

A Data Analysis and Comparison of Traditional and Alternative Powertrains in Motorsport

Hannah Zou

hannahzpiano@gmail.com

West Windsor Plainsboro High School North, Plainsboro, NJ, United States

ABSTRACT

Motorsport has depended on internal combustion engines (ICEs) for decades, but growing concerns about energy efficiency and environmental impact have increased interest in alternative powertrain technologies. This paper compares internal combustion engine (ICE), battery-electric vehicle (BEV), and hydrogen fuel-cell electric vehicle (FCEV) powertrains in motorsport. The three powertrains are evaluated according to well-to-wheels and powertrain efficiency, energy replenishment, environmental impact, economic factors, and regulatory development. Published data are collected and analyzed to quantify well-to-wheels energy consumption, greenhouse gas (GHG) emissions, and thermodynamic efficiency, with comparisons also made between motorsport and conventional vehicles to examine how the distinct performance requirements of motorsport affect powertrain efficiency and environmental impact. For the selected racing cases, BEVs and FCEVs exhibit approximately 42.4% and 47.6% of the WTW energy consumption of ICEs, respectively, while their estimated WTW GHG emissions are 21.5% and 3.25% of those of ICEs under the selected upstream energy pathways. The analysis shows that ICEs offer well-proven high-performance characteristics and fast refueling, but they have a lower energy-conversion efficiency and produce direct GHG emissions. BEVs offer highly efficient electric propulsion together with regenerative braking; however, limited capacity of battery energy storage and the demand for charging remain significant challenges. FCEVs combine electric propulsion with hydrogen energy storage, but currently they suffer from additional energy-conversion losses, substantial infrastructure demands, and difficulties in production. The future use of these powertrains will depend on the specific requirements of racing, technological developments, regulations, manufacturing infrastructure, and the energy sources employed in producing electricity, fuels, and hydrogen.

Keywords: Motorsport, Internal combustion engines, Battery electric vehicles, Fuel-cell electric vehicles, Well-to-wheels analysis, GHG emissions, Powertrain efficiency

Introduction

The majority of vehicles we see on the road today use gasoline or diesel internal combustion engines, or ICEs. The development of the ICE started with Nikolaus Otto's 1876 invention of the single-cylinder four stroke coal-powered engine, which was especially revolutionary because it was two to three times more efficient and had a much larger operation radius than the traditional steam-powered engine, and could start instantaneously. Over time, with many upgrades, Otto's four stroke engine gradually became the modern ICE, which is still the dominant automotive power source today¹.

Despite its longstanding presence in vehicles, ICEs are facing growing challenges concerning energy efficiency and environmental impact. More than 15% of total greenhouse gas emissions in the United States are released just by ICE-containing Light Duty Vehicles, such as passenger cars and small trucks. These emissions have been proven to be deadly to humans and the resulting air pollution is projected to cause between 6 and 9 million deaths a year by 2060. An analysis conducted by Ahmed et al. found that a lifetime 11.8 tons of emissions were released by one ICE vehicle. In addition to directly releasing greenhouse gases, ICE vehicles are relatively inefficient in many areas. They have a 12-30% tank-to-wheel efficiency; only a small amount of the fuel is actually being turned into power for the wheels². Overall, these environmental and efficiency issues demonstrate the need for alternative powertrains.

Historically, motorsport vehicles have depended heavily on ICEs. Internal combustion engines have been used in motorsport for decades, as high power output is essential to vehicle performance; in modern motorsport, combustion engines produce approximately 440–630 kW of power. However, this high power also comes with a cost: motorsport's historical reliance on fossil fuels contributes to greenhouse gas emissions and other environmental concerns³.

Formula 1, known as the “pinnacle of motorsport,” has served as an environment for new gasoline powertrain experimentation, and its innovative solutions have been implemented throughout the commercial automotive industry as well. Its rules and regulations have continued to evolve from traditional fully gas-powered ICEs to incorporate hybridized mechanisms³. As of 2025, Formula 1's Net Zero pledge to carbon neutrality by 2030 has already seen a 26% reduction in its carbon footprint compared with its 2018 baseline⁴. The new powertrain regulations ahead of the current 2026 season included a requirement for all teams to use Advanced Sustainable Fuels, which are sourced from carbon-capture, local waste, and biomass⁵. As a result of the new regulations, Formula 1's footprint is likely to diminish further.

