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Techno-Economic Modeling of the Life Cycle of Decentralized Hybrid Energy Systems as a Foundation for Enhancing Energy Independence and Sustainable Regional Development

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Abstract

The study presents a comprehensive techno-economic investigation of the life cycle of distributed hybrid energy systems in the context of enhancing regional energy independence and sustainable development. In the global transition to low-carbon energy and amid growing price volatility of fossil resources, the development of autonomous and environmentally safe solutions gains particular significance. The objective of the study is to evaluate the economic feasibility and autonomy potential of the Smart Adaptive Energy Optimization (SAEO) platform, which integrates renewable energy sources, hydrogen technologies and intelligent control methods. The research methodology is based on calculations of levelized cost of energy (LCOE), net present value (NPV) and the energy independence index over the life cycle. The results demonstrate that, due to component synergy and utilization of secondary energy resources, the SAEO system achieves a reduction in LCOE compared to traditional renewable-plus-battery and diesel-generator hybrid configurations. The scientific novelty lies in the life cycle assessment of a quadrigeneration system that combines renewable sources, a combined gas-steam cycle, hydrogen production and utilization under adaptive artificial intelligence control. The conclusions confirm that the implementation of such solutions is economically feasible and strategically important for isolated territories, industrial facilities and smart city concepts. The findings are relevant to energy sector investors, governmental bodies shaping energy policy and engineering specialists involved in designing sustainable energy systems.

Keywords: *Decentralized Energy, Hybrid Energy Systems, Techno-Economic Modeling, Life Cycle, Renewable Energy Sources, Hydrogen Energy, Energy Independence, LCOE, Sustainable Development, SAEO.*

INTRODUCTION

The modern energy system is undergoing profound restructuring driven by the need to reduce carbon emissions, enhance the reliability of energy supply and ensure balanced socio-economic development. According to the International Renewable Energy Agency (IRENA), by 2024 the installed capacity of renewable energy sources reached unprecedented levels; however, their inherent intermittency still poses significant technical challenges for stable grid operation [1]. Continued reliance on fossil fuels not only exacerbates anthropogenic climate change but also increases the vulnerability of national economies to fluctuations in global energy prices. In this context distributed hybrid energy systems (HES) acquire strategic importance for states seeking to localize electricity generation and enhance the resilience of critical infrastructure. Through the integration of heterogeneous generators and energy storage devices hybrid systems provide reliable power supply to remote regions, industrial clusters and urban agglomerations [11].

Although individual components of HES—such as photovoltaic panels, wind turbines, and energy storage devices—have been extensively studied, the scientific literature lacks a comprehensive techno-economic life cycle analysis of systems featuring complex multi-component architectures that include multiple generation loops and diverse storage types. Existing models predominantly focus on simplified configurations (e.g., a solar–wind installation paired with a battery), while the integration of hydrogen technologies, combined gas-steam units, and intelligent control systems capable of real-time optimization of energy flows remains largely unexplored. A hybrid, holistic approach is therefore required for an objective assessment of the long-term profitability and sustainability of such projects.

The objective of the research is to analyze the techno-

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economic life cycle model of an advanced decentralized hybrid energy system and to evaluate its contribution to enhancing energy independence and sustainable development of regions.

The scientific novelty of the research lies in the integrated life cycle assessment of a quad-generation hybrid system—comprising RES, gas and steam turbines, and a hydrogen cycle—managed by adaptive artificial intelligence to identify its comprehensive techno-economic advantages.

The hypothesis of the research posits that the SAEO system, through technological integration and intelligent management of energy and material flows, will demonstrate a low levelized cost of energy (LCOE) and an increased degree of energy autonomy compared to existing analogues of hybrid energy systems throughout the project life cycle.

MATERIALS AND METHODS

Soliman A. M., Alharbi A. G., Sharaf Eldean M. A. [2] employs mathematical programming to optimally size solar and wind installations, targeting the minimization of the levelized cost of energy (LCOE) for powering a large-scale desalination plant. Kumar R., Channi H. K. [3] extend this framework by incorporating biomass into the model, performing a multi-criteria analysis (economic, environmental and reliability), and proposing a genetic-algorithm-based optimization for off-grid systems in rural areas. Okonkwo P. C. et al. [4] investigate hybrid systems for hydrogen production at refueling stations, combining wind, solar and battery storage, and evaluate the optimal component mix in terms of levelized cost of hydrogen (LCOH). Agajie T. F. et al. [5] present a comprehensive review of existing techno-economic analysis methods and optimal component sizing for hybrid systems. They classify approaches into analytical formulations, empirical correlations and artificial-intelligence techniques, examine energy storage integration in detail, and propose a unified methodology for comparing results across different studies.

