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Integrated Energy, Economic, and Environmental Assessment of BEVs, FCEVs, and ICEVs Using the Triple-E Efficiency Framework

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Abstract

Vehicle technologies are commonly evaluated using energy consumption, operating cost, and environmental impact as separate indicators, which can lead to conflicting technology rankings. This study applies the Triple-E Efficiency (η_{3e}) framework to integrate energy efficiency (η_e), economic efficiency (η_o), and environmental efficiency (η_v) into a single indicator for comparing battery electric vehicles (BEVs), fuel-cell electric vehicles (FCEVs), and petrol internal combustion engine vehicles (ICEVs). We adopted a functional unit of 1 vehicle-kilometre travelled and equal weighting across the three dimensions. The BEV exhibited the lowest energy consumption (0.547 MJ/km) and operating energy cost (A$0.0504/km). At the same time, the FCEV achieved the highest environmental-efficiency score ($\eta_v = 0.3263$) under the adopted low-emission hydrogen scenario, based on a hydrogen emission factor of 0.60 kg CO_2-e/kg H_2. The resulting (η_{3e}) values were 66.51% for the BEV, 65.56% for the FCEV, and 17.27% for the ICEV, indicating that the BEV achieved the most balanced performance. Sensitivity analysis further indicates that reducing the hydrogen price from the assumed A$15.50/kg to approximately A$14.90/kg would allow the FCEV to achieve an overall η_{3e} comparable to that of the BEV under the assumptions adopted in this study. The study's novelty lies in proposing a unified, adjustable metric that captures energy, economic, and environmental performance and allows for policy-sensitive variables within a common framework. The approach provides a transparent decision-support tool for comparing competing vehicle technologies. However, the present environmental assessment represents an operational energy-supply comparison rather than a complete vehicle life-cycle assessment. The proposed framework can also be applied to other types of energy conversion, generation, and consumption, such as power generation, without any major modification. Future extensions could integrate well-to-wheel or life-cycle environmental inventories and monetised external-cost estimates for energy supply, enabling an evaluation of the environmental dimension alongside energy and economic performance within the Triple-E framework.

Keywords: η_{3e}; Triple-E Efficiency; battery electric vehicle; hydrogen fuel-cell vehicle; internal combustion engine vehicle; vehicle efficiency standards; transport decarbonisation

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1. Introduction

The transport sector is undergoing a fundamental transition driven by concerns over energy security, fuel consumption, greenhouse gas (GHG) emissions, urban air quality, and the economic cost of mobility. Road transport remains heavily dependent on petroleum fuels, while the rapid development of battery electric vehicles (BEVs), hydrogen fuel cell electric vehicles (FCEVs), hybrid vehicles, and other alternative powertrains is reshaping the technological landscape. Consequently, governments are increasingly adopting regulatory standards and economic instruments to improve vehicle efficiency and accelerate the transition towards lower-emission transport. However, these policies generally address energy, environmental, and economic performance through separate mechanisms rather than through a unified measure of overall vehicle efficiency.

Fuel-economy standards are among the principal mechanisms for reducing transport energy consumption. In the United States, the Corporate Average Fuel Economy (CAFE) programme regulates the fuel economy of passenger cars and light trucks at the manufacturer fleet level [1]. Fuel economy is fundamentally an energy-performance criterion because it measures the distance travelled relative to fuel consumed. The standards therefore encourage manufacturers to reduce the amount of fuel required to provide a given transportation service. The U.S. National Highway Traffic Safety Administration (NHTSA), for example, has historically used CAFE standards to improve vehicle fuel economy and reduce petroleum consumption in the country [1].

Australia recently introduced a comparable approach through the New Vehicle Efficiency Standard (NVES). The NVES commenced on 1 January 2025, with compliance requirements applying to covered new vehicles supplied from 1 July 2025 [2]. Rather than prescribing each vehicle's efficiency, the scheme sets average CO_2 Emission targets for the fleets supplied by regulated entities. Manufacturers and suppliers can continue to offer higher-emitting vehicles, but they must balance this by supplying enough more efficient, low-emission, or zero-emission vehicles. The legislated headline limits become progressively more stringent: for Type 1 vehicles, the headline value declines from 141 g CO_2/km in 2025 to 58 g CO_2/km in 2029, while the corresponding Type 2 values decline from 210 to 110 g CO_2/km [3].

Environmental regulation provides another major policy mechanism. While conventional fuel-economy standards primarily reduce fuel consumption, vehicle CO_2 standards directly target environmental performance. For example, the European Union (EU) regulates fleet-wide CO_2 emissions from new passenger cars and vans. The applicable fleet-wide targets for passenger cars are 93.6 g CO_2/km for 2025–2029 and 49.5 g CO_2/km for 2030–2034 under the current regulation [4]. These standards provide a strong regulatory signal for vehicle decarbonisation and have helped increase the deployment of zero-emission powertrains.

Although fuel economy and emission standards address important energy and environmental objectives, economic policy also strongly influences vehicle technology choices. Fuel prices, fuel taxation, subsidies, electricity tariffs, hydrogen prices, purchase incentives, tax exemptions, registration charges, and other fiscal instruments can substantially alter the relative cost competitiveness of different powertrains. This creates an important interaction between engineering efficiency and government policy. A vehicle may show relatively poor energy or environmental performance yet remain economically attractive to consumers because its fuel is subsidised. Conversely, a technically efficient and environmentally favourable technology may remain economically unattractive because of high vehicle purchase prices, expensive energy carriers, or immature supporting infrastructure.

Fuel subsidies provide a particularly clear example of this interaction. Malaysia currently applies a targeted subsidy to RON95 petrol through the subsidised RON95

programme. When the programme commenced in September 2025, eligible Malaysians could purchase RON95 petrol at RM1.99/L, compared with an initially specified non-subsidised price of RM2.60/L, representing a subsidy of RM0.61/L. Such policies reduce the effective operating costs of conventional internal combustion engine vehicles (ICEVs) [5]. Consequently, the economic attractiveness of an ICEV may remain relatively high even when its energy consumption and CO_2 emissions are substantially greater than those of competing low-emission technologies.

The opposite economic intervention takes the form of incentives for low-emission vehicles. China, for example, has used vehicle purchase-tax concessions to promote new-energy vehicles (NEVs), including battery electric, plug-in hybrid, and fuel-cell vehicles. Under the current policy, qualifying NEVs purchased during 2026–2027 receive a 50% reduction in vehicle purchase tax, capped at RMB 15,000 per passenger vehicle [6]. China has also linked eligibility for these concessions to technical requirements, including limits on the electricity consumption of battery-electric passenger vehicles. These measures show how economic incentives and technical efficiency requirements can work together to influence the adoption of vehicle technology.

These examples reveal an important limitation in conventional vehicle-policy assessment. Fuel-economy standards primarily measure energy performance; vehicle emission standards primarily measure environmental performance; and subsidies, taxes, incentives, and ownership costs primarily influence economic performance. Each indicator serves its intended purpose, but none alone captures a transportation technology's overall efficiency or sustainability performance. Consequently, policy conclusions may vary depending on the indicators selected. Although BEVs offer high energy efficiency and zero tailpipe CO_2 emissions, their sustainability remains influenced by electricity sources, battery production, high initial costs, and critical mineral supply chains, highlighting the importance of sustainable resource management and effective mineral policies [7]. A FCEV similarly produces no tailpipe CO_2 during operation and can achieve very low life-cycle emissions when supplied with low-carbon hydrogen; however, hydrogen production, compression, transportation, and conversion involve additional energy losses, while hydrogen production and refuelling costs can reduce its economic competitiveness. Conversely, an ICEV may have relatively low acquisition costs and may benefit from subsidised fuel in some countries. Still, it generally exhibits substantially greater direct fossil-energy consumption and operational CO_2 emissions.

