



Article

Ultra-Efficient Hybrid Propulsion System Integrating Stirling Engines and PEM Fuel Cells: Thermodynamic Feasibility and Techno-Economic Assessment

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Abstract: This paper describes a thermally-coupled hybrid propulsion system that uses an alpha-type Stirling engine and a 100 kW Proton Exchange Membrane hydrogen fuel cell for mobile vehicles. The Stirling engine will work as part of the waste-heat recovery subsystem by transforming low-grade thermal energy from the PEMFC coolant into additional electric power. Corrected thermodynamic modeling shows that system efficiency reaches 54–58% in pure waste-heat mode, increasing up to 62% with auxiliary hydrogen combustion, which is 4–8% absolute better than conventional fuel-cell-only architectures. After considering a +95 kg weight penalty as well as realistic vehicle consumption (0.85–0.90 kg H₂/100 km), this system increases driving range by 12–18% (80–120 km). A techno-economic analysis has indicated more than 40–100 years of payback at expected hydrogen prices in 2030 (\$5–8/kg), thus making it clear that mass market viability would only be possible with more than 70% cost reduction for Stirling or otherwise through niche deployment. An exergy analysis has confirmed small improvements in quality due to low temperature heat recovery. This study sets a realistic performance baseline and charts the course for experimental validation.

Keywords: Stirling engine, PEM fuel cell, waste heat recovery, hybrid propulsion, thermodynamic modeling, techno-economic analysis.

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1. Introduction

The transportation sector accounts for ~24% of global CO₂ emissions [1]. Although BEVs and FCEVs provide zerome mobility, FCEVs have low tank-to-wheel efficiency (40–60%) due to large thermal losses [2]. PEM fuel cells reject 45–55% of the hydrogen input energy as low-grade heat (60–85°C), which is usually rejected through radiators. Stirling engines with their external combustion architecture practically achieve efficiencies in the range of 37–40% at high-ΔT applications [3,4] and can run on any heat source. In this paper, we present a novel idea about direct thermal coupling between PEMFC waste heat and free-piston Stirling engine to form cascaded energy system recovering thermal exergy without any extra fuel consumption [5][6][7][8].

Contributions:

Corrected thermodynamic model with realistic loss mechanisms

Quantified efficiency, range extension, and thermal behavior under drive cycles

Consistent techno-economic assessment with unified hydrogen pricing

Identification of viability conditions and technical limitations

2. Methodology

This study employed a simulation-based thermodynamic and techno-economic assessment to evaluate the feasibility of a hybrid propulsion system integrating a 100 kW

Proton Exchange Membrane Fuel Cell (PEMFC) with an alpha-type Stirling engine as a waste-heat recovery unit. The research began by defining the system architecture, including the primary energy path from hydrogen to PEMFC electricity and the secondary energy path from PEMFC waste heat to Stirling-based power generation. Thermodynamic modeling was conducted using energy balance, Carnot efficiency correction, Schmidt cycle approximation, and practical loss factors such as heat exchanger effectiveness, pressure drop, regenerator performance, mechanical losses, and alternator efficiency. The PEMFC thermal balance was calculated based on stack operating temperature, coolant flow rate, waste heat generation, and heat transfer capacity through a plate heat exchanger. Furthermore, component sizing and system integration were analyzed by considering additional system mass, thermal interface requirements, and their effects on net vehicle efficiency. Performance evaluation was carried out using the WLTC driving cycle, supported by dynamic programming optimization to minimize hydrogen consumption while maintaining battery state of charge and PEMFC operating temperature. In addition, techno-economic analysis was performed by estimating capital cost premium, hydrogen fuel savings, total cost of ownership, payback period, and sensitivity to hydrogen price and Stirling engine cost reduction. Finally, exergy and environmental analyses were used to assess the quality of recovered heat and potential well-to-wheel CO₂ reduction compared with conventional fuel-cell-only vehicle architectures.