In contrast, Formula E, a racing series established in 2014, was built entirely around sustainable battery-electric vehicles (BEVs). The Fédération Internationale de l'Automobile (FIA), which oversees Formula E, states that the goal of this series is to accelerate net zero transformation, foster sustainable and innovative solutions, and drive sustainable change⁶. Compared to ICE vehicles, battery-electric vehicles have a higher energy efficiency and zero direct tailpipe emissions. However, their overall

environmental impact depends on factors such as the source of the electricity used for charging⁷. Further limitations to the widespread adoption of BEVs in motorsport include battery capacity, range, and charging requirements.

Lastly, though less common, green hydrogen has also been proposed as an alternative to fossil fuels for motorsport in the Middle East and North Africa Region (MENA)⁸. Hydrogen fuel-cell vehicles (FCEVs) generate electricity through a reaction between hydrogen and oxygen that have no direct GHG emissions. Compared with ICEs and BEVs, hydrogen vehicles also take less time to refuel and have longer driving ranges. However, their usage is limited by high costs, few hydrogen stations, and the large amount of energy required to produce hydrogen⁷. Furthermore, hydrogen generated using renewable electricity produces less emissions than hydrogen derived from fossil fuels, so green hydrogen has also been an option for a component of Formula 1's transition toward greater sustainability, although its application within F1 remains relatively new⁸.

Though each engine has its own advantages against the others, there is no single universal environment-friendly powertrain that fits for all forms of motorsport. The goal of this paper is to compare the benefits and limitations of three possible powertrain options for motorsport: internal combustion, battery-electric and fuel-cell powertrains. They will be evaluated based on the following dimensions: well-to-wheels analysis, thermodynamic performance, and environmental impact. Well-to-wheels analysis entails studying the total emissions and energy use in the whole journey from extracting the fuel to the vehicle usage. Thermodynamic performance stands for the efficiency at which each powertrain converts its fuel into mechanical energy. And finally, the environmental impact measures the footprint, both direct and indirect, that the powertrain has induced across its whole lifecycle. This comparison of powertrains will help to determine the best path forward for a more sustainable future in motorsport.

Methods

Well-to-Wheels Energy Consumption and GHG Emissions

WTW analysis combines well-to-tank (WTT) emissions from producing and delivering an energy carrier with tank-to-wheel (TTW) emissions from using that energy onboard the vehicle. The JEC Well-to-Wheels framework⁹ is used to standardize the upstream pathways. For each powertrain, the same selected energy pathway is applied to the ordinary and race vehicle so that the effect of race energy consumption and GHG emissions could be compared consistently.

Under the JEC framework, the WTW energy consumption is defined as
$$\text{WTW energy consumption (MJ/km)} = \text{TTW energy consumption (MJ/km)} \cdot (1 + \text{WTT expended energy (MJ/MJ fuel)})$$
,
where the WTT expended energy factor represents upstream energy expenditure per unit of delivered energy and excludes the energy content delivered to the vehicle.

The WTW GHG emission is defined as

$$\text{WTW GHG emission (g CO}_2\text{ eq/km)} = \text{TTW GHG emission (g CO}_2\text{ eq/km)} + \text{TTW energy consumption (MJ/km)} \cdot \text{WTT GHG (g CO}_2\text{ eq/ MJ fuel)}$$

The JEC WTW framework publishes data for energy consumption and GHG emissions for ordinary vehicles as well as the upstream pathway expended energy and GHG emission factors.

Published motorsport data for gasoline, electricity, and hydrogen consumption are used for the ICEV, BEV, and FCEV analyses, respectively^{10,11,12}.

In Summa et al.¹⁰, the TTW gasoline consumption of ICE cars in three motorsport races are reported together with the gasoline's low heating value (LHV). The TTW energy consumption $E_{\text{TTW,ICE}}$ is calculated as

$$E_{\text{TTW,ICE}} = \text{average of the gasoline consumption} \times \text{LHV} / \text{distance of the race}$$

Ros et al.¹¹ reports 635 kWh of charging electricity over the assumed 2,000-km life of eVarta. The electricity consumption per km can be converted to TTW energy consumption and further to WTW energy consumption through the JEC framework. The only GHG emission contribution comes from the WTT stage whose value can be evaluated as TTW energy consumption x WTT GHG by the JEC framework.

David et al.¹² models a Formula Student endurance event in a simulation and calculates H₂ consumption of 16.4 g for one approximately 1-km lap. Using H₂ LHV, the TTW energy consumption is estimated. Similarly to ICE and BEV, the WTW energy consumption and GHG emission can be calculated through the JEC framework.