The policy problem can therefore be represented conceptually as follows:

Fuel-economy standard $\rightarrow$ *Energy efficiency*

CO_2/emission standard $\rightarrow$ *Environmental efficiency*

Fuel subsidy, taxation, purchase incentive and operating cost $\rightarrow$ *Economic efficiency*

Energy, economic, and environmental performance are interconnected, and improvements in one dimension do not necessarily enhance the others. For example, BEVs may offer superior energy efficiency, FCEVs supplied with low-carbon hydrogen may achieve lower operational emissions, and ICEVs may retain economic advantages in markets with subsidised fuel. These trade-offs demonstrate the limitations of single-dimensional assessments and support the need for an integrated vehicle-performance indicator.

Another advantage of the η_{3e} framework is that it incorporates weighting variables. The relative weights assigned to energy, economic, and environmental performance can be modified to represent different national circumstances and policy priorities. This characteristic is particularly important because transportation policies vary substantially among countries. A country primarily concerned with petroleum import dependence may place greater importance on energy efficiency; a developing economy facing affordability constraints may place greater emphasis on economic efficiency, while a jurisdiction pursuing

aggressive decarbonisation targets may assign a higher weighting to environmental efficiency. The weighting structure therefore enables η_{3e} to serve not only as an engineering performance indicator but also as a flexible framework for policy analysis.

Economic efficiency is an essential component of the η_{3e} framework because subsidies, taxation, and energy prices can influence vehicle competitiveness without changing underlying technical performance. Incorporating this dimension allows the framework to account for how economic policies influence vehicle-technology selection. The references discuss leading papers on the relationships between energy, environment, and economics [8–11]. The proposed η_{3e} framework complements rather than replaces existing fuel-economy, emissions, and economic policy instruments. By integrating these dimensions, it provides a common analytical basis for evaluating their combined influence on vehicle performance. Table 1 presents the corresponding performance indicators for different engineering applications.

Table 1. Energy, economic, and environmental indicators for potential applications of the η_{3e} framework.

Application	Energy Indicator	Economic Indicator	Environmental Indicator
BEV/ICEV/FCEV	Energy consumption (MJ/km)	Operating cost (A$/km)	GHG emissions (kg CO_2-e/km)
Power plants	Primary energy input (MJ/kWh)	LCOE (A$/kWh)	GHG emissions (kg CO_2-e/kWh)
Solar/wind/storage	Energy input or loss (MJ/kWh)	LCOE/LCOS (A$/kWh)	Life-cycle GHG emissions (kg CO_2-e/kWh)
Desalination	Specific energy consumption (kWh/m^3)	Water production cost (A$/$m^3$)	GHG emissions (kg CO_2-e/m^3)
Buildings	Energy use intensity (kWh/m^2·yr)	Life-cycle cost (A$/$m^2$·yr)	GHG emissions (kg CO_2-e/m^2·yr)
Industrial systems	Specific energy consumption (MJ/unit product)	Production cost (A$/unit product)	GHG emissions (kg CO_2-e/unit product)

2. Methodology

The proposed η_{3e} framework extends the theoretical approach introduced by Mahlia [12] by integrating energy, economic, and environmental performance into a single dimensionless indicator. The methodology defines the three efficiency components, establishes their weighting coefficients and reference benchmarks, and combines them to calculate the overall η_{3e}. A sensitivity analysis is then conducted to evaluate how key input parameters affect the resulting efficiency.

2.1. Basic Concept

This fragmentation creates the need for a more integrated efficiency indicator. The η_{3e} framework addresses this gap by integrating η_e, η_o, and η_v (weighted-energy-, economic-, and environmental-efficiency components) into a single quantitative indicator. Rather than treating energy consumption, economic cost, and environmental impact as independent

criteria, the framework evaluates their combined performance and the trade-offs among these three dimensions. The η_{3e} can therefore be expressed as:

$$\eta_{3e} = f(\eta_e, \eta_o, \eta_v) \tag{1}$$

where

η_{3e} = Triple-E Efficiency;
η_e = energy efficiency;
η_o = economic efficiency;
η_v = environmental efficiency.

Each component represents the evaluated system's relative performance compared with a predefined reference value. Higher performance relative to the reference produces a higher efficiency component, whereas poorer performance produces a lower value. The framework uses weighting coefficients c_e, c_o, and c_v to represent the relative importance assigned to energy, economic, and environmental performance, respectively. To maintain a normalised overall indicator, the weighting coefficients are constrained by:

$$c_e + c_o + c_v = 1 \tag{2}$$

with:

$$0 \leq c_e, c_o, c_v \leq 1 \tag{3}$$

For the baseline vehicle comparison in this study, the three dimensions are assigned equal importance:

$$c_e = c_o = c_v = 1/3 \approx 0.3333 \tag{4}$$

Equal weighting is used as the baseline case because no predefined policy priority is imposed on any one dimension. The weighting structure nevertheless remains adjustable for applications in which energy security, economic affordability, or environmental protection is given greater importance.

2.2. Energy-Efficiency Component

The energy dimension evaluates the actual energy requirement relative to a selected reference energy requirement. The normalised energy-performance score is expressed as:

$$S_e = 1 - \frac{E_p}{E_s} \tag{5}$$

where

E_p = the actual energy consumption per functional unit;
E_s = the reference energy consumption per functional unit.

The weighted energy-efficiency component is:

$$\eta_e = c_e\left(1 - \frac{E_p}{E_s}\right) \tag{6}$$

A lower value of E_p relative to E_s results in a higher energy-efficiency component. When comparing different energy carriers, their consumption is first converted to a common energy basis before applying Equation (6).

2.3. Economic-Efficiency Component

The economic dimension evaluates the operating energy or fuel cost required to deliver the selected functional unit. The actual operating cost is calculated as:

$$Pp = q \times C \tag{7}$$

where

q = the quantity of energy or fuel consumed per functional unit;

C = the corresponding unit energy or fuel price.

The normalised economic-performance score is:

$$\eta_o = c_o\left(1 - \frac{P_p}{P_s}\right) \tag{8}$$

A lower operating cost relative to the reference value therefore produces a higher economic-efficiency component.

2.4. Environmental-Efficiency Component

The environmental dimension evaluates emissions associated with delivering the selected functional unit. The actual environmental impact is calculated as:

$$Gp = q \times EF \tag{9}$$

where

q = the quantity of energy or fuel consumed per functional unit;

EF = the corresponding emission factor.

The normalised environmental-performance score is:

$$S_v = 1 - \frac{G_p}{G_s} \tag{10}$$

where

G_p = the actual emissions per functional unit;

G_s = the selected reference emissions.

The weighted environmental-efficiency component is:

$$\eta_v = c_v\left(1 - \frac{G_p}{G_s}\right) \tag{11}$$

A lower environmental impact relative to the reference value produces a higher environmental-efficiency component.