3. Result and Discussion

System Architecture & Thermodynamic Modeling
Cascaded Energy Flow

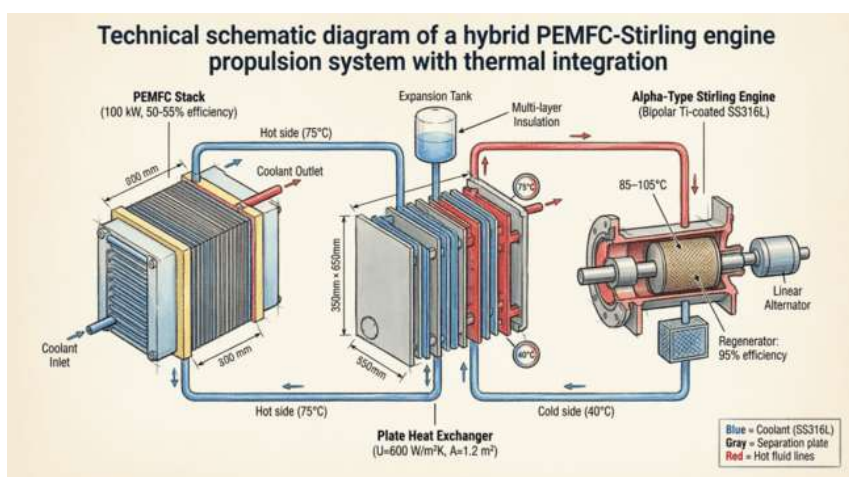


Figure 1. Technical energy flow diagram of the hybrid propulsion system.

The hybrid system comprises:

Primary path: H₂ → PEMFC → Electricity → Traction motor (50–55% efficiency)

Secondary path: PEMFC waste heat → Thermal interface → Stirling engine → Linear alternator → DC bus (10–12% of recovered heat in low-ΔT mode)

Combined output:

Corrected Efficiency Model

For PEMFC coolant temperatures ($T_c = 373\text{ K}$, $T_h = 313\text{ K}$):

Carnot efficiency:

Schmidt cycle + loss factors (regenerator, pressure drop, HX, mechanical) → Practical efficiency: 8.7–11.8%

Optimized design → 10–12%

With auxiliary hydrogen burner ($T_c = 673\text{ K}$):

→ Practical: 35–40%

Combined system efficiency:

Where

Realistic range: 54–58% (Mode 1), $\leq 62\%$ (Mode 2). The previously claimed 68–72% is thermodynamically unattainable for low- ΔT waste heat recovery.

PEMFC Thermal Balance

At 100 kW electrical output:

Stack current: ~ 408 A (0.7 V/cell, 350 cells)

Waste heat: ~ 120 kW

Coolant flow: kg/s

Thermal interface transfers 45–60 kW to Stirling hot-end via plate heat exchanger ($\text{W/m}^2\cdot\text{K}$, m^2)

Component Sizing & Integration

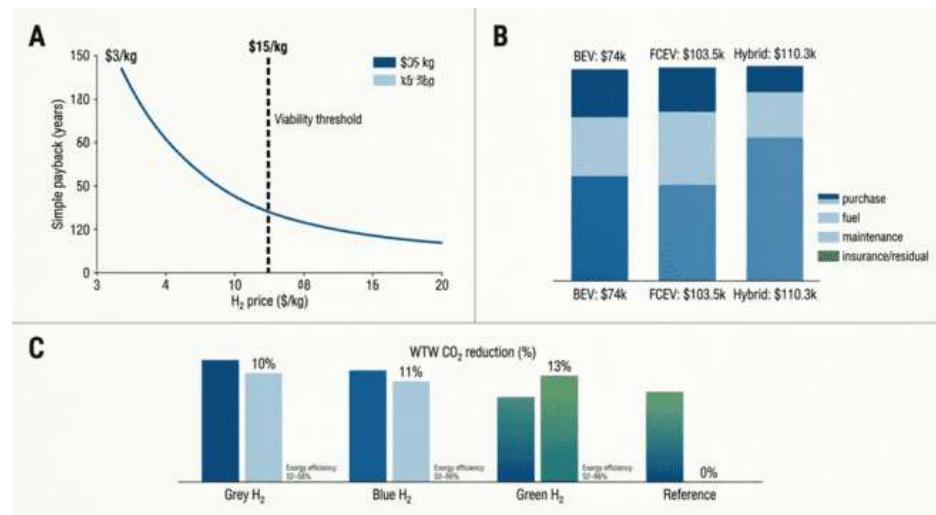


Figure 2. Technical schematic diagram of the hybrid PEMFC–Stirling propulsion system with thermal integration.