Powertrain Thermodynamic Efficiency

Unlike well-to-wheels efficiency, powertrain thermodynamic efficiency measures the fraction of onboard stored energy converted into useful mechanical output. ICEs lose a substantial portion of fuel energy through heat and other losses, while electric motors convert much more electrical energy into mechanical power. Thermodynamic efficiency is evaluated using TTW efficiency, $\eta_{\text{TTW}} = (\text{useful mechanical energy} / \text{stored onboard energy}) \times 100\%$. Racing raises energy demand primarily through high-power acceleration, aerodynamic drag at higher speeds, tire losses, braking, and other performance demands, rather than simply through a large reduction in conversion efficiency. However, the TTW efficiency does not necessarily increase accordingly. Published data for TTW efficiency is collected through various sources to compare the energy conversion for ordinary and motorsport vehicles with the three powertrains.

Results

Data of WTW energy consumption and GHG emissions

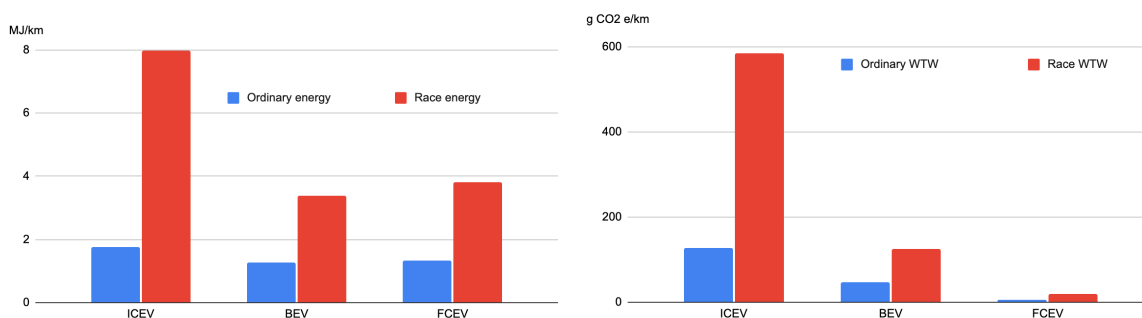
WTW energy consumption and GHG emissions data are listed in Table 1 and plotted in Figure 1 for the three types of powertrains in ordinary and motorsport vehicles. For the selected racing cases, the motorsport vehicles have greater WTW emissions per kilometer than their ordinary counterparts because they require more energy per kilometer. The ICEV increase is especially large because the Formula SAE car reported by Summa et al.¹⁰ consumes substantially more fuel per kilometer than the JEC passenger-car reference. Race-vehicle WTW energy consumption is approximately 4.57, 2.66, and 2.86 times the corresponding ordinary-vehicle values for ICEV, BEV, and FCEV powertrains, respectively. In all three selected powertrain comparisons, the racing cases exhibit substantially greater energy consumption per kilometer than their ordinary-vehicle counterparts, reflecting differences in vehicle design and operating conditions associated with motorsport. At the same time, the emissions consequences differ strongly because the upstream pathway and direct combustion emissions differ.

Table 1. WTW energy consumption and GHG Emissions: Ordinary vs. Race Vehicles

Powertrain	Ordinary WTW energy (MJ/km)	Race WTW energy (MJ/km)	Ordinary WTW (g CO ₂ e/km)	Race WTW (g CO ₂ e/km)
ICEV	1.75	7.99	127.8	585.0
BEV	1.27	3.38	47.1	125.8
FCEV*	1.33	3.80	6.6	19.0

* FCEV values use a selected JEC renewable-electricity hydrogen pathway (WDEL1/CH₂ - hydrogen generated through centralized electrolysis powered by wind electricity). See detailed calculations in Appendix A1-A6.

Figure 1. Comparison of WTW energy consumption and GHG Emissions



Data of Powertrain Efficiency

Ren et al.¹³, for example, uses 95% motor and controller efficiencies and 96% reducer and differential efficiencies in a Formula Student EV model, corresponding to a

combined drivetrain efficiency of about 83.2%. Di Pierro et al.¹⁴ provides production-FCEV efficiency context, while Büchi et al.¹⁵ supplies the race FCEV system efficiency value (Table 2).

Table 2. Published Powertrain Efficiency Estimates: Ordinary vs. Race Vehicles

Powertrain	Ordinary efficiency estimate	Race efficiency estimate
ICEV	16–25% ¹⁶	50% ¹⁷
BEV	65–69% ¹⁸	83%*, ¹³
FCEV	50–60% ¹⁴	60% ¹⁵

* See estimation of this value in Appendix A7.

