

Research Paper

Simulation of a Multi-Source Hybrid Electric Vehicle Integrating Battery, Fuel Cell, Photovoltaic, and Compressed-Air Systems

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Abstract

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This paper presents a simulation-based system-level evaluation of a four-source hybrid electric vehicle integrating a LiFePO₄ battery, a PEMFC, a VIPV, and a compressed-air energy storage subsystem. A detailed MATLAB/Simulink model is developed using a common DC-bus architecture and four independent in-wheel hub motors with a total rated power of 12 kW. A rule-based energy management system is used to control how power is shared among different sources, maintain the battery's charge, and regulate the DC-bus voltage. The vehicle's performance is evaluated using the WLTP Class 2 driving cycle, and seven hybrid configurations are systematically compared under the same operating conditions. Simulation results confirm accurate tracking of the reference velocity profile and stable DC-bus regulation at 225 ± 3 V across all configurations. The measured specific energy consumption is approximately 5.05 kWh/100 km, including regenerative braking. Energy flow analysis shows that the battery provides short bursts of power and recovers energy from braking. In contrast, the fuel cell offers a consistent power source, which is especially useful for long-distance travel. With a 50 L hydrogen tank at 350 bar, the fuel cell extends the estimated driving range from about 95 km in battery-only operation to approximately 513 km. The integration of VIPV and compressed-air subsystems provides additional auxiliary contributions, increasing the total achievable range to roughly 606 km under full battery utilization, while improving current smoothing and transient load support. Parametric assessment of hydrogen and compressed-air storage systems reveals that hydrogen storage capacity is the principal determinant of operational duration, while compressed air provides only a modest increase in range, though it is useful for short-term support. These findings validate the technical viability of four-source hybridization and elucidate the complementary functions of electrochemical, photovoltaic, and pneumatic energy sources within a practical multi-motor vehicle framework.

Keywords: Hybrid electric vehicle; Fuel cell; Vehicle-integrated photovoltaics; Compressed-air energy storage; Energy management; Range estimation

1. Introduction

Hybrid vehicles combine multiple onboard energy sources to compensate for individual source limitations. This family ranges from conventional hybrid electric vehicles (HEVs) and plug-in hybrids (PHEVs) to battery electric vehicles (BEVs), fuel-cell electric vehicles (FCEVs), and newer multisource/multi-energy architectures that pair batteries with fuel cells, photovoltaics (PV), compressed-air storage,

supercapacitors, and other devices. Recent reviews highlight that such multisource electric vehicles and hybrid energy storage systems (HESS) can improve overall energy density, power response, range, durability, and operational flexibility compared with single-source designs, provided that sizing and energy management are carefully coordinated [1], [2].

BEVs, particularly those based on Lithium iron phosphate (LiFePO₄) batteries, offer high



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drivetrain efficiency and zero tailpipe emissions, but their gravimetric energy density remains modest. Achieving long driving ranges typically requires large and heavy packs, which increase vehicle mass, cost, and embodied environmental impacts [3]. Life-cycle assessments and sustainability studies further show that BEV performance depends strongly on charging-mix carbon intensity, battery production, and end-of-life handling. In addition, long charging times and uneven charging-infrastructure deployment—especially on intercity routes—still contribute to user “range anxiety” and limit practical usability in some regions.

LiFePO₄ batteries are increasingly adopted as traction energy storage systems due to their high round-trip efficiency, robust power capability, and intrinsically high thermal and chemical stability. While LiFePO₄ cells exhibit lower gravimetric energy density than other lithium-ion chemistries, recent literature emphasizes system-level trade-offs beyond energy density alone, including extended cycle life, enhanced safety under abuse conditions, and degradation mechanisms that influence state-of-health (SOH) and capacity retention [5]. LiFePO₄ batteries demonstrate impressive cycle life, retaining around 90% of their capacity after 1,700 cycles, making them ideal for long-term vehicle use [5]. Their high thermal stability improves safety and supports long-term operation under demanding automotive conditions [5], [6]. However, degradation is influenced by operational factors such as depth of discharge (DOD) and charging protocols, with these elements significantly affecting both SOH and capacity retention [5], [6]. As a result, battery management systems (BMS) are essential for real-time monitoring and management of these factors, optimizing both performance and safety while addressing the nonlinear aging processes [5]. While LiFePO₄ batteries offer substantial advantages, careful management of operational parameters is critical to maximize their performance in electric and hybrid vehicle applications [5], [6].

Fuel cells, particularly proton-exchange membrane fuel cells (PEMFCs), offer high specific energy and fast hydrogen refuelling, making them attractive for long-range or high-duty applications. In fuel-cell hybrid electric vehicles (FCHEVs), the PEMFC typically supplies steady

cruise power while the battery buffers transients and recuperates braking energy. Comprehensive reviews of fuel-cell vehicle energy management systems (EMS) report a progression from rule-based strategies to optimization-based and learning-based methods, with a strong focus on protecting fuel-cell durability while minimizing hydrogen consumption [7], [8], [9]. Recent assessments of FCEVs underline both their potential role in sustainable transport and their challenges: lower well-to-wheel efficiency than BEVs, high stack and balance-of-plant cost, and sparse refuelling infrastructure [8], [9], [10]. Driving-cycle-aware EMS designs that exploit predictive information are increasingly proposed to improve real-world efficiency and component lifetime [11].

Vehicle-integrated photovoltaics (VIPV) have emerged as an attractive auxiliary source that can harvest solar energy while the vehicle is parked or driving, thereby reducing net grid or hydrogen consumption and modestly extending range. Reviews of VIPV technologies for passenger vehicles highlight realistic gains in the form of a few additional kWh per day under favourable insolation, constrained by limited surface area, shading, orientation, soiling, and packaging constraints [12]. System-level studies of PV–fuel-cell–battery HEVs and related architectures show that PV can effectively reduce fuel or hydrogen use but cannot replace primary storage or generation. Microgrid-oriented work on PV–regenerative hydrogen fuel-cell systems further shows that integrating intermittent solar with hydrogen storage and reconversion is technically feasible, but system complexity and cost must be justified by improved resilience or reduced emissions [15].

Compressed-air and pneumatic technologies—including on-vehicle compressed-air engines and compressed-air energy storage (CAES) subsystems—have also been explored as mechanically simple, long-lived, and potentially low-cost storage options. Experimental and review studies show that compressed-air engines can provide short-duration propulsion or assist power, but suffer from low volumetric and gravimetric energy density and significant thermodynamic losses during compression and expansion [16], [17], [18]. Recent work on advanced pneumatic concepts, adiabatic CAES,

and thermal-energy recovery indicates that multi-stage compression/expansion with appropriate heat management can improve round-trip efficiency, yet typical values remain substantially below those of electrochemical storage [18], [19]. Modern CAES reviews focused on renewable-energy grids describe evolving tank concepts, integration strategies, and techno-economic challenges, emphasising that compressed air is best suited as a niche or auxiliary storage medium rather than a primary long-range energy carrier [20], [21], [22]. For vehicle applications, this suggests that compressed-air subsystems may be more appropriate as auxiliary booster or load-leveling units in multi-energy architectures than as stand-alone propulsion sources.

In parallel with these energy-source developments, considerable research has been devoted to the configuration and control of electric powertrains. Several studies have compared single, dual, and quad-motor powertrain arrangements for battery electric vehicles using high-fidelity simulation environments such as MATLAB/Simulink and commercial vehicle modelling tools. Comparative analyses show that multi-motor architectures—particularly quad in-wheel or axle-mounted designs—can offer improved acceleration, energy consumption, and range by eliminating mechanical transmission elements and enabling more flexible torque distribution, provided that the control strategy is properly designed [23], [24]. Related work has demonstrated and experimentally validated low-cost electronic differential systems for quad in-wheel hub-motor EVs using embedded controllers, confirming that accurate torque (or speed) allocation can be achieved using relatively simple hardware and Ackermann-based control laws [25]. These contributions underline both the feasibility and the advantages of multi-motor architectures, and they provide a natural foundation for the in-wheel hub-motor drivetrain adopted in the present study.

Despite this rich body of research on batteries, fuel cells, VIPV, compressed-air storage, and powertrain topologies, there remains a noticeable gap in system-level evaluations of four-source HEVs that combine all of these elements in a single vehicle under identical driving conditions. Most published works focus on pairwise or three-

element hybrids (e.g., battery + fuel cell, battery + ultracapacitor, PV + fuel cell) or treat CAES mainly in stationary or grid applications rather than in integrated vehicle-scale architectures [1], [3], [12], [16], [20]. Moreover, component sizing is often tackled via heuristic or multi-objective optimization without explicitly linking capacities to propulsion-energy demands over standard driving cycles. This makes it difficult to judge the feasibility of proposed designs in terms of packaging, mass, and realistic operating ranges.

Table 1 shows that most studies focus on medium- to high-power electric vehicles (>50 kW). For example, Iqbal et al. study a system with more than 100 kW, and Valizadeh et al. and Kurmi and Verma consider systems in the range of 70–90 kW. Similarly, Benhammou et al. evaluate a multi-source hybrid system at the vehicle level with enhanced efficiency and energy recovery mechanisms [25], [26], [27], [28], [29].

Conversely, this investigation focuses on a low-power vehicle configuration (12 kW), which inherently entails distinct energy demands, system dimensions, and operational limitations. This underscores the necessity of assessing hybrid electric vehicle architectures across a spectrum of power levels, given that findings from high-power systems are not readily transferable to low-power mobility platforms.