2.5. Overall Triple-E Efficiency

The weighting coefficients are incorporated directly into the individual energy, economic, and environmental components. Therefore, they are applied only once. The overall Triple-E Efficiency is calculated as:

$$\eta_{3e} = (\eta_e + \eta_o + \eta_v) \tag{12}$$

Substituting the three component equations gives:

$$\eta_{3e} = c_e\left(1 - \frac{E_p}{E_s}\right) + c_o\left(1 - \frac{P_p}{P_s}\right) + c_v\left(1 - \frac{G_p}{G_s}\right) \tag{13}$$

This formulation ensures that each dimension contributes to the final indicator according to its assigned weight and avoids double application of the weighting coefficient as it relates to Equation (2). The theoretical maximum of η_{3e} is 1 (100%) when the three normalised performance scores reach their maximum values. Figure 1 shows the conceptual framework for integrated assessment of vehicle efficiency.

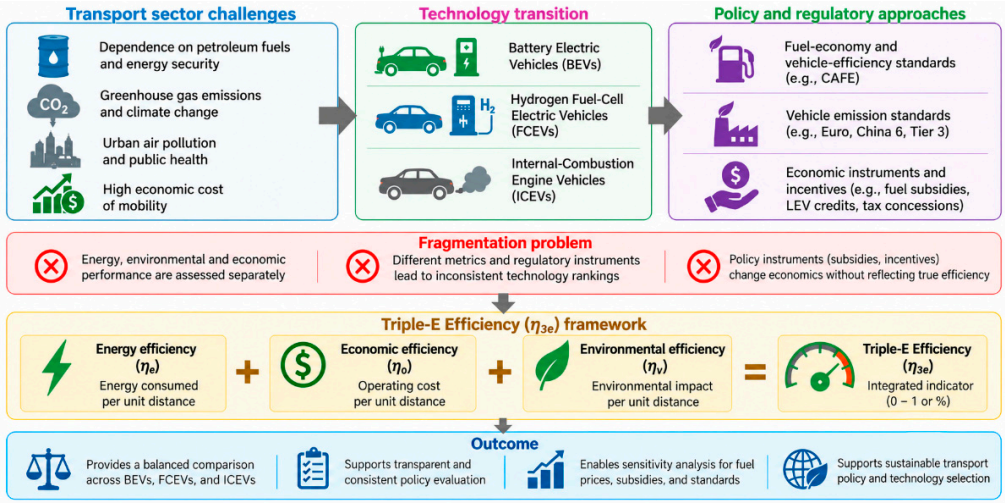


Figure 1. Conceptual framework for integrated assessment of vehicle efficiency. (CAFE = corporate average fuel economy; LEV = low-emission vehicle).

2.6. Sensitivity Analysis Calculations

A one-at-a-time sensitivity analysis is used to evaluate the influence of selected input parameters on the overall Triple-E Efficiency. Each selected parameter is varied independently around its baseline value while all other independent inputs, weighting coefficients, and reference values are held constant. For a generic input parameter X, the perturbed value may be expressed as:

$$X_\delta = X_0\ (1 + \delta) \tag{14}$$

where

X_0 = the baseline parameter value;

δ = the specified fractional variation.

For parameters that influence only one Triple-E dimension, only the corresponding component is recalculated. For energy consumption parameters, however, the consumption affects multiple Triple-E components because consumption enters the energy, operating-cost, and emission calculations simultaneously. Therefore, when a consumption parameter is varied, the modified value is propagated through all relevant downstream calculations before recalculating η_{3e}. The perturbed Triple-E Efficiency is therefore:

$$\eta_{3e,\delta} = (\eta_{e,\delta} + \eta_{o,\delta} + \eta_{v,\delta}) \tag{15}$$

where only those components affected by the selected input parameter are recalculated.

2.7. Quantification of Sensitivity

Sensitivity is quantified as the difference between the perturbed and baseline Triple-E Efficiency:

$$\Delta\eta_{3e} = (\eta_{3e,\delta} - \eta_{3e,0}) \times 100 \tag{16}$$

where

$\eta_{3e,\delta}$ = the Triple-E Efficiency after perturbing one input parameter;

$\eta_{3e,0}$ = the corresponding baseline Triple-E Efficiency.

The sensitivity response is expressed in percentage points, allowing for the direct comparison of the influence of different input parameters.

3. Results and Discussion

This section presents the results and discusses the performance of the BEV, FCEV, and ICEV evaluated using the proposed η_{3e} framework. The analysis first compares the three technologies in terms of energy consumption, operating cost, and GHG emissions, which are subsequently normalised into energy (η_e), economic (η_o), and environmental (η_v) efficiency components. These components are then integrated to determine the overall η_{3e} and establish the relative performance of each vehicle technology. Finally, sensitivity analysis assesses the robustness of the results and identifies the parameters that most influence η_{3e}.

3.1. Triple-E Efficiency (η_3e)

The η_{3e} framework was applied to compare the energy, economic, and environmental performance of a BEV, FCEV, and ICEV. The assessment uses a common functional unit of 1 vehicle-kilometre travelled and equal weighting of the three performance dimensions. The results are presented sequentially by vehicle operating data, energy consumption, operating cost, GHG emissions, individual efficiency components, and the resulting overall η_{3e}.

3.1.1. The Functional Unit and the Vehicle Data

The assessment includes three performance dimensions, as discussed in the methodology, with adjustable weighting variables to reflect different priorities. For this vehicle comparison, equal weighting is adopted because there is no predefined policy requirement to prioritise any one dimension, as the weighting coefficients are normalised such as in Equation (2) and therefore, under equal weighting, it can be written as Equation (4).

Thus, energy, economic, and environmental performance each receive approximately one-third weight. The representative vehicles and operating characteristics used to perform the calculation must be selected first. All three technologies are therefore compared on the same basis:

- BEV: Electricity consumed per kilometre.
- FCEV: Hydrogen consumed per kilometre.
- Petrol ICEV: Petrol consumed per kilometre.

Table 2 presents the representative vehicles and the basic operating data used in the η_{3e} calculation.

Table 2. Basic operating data used for η_{3e} calculation.

Parameter	BEV	FCEV	ICEV
Representative technology	Hyundai Kona Electric	Hyundai NEXO	Hyundai Tucson petrol
Primary energy carrier	Electricity	Hydrogen	Petrol
Consumption	15.2 kWh/100 km	0.706 kg H_2/100 km	7.2 L/100 km
Consumption per km	0.152 kWh/km	0.00706 kg/km	0.072 L/km

According to the literature, Hyundai reports an energy consumption of 15.2 kWh/100 km for the long-range Kona Electric [13]. For the NEXO, an Australian distance test recorded hydrogen consumption of 0.706 kg H_2/100 km [14], whereas the representative petrol vehicle,

the Hyundai Tucson, reports a combined fuel consumption of 7.2 L/100 km [15]. Because electricity, hydrogen, and petrol are measured in different energy units, conversion to a common energy basis for all three vehicle types is required. Therefore, this calculation uses MJ/km to allow for a direct comparison of energy consumption.