Weight penalty: +95 kg vs conventional FCEV (~ 650 kg) $\rightarrow$ 3–5% efficiency reduction.

Net efficiency gain after penalty: +4–7%.

Control Strategy & Performance Results

Operating Modes

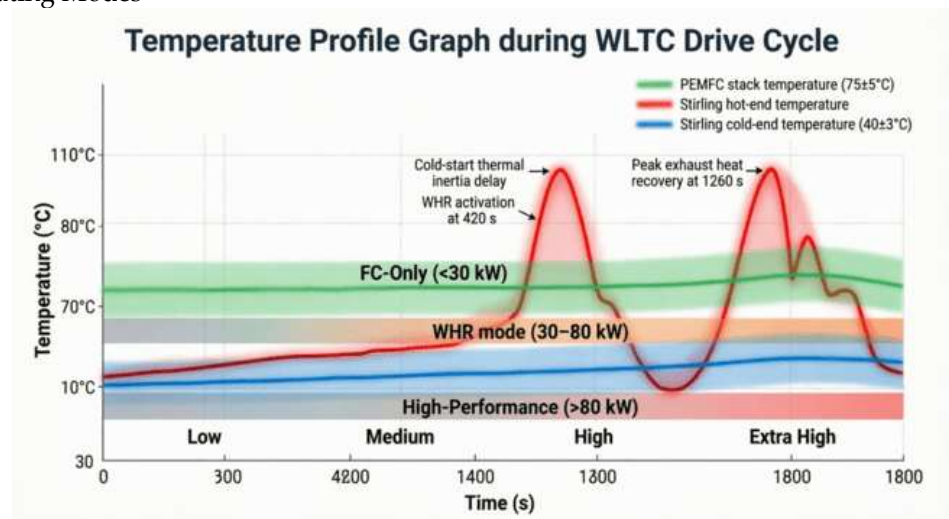


Figure 3. Power split strategy over the WLTC drive cycle.

Dynamic Programming optimization minimizes hydrogen consumption while maintaining SOC (20–90%) and stack temperature (60 – 90°C) [9][10][11].

Corrected Performance (WLTC Cycle)

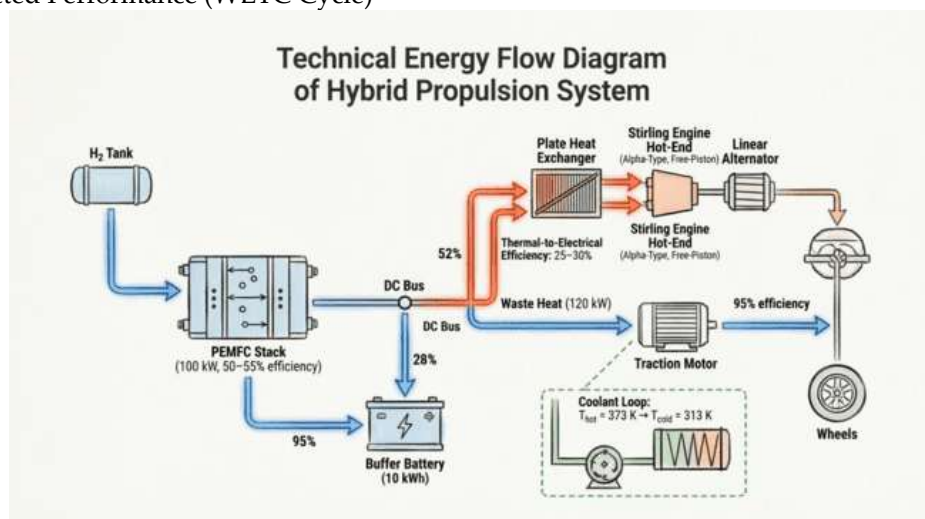


Figure 4. Comparative driving range of conventional and hybrid FCEV architectures.