This work develops and evaluates a simulation framework for a low-power multi-source hybrid electric vehicle integrating a LiFePO₄ battery, PEM fuel cell, vehicle-integrated PV array, and compressed-air subsystem. The framework applies a reverse energy-calculation methodology based on WLTP driving-cycle requirements to determine feasible component capacities. By co-simulating detailed subsystem models with an energy management strategy that explicitly coordinates electrochemical, photovoltaic, and pneumatic sources, the study aims to quantify the individual and combined contributions of each energy source to propulsion and range extension. Building on previous work on quad-motor EV powertrains and electronic differential control [23], [24], [30], the paper focuses on how multi-source hybridization and energy-management choices affect overall energy efficiency, achievable range, and the practical roles of PV and compressed air as auxiliary contributors in a realistic four-motor, four-source vehicle platform.

Table 1. Comparison of hybrid electric vehicle configurations in recent literature

Study	Sources	Power (kW)	Driving Cycle	Key Contribution
Iqbal et al. [25]	FC + Battery	110–114 kW	WLTP / NEDC / US06	High-power fuel cell hybrid with data-driven energy management and hydrogen consumption analysis
Valizadeh et al. [26]	FC + Battery + SC + PV	~70 kW (motor), 50 kW FC	FTP-72 + NEDC	Multi-source hybrid system with optimized control (WOA + FOPI) and improved energy distribution
Benhammou et al. [28]	FC + Battery + SC + AC/DC generators	Medium-power HEV (~150 km/h rated)	Vehicle-level evaluation	Improved supply efficiency (~96–97%) and reduced fuel consumption (25–35%)
Goswami et al. [29]	FC + Battery + SC	6 kW FC, 100 V system	Simulation-based	Improved efficiency and reduced hydrogen consumption using coordinated energy management
Kurmi & Verma [27]	Battery + PV + SC	70–90 kW	FTP-75	Multi-source EV with extended range and reduced energy consumption (28.85 kWh/100 km)
This study	FC + Battery + PV + CA (H ₂ tank)	~12 kW	WLTP Class 2	Low-power multi-source hybrid EV with dynamic hydrogen tank modeling and system-level energy analysis

The suggested vehicle architecture is tailored for low-speed, light-duty electric mobility applications, encompassing microcars, campus transport systems, and neighborhood electric vehicles. These vehicles typically function at moderate velocities, specifically below 100 km/h, and their design emphasizes energy efficiency, a compact form factor, and an extended driving range, rather than high power output.

The selected total drivetrain power of 12 kW aligns with the characteristics of light-duty electric vehicles, which generally exhibit power ratings between 5 and 15 kW, contingent upon vehicle mass and operational parameters. This power level facilitates a compromise, ensuring sufficient acceleration, the ability to ascend inclines, and a satisfactory cruising velocity, as per the WLTP Class 2 driving cycle. Furthermore, it enables the development of a compact, economically viable, and energy-efficient system.

2. Methods

This study evaluates the feasibility of a multi-source HEV integrating four onboard energy sources: battery, FC, PV, and compressed-air (CA) subsystems—using a unified MATLAB/Simulink

platform. The research approach is numerical–experimental in the sense that it uses a detailed dynamic model for energy-flow analysis under the WLTP Class 2 driving cycle, with realistic component parameters and a rule-based energy management strategy.

2.1. Overall System Architecture

The complete HEV model shown in [Figure 1](#) was implemented in MATLAB/Simulink R2024a using Simscape Electrical components. It comprises four independent in-wheel hub motors mechanically coupled to the wheels, with a combined rated power of 12 kW (4×3 kW). All sources are interfaced to a common DC bus via dedicated DC–DC (and AC–DC) converters.

The power-electronic interfaces were implemented using averaged converter models in the Simscape Electrical environment, enabling system-level analysis without explicit switching simulation. The battery is interfaced through a non-isolated bidirectional DC–DC converter with droop-based voltage control (0.1 V/A), allowing both propulsion and regenerative braking while supporting DC-bus stabilization. The fuel-cell subsystem connects through a buck–boost DC–DC converter, which operates in one direction. Its

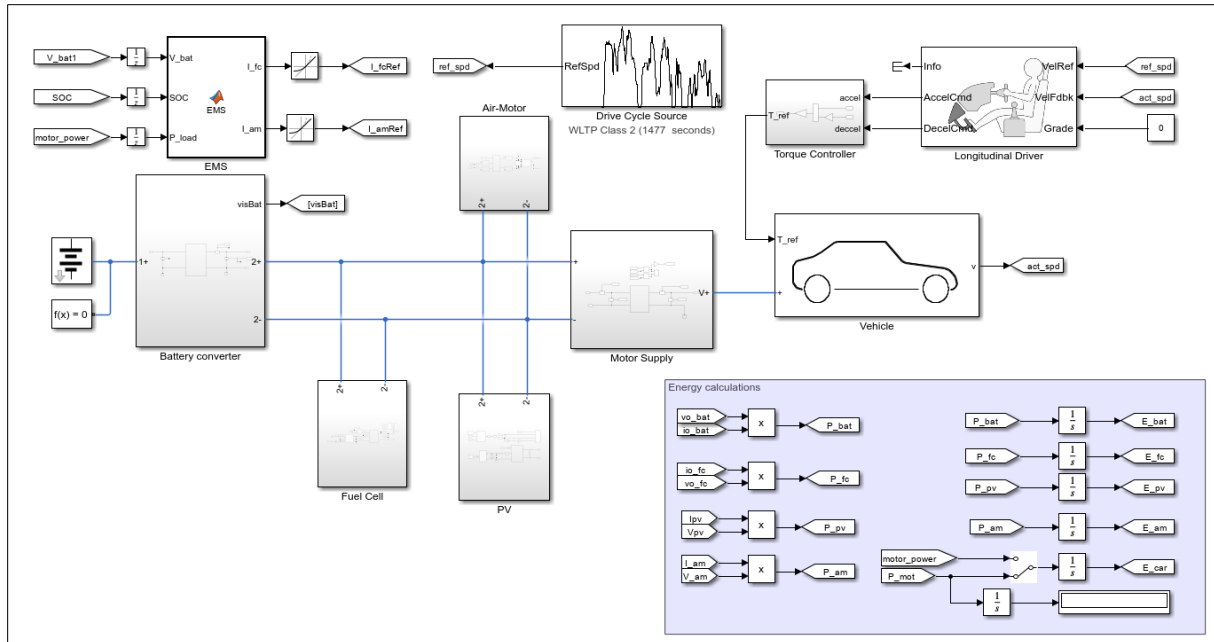


Figure 1. Overall simulink block diagram of the multi-source HEV model

operation is controlled by the energy management system, which adjusts the duty cycle. The photovoltaic subsystem uses a boost DC–DC converter with MPPT-based duty-cycle control. The compressed-air subsystem uses a multi-stage energy conversion process. This process includes pneumatic expansion, mechanical conversion, electrical generation, and rectification, before connecting to the DC bus.

The traction motor system is powered by bidirectional DC–DC converters. These converters use droop-based control (0.01 V/A) and have a first-order dynamic response. This setup enables stable load-side regulation and regenerative operation.

Converter losses are modeled using a hybrid approach: battery and motor converters include detailed loss models (97% efficiency), while fuel-cell and photovoltaic converters are treated as ideal averaged units, with PV system losses incorporated through an aggregated efficiency factor. The use of droop-controlled converters at both source and load interfaces enables decentralized voltage regulation and improves stability in the multi-source DC-bus architecture.

The EMS supervises power flows to meet the demanded traction power, maintain a charge-sustaining battery state of charge (SOC band, and keep the DC bus regulated at approximately 225 V. The system integrates both electrical and

pneumatic–electrical subsystems, linked through a unified control strategy.

2.2. Energy Source Models

Each source subsystem was modelled according to its physical and electrical characteristics. New connections and couplings were implemented for the compressed-air and PV integration, constituting the main methodological novelty of this study.

2.2.1. Battery subsystem

An equivalent-circuit model was used to represent a LiFePO₄ battery pack. This model included an open-circuit voltage that changed with the SOC and an internal resistance. The battery provided power for propulsion and also stored energy from regenerative braking. This two-way function was made possible by a non-isolated bidirectional DC–DC converter. This converter used droop-based voltage regulation, allowing for a smooth switch between charging and discharging. It also helped keep the DC-bus voltage stable. For this study, a 4.8 kWh pack (200 V, 24 Ah) was used as a standard. The main parameters are shown in Table 2.

2.2.2. Fuel cell subsystem

The fuel-cell subsystem presented in Figure 2 consists of a PEMFC stack connected to the DC

Table 2. Battery model parameters used in the simulation

Parameter	Value
Nominal voltage (V)	200
Nominal capacity (Ah)	24
Internal resistance (Ω)	0.05
SOC range (%)	5-95

bus via a DC–DC converter. The stack is modeled with an open-circuit voltage, Tafel losses, ohmic resistance, and limiting current, calibrated to yield approximately 2 kW nominal electrical power at 55% net efficiency.