IRENA [1] and NREL [8] provide statistics on installed capacities and projected cost-reduction trajectories for renewable technologies. IEA [9] and BNEF [11] offer an overview of current trends in the hydrogen economy and forecasts for “green” hydrogen availability. Lazard [10] supplies comparative data on levelized cost of energy (LCOE) and time-dependent CAPEX/OPEX values for various generation sources across regions.

Ibrahim O. et al. [6] and R. Singh A. et al. [7] focus on energy-flow management and forecasting. Ibrahim O. et al. [6] apply fuzzy-logic control to balance supply and demand in real time, while R. Singh A. et al. [7] use machine-learning techniques to predict generation and optimize power dispatch in networks with high shares of renewables.

Although all studies aim to minimize economic metrics, significant inconsistencies persist. Some authors consider LCOE as the sole performance indicator [2, 3], whereas others highlight the importance of LCOH and environmental KPIs [4, 5]. Optimization methods range from deterministic (linear and nonlinear programming) to stochastic (genetic algorithms, neural-network forecasting), complicating cross-study comparisons. Full life-cycle integration—particularly decommissioning and recycling phases—regulatory-risk impacts, electricity-price dynamics and socio-economic aspects of hybrid-system deployment in small or remote communities remain underexamined.

The techno-economic modelling of the SAEO hybrid energy system is based on a comprehensive lifecycle cash-flow analysis. The primary integrative performance metric is the levelized cost of energy (LCOE), defined as the ratio of discounted total costs to the present value of generated electricity:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (1)$$

Where:

It - denotes capital expenditures in year t;

Mt - represents operation and maintenance costs in year t;

Ft - is fuel expenditure in year t;

Et - is the volume of electricity produced in year ttt; rrr is the discount rate; and nnn is the system’s lifetime.

An Energy Independence Index (EII) quantifies system autonomy as the ratio of energy generated by the SAEO’s own generators to total energy consumption over a selected period (month or year).

The SAEO complex, shown in Figure 1, includes photovoltaic modules, wind turbines, an electrolyzer for hydrogen production, hydrogen storage, hydrogen and gas turbines, and a steam turbine that utilizes waste heat from the gas, hydrogen and solar-concentrator units. Lithium-ion batteries are incorporated to smooth peak loads. All components are integrated into a unified SCADA platform with an embedded artificial-intelligence module.

Literature analysis revealed two major gaps. First, most models omit the synergistic benefit of waste-heat recovery; only the SAEO design incorporates a steam turbine, significantly enhancing overall thermal and electrical efficiency. Second, operational-expenditure assessments frequently neglect gradual equipment degradation—such as declining PV output or battery-capacity loss—which can distort long-term economic feasibility.

RESULTS AND DISCUSSION

This section presents the outcomes of a comprehensive techno-economic analysis of the SAEO system in comparison with alternative power supply options. Calculations were conducted for a representative regional facility—whether a small rural settlement or a local industrial complex—with an annual electricity consumption of 10 GWh. Input data comprised current values of capital expenditures (CAPEX) and operational expenditures (OPEX) for major components and equipment, sourced from specialized industry reports and scientific publications [8, 9, 10].

Table 1. Techno-economic parameters of SAEO system components (compiled by the author based on [8, 9, 10]).