3.1.2. Energy Consumption Comparison

Energy consumption represents the first fundamental component of the η_{3e} framework and provides a common basis for evaluating the technical performance of the three vehicle technologies. Because the BEV, FCEV, and ICEV use different energy carriers expressed in different physical units, electricity in kWh, hydrogen in kg, and petrol in litres, their original consumption values cannot be compared directly. Therefore, we converted each vehicle's energy use to a common basis of MJ per vehicle-kilometre (MJ/km) using appropriate energy-conversion factors and lower heating values. This conversion enables a consistent comparison of the energy required to provide the same functional unit: 1 vehicle-kilometre travelled. The resulting energy consumption values are subsequently used to determine the energy-efficiency component (η_e) of the η_{3e} framework and to identify differences in energy performance among the BEV, FCEV, and ICEV. The calculation of the energy consumption comparison is discussed below:

BEV consumption

Electricity consumption per kilometre:

$$E_{EV} = \frac{15.2\ \text{kWh}}{100\ \text{km}} = 0.152 \frac{\text{kWh}}{\text{km}}$$

Using a conversion of 1 kWh = 3.6 MJ, therefore:

$$E_{EV} = 0.152 \frac{\text{kWh}}{\text{km}} \times 3.6\ \text{MJ} = 0.5472 \frac{\text{MJ}}{\text{km}}$$

FCEV hydrogen consumption:

$$E_{FCEV} = \frac{0.706\ \text{kg}\ H_2}{100\ \text{km}} = 0.00706\ \text{kg} \frac{H_2}{\text{km}}$$

Using an approximate lower heating value of hydrogen of 120 MJ/kg, the energy consumption becomes:

$$E_{FCEV} = 0.00706\ \text{kg} \frac{H_2}{\text{km}} \times 120 \frac{\text{MJ}}{\text{kg}} = 0.8472 \frac{\text{MJ}}{\text{km}}$$

ICEV consumption:

Using the fuel economy of 7.2 L/100 km, the fuel consumption per kilometre is as follows:

$$E_{ICEV} = \frac{7.2\ \text{L}}{100\ \text{km}} = 0.072 \frac{\text{L}}{\text{km}}$$

Using an approximate petrol energy content of 34.2 MJ/L, the fuel-energy consumption becomes:

$$E_{ICEV} = 0.072 \frac{\text{L}}{\text{km}} \times 34.2 \frac{\text{MJ}}{\text{L}} = 2.4624 \frac{\text{MJ}}{\text{km}}$$

After converting the original electricity, hydrogen, and petrol consumption data to a common energy basis, Table 3 summarises the energy consumption of the three vehicle technologies in MJ/km, enabling a direct comparison under the same functional unit.

Table 3. Energy consumption comparison of three types of vehicles.

Vehicle	Initial Consumption	Energy Consumption (MJ/km)
BEV	0.152 kWh/km	0.5472
FCEV	0.00706 kg H_2/km	0.8472
ICEV	0.072 L/km	2.4624

The BEV therefore requires the lowest direct energy input per kilometre, followed by the FCEV, whereas the ICEV has substantially higher energy consumption.

3.1.3. Economic Performance Calculation

Economic performance represents the second component of the η_{3e} framework and evaluates the operating energy cost associated with travelling the functional unit of 1 vehicle-kilometre. Unlike the energy comparison, which expresses all energy carriers on a common MJ/km basis, the economic assessment combines the actual consumption of electricity, hydrogen, and petrol with their respective unit prices to determine the operating energy/fuel cost in A$/km. This approach enables a consistent comparison of the economic competitiveness of BEVs, FCEVs, and petrol ICEVs and provides the operating-cost parameter subsequently used to calculate the normalised economic-performance score in Equation (8), where P_p is given in Equation (7). Because energy prices vary geographically and over time, the adopted electricity, hydrogen, and petrol prices are explicitly defined as inputs to the study, as presented in Table 4.

Table 4. Energy-price assumptions.

Energy Carrier	Price Used
Electricity	A$0.3314/kWh
Hydrogen	A$15.50/kg
Petrol	A$1.728/L

The electricity price was set at A$0.3314/kWh, corresponding to the 2026–27 residential flat-rate usage tariff cap for the Ausgrid distribution region, as specified by the Australian Energy Regulator [16]. The hydrogen price was assumed to be A$15.50/kg based on the reported ACT NEXO fleet and Canberra hydrogen-refuelling programme [17]. The petrol price was assumed to be A$1.728/L, representing the reported national average unleaded petrol price for the week ending 26 July 2026, subject to verification against the corresponding Australian Institute of Petroleum (AIP) weekly price report [18]. Therefore, the energy cost can be calculated as follows:

BEV electricity cost

$$P_{EV} = 0.152 \frac{\text{kWh}}{\text{km}} \times 0.3314 \frac{\text{A\$}}{\text{kWh}} = 0.05037 \frac{\text{A\$}}{\text{km}} = 5.04 \frac{\text{cents}}{\text{km}}$$

FCEV fuel cost

$$P_{FCEV} = 0.00706 \frac{\text{kg } H_2}{\text{km}} \times 15.50 \frac{\text{A\$}}{\text{kg } H_2} = 0.10943 \frac{\text{A\$}}{\text{km}} = 10.94 \frac{\text{cents}}{\text{km}}$$

ICEV fuel cost

$$P_{ICEV} = 0.072 \frac{\text{L}}{\text{km}} \times 1.728 \frac{\text{A\$}}{\text{L}} = 0.12442 \frac{\text{A\$}}{\text{km}} = 12.44 \frac{\text{cents}}{\text{km}}$$

Based on the adopted energy prices and vehicle consumption rates, the operating energy/fuel cost per kilometre was calculated for each vehicle. Because the functional unit is defined as 1 vehicle-kilometre travelled, the economic comparison is expressed on a per-kilometre basis (A$/km); therefore, annual mileage and vehicle lifetime are not required for the reported operating-cost calculation. Annual mileage and vehicle lifetime would only be required if the analysis were extended to annualised or lifetime operating costs. Table 5 summarises the resulting costs.

Table 5. Comparison of energy/fuel consumption and operating energy/fuel costs per vehicle-kilometre for BEV, FCEV, and ICEV.

Vehicle	Energy/Fuel Use	Price	Cost (A$/km)
BEV	0.152 kWh/km	0.3314 A$/kWh	0.05037
FCEV	0.00706 kg/km	15.50 A$/kg	0.10943
Petrol ICEV	0.072 L/km	1.728 A$/L	0.12442

The BEV has the lowest operating energy cost, approximately 54% lower than the FCEV and 59.5% lower than the ICEV.

3.1.4. Environmental Performance Comparison

Environmental performance is the third component of the η_{3e} framework and evaluates the GHG emissions associated with travelling 1 vehicle-kilometre. Because the BEV, FCEV, and ICEV use different energy carriers, their environmental impacts are determined by combining the respective energy/fuel consumption with the corresponding emission factor. The resulting emissions are expressed on a common basis of kg CO_2-e/km, enabling a consistent comparison among the three vehicle technologies. These values are subsequently used to calculate the η_v of the Triple-E framework. For the BEV, emissions are based on the NSW/ACT electricity emission factor; for the FCEV, a low-emission renewable hydrogen production scenario is used; and for the ICEV, the operational petrol emission factor is used. For the present illustrative Australian calculation, the NSW electricity factor is used for the BEV. The Australian National Greenhouse Account Factors report an NSW/ACT location-based Scope 2 factor of 0.64 kg CO_2-e/kWh [19].

