS, a well-designed control strategy is essential. This strategy must provide a stable power supply that meets demand while efficiently utilizing energy storage resources. Additionally, it should prevent unnecessary oversizing of components and minimize redundant equipment installation, thereby enhancing system cost-effectiveness and sustainability.

The control process is managed by a programmable logic controller (PLC) (26), which collects, processes, and analyzes real-time data from all system components. The PLC enables automatic regulation of equipment operation, continuously monitors critical parameters, and executes predefined actions to maintain optimal performance of the PV power plant with H_2 – SS.

The HI monitors the power output of the PV array (E_{PV}), the SoC_{bat}, as well as its charging and discharging power and energy (E_{bat}). Additionally, it tracks the power generated by the FC (E_{FC}). The smart meter (SM) (3) continuously monitors and records the energy consumption of the RL (E_{load}), providing real-time data for analysis and optimization.

Both the HI and SM communicate with the PLC via the Modbus RTU (RS-485) protocol. All system variables are stored in registers with specific numerical addresses. The PLC retrieves these values by reading the corresponding register numbers and positions. Based on this framework, a novel EM algorithm was developed, as shown in Fig. 2.

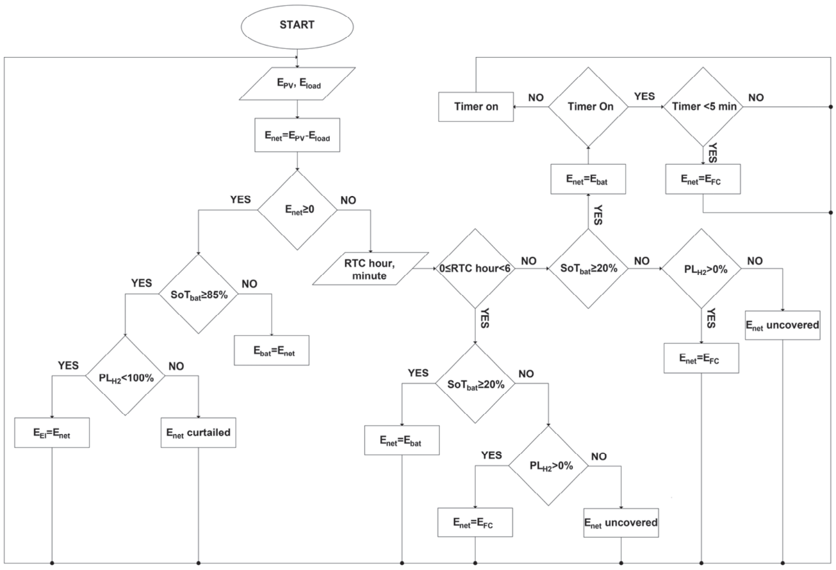

Fig. 2. EM algorithm for off-grid PV power plant with a H_2 - SS

First, the PLC monitors the current energy consumption E_{load} and the PV power generation $E_{\rho V}$. It then calculates whether there is an energy deficit or surplus. The PLC continuously tracks the SoC_{bat} and activates the electrolyzer (E_{El}) when SoC_{bat} reaches or exceeds 85% and surplus power is available ($E_{net} > 0$ *W*). This condition indicates that the Li-ion battery pack is in the charging phase, yet there is still excess energy that can be stored. The electrolyzer ceases operation under any of the following conditions: a) SoC_{bat} drops below 85%, b) the battery discharge power surpasses the power generated by the PV panels while the residential energy demand exceeds the available supply ($E_{net} < 0$), or c) the inlet pressure PL_{H2} of the ST reaches 100%, which indicates that ST is fully stored. The PLC interacts with the electrolyzer via the MODBUS TCP protocol.

When $E_{net} < 0$, the PLC utilizes the real-time clock (RTC) to record the time and determine whether the load is operating in a night standby mode. The FC operates E_{FC} in coordination with the Li-ion battery for efficiency and reliability.

At night, if the SoC_{bat} drops by 20% due to standby loads, the FC activates to cover the load preventing deep discharge. During the day, if the battery discharges continuously for more than 5 *min*, the FC starts operating. This delay allows the FC to warm up and distinguishes sustained loads from short-term peaks. For sudden peaks, the Li-ion battery responds immediately. If the demand lasts less than 5 *min*, the battery covers it. If it persists, the FC takes over to prevent excessive battery drain. The PLC communicates with the FC via the MODBUS TCP protocol.

During the entire operation of the hydrogen supply chain, the PLC opens and closes electro valves (11), (15) and (18) based on the PL_{H2} level of the ST.

Through these automated processes, the PLC ensures seamless integration between renewable energy generation, storage, and consumption, optimizing the overall performance of the energy management system.

Conclusion. The developed off-grid PV power plant with an H_2 – SS offers a robust and sustainable solution for remote energy applications. By integrating Li-ion batteries for short-term fluctuations and hydrogen storage for long-term stability, the system efficiently manages energy resources. A dedicated PLC-based energy management algorithm optimally coordinates the PV array, battery pack, electrolyzer, hydrogen storage unit and fuel cell, ensuring safe operation and maximizing surplus renewable energy utilization. This approach effectively mitigates solar power intermittency challenges, enhancing system reliability.

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ՋՐԱԾՆԱՅԻՆ ԿՈՒՏԱԿԻՉ ՀԱՄԱԿԱՐԳԻՆ ՀԱՄԱԿՑՎԱԾ ԻՆՔՆԱՎԱՐ ԱՐԵՎԱՅԻՆ ԿԱՅԱՆԻ ՄՇԱԿՈՒՄԸ

Մշակվել է ջրածնային կուտակիչ համակարգին համակցված ինքնավար ֆոտովոլ-տային կայան, որը նախատեսված է միասնական էլեկտրացանցից հեռու վայրերում հուսալի և կայուն էլեկտրաէներգիա ապահովելու համար: Համակարգը կառավարվում է էներգիայի կարգավորման նոր ալգորիթմով, համաձայն որի, կախված ընթացիկ պայմաններից, ինչ-պես նաև երկարաժամկետ և կարճաժամկետ պահանջներից, իրականացվում է էլեկտրա-էներգիայի օպտիմալ բաշխում լիթիում-իոնային մարտկոցների և ջրածնային կուտակիչի միջև:

Առանցքային բառեր. ֆոտովոլտային կայան, ջրածին, կուտակիչ համակարգ, լիթիում-իոնային մարտկոց, վառելիքային տարր, էլեկտրոլիզ, էներգիայի կառավարում:

Р.О. АВОЯН

РАЗРАБОТКА АВТОНОМНОЙ СОЛНЕЧНОЙ ЭЛЕКТРОСТАНЦИИ, ИНТЕГРИРОВАННОЙ С ВОДОРОДНОЙ СИСТЕМОЙ НАКОПЛЕНИЯ

Разработана автономная фотоэлектрическая электростанция с интегрированной системой хранения водорода для обеспечения надежного и устойчивого электроснабже-ния в удаленных районах. Инновационный алгоритм управления энергией оптимально балансирует распределение электроэнергии и между литий-ионными аккумуляторами, и системой хранения водорода, адаптируясь к условиям в реальном времени, а также к краткосрочным и долгосрочным энергетическим потребностям.

Ключевые слова: фотовольтаическая станция, водород, система накопления, литий-ионная батарея, топливный элемент, электролиз, управление энергией.