

Review

The Pro-Ecological Evolution of Powertrains and Fuels in Formula 1

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Abstract

This article describes the environmentally friendly evolution of Formula 1 powertrains and fuels since the start of the season. It is the only study of its kind to encompass a comprehensive analysis of various solutions designed to make Formula 1 powertrains more environmentally friendly. Despite the difficulties in accessing descriptions of many of the advanced, unique proprietary technologies used in Formula 1, many of them have been analyzed to whatever extent was possible. A significant portion of the article was devoted to discussing the new regulations that will apply to powertrains between 2026 and 2030. In particular, it addresses the increased thermal efficiency of Formula 1 combustion engines, the introduction of sustainable synthetic fuels, and the further reduction in harmful exhaust emissions, including CO₂, from future Formula 1 powertrains. A wide, tabular comparison of the parameters, requirements, and operational characteristics of powertrains compliant with the regulations between 2014 and 2025 and between 2026 and 2030 was provided.

Keywords: Formula 1; ecology; hybrid power units; engine efficiency; engine evolution



Academic Editor: Dimitrios C. Rakopoulos

Received: 27 October 2025

Revised: 12 November 2025

Accepted: 15 November 2025

Published: 17 November 2025

Citation: Stepień, Z. The Pro-Ecological Evolution of Powertrains and Fuels in Formula 1. *Energies* **2025**, *18*, 6013. <https://doi.org/10.3390/en18226013>

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1. Priorities in the Direction of Formula 1 Power Trains Development

In motorsport, Formula 1 (F1) is the pinnacle of achievement due to its design and technology. It provides the most technologically advanced platform for testing and developing new, broadly defined solutions and technical innovations. Ultimately, these solutions are often incorporated into commercial vehicles, contributing to the advancement of the automotive industry. Therefore, Formula 1 is a catalyst for technological advancement in the automotive industry and plays a key role in its technical development. However, since the early 21st century, the negative impact of F1 racing on the environment has been highlighted. It has even been argued that F1 is the most polluting sport in the world [1,2]. In 2007, it was estimated that each F1 car emits approximately 8.5 tons of CO₂ per season [3]. To date, the sport has relied primarily on fossil fuels, and cars consume large amounts of gasoline during races. This contributes to air pollution and greenhouse gas emissions, exacerbating climate change. As a result, steps were taken to address these issues. One of the first was the introduction by the FIA (Federation Internationale de l'Automobile) of a mandatory biofuel content of 5.75% (by weight) in F1 fuel from 2008, by setting a new upper limit for oxygen content in the fuel at 3.7% (by weight). Therefore, the use of E10 gasoline in F1 was possible more than two years before its widespread availability on the European road vehicles fuel market. The next significant environmentally friendly measure was the introduction of hybrid power units starting in 2009. This solution involved the use of a KERS (Kinetic Energy Recovery System) in the drivetrain, working in conjunction with the engine. Its purpose was to store some of the energy generated during braking,

a total of only 400 kJ, and convert it into a temporary increase in power, a maximum of approximately 60 kW, which drivers could use for 6.67 s per overtaking lap, Figure 1 [4].

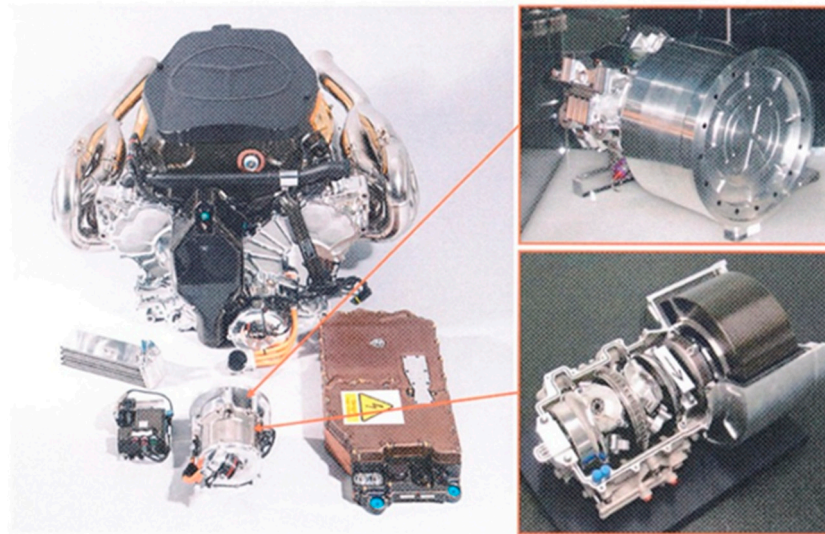


Figure 1. An image of the KERS (Kinetic Energy Recovery System) as part of the powertrain of an F1 race car from 2009 to 2013.