To represent finite hydrogen storage, the FC is associated with a 50 L tank at 350 bar, corresponding to approximately 1.15 kg of H_2 , consistent with gravimetric storage values reported for 350-bar compressed hydrogen tanks in vehicular applications [31]. Assuming a lower heating value (LHV) of 33.3 kWh/kg and net fuel-cell efficiency $\eta_{FC} = 0.55$ [32], the usable FC electrical energy is:

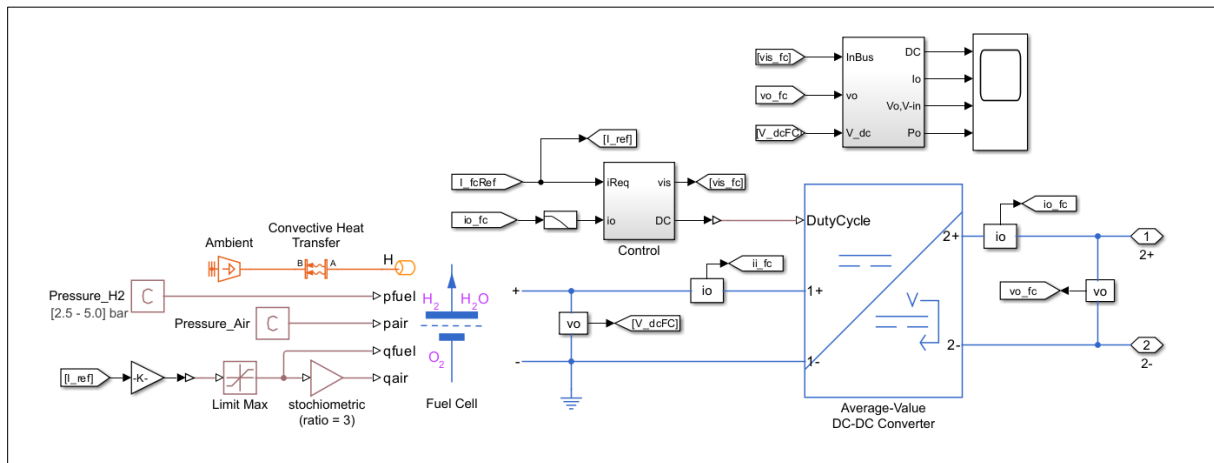
$$E_{FC} = \eta_{FC} \times m_{H_2} \times LHV_{H_2} \quad (1)$$

which yields about 21.08 kWh for the baseline tank. The corresponding hydrogen and stack parameters are summarized in Table 3.

The fuel-cell power is delivered to the DC bus through an average-value buck–boost DC–DC converter controlled via duty-cycle input, enabling direct regulation of output power according to the energy management system commands.

2.2.3. Photovoltaic subsystem

The photovoltaic subsystem is modeled as a vehicle-integrated PV array with two configurations: a 200 W rooftop installation, and a 400 W distributed installation covering roof, hood, and rear surfaces, consistent with realistic vehicle surface constraints and recent VIPV assessments [12]. The array is interfaced with the DC bus through a boost converter equipped with maximum power point tracking (MPPT), following

**Figure 2.** Fuel-cell subsystem schematic and integration into the DC bus**Table 3.** Fuel-cell and hydrogen tank parameters

Parameter	Value
H_2 tank volume (L)	50
Tank pressure (Bar)	350
Hydrogen mass (kg)	1.15
FC electrical energy (kWh)	21.08
Open-circuit voltage per cell (V)	1.0
Tafel slope (V)	0.23
Internal resistance (Ω)	0.5
Nominal exchange current (A)	30
Limiting current (A)	200
Number of cells per module	65
Module units (series)	100

established VIPV power-electronics architectures shown in [Figure 3](#).

To isolate the performance of each hybrid configuration, the simulations use Standard Test Condition (STC) irradiance of 1000 W/m² and constant cell temperature, as defined by IEC 61215 photovoltaic module standards [33]. This approach eliminates environmental variability and permits direct comparison of system-level interactions.

The daily PV energy contribution is estimated using the standard PV sizing relation:

$$E_{PV} = \eta_{PV} \times P_{PV} \times T_{sun} \quad (2)$$

where P_{PV} = 200W or 400W, η_{PV} is the net PV-to-bus conversion efficiency, and T_{sun} = 5 h represents the effective peak-sun-hours, a widely used metric in PV energy estimation.

Typical MPPT efficiencies of 95–99%, combined with DC–DC conversion losses, wiring losses, and temperature-related derating, yield an overall PV-to-DC-bus efficiency in the range of 75–85%, as commonly reported in vehicle-integrated PV studies [34], [35], [36], [37]. In this work, an intermediate value of $\eta_{pv} = 0.80$ is adopted. Under an effective peak-sun duration of 5 h, this corresponds to daily electrical energy yields of approximately 0.8 kWh for the 200 W configuration and 1.6 kWh for the 400 W configuration. These values are consistent with experimentally reported VIPV energy yields when scaled from full-size 1 kWp installations,

which typically produce 3–6 kWh/day under favorable irradiance conditions. To allow for a controlled comparison, the PV subsystem is evaluated under constant sunlight and a fixed temperature. This assumption doesn't consider real-world factors like shading, changing sunlight levels, and efficiency losses due to temperature. Therefore, it likely gives a too-optimistic view of how much solar panels can contribute.

The PV array connects to the DC bus through a boost converter. The converter, controlled by the MPPT algorithm's duty cycle, allows for efficient voltage adjustment, which helps to maximize power extraction.

2.2.4. Compressed-air subsystem

The compressed-air subsystem represents a small-scale pneumatic energy storage unit consisting of a 50 L high-pressure tank and an air-motor generator that converts pneumatic energy into electrical power ([Figure 4](#)). Compressed-air storage has been explored as a lightweight, mechanically simple auxiliary energy system for hybrid vehicles, owing to its fast charge capability, long cycle life, and absence of electrochemical degradation mechanisms [16], [17], [19]. However, its low volumetric and gravimetric energy density and thermodynamic losses during compression and expansion limit its use as a primary propulsion source; instead, it is more suitable as an auxiliary source in multi-energy architectures [20], [38].

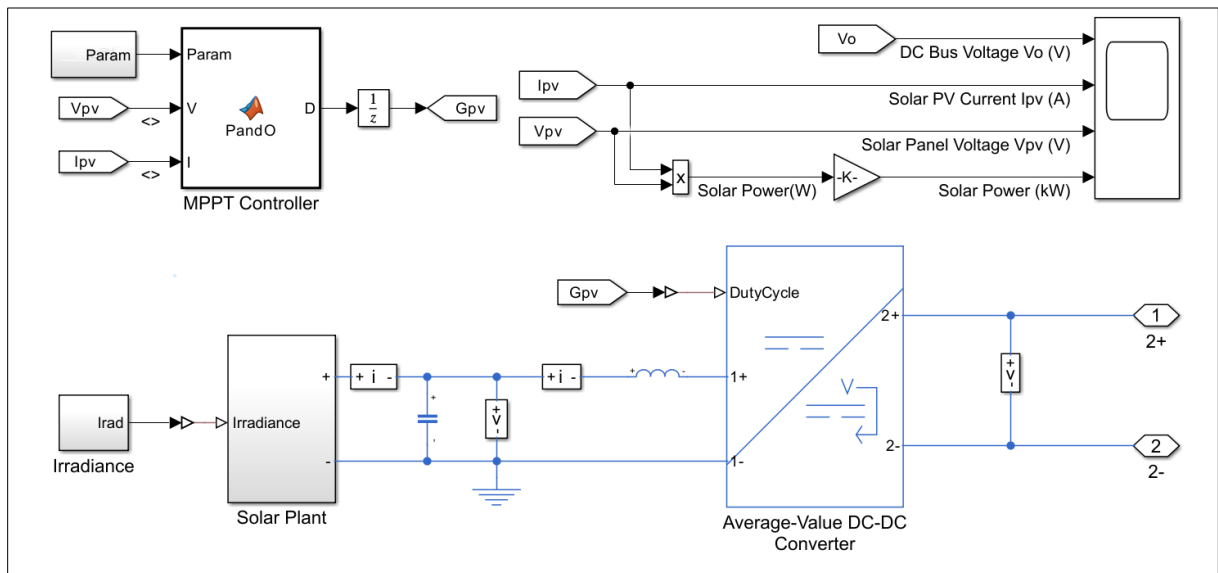


Figure 3. Photovoltaic subsystem with MPPT and DC–DC converter

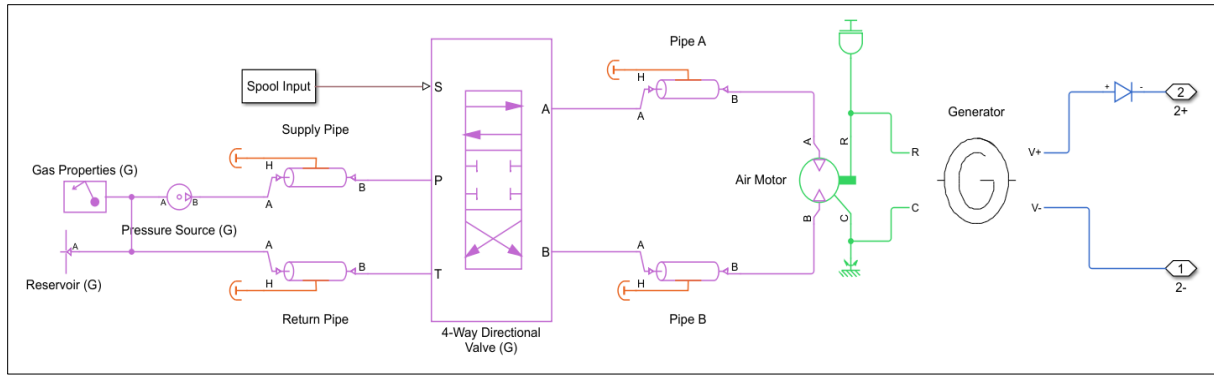


Figure 4. Compressed-air subsystem schematic

In this study, the tank is pressurized to 300 bar, consistent with high-pressure storage limits reported for experimental compressed-air vehicle prototypes and advanced pneumatic hybrid concepts [16], [20]. Using the ideal-gas approximation, the specific stored pneumatic energy for an isothermal expansion process can be estimated as:

$$E_{CA} = p_0 \times V \times \ln\left(\frac{p_i}{p_f}\right) \quad (3)$$

where:

p_i = 300 bar is the initial pressure

p_f = is the final tank pressure

p_0 = 1 bar is reference atmospheric pressure

V = 0.05 m³ is the tank volume

However, real pneumatic engines operate under near-adiabatic expansion, with significant cooling and exergy loss, reducing the usable fraction of stored energy to approximately 25–35% of the ideal value—consistent with experimentally reported round-trip efficiencies for pneumatic vehicular systems [20]. To reflect these combined thermodynamic, mechanical, and electrical losses, an overall tank-to-bus efficiency of 30% is adopted, aligned with reported pneumatic expander efficiencies in hybrid pneumatic vehicles (20–35%) [20], [38]. For a 50 L tank at 300 bar, the usable electrical energy delivered to the DC bus yields approximately 0.7 kWh, consistent with prior analyses of similar tank sizes and pressures in small hybrid vehicle applications [16], [20].

The air motor is modeled as a 0.3 kW micro-expander mechanically coupled to a permanent magnet generator whose output is rectified and injected into the DC bus through a DC-DC

converter as presented in Figure 4. The electrical output of the compressed-air subsystem is obtained through a generator–rectifier stage, enabling integration with the DC bus as a unidirectional auxiliary power source. Because pneumatic systems are not well suited for continuous operation due to rapid tank pressure decay, the EMS activates the air motor only when the battery SOC drops below 50%, providing short-duration support and reducing battery stress during transient load peaks. This operational philosophy aligns with prior studies showing that pneumatic units perform best as auxiliary boost systems rather than sustained propulsion devices [19].

2.3. Drivetrain and Vehicle Model

The traction system uses four independent brushless DC in-wheel motors with a combined mechanical rating of 12 kW. Motor torque commands are generated from the driver block based on WLTP-Class-2 velocity demand. Each motor controller uses a PWM inverter supplied by the DC bus, ensuring symmetric torque distribution among the four wheels. Motor parameters are listed in Table 4.

2.4. Energy Management and Control

The EMS shown in Figure 5 governs how the different energy sources—battery, fuel cell, PV

Table 4. In-wheel motor parameters

Parameter	Value
Motor rated power (kW)	3.0
Rated voltage (V)	72
Peak current (A)	30
Motor efficiency (%)	90
Number of motors	4

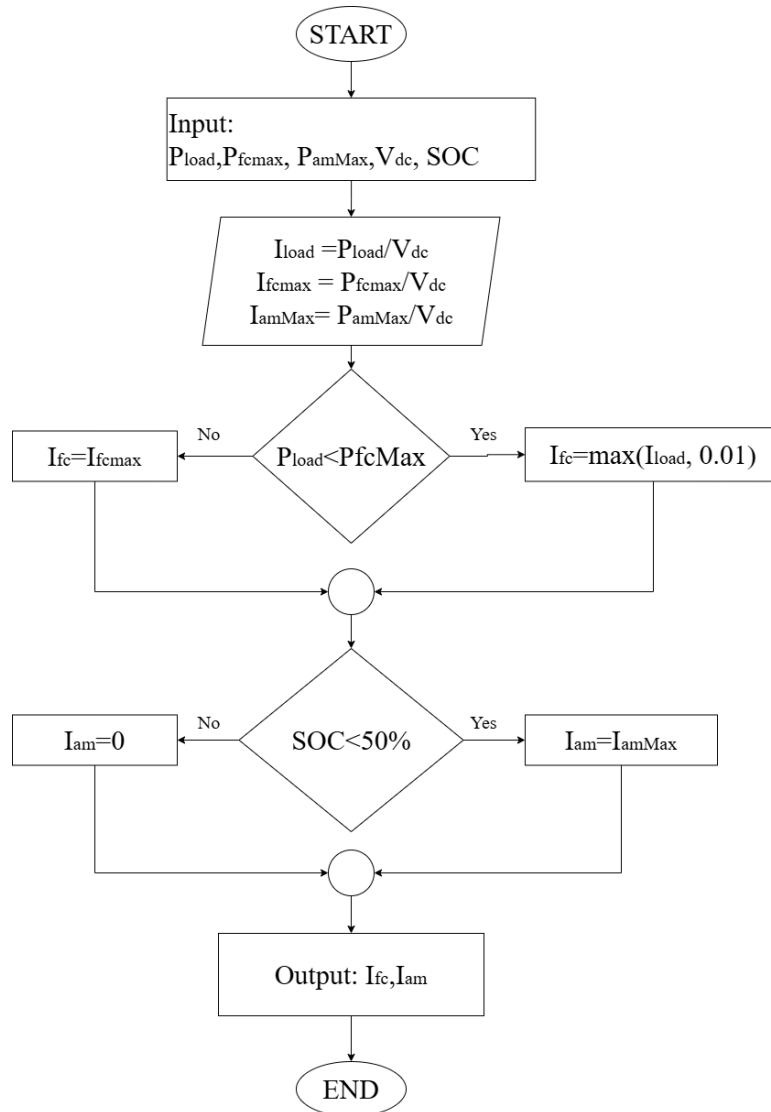


Figure 5. Flow diagram of the EMS control logic, showing decision paths for fuel-cell and air-motor activation

array, and compressed-air motor—interact to meet the instantaneous power demand of the vehicle while maintaining charge-sustaining operation. The EMS was implemented as a MATLAB function block that receives three inputs: the battery voltage, SOC, and traction load power. Based on these variables, it generates two control outputs: the fuel-cell current reference and the air-motor current reference. The battery provides the remaining balance of power automatically through its converter.

At every simulation step, the EMS calculates the load-equivalent current from P_{load} and compares it with predefined thresholds for the fuel cell and air motor. The fuel-cell subsystem has a maximum electrical power of 2 kW and is primarily responsible for sustaining the battery charge during steady-state driving. When the

required load power is below 2 kW, the fuel-cell current reference is set equal to the load-equivalent current (with a small minimum bias of 0.01 A to prevent shut-off). When the load exceeds this limit, the current is saturated at its maximum value. In this way, the fuel cell tracks the vehicle's base power demand without excessive transients or overloading.

The air-motor generator operates according to the battery's SOC level. When the SOC drops below 50 %, the EMS activates the air motor to generate auxiliary electrical power. The corresponding current reference is set to its maximum allowable value (1.0 A, for a 0.3 kW unit). Once the SOC rises above 50 %, the pneumatic system is deactivated. This binary behavior makes the air-motor contribution intermittent, assisting mainly during deep-

discharge or high-demand periods and providing short-duration auxiliary support.

The battery subsystem therefore acts as the main dynamic buffer, providing all transient power beyond the slower response of the fuel cell and air-motor systems. It absorbs regenerative braking energy and ensures smooth transitions between power sources. Meanwhile, the PV subsystem continuously injects any available solar energy via its MPPT converter, supplementing the DC bus without additional control intervention.

The entire control process can be represented by a simple flow diagram (Figure 5). Starting from the vehicle's instantaneous power demand, the EMS first checks whether the load power is below the fuel-cell capacity.

If so, it assigns the fuel-cell current proportionally to the load; otherwise, it limits it to the maximum. Next, it evaluates the battery SOC. If the SOC is under 50 %, the air-motor generator is enabled at full output; if not, it remains off. The resulting current references are then used by their respective DC-DC converters to regulate the actual power drawn from each source. The battery compensates for the difference between total source output and the demanded traction power, thereby maintaining DC-bus voltage stability.

This algorithm ensures that the vehicle operates in a charge-sustaining mode, with SOC oscillating within 45–55 %, while the DC bus voltage remains stabilized near 225 V. By limiting the fuel-cell output to its rated power and

activating the air-motor only at low SOC, the control strategy minimizes transient overshoot and distributes power smoothly among the available sources.

2.5. Driving Cycle and Simulation Scenarios

All simulation scenarios were executed under the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) Class 2 driving cycle, which provides a representative speed–time profile for medium-sized passenger vehicles. This cycle has a total distance of 23.26 km, a duration of 1477 s, and a maximum velocity of 97.4 km/h. The vehicle's reference velocity and the simulated velocity follow the same pattern, confirming accurate tracking performance by the traction and control subsystems as shown in Figure 6. The WLTP cycle was chosen for its realistic transient and steady-state conditions, making it suitable for evaluating hybrid energy management in both urban and suburban regimes.