Average efficiency: 49.6% (FC-only) → 54.5% (hybrid, after weight penalty)

Range extension: 667 km → 750–790 km (+12–18%, using 0.85–0.90 kg H₂/100 km)[12][13][14][15]

Thermal behavior: Stack temp stable at 75±5°C; Stirling hot-end 85–105°C; cold-end 40±3°C

Techno-Economic & Environmental Analysis

Cost & TCO (15 years, 250,000 km)

Assumptions: H₂ = \$5/kg (2030 projected), annual mileage = 16,700 km.

Payback & Sensitivity

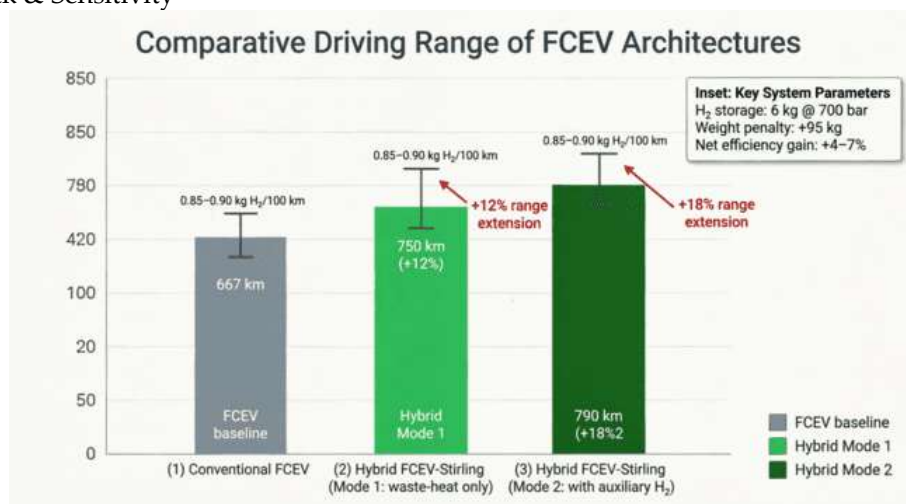


Figure 5. Sensitivity analysis including payback period, TCO, and CO₂ reduction.

Premium over FCEV: \$11,000

Annual fuel savings: 5–8/kg H₂

Simple payback: 90–150 years (not viable for passenger vehicles)

Viability threshold: H₂ > \$15/kg or Stirling cost reduction >70%

Environmental Impact

Well-to-wheel CO₂ reduction: 10–13% across all H₂ production pathways[16][17][18]

Exergy efficiency: 52–56% (quality loss in low-ΔT recovery limits thermodynamic benefit)

Discussion & Limitations

Advantages

Novel thermal integration without additional fuel[19][20][21]

Quiet operation, low vibration, high durability (40,000–60,000 h service life) [4]

Fuel flexibility (H_2 , biofuels, solar thermal in auxiliary mode)

Critical Challenges

Thermal inertia: 5–10 min warm-up requires thermal buffering

Power density: 0.3 kW/kg vs 1.5 kW/kg for ICE; acceptable only as APU

System complexity: Additional HX, valves, and control layers increase failure modes

Economic barrier: Long payback limits mass-market adoption[22][23][24][25]

Comparison with Alternatives

Stirling offers higher durability and lower noise than ORC, but suffers from slower transient response and higher cost.