Among the three powertrain types, ICE vehicles show the largest difference in thermodynamic efficiency between ordinary and race vehicles, with a factor between 2 and 3.125. BEVs show a smaller difference, with a factor between 1.203 and 1.277, while FCEVs exhibit the smallest difference, with a factor between 1 and 1.2.

Discussion

Energy Replenishment

Although WTW analysis and TTW efficiency evaluate the total energy required across each powertrain's energy pathway and thermodynamic efficiency onboard the vehicles, motorsport performance also depends on how efficiently and rapidly that energy can be replenished during competition. The method used to replenish energy is especially important in motorsport because the time spent charging or refueling directly plays a role in race strategy. Liquid fuels are advantageous in these situations because large amounts of energy can be transferred into a vehicle quickly. In contrast, battery-electric vehicles require electricity to be transferred and chemically stored into a physical battery. Faster charging can reduce this disadvantage, but there is still the problem of charging power, battery temperature, and battery degradation. As a solution, Formula E uses a combination of battery storage and regenerative braking, which allows cars to recover a substantial amount of energy during the race rather than fully relying on external charging¹⁹. Hydrogen can be replenished more rapidly than conventional battery charging, which gives FCEVs a potential advantage for endurance races with a longer range⁷. However, the hydrogen first needs to be produced, compressed, transported, and stored before it can be transferred to the vehicle. On top of this, the U.S. Department of Energy reports that low-temperature PEM electrolysis systems had an energy efficiency of approximately 61% in 2022, demonstrating that significant energy may be lost before hydrogen even reaches the vehicle.

These differences present a significant tradeoff between energy efficiency and energy replenishment. Battery-electric powertrains offer highly efficient conversion of onboard energy to wheel power and can recover energy through regeneration, making them

particularly attractive for races which are designed around limited energy use. However, battery capacity, mass, charging, and thermal management can become increasingly important factors as the race distance increases. Hydrogen reduces the dependence on a large traction battery and potentially permits faster energy replenishment, but its overall pathway encompasses additional conversion steps and specialized high-pressure infrastructure. ICEs have lower powertrain efficiency but benefit from compact, energy-dense liquid fuels and rapid refueling. Consequently, the suitability of each system for motorsport cannot be determined from drivetrain efficiency alone. Race duration, vehicle mass, permitted refueling, energy-storage regulations, and the source of the energy must all be weighed. Formula 1 itself increasingly reflects this compromise: its 2026 regulations raise the electrical contribution from roughly 20% to around 50% while retaining an ICE rather than transforming entirely to battery-electric propulsion²⁰.

Environmental, Economic, and Government Policy Considerations

The environmental performance of each powertrain is influenced by more than just the emissions of the race car itself. ICEs directly produce GHG via combustion of fuel, while also creating upstream emissions via the creation, refining, and transportation of fuel. BEVs do not produce tailpipe GHG emissions, but their environmental impact is influenced by both the generation of the electricity for their battery and the production of the vehicle and its battery. Similarly, hydrogen FCEVs do not directly create GHG emissions from the proton-exchange membrane fuel cell, while the production of hydrogen can create substantial upstream emissions. Ahmed et al.² therefore highlights the need to consider production and lifecycle costs in comparing ICEVs, BEVs, and FCEVs, while Brousek et al.²¹ demonstrates that the comparative GHG performance of these powertrains depends on the country in question since electricity and hydrogen production are dependent on local energy systems. This is particularly important for hydrogen, as U.S. Department of Energy highlights that most hydrogen in the United States is currently produced from natural-gas reforming, while electrolysis can achieve significantly lower emissions when using low-carbon electricity. In addition, WTW greenhouse gas emissions do not represent every environmental burden. Life-cycle assessment¹¹ can also include fossil-resource depletion, particulate-matter formation, toxicity, mineral-resource scarcity, manufacturing, transportation, and end-of-life processes. Therefore, the WTW results in Table 1 should not be interpreted as a complete life-cycle assessment of the three powertrains.

Economic factors represent a further barrier to replacing conventional powertrains with alternatives. ICE technology benefits from a well-established fuel-production and vehicle-transportation infrastructure, while BEVs require battery and charging systems and hydrogen requires both fuel-cell technology and an entirely new set of hydrogen production, transportation, storage, and refueling systems. Ajanovic and Haas⁷ find that costs and infrastructure are critical factors in determining the prospects of BEVs and FCEVs, while Méndez et al.²² shows that the economics of conventional, battery, and hydrogen vehicles are closely tied to their local energy and operating conditions.