Much more significant, environmentally friendly changes to the powertrains have been made since 2014. Since then, F1 cars have been powered by 1.6-L turbocharged V6 hybrid engines, replacing the 2.4-L V8 engines used between 2006 and 2013, which consumed significantly more fuel. Current regulations call for the use of hybrid powertrains, which consist of a turbocharged V6 engine linked to an energy recovery system (ERS). The ERS recovers energy from the F1 car's braking and exhaust systems, converting it into electrical energy that can be used to further boost the powertrain's output. These hybrid powertrains incorporate an electrical energy storage system capable of delivering 120 kW for 33 s [5–9]. The introduced fuel consumption limits (from 150 l/race to 105 kg/race, and from 2019 to 110 kg/race) and maximum fuel flow rate to 100 kg/h have meant that F1 cars use about a third less fuel to cover the same distance at the same speed. This change is estimated to reduce CO₂ emissions per kilometer by about 35% [10]. Consequently, until 2013, engine power was limited by limiting its maximum engine speed to 18,000 rpm. Under the engine regulations in force since 2014, their maximum power is regulated by limiting the maximum fuel flow (100 kg/h at 10,500 rpm). Their power is calculated by multiplying the engine's thermal efficiency by the fuel's calorific value. Therefore, power increases by the amount of any improvement in thermal efficiency. This improvement in thermal efficiency can also be translated into fuel consumption. Hence, since then, engine development has had to focus on converting the limited energy available in the fuel into engine power as efficiently as possible, i.e., increasing its thermal efficiency (Figure 2). The goal is to achieve the highest possible power at a given permissible fuel flow of 100 kg/h (i.e., the best efficiency), and thus the lowest specific fuel consumption.

The further development of F1 powertrains presents the following technical challenges, requiring engineers to be highly creative and employ innovative solutions:

- achieving maximum possible engine thermal efficiency,
- power unit thermal management, which involves efficient cooling and heat dissipation within the propulsion system to maintain optimal performance and avoid overheating,
- increasing the capacity of energy storage systems without increasing their weight or size,
- reducing the engine weight while maintaining its structural integrity and reliability.

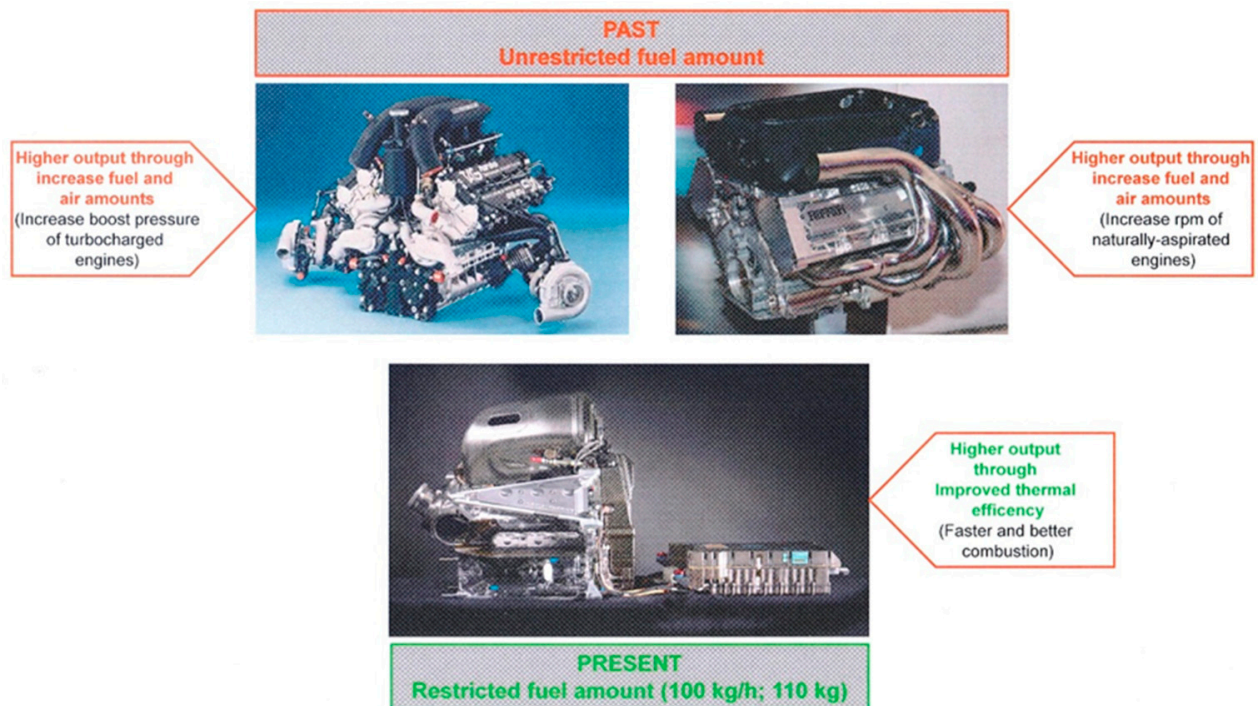


Figure 2. Changes in the development direction of F1 engines in efforts to achieve maximum power.

