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Energy, exergy, economic and environmental analysis of an energy production system based on a combination of compressed air energy storage, hot and cold storage, electrolyzer and organic Rankine cycle

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Extended Abstract

1. Introduction

The growing global dependence on energy necessitates advanced solutions that enhance efficiency, reduce costs, and minimize environmental impact, particularly CO_2 emissions from fossil fuels. Multi-generation systems that co-produce various outputs like electricity, hydrogen, and heating/cooling present a promising pathway toward sustainable energy. Recent research has focused on integrating renewable sources and advanced cycles, such as solar-powered polygeneration, biomass-integrated systems, and configurations combining CAES with desalination or refrigeration cycles. Building upon this foundation, this paper introduces a novel hybrid system that synergistically combines a modified Brayton cycle, an ORC, a PEM electrolyzer, and a CAES unit with integrated hot/cold storage. The primary objectives are to thermodynamically model this system, perform a parametric analysis to identify key performance drivers, and evaluate its economic viability and environmental benefits across different climatic conditions in Iran.

2. Methodology

2.1. System Description

The proposed hybrid system, illustrated schematically in Figure 1, operates in two main modes: charging and discharging.

- **Charging Mode:** During off-peak hours, low-cost or surplus electricity drives a series of compressors. Intercoolers and an aftercooler improve compressor efficiency by reducing air temperature; the absorbed compression heat is transferred via water to the ORC. The compressed air is stored in the CAES tank, while the ORC generates electricity to power a PEM electrolyzer, which produces and stores hydrogen.
- **Discharging Mode:** During peak demand, stored compressed air is preheated by gas turbine exhaust in a recuperator before being injected into the combustion chamber. The stored hydrogen is mixed with natural gas (methane) to fuel the modified Brayton cycle. The combustion gases expand through a gas turbine to produce electricity. The exhaust heat then drives the ORC, which further contributes to power generation.

2.2. Thermodynamic, Economic, and Environmental Analysis

A steady-state model was developed based on mass, energy, and exergy balance equations for each component. Key assumptions included negligible pressure drops in pipelines and negligible kinetic/potential energy changes. The net power output, overall energy efficiency, and exergy efficiency (Round-Trip Exergy Efficiency, ERTE) were calculated. An economic analysis was conducted using cost balance equations for all major components to determine the total system cost rate. Finally, an environmental assessment quantified CO_2 emissions avoided compared to conventional power generation, translating this into a monetary environmental cost saving and an equivalent area of green space preservation.

2.3. Input Parameters and Validation

Simulation inputs included ambient conditions (T_0 =25°C, P_0 =101.3 kPa), component efficiencies (e.g., gas turbine η=0.88), key pressures (CAES inlet: 5000 kPa), and temperatures (gas turbine inlet: 1000°C). The PEM electrolyzer sub-model was validated against published literature, showing good agreement and confirming the reliability of the developed model.

3. Results and Discussion

3.1. Parametric Study

A sensitivity analysis was performed on three key design parameters:

1. **ORC Turbine Isentropic Efficiency (0.75–0.95):** Increasing efficiency led to a slight increase in net power and exergy efficiency, with a corresponding rise in system cost and emissions due to increased output.
2. **Gas Turbine Inlet Temperature (1100–1500 K):** This was identified as a highly influential parameter. Increasing the temperature significantly boosted net power output and exergy efficiency. However, it also increased the system cost rate and CO_2 emissions due to higher fuel consumption.
3. **CAES Storage Pressure (2500–7000 kPa):** Increasing storage pressure negatively impacted performance, reducing net power and exergy efficiency. This was due to the increased parasitic load on the compressors. Higher pressure also raised both the system cost and CO_2 emissions.

3.2. Case Study: Performance in Different Climates

The system's annual performance was simulated for Dezful (hot), Tehran (temperate), and Tabriz (cold).

- **Exergy Efficiency (ERTE):** The system performed best in colder climates. Tabriz exhibited the highest annual average ERTE. Efficiency generally increased in warmer months but was higher overall in colder cities.
- **Net Power Output:** The trend mirrored exergy efficiency. The highest net power generation was achieved in Tabriz. Power output decreased in hotter months across all cities due to increased compressor power consumption.
- **Environmental Impact (CO_2 Emissions):** Emissions were directly tied to power output. Therefore, Tabriz, with the highest output, showed the highest absolute emissions. However, the *emissions intensity* relative to the conventional grid power displaced was favorable.
- **Hydrogen Production:** Hydrogen production via the PEM electrolyzer followed the power trend of the ORC, with higher yields in warmer months when ORC performance improved.
- **System Cost Rate:** The cost rate was directly proportional to the power output and system activity, thus being highest in Tabriz where the system was most productive.

3.3. Environmental and Practical Output Analysis

- **Environmental Benefit:** Operating in Tabriz, the system could prevent approximately 622.16 tons of CO_2 emissions annually, equivalent to an environmental cost saving of about $14,932 and the preservation/expansion of 3 hectares of green space.
- **Practical Output:** Based on an average annual per capita electricity consumption of 3072 kWh, the system installed in Tabriz could supply the yearly electricity needs of approximately **992 people**. The corresponding figures for Tehran and Dezful were 955 and 889 people, respectively.

4. Conclusion

This research designed and analyzed a novel hybrid system for co-producing hydrogen and electricity by integrating CAES, PEM electrolysis, a modified Brayton cycle, and an ORC. The key findings are:

1. **Key Parameters:** Gas turbine inlet temperature and CAES storage pressure are the most critical design parameters affecting system performance, cost, and emissions.
2. **Climatic Suitability:** The system demonstrates significantly better thermodynamic and economic performance in **colder climates** (e.g., Tabriz) compared to hot (Dezful) or temperate (Tehran) regions. Operation in hot climates is not recommended.
3. **Output Potential:** In an optimal location like Tabriz, the system can generate sufficient power to meet the annual electricity demands of nearly a thousand individuals.
4. **Environmental Benefit:** The system offers substantial CO_2 emission avoidance, contributing to environmental sustainability.

The study provides a robust framework for the design and site selection of such advanced multi-generation energy systems, emphasizing the importance of climatic conditions in achieving technical, economic, and environmental objectives.

Key words: Multi energy production system, compressed air energy storage, proton exchange membrane electrolyzer

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