BEV emissions

$$G_{EV} = 0.152 \frac{\text{kWh}}{\text{km}} \times 0.64 \frac{\text{kg CO}_2 - \text{e/kWh}}{\text{kWh}} = 0.09728 \frac{\text{kg CO}_2 - \text{e}}{\text{km}} = 97.28 \frac{\text{kg CO}_2 - \text{e}}{\text{km}}$$

FCEV emissions

For this calculation, we assume a low-emission renewable hydrogen production intensity of 0.60 kg CO_2-e/kg H_2. This study-defined value falls within the approximately 0.3–0.8 kg CO_2-e/kg H_2 range reported for electrolytic hydrogen produced using renewable electricity [20]. The actual emission intensity depends on the electricity source, hydrogen production technology, and emission-accounting boundary. Based on the adopted value, the FCEV GHG emissions per kilometre are calculated as follows:

$$G_{H_2} = 0.00706 \frac{\text{kg}}{\text{km}} \times 0.60 \frac{\text{kg CO}_2 - \text{e}}{\text{kg H}_2} = 0.004236 \frac{\text{kg CO}_2 - \text{e}}{\text{km}} = 4.24 \frac{\text{g CO}_2 - \text{e}}{\text{km}}$$

Hydrogen's environmental performance depends strongly on its production energy source, and hydrogen emission intensity should include production and relevant post-production emissions.

ICEV emissions

Using an operational petrol emission factor of approximately 2.31 kg CO_2-e/L, the emissions therefore become:

$$G_{ICEV} = 0.072\ \frac{\text{L}}{\text{km}} \times 2.31\ \frac{\text{kg CO}_2 - \text{e}}{\text{L}} = 0.16632 \frac{\text{kg CO}_2 - \text{e}}{\text{km}} = 166.32 \frac{\text{g CO}_2 - \text{e}}{\text{km}}$$

Using the adopted energy/fuel consumption rates and corresponding emission factors, we calculated GHG emissions per kilometre for each vehicle technology. Table 6 summarises the environmental performance of the BEV, FCEV, and ICEV on the common functional basis of 1 vehicle-kilometre travelled.

Table 6. Comparison of energy/fuel consumption, emission factors, and GHG emissions for BEV, FCEV, and petrol ICEV.

Vehicle	Energy/Fuel Consumption	Emission Factor	GHG Emissions
BEV	0.152 kWh/km	0.64 kg CO_2-e/kWh	0.09728 kg CO_2-e/km
FCEV	0.00706 kg/km	0.60 kg CO_2-e/kg H_2 *	0.004236 kg CO_2-e/km
Petrol ICEV	0.072 L/km	2.31 kg CO_2-e/L	0.16632 kg CO_2-e/km

* Study-defined low-emission renewable hydrogen scenario. The adopted hydrogen emission factor of 0.60 kg CO_2-e/kg H_2 falls within the approximately 0.3–0.8 kg CO_2-e/kg H_2 range reported for electrolytic hydrogen produced using renewable electricity, including emissions associated with the manufacture of hydrogen-production units [20]. Actual hydrogen GHG intensity varies with the electricity source, hydrogen production technology, and emissions-accounting system boundary.

3.1.5. Selection of Standard/Reference Values

To provide a consistent normalisation basis and avoid assigning zero efficiency automatically to the worst-performing vehicle, fixed external reference values were adopted for the three performance dimensions. The paper explains that the standard cost and standard environmental impact serve as benchmark/reference parameters in the calculation. Therefore, this comparative study adopts fixed external calculation benchmarks. Table 7 presents the reference benchmark values adopted for the η_{3e} assessment of vehicle technologies.

Table 7. Reference benchmark values adopted for the Triple-E Efficiency assessment of vehicle technologies.

Indicator	Symbol	Standard
Energy consumption	E_s	3.00 MJ/km
Operating cost	P_s	A$0.150/km
GHG emissions	G_s	0.200 kg CO_2-e/km

These are study-defined normalisation/reference limits, not official Australian regulatory thresholds. They are deliberately set above all three actual observations so that each vehicle obtains a positive efficiency value, while poorer performance results in a lower efficiency score. This should be stated explicitly in the report to avoid presenting them as government standards.

3.1.6. Energy Efficiency Calculation

Energy efficiency represents the first normalised performance component of the η_{3e} framework. It evaluates each vehicle according to its energy consumption per kilometre relative to the adopted reference energy consumption of 3.00 MJ/km. Using an equal

weighting factor of 0.3333, vehicles with lower energy consumption receive a higher energy-efficiency score, whereas those with higher energy requirements receive a lower score. This approach expresses the energy performance of the BEV, FCEV, and ICEV on a common dimensionless basis for subsequent integration with the economic and environmental efficiency components. The vehicle energy-efficiency component is written as:

BEV energy efficiency,

$$\eta_{e,EV} = 0.3333\left(1 - \frac{0.5472}{3.00}\right) = 27.25\%$$

FCEV energy efficiency,

$$\eta_{e,EV} = 0.3333\left(1 - \frac{0.8472}{3.00}\right) = 23.92\%$$

ICEV energy efficiency,

$$\eta_{e,EV} = 0.3333\left(1 - \frac{2.4624}{3.00}\right) = 5.97\%$$

Using the adopted reference energy consumption and equal weighting factor, we calculated the η_e for each vehicle technology. Table 8 summarises the resulting energy-efficiency values.

Table 8. Energy-efficiency (η_e) results for the BEV, FCEV, and petrol ICEV.

Vehicle	E_p (MJ/km)	E_s	Weight	η_e
BEV	0.5472	3.000	0.3333	0.2725
FCEV	0.8472	3.000	0.3333	0.2392
Petrol ICEV	2.4624	3.000	0.3333	0.0597

3.1.7. Economic Efficiency Calculation

Economic efficiency is the second normalised component of the η_{3e} framework and evaluates each vehicle's operating energy/fuel cost relative to the adopted reference cost of A$0.150/km. Using an equal economic weighting factor of 0.3333, vehicles with lower operating costs achieve higher economic-efficiency scores. The actual costs calculated for the BEV, FCEV, and ICEV are therefore normalised against the same reference value, allowing for the comparison of their economic performance on a common dimensionless basis. The resulting η_o is subsequently integrated with the energy and environmental efficiency components to determine the overall η_{3e}. The vehicle economic-efficiency component is written as:

BEV economic efficiency,

$$\eta_{o,EV} = 0.3333\left(1 - \frac{0.0503728}{0.150}\right) = 22.14\%$$

FCEV economic efficiency,

$$\eta_{o,H_2} = 0.3333\left(1 - \frac{0.10943}{0.150}\right) = 9.02\%$$

ICEV economic efficiency,

$$\eta_{o,ICEV} = 0.3333\left(1 - \frac{0.124416}{0.150}\right) = 5.69\%$$

Using the adopted reference operating cost and the equal economic weighting factor, we calculated the η_o for each vehicle technology. Table 9 summarises the resulting economic-efficiency values, enabling a direct comparison among the BEV, FCEV, and petrol ICEV.

Table 9. Economic-efficiency (η_o) results for the BEV, FCEV, and ICEV based on the adopted reference operating cost and equal weighting factor.