However, the economics of EVs continue to change rapidly: the International Energy Agency reports on both the decrease in battery prices and the ability of electric cars in several circumstances to have lower costs of ownership over their lifetimes than ICE vehicles, although purchase prices still remain higher in many markets²³. Meanwhile, hydrogen remains heavily dependent on lowering production costs; the current U. S. Department of Energy initiatives target substantial reductions in electrolyzer and clean-hydrogen costs.

Aside from the technical considerations, regulation can either promote or restrict the adoption of each technology in motorsport. The FIA has explicitly highlighted sustainable-energy and low-carbon technology as priorities, while different championships are pursuing different solutions rather than converging on a common powertrain. Formula E provides a completely electric platform, while Formula 1's 2026 regulations retain a turbocharged V6 ICE but significantly increase electrical power and require fully sustainable fuels^{5,6}. The FIA has produced dedicated technical rules for hydrogen-powered competition vehicles, including both fuel-cell and hydrogen-combustion systems, thus showing that hydrogen continues to be considered for its potential in future motorsport applications. Therefore, the future of motorsport is unlikely to solely depend on which technology has the highest theoretical efficiency: the environmental performance, cost, available infrastructure, safety standards, and championship regulations will dictate where ICE-hybrid, battery-electric, and hydrogen technology can practically be used.

Limitations

This research uses data published in academic journals and industry reports to calculate energy consumption, GHG emissions and powertrain efficiency. A major limitation of this study is the heterogeneity of the available data. Unlike ordinary vehicles, motorsport vehicles do not have standardized energy-consumption testing procedures, and the ICEV, BEV, and FCEV data used in this study were obtained from different vehicle designs, racing conditions, tracks, and research methods. Some values may also include testing or simulation rather than exclusively competitive racing. Therefore, differences among the three powertrains cannot be attributed solely to powertrain technology, and the calculated results should be interpreted as representative case comparisons rather than direct controlled comparisons. In addition, the WTW results depend strongly on the selected WTT pathways. Electricity and hydrogen can be produced through multiple pathways with substantially different energy requirements and GHG emissions, while gasoline production also varies according to crude-oil source and refining conditions. The standardized JEC pathways used in this study provide a consistent basis for comparison, but they may not represent the actual energy supply used by each motorsport vehicle. Consequently, the WTW results illustrate the performance of the selected vehicle-pathway combinations rather than universal values for ICEVs, BEVs, and FCEVs. Furthermore, applying the same JEC WTT pathway factors to ordinary and race vehicles assumes that both receive fuel, electricity, or hydrogen through the same upstream production and distribution pathway;

this improves comparability but may not reflect the actual energy sources used in individual motorsport events.

Summary

The study looked at internal combustion engines, battery-electric powertrains, and hydrogen fuel-cell powertrains in the context of their structure and power output, as well as their powertrain and well-to-wheels efficiency, energy replenishment, environmental impact, economic aspects, and regulatory development. It shows that each of the technologies offers a different balance between performance, efficiency, and environmental sustainability.

For the selected motorsport cases, BEVs and FCEVs exhibit WTW energy consumption that is approximately 42.4% and 47.6% of the WTW energy consumption of ICEs, respectively. Their WTW GHG emissions are approximately 21.5% and 3.25% of that of ICEs. Although BEVs and FCEVs have relatively similar WTW energy demands in these cases, the FCEV exhibits substantially lower GHG emissions, primarily because the selected hydrogen pathway uses wind-powered electrolysis, whereas the BEV analysis assumes the EU 2016 electricity mix. These results therefore depend on the upstream energy-production pathways rather than solely on the powertrain technologies. In addition, representative racing BEV and FCEV powertrain thermodynamic efficiencies are approximately 1.66 and 1.20 times that of the racing ICE powertrain, respectively, based on published efficiency estimates. Because the analysis combines published data from different racing vehicles and operating conditions, these numerical comparisons represent selected vehicle-pathway scenarios rather than universal performance differences among the three technologies.

ICEs have benefited from extensive development in the field of motorsport, together with high power output and the use of high energy density fuels, and also feature quick refueling times. Nevertheless, their relatively low energy-conversion efficiency and the fact that they produce direct combustion emissions are important drawbacks. BEVs offer highly efficient electric propulsion as well as regenerative braking, together with zero tailpipe emissions, although in some racing applications the battery's mass, its energy capacity, and the need for charging can be limiting factors. FCEVs also benefit from electric-motor propulsion and an alternative means of storing energy using hydrogen, but there are significant challenges associated with hydrogen production, conversion losses, storage, the existing infrastructure, and the cost. Moreover, the environmental benefits of BEVs and FCEVs cannot be judged solely on the basis of tailpipe emissions, since electricity generation and hydrogen production can result in considerable upstream emissions.