To evaluate the feasibility and performance impact of each energy source, a set of seven hybrid configurations was simulated using the same vehicle model, component parameters, and control logic. In all cases, the battery was retained as the primary energy source to ensure comparability, while the auxiliary sources were activated selectively according to the scenario definitions. The purpose was not to optimize sizing, but rather to understand how each source combination affects overall energy balance, range

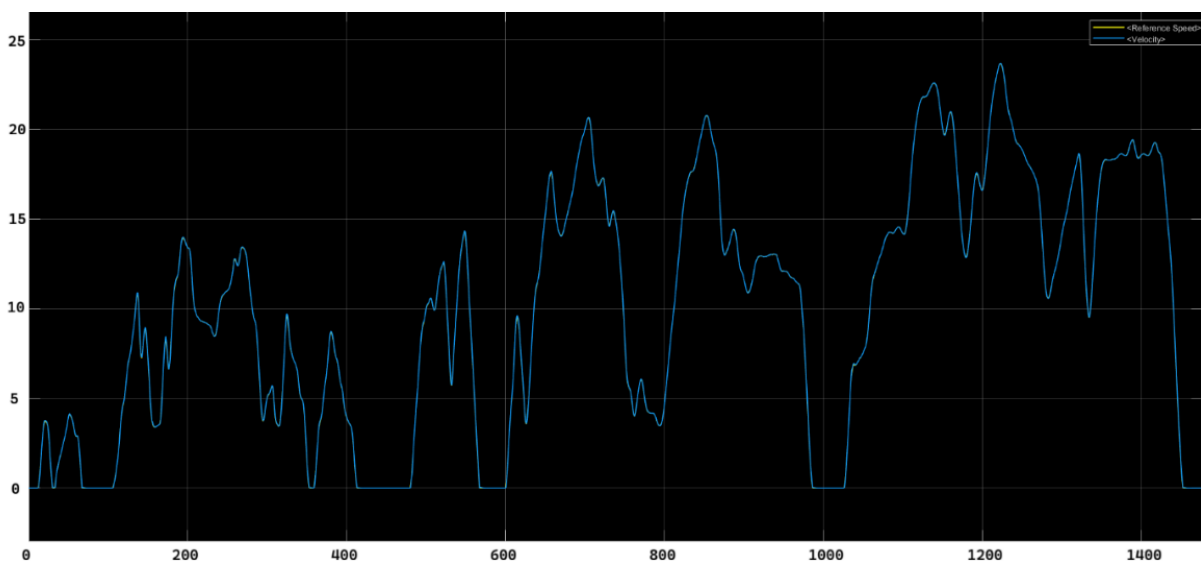


Figure 6. Reference and actual vehicle velocity profiles in m/s (WLTP-Class-2)

potential, and bus stability. The following configurations were assessed:

- Case 1 — Battery + Fuel Cell
- Case 2 — Battery + PV
- Case 3 — Battery + Compressed-Air Motor
- Case 4 — Battery + Fuel Cell + PV
- Case 5 — Battery + Fuel Cell + Air Motor
- Case 6 — Battery + Fuel Cell + PV + Air Motor

Each scenario was simulated for the same WLTP Class 2 cycle, maintaining identical environmental and control conditions to ensure a consistent comparison. The total consumed and produced energies were recorded for each source, along with SOC variation, DC bus voltage profile, and motor power output.

3. Results and Discussion

This section presents the main findings obtained from the MATLAB/Simulink simulation of the proposed four-source HEV model. Results are presented following the methodology sequence: driving-cycle validation, energy-flow analysis, configuration comparison, and range estimation. Representative figures illustrate key behaviors, and the discussion interprets their technical significance relative to the study objectives.

3.1. Vehicle Performance Under WLTP Class 2 Cycle

Before comparing hybrid configurations, the model's accuracy in reproducing the WLTP Class

2 driving cycle was verified. [Figure 6](#) shows that the simulated velocity closely follows the reference cycle, confirming accurate driver tracking and inverter-motor response during both urban and extra-urban phases. The vehicle's energy demand was therefore representative of real-world operating conditions.

Across all configurations, the DC-bus voltage remained close to its nominal value of 225 V, indicating effective coordination between the energy sources and the control system. In the full hybrid configuration, the voltage remained within 225 ± 3 V throughout the WLTP Class 2 cycle, including acceleration and regenerative braking phases. Transient deviations were short-lived and non-oscillatory, indicating stable subsystem interaction. The system's stability is largely due to the droop-based control strategy used at the battery and motor interfaces. This method enables decentralized voltage regulation and balanced power distribution. The corresponding DC-bus voltage profile is shown in [Figure 7](#).

3.2. Source Power Distribution and Energy Flow

The dynamic power exchange among sources is illustrated in [Figure 8](#) for the full hybrid configuration (Battery + Fuel Cell + PV + Air Motor). The battery handled transient loads during acceleration and absorbed regenerative energy during braking. The fuel cell delivered up to 2 kW of steady electrical power, maintaining the DC bus and sustaining the battery SOC near

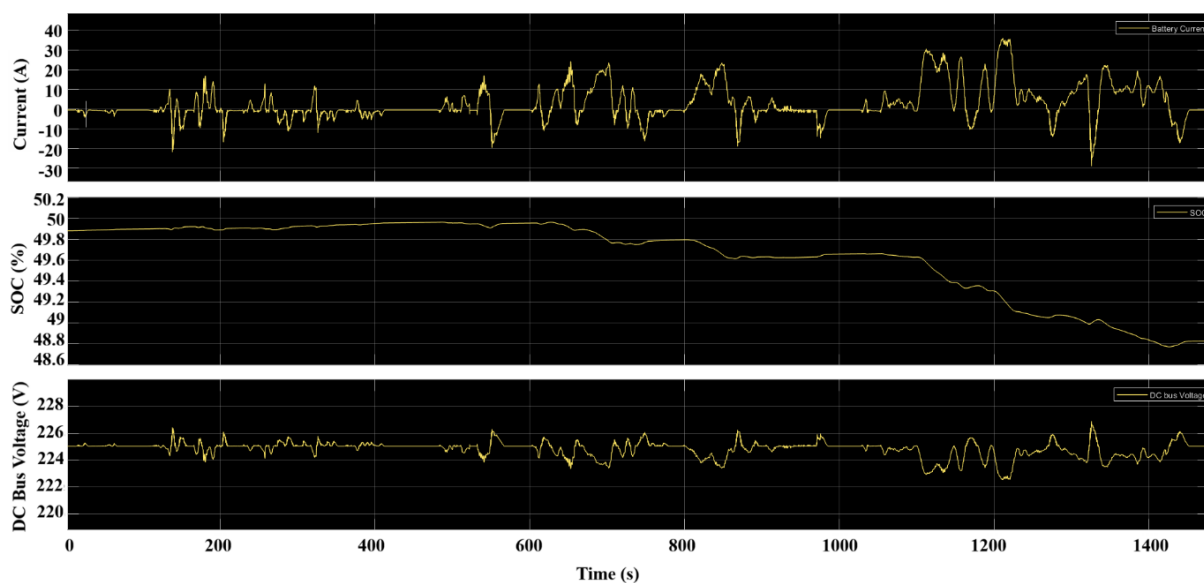


Figure 7. Battery current, state-of-charge, and DC-bus voltage during one WLTP Class 2 cycle (full hybrid case)

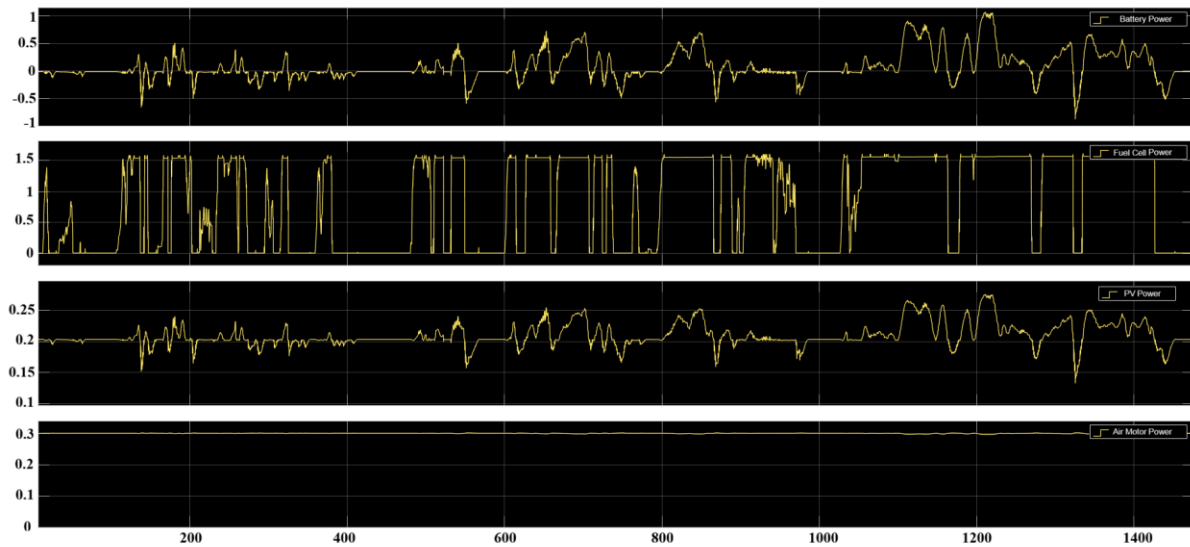


Figure 8. Instantaneous power of each energy source in kW (Battery, Fuel Cell, PV, and Air Motor) for the full hybrid configuration

50 %. The PV array injected a nearly constant 40–70 W under uniform irradiance, while the air motor generator activated intermittently when $SOC < 50\%$, contributing short power bursts (~300 W). This coordination resulted in smooth power balance with minimal current ripple.

Battery voltage, current, and SOC profiles are presented in Figure 7. SOC remained confined between 45 % and 55 %, confirming charge-sustaining operation. Alternating positive and negative current intervals indicate discharge during acceleration and recuperation during braking, typical of hybrid operation.