Vehicle	Operating Cost, P_p (A$/km)	Reference Cost, P_s (A$/km)	Weight	Weighted Economic Efficiency, η_o
BEV	0.05037	0.150	0.3333	0.2214
FCEV	0.10943	0.150	0.3333	0.0902
ICEV	0.12442	0.150	0.3333	0.0568

3.1.8. Environmental Efficiency Calculation

Environmental efficiency represents the third normalised performance component of the η_{3e} framework. It evaluates each vehicle according to its GHG emissions per kilometre relative to the adopted reference value of 0.200 kg CO_2-e/km. Using an equal environmental weighting factor of 0.3333, vehicles with lower GHG emissions achieve higher environmental efficiency scores, while those with higher emissions achieve lower scores. This normalisation enables a comparison of the environmental performance of the BEV, FCEV, and ICEV on a common dimensionless basis and subsequent integration with the energy and economic efficiency components to determine the overall η_{3e}. The vehicle's environmental-efficiency component is as follows:

BEV environmental efficiency,

$$\eta_{v,EV} = 0.3333\left(1 - \frac{0.09728}{0.200}\right) = 17.12\%$$

FCEV environmental efficiency,

$$\eta_{v,H_2} = 0.3333\left(1 - \frac{0.004236}{0.200}\right) = 32.63\%$$

ICEV environmental efficiency,

$$\eta_{v,ICEV} = 0.3333\left(1 - \frac{0.16632}{0.200}\right) = 5.61\%$$

Using the adopted reference GHG emission value and the equal environmental weighting factor, we calculated the η_v for each vehicle technology. Table 10 summarises the resulting environmental efficiency values for the BEV, FCEV, and petrol ICEV.

Table 10. Environmental efficiency (η_v) results for the BEV, FCEV, and petrol ICEV, based on the adopted reference GHG emissions and an equal weighting factor.

Vehicle	GHG Emissions, G_p (kg CO_2-e/km)	Reference GHG Emissions, G_s	Weight	η_v
BEV	0.09728	0.200	0.3333	0.1712
FCEV	0.004236	0.200	0.3333	0.3263
ICEV	0.16632	0.200	0.3333	0.0561

3.1.9. Triple-E Efficiency Calculation

The η_{3e} represents the integrated performance indicator of the proposed framework, combining the previously calculated η_e, η_o, and η_v into a single measure. This integration enables the assessment of the overall performance of BEVs, FCEVs, and petrol ICEVs while simultaneously accounting for energy consumption, operating costs, and GHG emissions. Under the equal-weighting approach adopted in this study, the three underlying efficiency dimensions contribute equally to the final η_{3e} value through their respective weighting coefficients. This indicator provides a common basis for comparing the overall performance of the three vehicle technologies and identifying trade-offs among their energy, economic, and environmental characteristics.

Because the weighting coefficients are incorporated into the individual efficiency components, the weights are applied only once in the Triple-E calculation. Thus, η_e, η_o, and η_v represent the already weighted energy, economic, and environmental efficiency components, respectively. The overall η_{3e} is therefore obtained by summing these three components withr out an additional weighting operation, as given in Equation (12). Under equal weighting ($c_e = c_o = c_v = 1/3$), the maximum value of η_{3e} is 1 (100%), which occurs when the three underlying unweighted efficiency measures each equal 1. Therefore, the overall η_{3e} for each vehicle technology is as follows:

BEV Triple-E Efficiency,

$$\eta_{3e,\,EV} = (0.2725 + 0.2214 + 0.1712) = 66.51\%$$

FCEV Triple-E Efficiency,

$$\eta_{3e,\,FCEV} = (0.2392 + 0.0902 + 0.3263) = 65.56\%$$

ICEV Triple-E Efficiency,

$$\eta_{3e,\,ICEV} = (0.0597 + 0.0568 + 0.0561) = 17.27\%$$

After integrating the energy, economic, and environmental efficiency components, we determined the overall η_{3e} for each vehicle technology. Table 11 summarises the individual efficiency components and the resulting η_{3e} values, enabling an integrated comparison of the BEV, FCEV, and petrol ICEV. Figure 2 presents the overall η_{3e} comparison of the BEV, FCEV, and ICEV.

Table 11. Overall η_{3e} results for the BEV, FCEV, and ICEV based on the integration of energy, economic, and environmental efficiency components.

Vehicle Type	Energy Efficiency (η_e)	Economic Efficiency (η_o)	Environmental Efficiency (η_v)	Triple-E Efficiency (η_{3e})
BEV	0.2725	0.2214	0.1712	66.51%
FCEV	0.2392	0.0902	0.3263	65.56%
Petrol ICEV	0.0597	0.0568	0.0561	17.27%

Overall, the three vehicle technologies exhibited distinct performance profiles across the three dimensions of the η_{3e} framework. The BEV achieved the highest overall η_{3e} (66.51%) because of its strong energy and economic performance, whereas the FCEV achieved the highest environmental-efficiency component (η_v = 0.3263) but was constrained by its comparatively higher energy requirement and hydrogen cost. The ICEV performed substantially lower across all three dimensions under the adopted reference conditions. The

relatively small difference between the BEV and FCEV overall η_{3e} values (0.95 percentage points in absolute efficiency) highlights the importance of energy-supply characteristics and operating costs in determining their integrated performance.

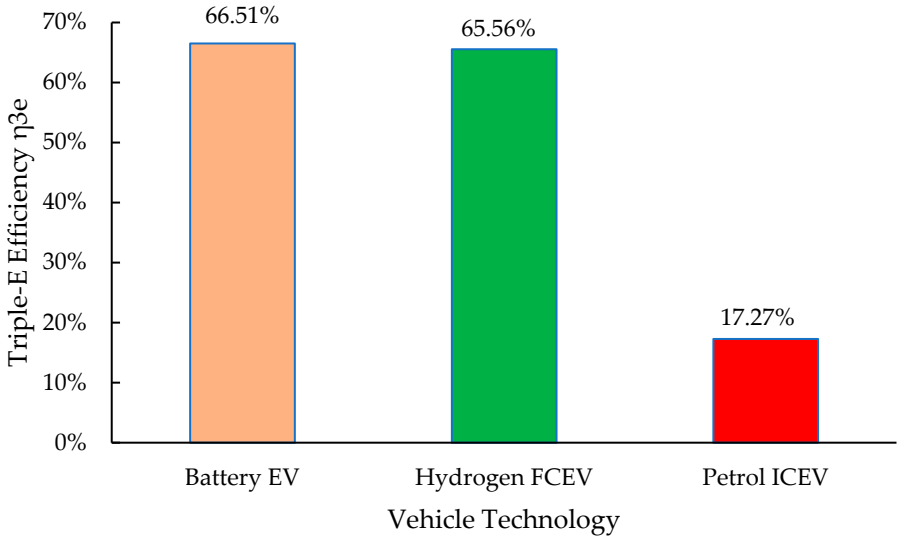


Figure 2. Overall Triple-E Efficiency (η_{3e}) comparison of the BEV, FCEV, and petrol ICEV.

Based on the calculated overall η_{3e}, the three vehicle technologies were ranked by integrated performance. Table 12 presents the resulting ranking. The BEV achieved the highest overall η_{3e} because it combined energy and economic efficiency. Its energy consumption was approximately 0.547 MJ/km, compared with 0.847 MJ/km for the FCEV and 2.462 MJ/km for the petrol ICEV, resulting in the highest energy-efficiency component (ηe = 0.2725). Similarly, the BEV recorded the lowest operating energy cost at approximately A$0.0504/km, compared with A$0.1094/km for the FCEV and A$0.1244/km for the ICEV, resulting in the highest economic-efficiency component (η_o = 0.2214). These advantages compensated for its lower environmental-efficiency component relative to the FCEV.