Overall, the analysis indicates that no single powertrain offers the optimal solution combining considerations of emissions performance, energy efficiency, and operational practicality across all motorsport applications. The future of sustainable motorsport will likely involve multiple powertrains, with their suitability determined by race requirements, energy-production pathways, infrastructure availability, and continued technological development.

References

1. K. Reders, A. Schütze. Introduction. In B. Elvers & A. Schütze (Eds.), *Handbook of fuels: Energy sources for transportation*, Wiley-VCH, 2nd ed. pg. 1–64, 2022.
2. A. A. Ahmed, M. A. Nazzal, B. M. Darras, I. M. Deiab. A Comprehensive Sustainability Assessment of Battery Electric Vehicles, Fuel Cell Electric Vehicles, and Internal Combustion Engine Vehicles through a Comparative Circular Economy Assessment Approach. *Sustainability*. Vol. **15**, Iss. 1, pg. 171, 2023, <https://doi.org/10.3390/su15010171>.
3. Z. Stepien. The Pro-Ecological Evolution of Powertrains and Fuels in Formula 1. *Energies*. Vol. **18**, Iss. 22, pg. 6013, 2025, <https://doi.org/10.3390/en18226013>.
4. Formula 1. Formula 1 on track to be Net Zero by 2030 with 26% reduction in carbon footprint. July 23, 2025, <https://www.formula1.com/en/latest/article/formula-1-on-track-to-be-net-zero-by-2030-with-26-reduction-in-carbon.4p2vZMDrgDu6IVHLvOcLPy>.
5. Formula 1. 2026 Regulations explained: All you need to know about F1's Advanced Sustainable Fuels. Jan 30, 2026, <https://www.formula1.com/en/latest/article/2026-regulations-explained-all-you-need-to-know-about-f1s-advanced.4h53Szn4Z3VsD6rGcR3LtU>.
6. Fédération Internationale de l'Automobile. FIA environmental report. 2023, https://www.environmentalreport.fia.com/wp-content/uploads/2023/06/FIA__ENVIRONMENTAL_REPORT__2023.pdf.
7. A. Ajanovic, R. Haas. Economic and Environmental Prospects for Battery Electric- and Fuel Cell Vehicles: A Review. *Fuel Cells*. Vol. **19**, pg. 515-529, 2019, <https://doi.org/10.1002/fuce.201800171>.
8. F. Fekri. Green Hydrogen and Formula 1 (F1): Advancing Sustainable Comprehensive Approaches for F1 Events in the MENA Region. *Journal of Sustainable Development Law and Policy (The)*. Vol. **15**, Iss. 2, pg. 114-140, 2024, <https://doi.org/10.4314/jsdlp.v15i2.5>.

9. M. Prussi, M. Yugo, L. De Prada, M. Padella, and R. Edwards. JEC Well-To-Wheels report v5, EUR 30284 EN. *Publications Office of the European Union, Luxembourg*. 2020, <https://doi.org/10.2760/100379>.
10. D. Summa, S. Raimondi, V. Mangeruga, M. Giacomini, E. Tamburini, A. Amaretti. A Well-to-Wheel Comparative Life Cycle Assessment (LCA) of First- and Second-Generation Bioethanol as Alternatives to Gasoline in Motorsport Races. *Energies*, Vol. **19**, Iss. 9, p.g. 2155, 2026, <https://doi.org/10.3390/en19092155>.
11. B. Ros, J. Selech, J. Kasprzak. An environmental life cycle assessment of electric race car: a case study of eVarta. *Clean Technologies and Environmental Policy*, Vol. **27**, p.g. 117–139, 2025, <https://doi.org/10.1007/s10098-024-02836-9>.
12. D. David, N. Burnete, A. Todoruț, N. Cordoș, T. Buidin, I. Duma. Energy consumption and thermal analysis model for a Formula Student electric vehicle. *Annals of the University of Oradea, Fascicle of Management and Technological Engineering*. Vol. **34**, Iss. 1, 2025.
13. C. Ren, Z. Xiong, K. Liu, J. Shen, D. Shi, X. Yang. Multi-Parameter Optimization of Vehicle Performance for a Four-Wheel-Drive Formula Student Electric Race Car. *Vehicles*. Vol. **8**, Iss. 5, p.g. 111, 2026, <https://doi.org/10.3390/vehicles8050111>.
14. G. Di Pierro, E. Bitsanis, A. Tansini, C. Bonato, G. Martini, G. Fontaras. Fuel Cell Electric Vehicle Characterisation under Laboratory and In-use Operation. *Energy Reports*. Vol. **11**, p.g. 611–623, 2024, <https://doi.org/10.1016/j.egyr.2023.12.013>.
15. F. N. Büchi, A. Delfino, P. Dietrich, S. A. Freunberger, R. Kötz, D. Laurent, P. A. Magne, D. Olsommer, G. Paganelli, A. Tsukada, P. Varenne, D. Walser. Electrical drivetrain concept with fuel cell system and supercapacitor - Results of the HY-LIGHT vehicle. *VDI-Berichte*. Vol. **1975**, p.g. 415–429, 2006.
16. U.S. Department of Energy. FOTW #1044, 12–30% of energy put into a conventional car is used to move the car down the road. August 27, 2018, <https://www.energy.gov/cmei/vehicles/articles/fotw-1044-august-27-2018-12-30-energy-put-conventional-car-used-move-car>.
17. B. Bradshaw. A 1-D theoretical performance analysis and optimisation of a bespoke Formula Student V-twin engine. *Master's thesis, Oxford Brookes University*. 2019, <https://scispace.com/pdf/a-1-d-theoretical-performance-analysis-and-optimisation-of-a-cl1b9i0dgl.pdf>.