The technologically advanced F1 hybrid power units introduced in 2014 not only increased the total power output of the vehicles (to around 736 kW) but also improved fuel efficiency and reduced exhaust emissions [6,11,12]. The thermal efficiency of engines increased from around 30–33% in 2009–2013 to around 45–52% in 2014–2025. This technology has had a significant impact on the entire automotive industry, supporting the development of more sustainable and eco-friendly powertrain solutions [13,14]. Furthermore, from 2022, the mandatory share of bio-component in F1 fuel was increased to 10% (by weight). The new, radically revised technical regulations for F1 power units from 2026 will place even greater emphasis on improving the environmental credentials of F1 engines. These regulations are intended to demonstrate Formula 1's growing commitment to the reduction of its carbon footprint, focusing on two key pillars: carbon neutrality and energy efficiency. One of the most important planned changes is the introduction of engines powered 100% by sustainable fuels, completely eliminating the need for fossil fuels. Last but not least, the ERS will play a more significant role, as the electricity generated by it will account for almost 50% of the power unit's total power. The upcoming regulations are intended to prioritize energy efficiency and environmental advancements in F1 power units. These changes aim to introduce a different operation and role for the Motor Generator Unit-Kinetic (MGU-K), potentially increasing its energy recovery capabilities and expanding its role in creating cleaner and more efficient power units [15,16]. In 2026, the F1 power units, the MGU-K, are expected to have a recovered power of ~350 kW, a significant increase from the 120 kW recovered power by the MGU-K in the 2025 power units. As is typical for F1, technical details are still shrouded in secrecy; the changes are expected to improve the integration of the MGU-K with the power unit, increasing overall performance and efficiency, and significantly reducing the F1 cars' greenhouse gas emissions.

2. The Formula 1 Combustion Engines Evolution in the Hybrid Era

From 2006 to 2013, Formula 1 used smaller 2.4-L V8 combustion engines with a 90-degree cylinder bank angle. Initially, their engine speed reached 20,500 rpm, in 2007 it was limited to 19,000 rpm, and in 2009 down to 18,000 rpm, but since then they have

been combined with a KERS, thus creating the first hybrid F1 power units. In the years when these engines were in use, their power was increased from ~530 to ~590 kW. The fuel consumption of this generation of engines was not limited and was typically around 150–160 kg/race [4,9,11]. Turbocharged engines started being used in 2014, designed as a system integrated into advanced hybrid powertrains [15]. These were V6 engines with a 90-degree cylinder bank angle, a 1.6-L displacement, and a maximum engine speed limited to 15,000 rpm (in practice, the engine speed would not exceed 12,000 rpm due to fuel combustion rate constraints). Maximum power was gradually increased from ~440 kW to ~630 kW. Such engines are powered using a direct injection fuel system with a maximum pressure of 500 bar and supercharged using a single turbocharger. Current F1 engines consume around 40 L/100 km of gasoline, which is a significantly lower fuel consumption than in the past. For example, in the early years of F1, cars consumed almost 190 L/100 km. The combustion engine was integrated with an ERS, which increased the overall efficiency of the powertrain by recovering waste energy from the brakes and the exhaust gases. The ERS consists of two motor-generator units: the Motor Generator Unit–Kinetic (MGU-K) and the Motor Generator Unit–Heat (MGU-H), as well as an energy storage system. The motor-generator units convert mechanical and thermal energy into electrical energy and vice versa [4,9,11,17]. The design of F1 engines requires advanced manufacturing and technological processes. Component parts are machined to extremely tight tolerances using CNC (Computer Numerical Control) machines, ensuring optimal fit and performance. Complex shapes, such as cylinder heads and engine blocks, are cast or forged from high-strength alloys, enabling intricate designs and excellent material properties. Three-dimensional printing techniques such as selective laser melting (SLM) are being used increasingly more often. Specialized coatings and surface treatments, such as thermal barrier coatings and nitriding, are applied to critical components to enhance wear resistance, thermal protection, and durability. Table 1 presents a comparative summary of the parameters of engines used in the years 2009–2013 and 2014–2025.

Table 1. Data of F1 engines used in the years 2009–2013 and 2014–2025.