Component	Unit of Measurement	CAPEX	OPEX (% of CAPEX per year)	Service Life (years)	Efficiency (%)
Photovoltaic (PV) panels	$/kW	850	1.5 %	25	22
Wind turbines	$/kW	1 300	2.5 %	20	45
Lithium-ion battery storage	$/kWh	250	1.0 %	15	92
Proton exchange membrane (PEM) electrolyzer	$/kW	700	3.0 %	15	75
Compressed hydrogen storage	$/kg	600	1.0 %	30	99
Hydrogen-fired turbine	$/kW	1 100	2.0 %	20	40
Natural gas turbine	$/kW	600	3.5 %	20	38
Steam turbine (Rankine cycle)	$/kW	900	2.0 %	25	35

Figure 1 shows a block diagram of the interconnection among the system's main components. Renewable energy sources (solar and wind installations) serve as the primary generator. When excess electricity is produced, it is directed to charge battery storage (to cover short-term consumption peaks), to heat the steam turbine's working fluid, and to feed the electrolysis module for hydrogen production. The generated hydrogen functions as long-term energy storage and serves as fuel for the hydrogen turbine. The gas turbine operates as a backup and peaking power source. The scheme's central feature is the use of heat recovered from the gas and hydrogen turbines to drive the steam section, thereby creating a highly efficient combined cycle. Coordination and distribution of all electrical and thermal flows are handled by an artificial intelligence module.

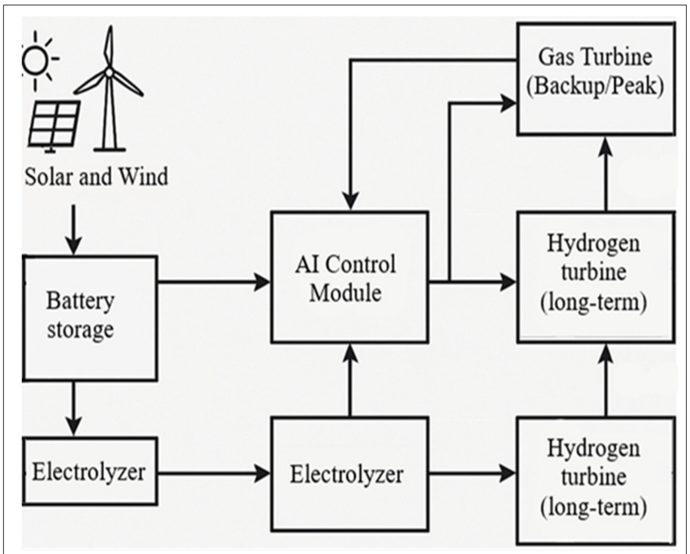

Fig. 1. Schematic block diagram of the SAEO hybrid energy system (compiled by the author based on [5-7]).

Comparative modeling of four power-supply pathways was conducted to assess the economic feasibility of the SAEO system:

1. Full supply from the centralized grid at a tariff of $0.15 per kWh, with an expected annual increase of 3 % [1].
2. Standalone generation using diesel generators at a fuel cost of $1.20 per liter [2].
3. A conventional hydropower system supplemented by solar and wind installations with lithium-ion batteries [3].
4. The SAEO configuration currently under development [4].

Figure 2 presents the calculated levelized cost of electricity (LCOE) for each scenario over a 25-year life cycle.

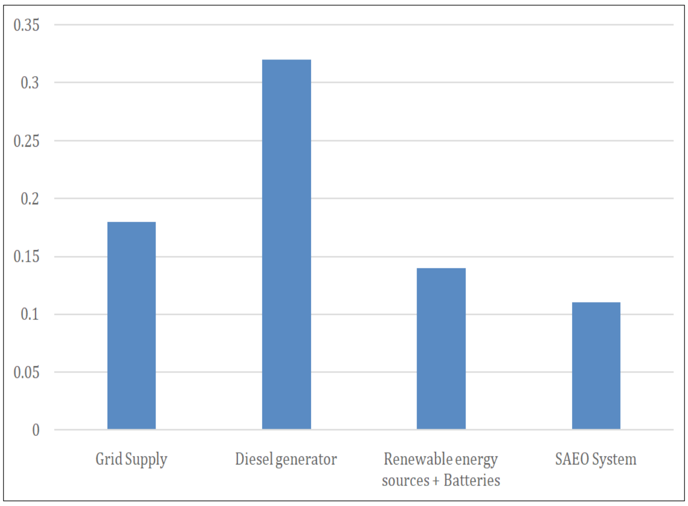

Fig. 2. Comparative analysis of LCOE for different energy supply scenarios ($/kWh) (compiled by the author based on [1-4]).