18. U.S. Department of Energy. FOTW #1360: A typical EV is 87%–91% efficient compared to 30% for a conventional gasoline vehicle. Sept. 16, 2024, <https://www.energy.gov/cmei/vehicles/articles/fotw-1360-sept-16-2024-typical-ev-87-91-efficient-compared-30-conventional>.

19. Fédération Internationale de l'Automobile. FIA and Formula E reveal all-electric Gen3 race car in Monaco. April 28, 2022, <https://www.fia.com/news/fia-and-formula-e-reveal-all-electric-gen3-race-car-monaco>.

20. Formula 1. 2026 regulations explained: All you need to know about F1's new power units. Jan 14, 2026, <https://www.formula1.com/en/latest/article/2026-regulations-explained-all-you-need-to-know-about-f1s-new-power-units.14jfv7a36905uDJDdNyfQd>.

21. J. Brousek, T. Petr, P. Brabec. Comparative analysis of CO₂ emissions from conventional internal combustion engine vehicles, battery electric vehicles, and fuel cell electric vehicles in selected Central European countries. *Journal of Cleaner Production*. Vol. **544**, Article 147706, 2026, <https://doi.org/10.1016/j.jclepro.2026.147706>.

22. C. Méndez, M. Contestabile, Y. Bicer. Driving toward hydrogen mobility: A life cycle cost analysis of conventional, electric, and hydrogen fuel cell vehicles in Qatar. *Energy*. Vol. **330**, Article 136899, 2025, <https://doi.org/10.1016/j.energy.2025.136899>.

23. International Energy Agency. Global EV outlook 2025. IEA. 2025, <https://www.iea.org/reports/global-ev-outlook-2025>.

24. M. Prussi, M. Yugo, L. De Prada, M. Padella, R. Edwards, L. Lonza. JEC Well-to-Tank report v5. *Publications Office of the European Union, Luxembourg*. 2020, <https://data.europa.eu/doi/10.2760/959137>.

Appendix A. Calculation of Comparative Results

A.1 Ordinary ICEV

JEC COG1 energy consumption = 140.74 MJ/100 km = 1.4074 MJ/km.

JEC conventional-gasoline WTT expended energy factor ≈ 0.24 MJ/MJ, estimated from Figure 55 of the JEC Well-to-Tank Report v5²⁴.

WTW energy consumption = 1.4074 × (1 + 0.24) = 1.75 MJ/km.

JEC conventional-gasoline WTT GHG factor = 17.0 g CO₂ e/MJ.

WTT GHG emission = 1.4074 × 17.0 = 23.9 g CO₂ e/km.

JEC TTW GHG emission = 103.92 g CO₂ e/km.

WTW GHG emission = 23.9 + 103.92 = 127.8 g CO₂ e/km.

A.2 Race ICEV

Summa et al.¹⁰ reports gasoline consumption of 4.39, 4.70, and 4.10 L for three 22-km Formula SAE endurance events.

Average fuel = $(4.39 + 4.70 + 4.10) / 3 = 4.397$ L/22 km.