Engine	2009–2013	2014–2025
Stroke	Not regulated	53 mm
Crank height	Min. 58 mm	90 mm
Number of valves	4 per cylinder (32)	4 per cylinder (24)
Pressure charging	Normally aspirated	Single turbocharger, unlimited boost pressure (typical maximum 3,5 bar abs due to fuel limit)
Max. rpm	18,000 rpm	15,000 rpm
Max. power	530–590 kW	440–630 kW
Engine torque	About 350 Nm	500–600 Nm
Fuel injection	Indirect fuel injection	Direct fuel injection
Variable intake system	Not allowed	Allowed
Compression ratio	1:12–1:13	<1:18
Injection pressure	Max. 100 bar	Max. 500 bar
Max. fuel flow	Unlimited but typically 150–160 kg/h	Max. 100 kg/h
Thermal efficiency	30–33%	45–52%

3. Current Hybrid Drivetrains in F1—Up Until 2025

The introduction of advanced hybrid power units in F1 in the year 2014 represented a significant technological breakthrough [4]. These power units combined a traditional internal combustion engine with energy recovery systems, such as the MGU-K kinetic energy recovery system and the MGU-H thermal energy recovery system. Hybrid power units

have not only increased the overall power of cars but also allowed them to reduce the fuel consumption and exhaust emissions, including CO₂ [11,14,18]. This technology has since had a significant impact on the entire automotive industry, supporting the development of more sustainable and eco-friendly powertrain solutions. A hybrid powertrain consists of the following components:

- The 1.6-L, four-stroke, turbocharged V6 gasoline engine, limited to 15,000 rpm, generates approximately 610–625 kW on its own. This small engine is remarkably efficient, generating over 370 kW per liter of displacement. FIA regulations limiting the maximum fuel flow to 100 kg/h (above 10,500 rpm) limit the power output of the internal combustion engine, forcing manufacturers to improve its efficiency, not just increase boost pressure or engine speed. Consequently, Formula 1 engine designers continually optimize fuel consumption through advanced technologies such as Turbulent Jet Ignition (TJI) [18] and direct fuel injection. These advancements increase combustion efficiency and increase engine power (Table 1, Figure 3).
- The Motor Generator Unit-Kinetic (MGU-K) is a brushless AC electric motor with permanent magnets mechanically connected to the engine's crankshaft, and it plays a key role during vehicle braking. Instead of dissipating kinetic energy as heat, the MGU-K captures it and converts it into electrical energy. This system is used not only to regenerate energy but also to deliver power when it is needed most. In motor mode, the MGU-K can generate 200 Nm of torque and deliver up to 120 kW, while in generator mode, it can conserve up to 2 MJ of battery energy. This means the motor only has enough energy for about 33 s of boost per lap.

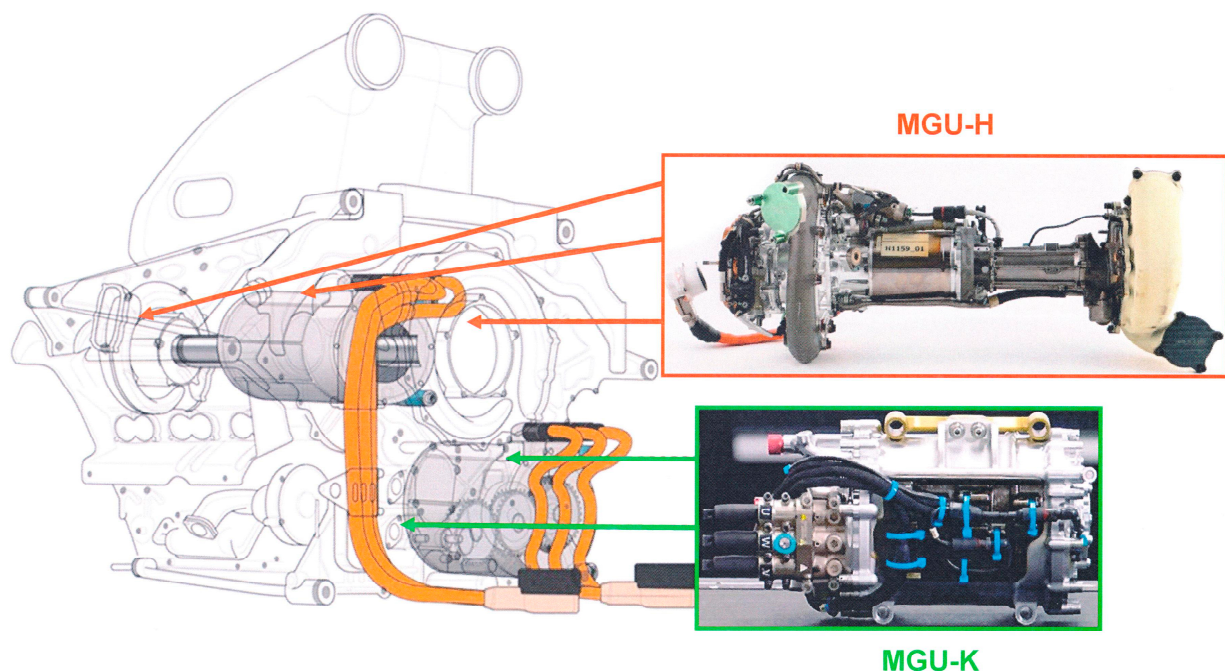


Figure 3. Formula 1 hybrid powertrain diagram [19]. The ERS-MGUH (Energy Recovery System–Motor Generator Unit Heat); ERS-MGUK (Energy Recovery System–Motor Generator Unit Kinetic).