Table 12. Ranking of the BEV, FCEV, and ICEV based on overall Triple-E Efficiency (η_{3e}).

Rank	Vehicle Type	Triple-E Efficiency (η_{3e})
1	BEV	66.51%
2	FCEV	65.56%
3	ICEV	17.27%

In contrast, the FCEV demonstrated the strongest environmental performance under the adopted low-emission hydrogen scenario. Its operational emissions were approximately 0.00424 kg CO_2-e/km, resulting in an environmental-efficiency value of 0.3263, substantially higher than those of the BEV (0.1712) and ICEV (0.0561). However, this environmental advantage was offset by its higher energy requirement and, particularly, its hydrogen cost, which reduced its economic-efficiency component to 0.0902. Consequently, despite achieving the highest environmental-efficiency score, the FCEV did not achieve the highest overall η_{3e}. This result demonstrates the trade-off inherent in the η_{3e} framework, whereby superior environmental performance does not necessarily translate into superior integrated performance when energy and economic dimensions are considered simultaneously.

Meanwhile, the petrol ICEV ranked third across all three dimensions, with an energy requirement of 2.462 MJ/km, an operating fuel cost of approximately A$0.1244/km, and operational emissions of approximately 0.166 kg CO_2-e/km. These values resulted in comparatively low energy, economic, and environmental efficiency components of 0.0597,

0.0568, and 0.0561, respectively, giving an overall η_{3e} of only 17.27%. The consistently lower performance of the ICEV across all three dimensions contrasts with the more balanced performance profiles of the BEV and FCEV.

Importantly, the results should not be interpreted as indicating that FCEVs inherently have lower overall sustainability performance than BEVs. Rather, the results demonstrate that the integrated performance of an FCEV is strongly dependent on the characteristics of its hydrogen supply pathway. Under the low-emission hydrogen scenario adopted in this study, the FCEV achieved the highest environmental-efficiency component (η_v = 0.3263), substantially exceeding the BEV (η_v = 0.1712). However, this environmental advantage was offset by the FCEV's lower energy-efficiency and economic-efficiency components, particularly its higher hydrogen cost. The resulting overall η_{3e} values of 65.56% for the FCEV and 66.51% for the BEV indicate that the two technologies have relatively similar integrated performance under the baseline assumptions, despite their contrasting performance profiles. This finding highlight that the environmental performance of low-emission vehicles cannot be considered independently of the energy system supplying them. Changes in hydrogen production pathways, hydrogen carbon intensity, and hydrogen price could substantially alter the relative performance of FCEVs, while changes in electricity-generation pathways and electricity prices could similarly affect BEV performance. The η_{3e} framework therefore captures vehicle performance as a system-dependent outcome, rather than treating the environmental performance of a vehicle technology as an intrinsic and fixed characteristic.

3.2. Sensitivity Analysis

The sensitivity analysis evaluates how changes in key input parameters influence the overall Triple-E Efficiency, η_{3e}, of the BEV, FCEV, and petrol ICEV. A one-at-a-time sensitivity approach was applied in which each selected parameter was varied independently by ±20% relative to its baseline value, while all other input parameters, weighting coefficients, and reference values were held constant. For vehicle-consumption parameters, we propagated the change in consumption through the corresponding energy-use, operating-cost, and GHG-emission calculations before recalculating the overall η_{3e}. This differs from varying the three efficiency dimensions independently, because only one physical input parameter is perturbed at a time.

Table 13 shows that petrol consumption is the most influential parameter in the sensitivity analysis. A 20% reduction in ICEV petrol consumption from 7.20 to 5.76 L/100 km increases ICEV η_{3e} by about 16.55 percentage points, whereas a 20% increase to 8.64 L/100 km reduces it by about 16.55 percentage points. The comparatively large response arises because petrol consumption simultaneously determines the ICEV's fuel-energy requirement, operating fuel cost, and operational GHG emissions. Consequently, improving ICEV fuel economy affects all three components of the Triple-E framework rather than a single dimension only. The corrected Table 13 identifies this parameter as the dominant sensitivity factor.

The next most influential inputs are FCEV hydrogen consumption and BEV electricity consumption. A ±20% variation in hydrogen consumption produces an approximately ±6.89 percentage-point change in FCEV η_{3e}, while the same proportional variation in BEV electricity consumption changes BEV η_{3e} by approximately ±6.70 percentage points. As with petrol consumption, these parameters affect several Triple-E components simultaneously. Lower hydrogen consumption improves the FCEV's energy efficiency, reduces hydrogen expenditure per kilometre, and lowers hydrogen-related emissions. Similarly, lower electricity consumption improves the BEV's energy-efficiency component while simultaneously reducing electricity cost and electricity-associated emissions. These results indicate that improvements in vehicle energy demand can generate simultaneous energy,

economic, and environmental benefits. Among the environmental parameters, the petrol GHG emission factor has the largest effect. A ±20% variation in the baseline petrol emission factor of 2.31 kg CO_2-e/L changes the ICEV η_{3e} by approximately ±5.54 percentage points. The electricity GHG factor produces a smaller but still meaningful effect of approximately ±3.24 percentage points for the BEV. In contrast, the hydrogen GHG factor changes the FCEV η_{3e} by only approximately ±0.14 percentage points. This comparatively small response reflects the very low baseline hydrogen GHG intensity adopted in the low-emission renewable-hydrogen scenario. The baseline environmental factors are 0.64 kg CO_2-e/kWh for electricity, 0.60 kg CO_2-e/kg H_2 for hydrogen, and 2.31 kg CO_2-e/L for petrol.

Table 13. Sensitivity of η_{3e} to ±20% variations in key input parameters.

Input Parameter	Baseline Value	−20% Variation	+20% Variation	Change in η_{3e}
Petrol consumption (ICEV), L/100 km	7.20	5.76	8.64	±16.54
Hydrogen consumption (FCEV), kg/km	0.00706	0.005648	0.008472	±6.89
BEV electricity consumption, kWh/km	0.152	0.1216	0.1824	±6.70
Petrol GHG factor, kg CO_2-e/L	2.31	1.848	2.772	±5.54
Petrol price (ICEV), A$/L	1.728	1.3824	2.0736	±5.53
Hydrogen price, A$/kg	15.50	12.40	18.60	±4.86
Electricity GHG factor, kg CO_2-e/kWh	0.64	0.512	0.768	±3.24
Electricity price, A$/kWh	0.3314	0.26512	0.39768	±2.24
Hydrogen GHG factor, kg CO_2-e/kg H_2	0.60	0.48	0.72	±0.14

The sensitivity analysis also demonstrates the importance of energy-carrier prices. A ±20% variation in petrol price changes the ICEV η_{3e} by approximately ±5.53 percentage points, making petrol price the most influential purely economic parameter considered. Hydrogen price produces an approximately ±4.86 percentage-point variation in FCEV η_{3e}, whereas electricity price produces a smaller change of approximately ±2.24 percentage points in BEV η_{3e}. These results reflect differences in the baseline operating-energy costs of the three vehicles. The BEV has the lowest baseline operating energy cost of approximately A$0.05037/km, compared with A$0.10943/km for the FCEV and A$0.12442/km for the ICEV. Although hydrogen price is not the largest sensitivity parameter overall, it remains particularly important for the relative ranking of the BEV and FCEV because their baseline Triple-E Efficiency values are very close. Under the baseline assumptions, the BEV achieves an η_3e of 66.51%, while the FCEV achieves approximately 65.56%. Reducing the hydrogen price from A$15.50/kg to approximately A$14.90/kg is sufficient for the FCEV to achieve an overall η_{3e} comparable to that of the BEV under the adopted assumptions. Consequently, the BEV–FCEV ranking should not be interpreted as fixed; rather, it is sensitive to the hydrogen supply cost and other upstream energy-system conditions.