The per-motor electrical power profiles presented in Figure 9 exhibit symmetrical load sharing among the four in-wheel motors, each delivering up to 3 kW at peak acceleration and entering regenerative mode during deceleration. This uniformity shows consistent torque distribution and balanced traction.

3.3. Comparative Performance Across Configurations

To evaluate the influence of each energy source, seven configurations were simulated under identical conditions. The total energy demand

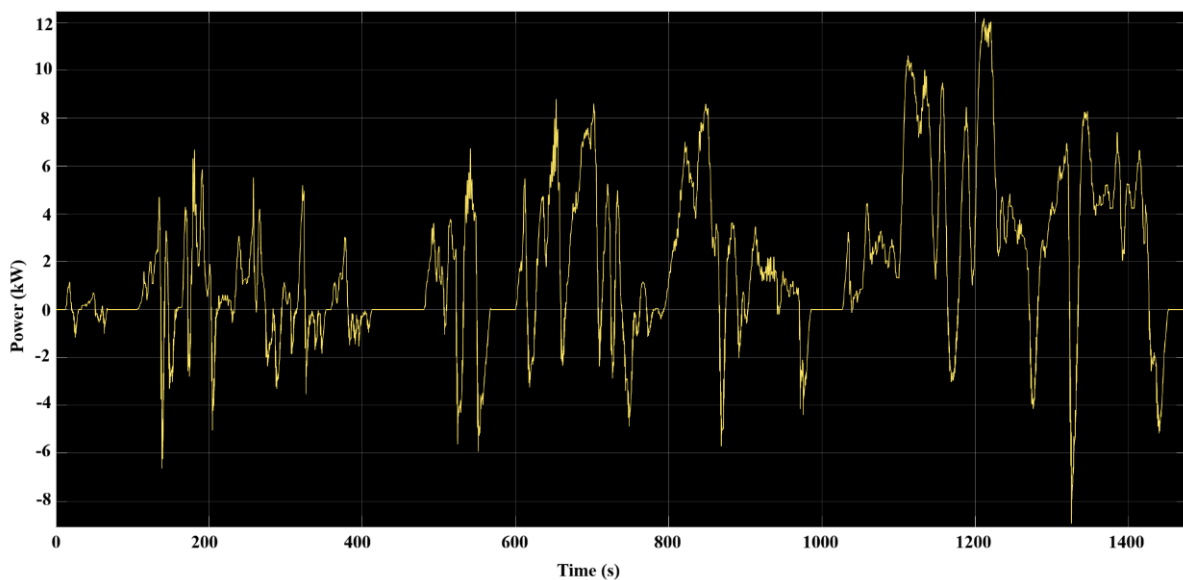


Figure 9. Electrical power of the four in-wheel motors over the WLTP Class 2 cycle

per WLTP Class 2 cycle was normalized to 0.753 kWh, allowing direct comparison of relative energy shares. **Figure 10** summarizes the percentage contribution of each source across all modes. The Battery + Fuel Cell (B+FC) configuration showed the most balanced energy split ($\approx 54\%$ battery, 46% fuel cell), producing the most stable SOC trajectory. Adding a PV subsystem (B+PV) contributed $\sim 6.5\%$ of the energy, slightly reducing battery discharge. The Air Motor (B+AM) delivered $< 1\%$ of total energy but effectively damped transient current peaks. The B+FC+PV and B+FC+AM modes further improved current smoothness and bus voltage regulation, while the full hybrid (B+FC+PV+AM) achieved the most uniform power-sharing— 48.5% battery, 45% fuel cell, 6.2% PV, 0.16% air motor. Although the compressed-air subsystem uses a small amount of the total energy, its primary function is transient power support rather than energy supply. Instead, it provides short-term support and smooths sudden power fluctuations. Therefore, it functions as an auxiliary system rather than a primary energy source.

3.4. Range Estimation and Energy Feasibility

The vehicle's range was evaluated by combining the stored energy of each onboard source with the measured energy consumption of $5.05\text{ kWh}/100\text{ km}$, obtained from the WLTP-Class-2 driving cycle under regenerative braking conditions. All range estimates are based on the effective energy available at the DC bus, including

the subsystem-level efficiency assumptions described in Section 2.

To validate the obtained energy consumption results, a comparison with reported values in the literature was conducted. For light-duty electric vehicles, energy consumption typically falls between 6.22 and $15.6\text{ kWh}/100\text{ km}$, as measured by standard driving cycles like WLTP and NEDC. For example, the Nissan Leaf showed energy consumption between 9.61 and $15.6\text{ kWh}/100\text{ km}$ in NEDC tests, and between 6.22 and $10.53\text{ kWh}/100\text{ km}$ in WLTP tests [39]. In contrast, larger electric passenger vehicles have higher consumption rates, averaging about $19 \pm 4\text{ kWh}/100\text{ km}$ in certified conditions and $21 \pm 4\text{ kWh}/100\text{ km}$ in real-world use [40].

The obtained consumption values are slightly lower due to the lightweight vehicle design and the lower-speed WLTP Class 2 driving conditions. This supports the model's accuracy for lightweight hybrid electric vehicles. The analysis considered two operational modes for the traction battery. In the full-use mode (100%), the entire 4.8 kWh capacity is available for discharge, representing battery-electric operation. In the partial-use mode (50%), the vehicle operates under a charge-sustaining strategy, where the energy management system maintains the state of charge within the $45\text{--}55\%$ range, allowing only half of the nominal capacity to be utilized.

In both modes, the fuel cell, PV system, and CA subsystem were modeled with fixed stored energy corresponding to their respective tanks and

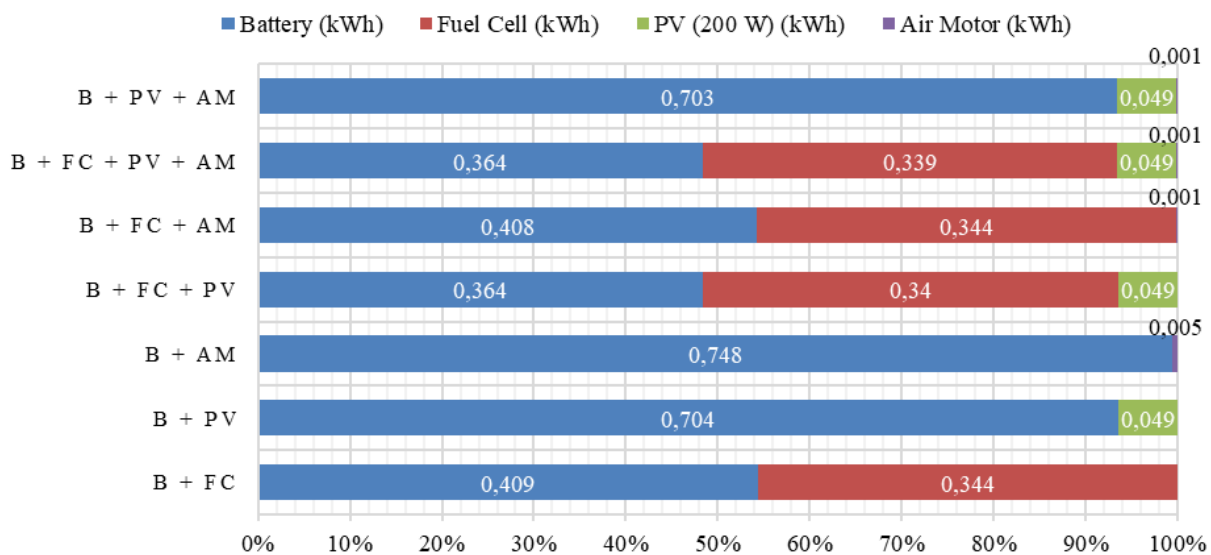


Figure 10. Energy contribution of each onboard source over one WLTP Class 2 cycle for all hybrid configurations, assuming a 200 W VIPV installation

generation potential. The total and individual source contributions were then converted into equivalent driving range values. When the entire battery capacity is available, the vehicle achieves its maximum theoretical range.

As shown in [Figure 11](#), the Battery + Fuel Cell configuration extends the baseline range from approximately 95 km (battery only) to about 513 km, dominated by the fuel cell's 50 L hydrogen tank at 350 bar (≈ 21 kWh usable). The photovoltaic subsystem provides a modest but measurable range extension, limited by available installation area and effective insolation. For a realistic 200 W VIPV installation operating under five effective peak-sun-hours with an overall conversion efficiency of 80%, the usable electrical energy is approximately 0.8 kWh, corresponding to a range contribution of about 16 km. A higher-coverage 400 W VIPV configuration increases the available PV energy to approximately 1.6 kWh, extending the PV-assisted range to roughly 32 km. These estimates reflect cumulative solar energy harvesting under constant irradiance assumptions and therefore represent optimistic operating conditions and therefore represent optimistic

estimates compared to real-world operating conditions.

In practical operation, the EMS restricts battery cycling to around 50 % of its nominal capacity to preserve longevity and maintain voltage stability. Under this mode, illustrated in [Figure 12](#), the total achievable ranges decrease proportionally with the usable battery fraction. The Battery + Fuel Cell system still provides ≈ 465 km, and the full four-source configuration reaches ≈ 559 km. The PV and CA systems continue to supplement the overall energy balance, though their direct contribution to extended range remains secondary to the fuel cell's stored hydrogen energy.