The MGU-K weighs no more than 7 kg and has a maximum speed of 50,000 rpm, Figure 3.

- The Motor Generator Unit-Heat (MGU-H) is a brushless, permanent magnet AC electric motor mechanically coupled to the turbocharger. In the MGU-H, exhaust gas entropy (the thermal energy remaining in the exhaust gas as a function of its

temperature, expansion, and mass flow rate) is used to rotate the turbine during the energy recovery phase, converting exhaust gas energy into electrical energy. Integrated directly into the turbocharger system, it performs two important functions: it recovers energy as the exhaust gas drives the turbine, and the MGU-H converts this rotational energy into electrical energy. It can also function as an electric motor, turning the turbocharger to eliminate lag and improve engine response (eliminating turbo lag). Unlike the MGU-K, there is no limit to the energy that can be recovered from this MGU. The capacity of both the MGU-K battery and the MGU-H battery is the same, at 2 MJ each. The MGU-H operates continuously, ensuring a constant stream of energy recovery and smoother power delivery. This continuous operation helps maintain the overall efficiency of the drive unit (Figure 3). The MGU-H can operate at speeds up to 125,000 rpm, Figure 3.

- The ERS + Battery and Control Electronics system acts as an intermediary, managing the energy flow between the MGU-K, MGU-H, and the engine. Formula 1 cars use high-capacity battery systems operating at 400 V and with a storage capacity of 4–6 kWh. The lithium-ion battery stores recovered energy and can transfer up to 4 MJ per lap to the MGU-K and accept up to 2 MJ per lap from the MGU-K (from braking). The battery allows the car to release an additional ~120 kW of electrical power over short distances. The battery weighs approximately 25 kg and has an operating temperature of 60–80 °C. Once the boost is activated, energy is replenished through regenerative braking and by the MGU-H, which recycles exhaust gas energy, allowing the cycle to repeat itself lap after lap, Figure 3.

In modern Formula 1 powertrains [20], the combustion engine is combined with the electric ERS (Electric Power Assist) to deliver maximum power in all operating conditions. The engine alone generates an impressive 440–630 kW, and the ERS, via the MGU-K (Electric Power Unit) system, adds an additional 120 kW, recovering 2 MJ per lap. Once the engine is started, the full power of the MGU-K can be used for approximately 33 s per lap [19,21–23]. The total maximum power of the powertrain is 736–760 kW. Figure 4 shows the energy flows within the powertrain, as well as the power and state-of-charge limits.

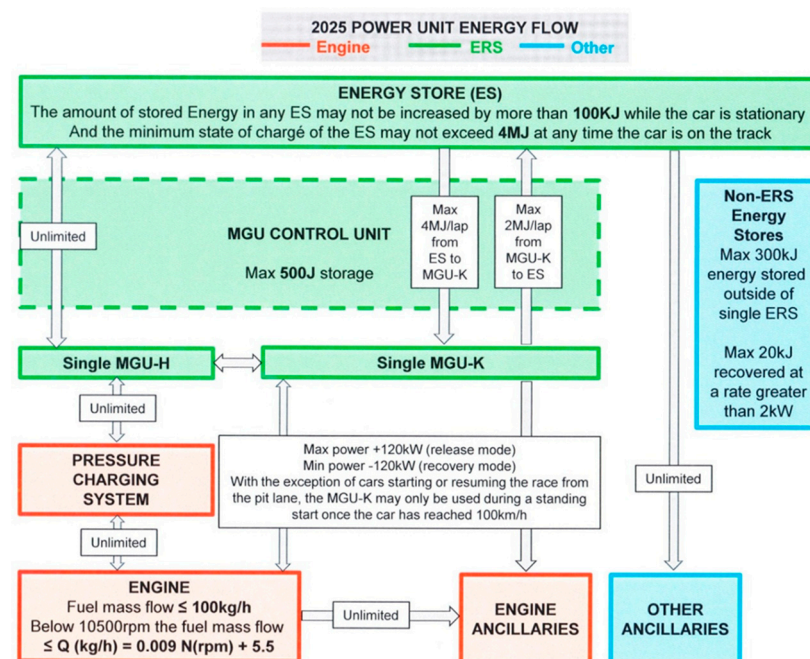


Figure 4. 2025 F1 power unit energy flow limitations [24].