JEC gasoline LHV ≈ 32.2 MJ/L.

TTW energy consumption $4.397 \times 32.2 = 141.6$ MJ.

TTW energy use per km = $141.6 / 22 = 6.44$ MJ/km.

JEC conventional-gasoline WTT expended energy factor ≈ 0.24 MJ/MJ.

WTW energy consumption = $6.44 \times (1 + 0.24) = 7.99$ MJ/km.

JEC conventional-gasoline WTT GHG factor = 17.0 g CO₂ e/MJ.

WTT GHG emission = $6.44 \times 17.0 = 109.48$ g CO₂ e/km.

JEC-consistent gasoline TTW intensity $\approx 103.92 / 1.4074 = 73.84$ g CO₂ e/MJ.

TTW GHG emission $\approx 6.44 \times 73.84 = 475.52$ g CO₂ e/km.

WTW GHG emission ≈ 585.0 g CO₂ e/km.

A.3 Ordinary BEV

JEC BEV200 reference vehicle with EMEL3A pathway energy consumption = 42.77 MJ/100 km.

Energy use = $42.77 / 100 = 0.4277$ MJ/km.

JEC EMEL3A WTT expended energy factor = 1.96 .

WTW energy consumption = $0.4277 \times (1 + 1.96) = 1.27$ MJ/km.

JEC BEV WTT GHG factor = 110.1 g CO₂ e/MJ.

WTW GHG emission = $0.4277 \times 110.1 = 47.1$ g CO₂ e/km.

Direct TTW GHG emissions are taken as zero.

A.4 Race BEV

Ros et al.¹¹ reports 635 kWh of charging electricity over the assumed 2,000-km life of eVarta.

Electricity use = $635 / 2000 = 0.3175$ kWh/km.

Using 1 kWh = 3.6 MJ: $0.3175 \times 3.6 = 1.143$ MJ/km.

JEC EMEL3A WTT expended energy factor = 1.96 .

WTW energy consumption = $1.143 \times (1 + 1.96) = 3.38$ MJ/km.

JEC BEV WTT GHG factor = 110.1 g CO₂ e/MJ.

WTW GHG emission = $1.143 \times 110.1 = 125.8$ g CO₂ e/km.

The reported electricity consumption represents an assumed vehicle operating lifetime that may include testing and other activities beyond competitive racing.

A.5 Ordinary FCEV

JEC FCEV 2015 WDEL1/CH2 energy consumption ≈ 69.74 MJ H₂/100 km.

Energy use = $69.74 / 100 = 0.6974$ MJ/km.

JEC hydrogen WTT expended energy factor ≈ 0.9 MJ/MJ, estimated from Figure 128 of the JEC Well-to-Tank Report v5²⁴.

WTW energy consumption = $0.6974 \times (1 + 0.9) = 1.33$ MJ/km.

Selected renewable-electrolysis hydrogen pathway = 9.5 g CO₂ e/MJ H₂.

WTW = $0.6974 \times 9.5 \approx 6.6$ g CO₂ e/km.

A.6 Race FCEV

David et al.¹² models a Formula Student endurance event in a simulation and calculates H₂ consumption of 16.4 g for one approximately 1-km lap.

For the full endurance event, the paper reports approximately 366 g H₂.

Using the standard 22-km endurance distance: $0.366 / 22 = 0.01664$ kg H₂/km.

Using H₂ LHV ≈ 120 MJ/kg: $0.01664 \times 120 \approx 2.00$ MJ/km.

JEC hydrogen WTT expended energy factor ≈ 0.9 MJ/MJ.

WTW energy consumption = $2.00 \times (1 + 0.9) = 3.8$ MJ/km.

Selected renewable-electrolysis hydrogen pathway = 9.5 g CO₂ e/MJ H₂.

WTW GHG emission = $2.00 \times 9.5 \approx 19.0$ g CO₂ e/km.

A.7 Representative BEV TTW Efficiency

Ren et al.¹³ provides values for the following metrics of a representative Formula Student drivetrain. Motor efficiency = 95%; Motor controller efficiency = 95%; Reducer efficiency = 96%; Differential efficiency = 96%.

As a result, $\eta_{\text{BEV}} = 0.95 \times 0.95 \times 0.96 \times 0.96 = 0.8317 \approx 83.2\%$.

The representative racing BEV drivetrain efficiency is estimated by multiplying the assumed efficiencies of the motor, motor controller, reducer, and differential. This value represents the combined conversion efficiency of the modeled drivetrain components rather than a complete vehicle-level tank-to-wheel efficiency.