To evaluate the sensitivity of range extension to increased photovoltaic surface coverage, an additional scenario was examined using a 400 W VIPV configuration, representing combined roof, hood, and rear-surface installation. Under the same assumption of five effective peak-sun-hours and an overall PV-to-bus efficiency of 80%, the available daily PV energy increases to approximately 1.6 kWh. This corresponds to an additional PV-assisted range of about 32 km at the measured WLTP consumption rate.

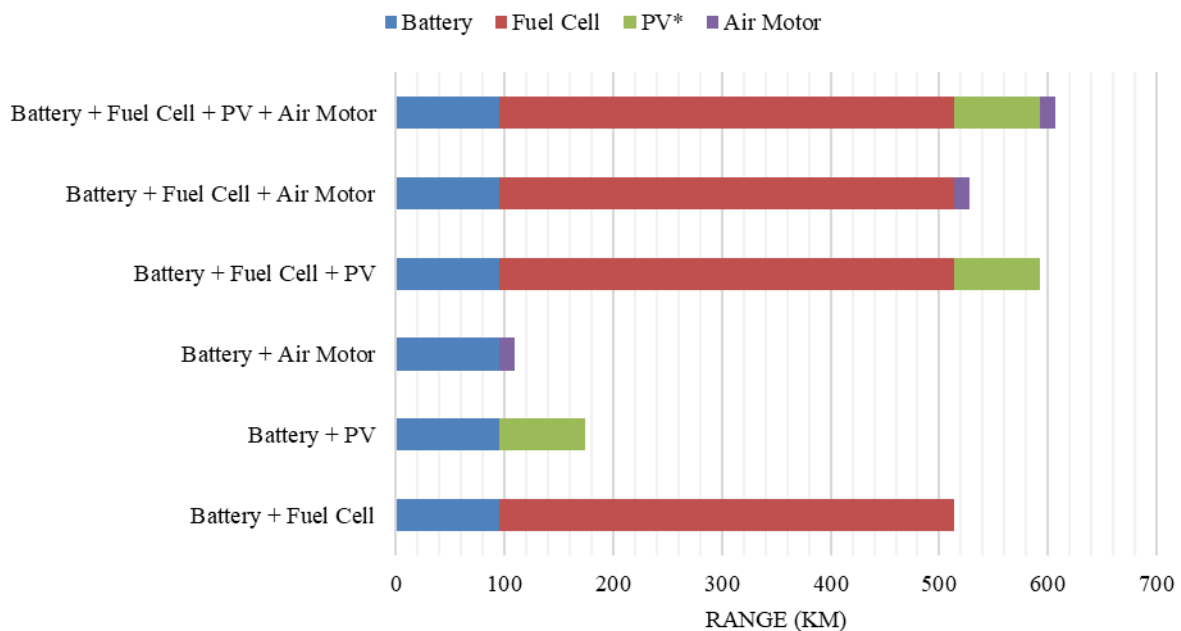


Figure 11. Estimated range contributions for all hybrid configurations under full battery utilization (100 % SOC), assuming a 200 W vehicle-integrated PV installation and five effective peak-sun-hours

As illustrated in [Figure 13](#), increasing the VIPV capacity from 200 W to 400 W produces a noticeable but still secondary increase in total

vehicle range when the full battery capacity is available. While the battery and fuel cell remain the dominant contributors, the enhanced PV

coverage raises the stacked PV contribution proportionally, highlighting the sensitivity of solar range extension to available surface area rather than instantaneous power capability. Figure 14 presents the corresponding results under partial battery utilization (50 % SOC), reflecting the charge-sustaining operating strategy imposed by the EMS. Although the absolute vehicle range is reduced compared to the full-discharge case, the relative contribution of the PV subsystem becomes more pronounced, as the usable battery energy is constrained by SOC limits.

Although Figure 11, Figure 12, Figure 13 and Figure 14 quantify the total and relative range contributions of the different onboard energy sources, these results implicitly depend on the selected storage pressure–volume combinations for the hydrogen and compressed-air tanks. To clarify the sensitivity of the achievable range to these design parameters, additional parametric evaluations were conducted for both subsystems, as discussed below.

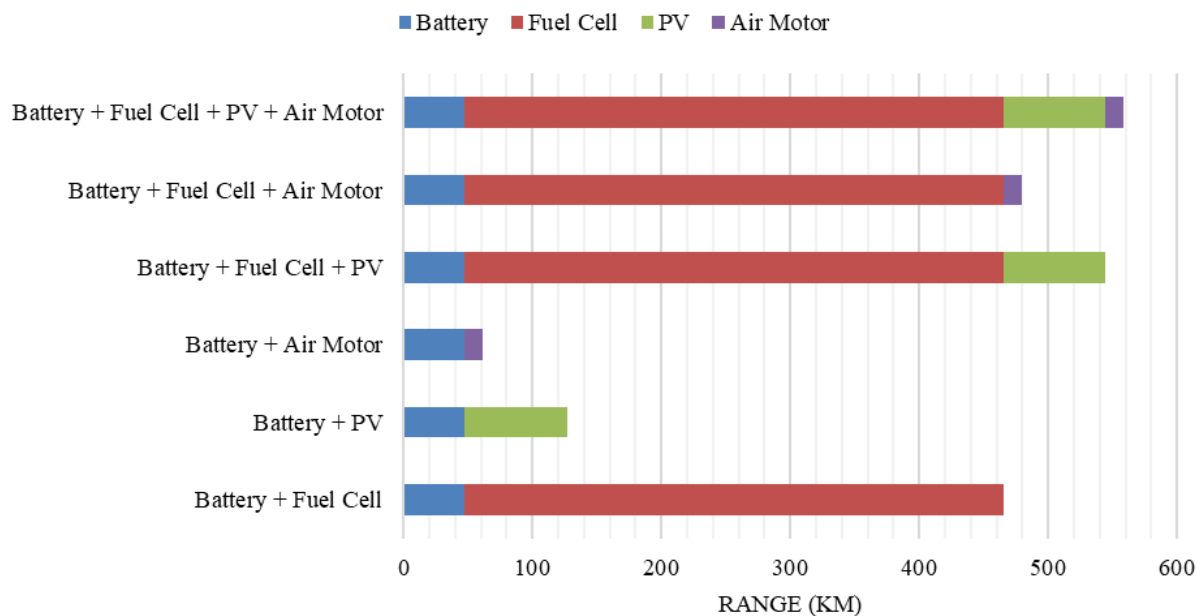


Figure 12. Estimated range contributions for all hybrid configurations under partial battery utilization (50 % SOC), assuming a 200 W vehicle-integrated PV installation and five effective peak-sun-hours

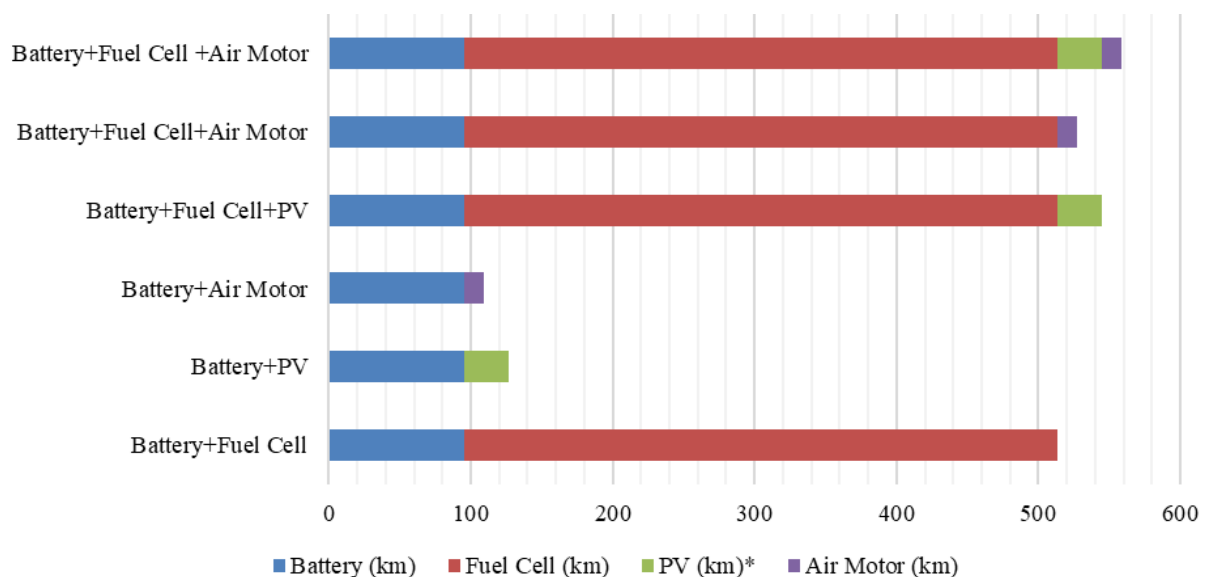


Figure 13. Estimated range contributions for all hybrid configurations under full battery utilization (100 % SOC), assuming a 400 W VIPV installation and five effective peak-sun-hours