4. Future Hybrid Drivetrains in F1—From 2026 to 2030

Starting from 2026, new technical regulations are to apply to the F1 cars' construction, including powertrains whose design is primarily dictated by pro-ecological and environmental considerations [15]. The main changes are the assumption that the engines will be powered by 100% sustainable (synthetic) fuel, and the powertrains will derive ~50% of their power from the combustion engine and ~50% from electricity. The new regulations introduce a thorough modernization of the energy recovery system (ERS), changing its role and enabling it to work exclusively with the combustion engine (ICE). A key element will be the expanded MGU-K system, which will deliver up to 350 kW of power to the powertrain, almost three times more than before. In an effort to reduce powertrain construction costs, the use of the MGU-H system will be prohibited and phased out due to its very high construction costs and high failure rate. Therefore, the following changes will be introduced to the distribution of power generated by the vehicle's powertrain [13,16]:

- ICE power will be reduced from the current 550–560 kW to 400 kW (in 2026), i.e., –27%.
 - ERS power will be increased from the current 120 kW to 350 kW (in 2026), i.e., +292%.
- The maximum energy charged to the energy storage (ES) has been increased from 2 MJ to 9 MJ, while the delta state of charge (SoC) limit for the ES remains at 4 MJ.
- Power balance change: the combustion engine to electric power ratio will change from 80/20 (2025) to 53/47 (2026).

The elimination of the MGU-H from Formula 1 power units starting from the 2026 season is expected to revolutionize how teams manage performance and energy recovery. Currently, the MGU-H plays a key role, recovering energy from exhaust gases. The 2026 regulations provide the desired balance between performance and environmental responsibility. Fully sustainable (synthetic) fuels, combined with improved electrical systems, demonstrate Formula 1's commitment to reducing environmental impact. These changes, combined with aerodynamic improvements, aim to improve the overall efficiency of F1 cars. Figure 5 shows the energy flows in the vehicle powertrain planned for the 2026–2030 period, as well as the power and state-of-charge limits.

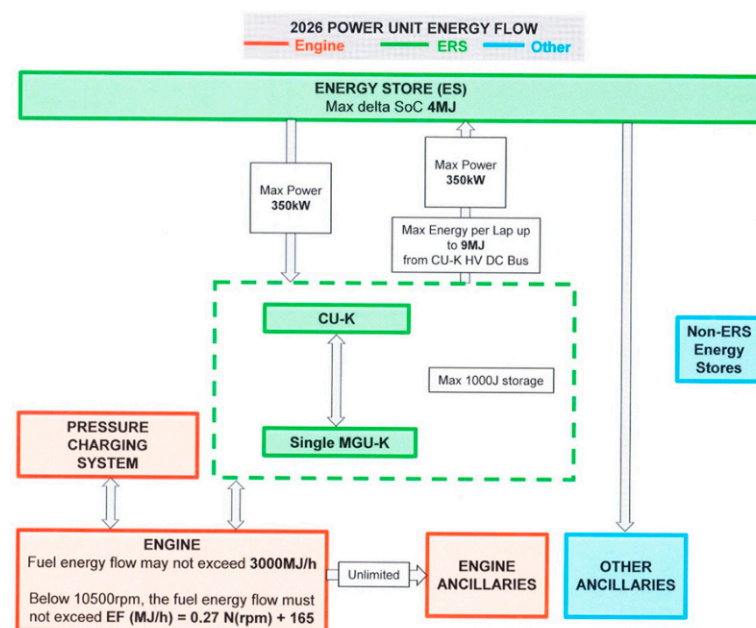


Figure 5. 2026 F1 powertrain energy flow limitations [16].

Table 2 presents a comparative summary of the parameters of the drive units used in the years 2014–2025 and 2026–2030.

Table 2. Data of F1 power units used in the years 2014–2025 and 2026–2030.

Power Unit	2014–2025	2026–2030
ICE-Cylinder	V6 90°	V6 90°
ICE-Displacement	1.6 L	1.6 L
ICE-Bore	80 mm	80 mm
ICE-Stroke	53 mm	53 mm
ICE-Piston weight	Free	>300 g
ICE-Number of valves	4 per cylinder (24)	4 per cylinder (24)
ICE-Intake valve size	free	32.5–34.5 mm
ICE-Exhaust valve size	free	27–29 mm
ICE-Pressure charging	Single turbocharger, unlimited boost pressure (typical maximum 3.5 bar abs due to fuel limit)	<4.8 bar abs
ICE-Max. rpm	15,000 rpm	15,000 rpm
ICE-Max. power	440–630 kW	?
ICE-Engine torque	500–600 Nm	?
ICE-Fuel injection	Direct fuel injection	Direct fuel injection
ICE-Variable intake system	Allowed	Not allowed
Compression ratio	<1:18	<1:16
ICE-Injection pressure	Max. 500 bar	Max. 350 bar
ICE-Max. fuel flow	Max. 100 kg/h	<3000 MJ/h (70 kg/h)
ICE-fuel	10% biofuel	100% sustainable
MGU-H	Harvest unlimited Energy capped at 2 MJ per lap deployment	Not allowed
MGU-K Build	Enclosed with the engine Non-standardized components	Inside chassis with battery in a safety cell Standard component
MGU-K Power	120 kW	350 kW
Max. power	>736 kW	~736 kW
Energy recovery system	MGU-K (Energy recovered from deceleration) MGU-H (Exhaust gas heat turned to Energy)	MGU-K
Power breakdown (ICE/Hybrid)	~80%/~20% ~630 kW/~120 kW	53%/47% (~390 kW/~350 kW)