For vehicle-consumption parameters, the ±20% variation was applied once to the consumption input parameter. Because consumption directly enters the energy-use, operating-cost, and GHG-emission calculations, the resulting change was propagated deterministically through the corresponding η_e, η_o, and η_v calculations. Thus, the reported change in η_{3e} represents the combined downstream effect of a single ±20% perturbation of the consumption parameter, rather than independent variations in the three Triple-E dimensions. The tornado diagram in Figure 3 presents the sensitivity parameters in descending order of their absolute effect on η_{3e}, highlighting petrol consumption as the most influential

input, followed by hydrogen consumption and BEV electricity consumption. The ranking illustrates the relative importance of vehicle energy demand, energy-carrier prices, and GHG emission factors in determining the overall Triple-E Efficiency.

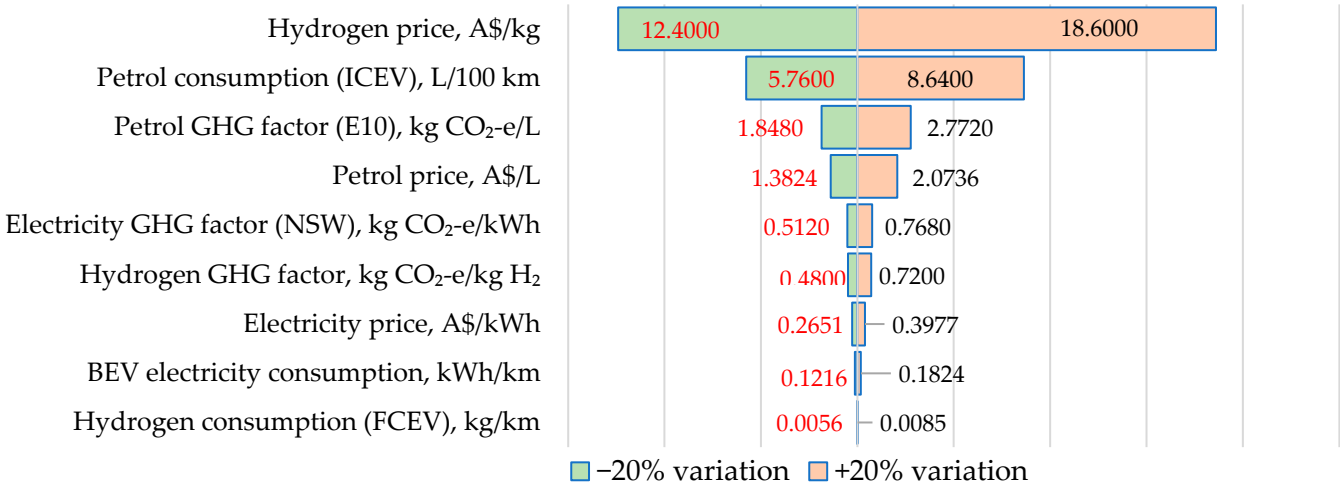


Figure 3. Sensitivity of Triple-E Efficiency (η_{3e}) to ±20% variations in key input parameters, ranked in descending order of their absolute effect on η_{3e}.

4. Conclusions

This study applied the η_{3e} framework to compare the energy, economic, and environmental performance of a BEV, hydrogen FCEV, and petrol ICEV using a common functional unit of 1 vehicle-kilometre. Under the equal-weighting approach and the reference conditions adopted in this study, the BEV achieved the highest overall η_{3e} of 66.51%, followed closely by the FCEV at 65.56%, while the petrol ICEV recorded substantially lower performance at 17.27%. These results demonstrate that integrating energy, economic, and environmental dimensions provides a more comprehensive basis for vehicle comparison than considering any single performance indicator independently.

The BEV achieved the highest energy-efficiency (η_e = 0.2725) and economic-efficiency (η_o = 0.2214) components, primarily due to its comparatively low energy consumption of 0.547 MJ/km and operating energy cost of A$0.0504/km. In contrast, the FCEV achieved the highest environmental-efficiency component (η_v = 0.3263), based on the low-emission hydrogen scenario adopted in this study. However, its higher energy requirement and hydrogen cost reduced its economic and overall performance. The ICEV recorded the lowest efficiency across all three dimensions, resulting in an overall η_{3e} of only 17.27%. The results therefore demonstrate the trade-offs among energy, economic, and environmental performance that are captured by the Triple-E framework.

The sensitivity analysis further demonstrated that the relative performance of the BEV and FCEV is conditional on the adopted input parameters, particularly hydrogen price. At the baseline hydrogen price of A$15.50/kg, the FCEV achieved an η_{3e} of 65.56%, compared with 66.51% for the BEV. Reducing the hydrogen price to approximately A$14.90/kg resulted in an η_{3e} comparable to that of the BEV under the assumptions of this study. This finding indicates that hydrogen cost is an important determinant of FCEV competitiveness, although the identified crossover should be regarded as scenario-specific rather than as a universal threshold. The sensitivity analysis also showed that petrol consumption was the most influential parameter for the ICEV, with a ±20% variation resulting in a change of approximately ±16.54 percentage points in its overall η_{3e}.

Overall, the findings demonstrate that the Triple-E framework can identify technology-specific trade-offs while integrating energy consumption, operating cost, and environmental

performance into a single adjustable indicator. The results support the use of the framework as a comparative screening tool for vehicle technologies under specified energy-supply and economic conditions. However, the present assessment represents an operational energy-supply comparison rather than a full life-cycle assessment, and the environmental system boundaries are not fully harmonised across the three vehicle technologies. Future applications should therefore incorporate consistent well-to-wheel or life-cycle inventories, including vehicle manufacturing, battery and fuel-cell production, upstream energy and fuel production, infrastructure, maintenance, and end-of-life stages. Further assessment of the study-defined reference benchmarks and upstream energy-supply assumptions would also improve the robustness and transferability of the η_{3e} framework.

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Nomenclatures

Symbol	Definition
E_p	Actual vehicle energy consumption (MJ/km)
Es	Reference energy consumption (MJ/km)
BEV	Battery Electric Vehicle
$FCEV$	Fuel Cell Electric Vehicle
$ICEV$	Internal Combustion Engine Vehicle
P_p	Actual operating energy/fuel cost (A$/km)
P_s	Reference operating cost (A$/km)
G_p	Actual GHG emissions (kg CO_2-e/km)
G_s	Reference GHG emissions (kg CO_2-e/km)
c_e	Energy weighting coefficient (0–1)
c_o	Economic weighting coefficient (0–1)
c_v	Environmental weighting coefficient (0–1)
η_e	Weighted energy-efficiency component
η_o	Weighted economic-efficiency component
η_v	Weighted environmental-efficiency component

η_{3e}	Overall Triple-E Efficiency
Wp	Energy wasted from the system
Ws	Energy input to the system

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