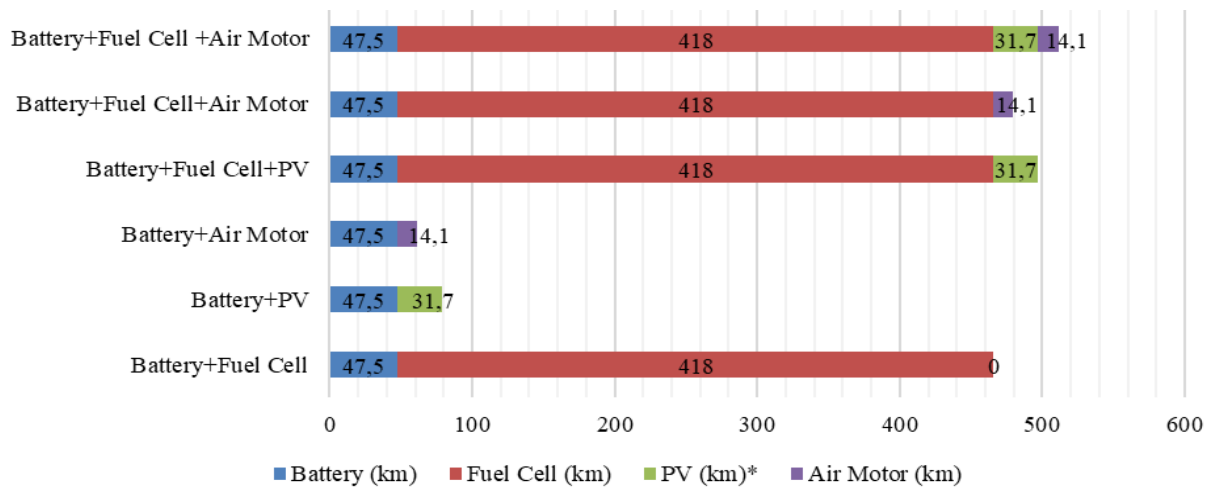


Figure 14. Estimated range contributions for all hybrid configurations under partial battery utilization (50 % SOC), assuming a 400 W VIPV installation and five effective peak-sun-hours

For the fuel-cell subsystem, the achievable driving range scales primarily with the effective hydrogen storage capacity, which is governed by the tank pressure–volume product. [Table 5](#) summarizes representative hydrogen tank designs for the 12 kW vehicle, illustrating how different pressure and volume combinations translate into equivalent fuel-cell-only driving range. Representative hydrogen storage configurations evaluated in this study are listed in [Table 5](#).

Increasing storage pressure beyond 350 bar does not inherently increase range unless accompanied by additional storage volume or higher total hydrogen mass. For example, the 350 bar–50 L and 700 bar–25 L designs achieve similar driving ranges despite significantly different pressures, because they store comparable usable hydrogen energy. Higher pressures therefore mainly enable packaging benefits, allowing a given range to be achieved with reduced tank volume.

A similar sensitivity analysis was performed for the compressed-air subsystem, focusing on the influence of tank pressure and volume on auxiliary range contribution. The results summarized in [Table 6](#), confirm that compressed-air storage provides only a limited increase in driving range, even at higher pressures and volumes. Corresponding compressed-air storage configurations and their auxiliary range contributions are summarized in [Table 6](#).

Although raising tank pressure or volume increases the available pneumatic energy, thermodynamic losses during expansion and conversion constrain the usable fraction delivered

to the DC bus. As a result, the compressed-air system is most effective as a transient support and load-leveling mechanism rather than a primary range extender. The baseline design represents a balanced compromise between auxiliary range contribution, mass, and packaging constraints for a compact 12 kW hybrid vehicle. From a system design perspective, this limited contribution must be balanced against the added complexity of the compressed-air subsystem. The findings suggest this technology is not suitable as a primary range-extension method of low-power vehicles. Conversely, its utility as a supplementary system remains, offering temporary power and alleviating battery stress. Furthermore, the practice of compressing air for energy storage presents pragmatic advantages, including rapid replenishment and a less complex infrastructure relative to conventional charging techniques. Across all configurations, the fuel cell subsystem proves to be the most effective secondary source, providing continuous energy delivery and significantly extending the operating range without rapid voltage drop.

The PV array contributes meaningfully under daylight conditions but is inherently limited by insolation duration, while the compressed-air subsystem offers valuable transient power support and regenerative absorption capability, albeit with minimal direct range impact. Because the reported consumption values already include regenerative braking, the calculated ranges inherently reflect its benefit; omitting regeneration would reduce total ranges by roughly 9–10 %.

Table 5. Effect of hydrogen tank pressure and volume on FC-only vehicle range

Pressure (bar)	Volume (L)	Range (km)	Comment
350	35	293	Small city tank
350	40	334	Compact design
350	50	418	Reference design
350	60	502	Long-range tank
700	25	418	Same range, reduced volume

Table 6. Effect of compressed-air tank pressure and volume on air-motor-assisted range

Pressure (bar)	Volume (L)	Range (km)	Comment
200	50	8.7	Low-pressure, simple integration
250	40	9.1	Compact tank
250	50	11.4	Moderate pressure
300	40	11.3	Same range with less volume
300	50	14.1	Balanced choice
300	60	16.9	Higher range, larger mass

These results confirm that hybridization—especially the inclusion of a fuel cell as a continuous energy source—can more than quintuple the effective range of a small-scale electric vehicle, while PV and pneumatic systems act as strategic auxiliary contributors for efficiency and power stability.

3.5. Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the influence of key parameters on system performance. The fuel cell efficiency was varied by $\pm 10\%$, while PV efficiency was varied between 75–85%, and compressed-air subsystem efficiency between 20–35%. The results indicate that fuel cell efficiency has the most significant impact on system performance, directly affecting hydrogen consumption and overall energy efficiency. In contrast, variations in PV and compressed-air efficiencies have a relatively minor influence due to their limited contribution to the total energy balance. These findings confirm that the proposed system remains stable under parameter variations, demonstrating the robustness of the model.

3.6. Practical Integration Considerations

The practical implementation of the proposed multi-source architecture requires consideration of scalability, packaging, and the complexities inherent in system integration. While the existing configuration is suitable for low-power vehicles, specifically those operating at around 12 kW, scaling the system to meet increased power requirements would demand the integration of larger energy storage components, converters

with elevated ratings, and more advanced thermal and control management systems.

Packaging constitutes a significant limitation, given that the integration of various subsystems such as the battery, fuel cell, hydrogen tank, photovoltaic modules, and compressed-air storage demands meticulous spatial organization and structural design within a confined vehicle platform. Specifically, pressure vessels and ancillary components present additional design challenges concerning safety and the allocation of volume.

Furthermore, adding more energy sources on board increases the system's complexity, particularly in control coordination, sensing, and protection. Therefore, while the proposed architecture is technically sound and flexible, its practical use requires a careful balance between performance benefits and the added costs, space limitations, and control complexities.

4. Conclusion

This work presented a comprehensive simulation-based evaluation of a four-source HEV that integrates a LiFePO_4 battery, a proton exchange membrane fuel cell, vehicle-integrated photovoltaics, and a compressed-air energy storage subsystem within a unified MATLAB/Simulink framework. By employing a quad in-wheel hub-motor drivetrain and a rule-based energy management strategy, seven hybrid configurations were systematically compared under identical WLTP Class 2 driving conditions.

The results show that the fuel-cell subsystem is the dominant secondary energy source for range

extension, providing sustained electrical power, stabilizing the DC bus, and enabling charge-sustaining battery operation. When integrated with the battery, the fuel cell significantly extends the projected driving range, exceeding five times that of battery-only operation, thereby validating its appropriateness for long-range HEVs. The battery's role as the principal energy reservoir is indispensable, facilitating the absorption of regenerative braking energy, meeting transient power requirements, and ensuring seamless source coordination.

Vehicle-integrated photovoltaics provide a small but continuous energy source during the day. This leads to a measurable increase in the total distance a vehicle can travel, which is mainly determined by the available surface area, rather than the immediate power produced. Conversely, the compressed-air subsystem offers limited direct range enhancement and is not viable as a primary energy source; however, it provides supplementary advantages in transient support and battery current stabilization.

The fully integrated four-source configuration indicates the greatest overall range and the most equitable energy distribution, thereby illustrating the technical viability and operational benefits of integrating electrochemical, renewable, and pneumatic energy sources within a unified vehicular design. These results are consistent with contemporary scholarly discourse, which highlights system-level hybridization, pragmatic expectations for VIPV, and the use of auxiliary storage for power buffering, as opposed to serving as a primary energy source.

This research provides a structured and comparable evaluation framework for multi-source HEVs, elucidating the practical functions and constraints of each energy source within standardized driving scenarios. The methodology presented here effectively connects theoretical multi-energy architectures with practical vehicle-level performance evaluation.

Future research will prioritize experimental validation of the proposed system through hardware-in-the-loop implementation and prototype development. Furthermore, advanced energy management strategies, including model predictive control and learning-based methodologies, will be explored, with the anticipation of reducing hydrogen consumption

by 10–20% relative to the existing rule-based strategy.

Additional enhancements will concentrate on improving coordination among energy sources, specifically optimizing the interaction between the fuel cell and battery to mitigate transient losses and enhance overall system efficiency by approximately 5–10%. The influence of real-world operating conditions, encompassing solar variability and thermal effects, will also be assessed, with the objective of refining system performance under practical deployment scenarios. These advancements will facilitate the transition from simulation-based evaluation to the real-world implementation of multi-source hybrid electric vehicles.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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The authors declare no competing interest.

Generative AI statement

During the preparation of this work the author used Claude (Anthropic) in order to assist with drafting and language editing of the manuscript text and to generate the figures from the author's own data and computations. All AI-assisted output was subsequently reviewed and, where necessary, edited by the author(s), who takes full responsibility for the final content of the manuscript.

Additional information

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