5. Fuels for F1 Engines

As with the design of F1 powertrains as well as entire vehicle construction, FIA regulations require F1 to lead the way in road fuel innovation. Furthermore, components found in conventional road fuels are used in F1 race fuels. The main direction of F1 fuel development in terms of composition is to make it increasingly environmentally friendly. Therefore, in 2008, a mandatory bioethanol blend of 5.75% (by weight) was introduced in F1 fuel. From 2022, this blend has been increased to 10.0% (by weight). While ethanol improves anti-knock properties, it reduces the lower heating value (LHV) by 2.5–3%, which directly impacts engine power. This is why a slight performance drop was observed at the start of the 2022 season before teams optimized their engines for the new fuel.

From 2026, only 100% sustainable (synthetic) fuel will be used to power F1 engines. The full regulations for F1 fuels can be found in Article 19 of the FIA Formula 1 Technical Regulations. They are divided into two parts [25]:

- Physical properties: The limits on standard fuel properties are inspired by the European standard for gasoline: EN228 [5,10,13,16].
- Chemical composition: Formula 1 fuel contains 99% of the same chemical compounds as road fuels [5,10,13,16].

Table 3 compares the physicochemical properties of F1 fuels used in 2025 and those planned for use from 2026 onwards.

Table 3. F1 fuel properties and composition in the years 2025 and 2030 [16,17,26].

F1 Fuel Property	Units	2025		2026	
		Min	Max	Min	Max
(RON + MON)/2		87			
RON				95	102
Sensitivity (RON-MON)					15
Density (at 15 °C)	kg/m ³			720.0	785.0
Methanol	%v/v				3.0
Oxygen	wt%	3.45		6.70	7.10
Nitrogen	mg/kg		500		500
Benzene	wt%		1		1
DVPE (Dry vapor pressure equivalent)	kPa	45	68	45	68
Lead	mg/L		5		5
Manganese	mg/L		2		2
Metals (excluding alkali metals)	mg/L		5		5
Oxidation stability	minutes	360		360	
sulfur	mg/kg		10		10
Electrical conductivity	pS/m	200		200	
At E70 °C	%v/v			20.0	52.0
At E100 °C	%v/v			40.0	80.0
At E150 °C	%v/v			75.0	
Final Boiling Point	°C		210		210
Distillation Residue	%v/v		2		
F1 fuel composition					
Aromatics	wt%		40		40
Olefins	wt%		17		17
Total diolefins	wt%		0.1		0.1
Total styrene and alkyl derivatives	wt%		0.1		0.1

Since the fuel mass flow and the maximum amount of fuel consumed during a race have been limited, the key factor in assessing fuel efficiency is the maximum power output of the engine derived from this limited amount of fuel. During the engine design process, this required that all parameters be reoriented from the optimal configuration for a limited airflow engine (naturally aspirated, limited displacement, and rpm) to the optimal configuration for a fuel-flow limited engine [23]. The goal was to achieve the highest possible power for a given fuel-flow limited to 100 kg/h (i.e., the best efficiency), and therefore the lowest specific fuel consumption in g/kWh.

Given these assumptions, there are three fuel parameters that should be considered as being of key importance:

- **Anti-knock properties.** A high octane number allows for high efficiency in spark-ignition (SI) engines. The improved anti-knock properties of high-octane fuels allow for increased ignition timing, leading to a more complete combustion process and thus increased engine efficiency.
- **Fuel energy content per mass.** Since the fuel mass flow rate is set at 100 kg/h, it is possible to select compounds with higher combustion energy per mass.
- **Combustion rate.** In the case of a fuel formulation that ensures high flame propagation speed in the combustion chamber, the speed, quality, and completeness of the combustion process are always the main objectives, as these factors directly impact the thermodynamic efficiency of the internal combustion engine.