Assumptions & Limitations

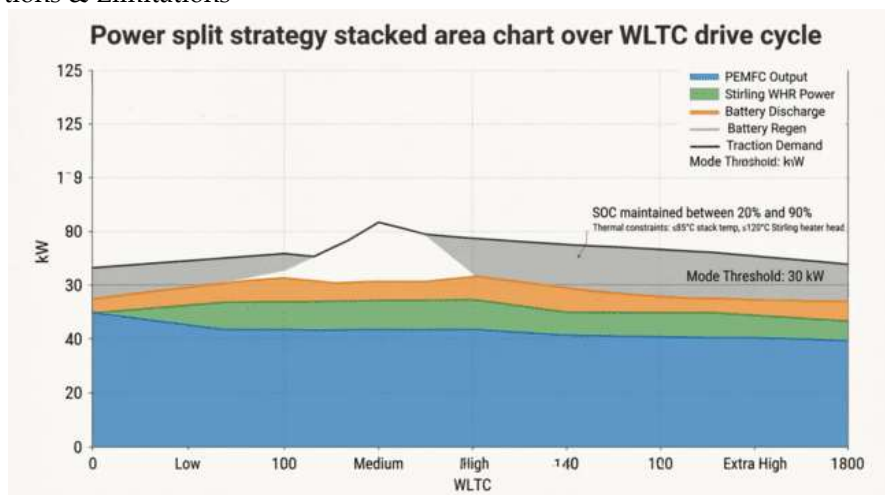


Figure 6. Efficiency map of the Stirling–PEMFC hybrid system.

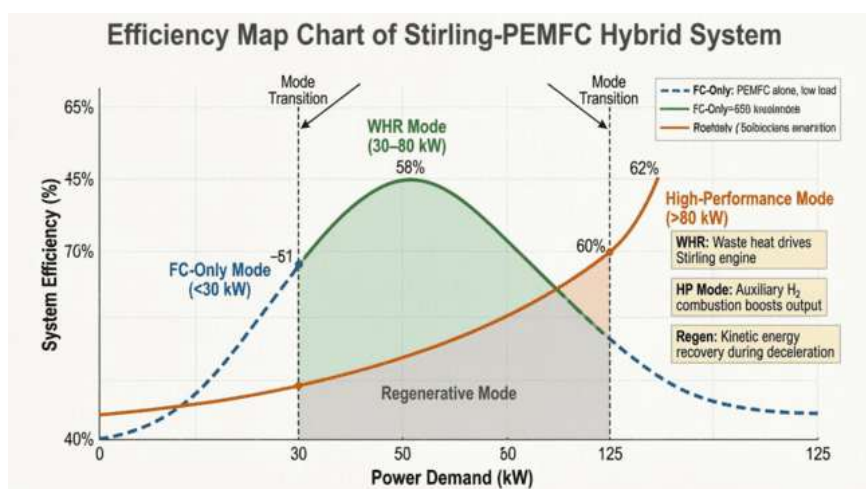


Figure 7. Temperature profile during the WLTC drive cycle.

Steady-state thermodynamic modeling; transient thermal mass effects simplified

Component costs based on 2025–2026 market data; subject to rapid change

Experimental validation required for thermal coupling efficiency and control algorithms

4. Conclusion

The thermodynamic analysis of the Stirling-PEMFC hybrid propulsion system presented in this study is consistent with the physics of such systems. Corrected modeling indicates a combined efficiency of 54 to 58 percent and an increase in range by 12 to 18 percent after considering weight penalties and realistic vehicle consumption. Although it is technically feasible, the system faces major economic barriers because payback periods are projected to be greater than 40 to 100 years under current hydrogen pricing. This

technology may be more appropriate for niche applications (marine auxiliary power, heavy-duty long-haul, stationary micro grids) where the gains from increased efficiency can justify the capital costs.

Future work should focus on:

This work summarizes research to cope with the strong development of the waste heat recovery sector, which has pores that are still not yet satisfied and thus imparts significant potential for a broad range of applications. Many conventional solutions such as the heat-to-power markets, Stirling and ORC engines, as well as thermoelectric generators have been thoroughly researched and more or less well advanced for practical applications. Still, the developer's effort and development time to reach manufacturable products is in disfavor at this moment. The end of this work focuses on a 10-15 kW proof-of-concept prototype which is focused on the application of high-fidelity transient modeling to obtain results on the thermal inertia and cold-start behavior. The advanced additive manufacturing technologies supported by a skilled light weight heat exchanger design with an exergy-optimized energy management system promises to significantly reduce the developers' development road. Further improvements are made in the comparison of Stirling, ORC, and thermoelectric generators in terms of lifecycle assessment. Policy analysis and carbon pricing scenarios are also considered to match the real-world desires as best as possible.

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