The chart clearly shows that the SAEO system achieves a minimum LCOE of $0.11 /kWh. This outcome results from a combination of factors. First, the deep utilization of thermal energy generated by the gas and hydrogen turbines enables the steam turbine to produce additional "free" electricity, which in combined-cycle operation raises the overall system efficiency to 60–70 %. Second, using hydrogen as a long-term storage medium eliminates the need for costly, high-capacity battery systems required in Scenario 3 to maintain autonomy during windless and sunless periods. Third, the intelligent control system conserves natural gas by operating the gas turbine only at peak demand or after all "green" reserves have been depleted [2, 9].

The adaptive control algorithm is the central element ensuring the high efficiency of the SAEO system. In operational mode, the system continuously aggregates data on renewable energy output, current battery state of charge, hydrogen reservoir levels, actual consumption, and weather forecasts. Based on this input set, the predictive module—for example, implemented with LSTM-based recurrent neural networks—constructs a quantitative estimate of the energy balance for the forthcoming hours. The optimization unit then applies dynamic programming techniques or swarm-intelligence algorithms to determine the flow distribution strategy: how much energy to allocate to the load, how much to battery recharging, what portion to dedicate to hydrogen production, and when to activate reserve turbines. This approach shifts the system from a reactive to a proactive operating mode, enabling advance preparation for peak loads and generation shortfalls.

Analysis of the presented data indicates that the integrated SAEO system maintains a continuous Energy Independence Index (EII), scarcely dropping below 100 % throughout all seasons. In contrast, the conventional configuration of renewable energy sources with battery storage exhibits significant performance shortfalls during the autumn–winter period, driven by reduced solar irradiance and frequent calm intervals. During these phases, battery capacity proves insufficient to meet consumer demand, whereas the SAEO system effectively compensates for the energy deficit by utilizing hydrogen stored during warmer months, thereby ensuring long-term stability of power supply and near-complete system autonomy [1, 11].

The foremost obstacle to the implementation of solid-oxide electrolyzer (SAEO) systems lies in their substantial upfront capital requirements. However, a comprehensive life-cycle cost assessment reveals that these initial expenditures are offset over time by markedly lower operating costs and by decoupling from escalating electricity tariffs and fossil fuel price volatility. These findings are corroborated by projections from BloombergNEF, which anticipate continued declines in the costs of electrolyzer units and associated hydrogen production infrastructure, thereby bolstering the economic viability of SAEO installations. Moreover, monetizing any surplus hydrogen or electricity through local market channels—an aspect beyond the scope of the baseline financial model—offers a compelling avenue for enhancing overall project returns.

Thus, the conducted techno-economic modeling confirms the initial hypothesis that complex hybrid energy systems like SAEO, despite their technological sophistication and high capital intensity, are justified both in terms of reliability and economic efficiency. Implementing these solutions contributes not only to reducing the carbon footprint but also to establishing a fault-tolerant energy infrastructure that is effectively insulated from external climatic and market shocks.

CONCLUSION

The study focused on a comprehensive techno-economic assessment of the life cycle of decentralized hybrid energy systems based on the innovative SAEO concept. A detailed model was developed, accounting for the synergistic interaction among renewable energy sources, short- and long-term storage systems (battery energy storage and hydrogen storage), and a high-efficiency combined cycle gas turbine under the control of adaptive artificial intelligence.

The results support the initial hypothesis. First, the proposed integrated approach reduces the levelized cost of electricity (LCOE) compared to both conventional schemes (grid connection and diesel generation) and simplified hybrid systems. Savings of 15–25 % relative to "renewables + batteries" configurations are achieved through waste-heat recovery and precise optimization of the operating modes of all system components.

Second, numerical modelling confirmed that incorporating the hydrogen cycle as a seasonal storage element is critical for maintaining near-complete energy autonomy. The SAEO system's energy independence remains consistently close to 100 % throughout the year, whereas simpler hybrid schemes exhibit significant fluctuations depending on the seasonality of renewable generation.

The study clearly demonstrates that the future of decentralized energy lies not in the sequential coupling of disparate technologies, but in their deep interconnection and synergistic integration.

Thus, the research objectives have been achieved: the developed techno-economic model confirms the potential and economic viability of deploying SAEO-class systems to strengthen energy independence and ensure sustainable regional development, particularly in isolated territories, strategic facilities, and smart-city projects.

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