At the same time, one of the key parameters for assessing the sustainability of F1 engines is energy consumption in the context of greenhouse gas (GHG) emissions. In this case, not only the amount of fuel consumed during a race, but also the fuel composition and

the emission efficiency of its components are key factors influencing the overall assessment of GHG emissions. Therefore, starting in 2026, F1 will be required to use fuel composed exclusively of sustainable ingredients, particularly synthetic fuel, and more specifically e-fuel, which is key to carbon neutrality. When using synthetic fuels, the reduction in CO₂ emissions, calculated well-to-wheel, depends on the production methods of these fuel components and can be as high as 100% when the CO₂ emitted by a synthetic fuel vehicle is fully neutralized by capturing CO₂ from the atmosphere while simultaneously producing electricity from renewable energy sources [27,28]. E-fuels are synthetic fuels created by combining (synthesizing) “green hydrogen” produced by electrolysis of water (e.g., seawater) using renewable electricity and CO₂ captured from a concentrated source (e.g., exhaust gases from an industrial plant) or directly from the air. Therefore, e-fuels are fuels synthesized using renewable electricity, often using inorganic raw materials. E-fuels include liquid and gaseous hydrocarbons such as methane and various gasoline-like fuels, diesel, alcohols such as ethanol and methanol, and non-carbon fuels such as hydrogen and ammonia. Once the refining process is complete, the e-fuels produced can be used as e-petrol, e-diesel, e-fuel oil, and e-kerosene, and these can completely replace conventional fuels. Thanks to their drop-in properties, e-fuels can be blended with conventional fuels in any proportion [28]. Therefore, the use of synthetic fuels in Formula 1 will not only contribute to the development of motorsport but also to the decarbonization of the global transportation sector. According to the standards set by the FIA for 2026, both e-fuels and biofuels are treated equally, and blending is permitted. Advanced biocomponents must be derived from municipal waste, including non-food biomass (e.g., lignocellulosic biomass, used vegetable oil), and must not originate from biodiverse areas, such as intact primary forests or woodlands, nature conservation areas, or biodiverse grasslands [26]. Table 3 shows the requirements that F1 fuel must meet from the year 2026 onward. The fuel must not contain any substance capable of undergoing an exothermic reaction in the absence of external oxygen. The sum of individual hydrocarbon components present in concentrations below 5% *w/w* of the total fuel must constitute at least 30% *w/w* of the fuel hydrocarbon component. The only permitted oxygenates are paraffinic monoalcohols and paraffinic monoethers with a final boiling point below 210 °C [17]. An additive mix made using unsustainable sources, or containing additives and denaturants from unsustainable sources, may be used in a total concentration of no more than 1.0% *w/w* of the fuel blend [16,17,26].

6. Lubricating Oils for F1 Engines

Formula 1 engines operate under extreme conditions, requiring dedicated lubricants to ensure optimal performance and reliability. The very high engine speeds, currently limited to 15,000 rpm, generate significant heat and significant mechanical stresses and strains on engine components, which is only possible when using specialized lubricants. Combustion chamber temperatures can exceed 1000 °C, and oil temperatures can reach 300 °C, making effective thermal management crucial to the durability, reliability, and efficiency of Formula 1 engines. Thermal stability and oxidation resistance are crucial for F1 lubricants. The oil must resist high-temperature breakdown to maintain its protective properties. Oxidation can lead to the formation of harmful deposits and sludge, which can negatively impact engine performance and longevity. Simultaneously, minimizing friction is essential to maximizing power output and engine efficiency. Formula 1 engines are designed with minimal manufacturing tolerances, and the oil must provide a thin yet durable lubricating film to ensure fluid friction, reduce boundary friction, and prevent semi-dry or dry friction. This helps reduce wear on the engine’s moving parts, thus increasing its lifespan and efficiency. Furthermore, given that F1 engines are constructed using advanced materials such as titanium, carbon fiber, and various alloys, whose compositions are often kept secret,

the lubricant must be compatible with these materials to prevent chemical reactions that could lead to corrosion or degradation. Current Formula 1 regulations place a strong emphasis on fuel economy and reducing exhaust emissions, particularly GHG emissions. The oil used in Formula 1 engines must contribute to these goals by minimizing internal friction, thereby improving mechanical efficiency and combustion efficiency. The lubricant must meet FIA-specified requirements and standards (Table 4) [16].

Table 4. F1 engine oil properties in the years 2025 and 2030 [16].

Property	Units	Min	Max
Kinematic Viscosity (100 °C)	cSt	2.8	
HTHS Viscosity at 150 °C and Shear Rate of 10^6 s^{-1}	mPa·s	1.4	
Initial Boiling Point	°C	210	
Flashpoint	°C	93	

The sum of components with a boiling point below 210 °C must not exceed 0.5% *w/w*. Lubricating engine oil must not contain any organometallic gasoline additives or other additives that increase the octane number of gasoline. The additive packages in F1 lubricating oils are highly specialized. These additive packages include anti-wear additives, detergents, dispersants, and friction modifiers. Anti-wear additives, such as zinc dialkyldithiophosphate (ZDDP), form a protective layer on engine components, preventing metal-to-metal contact. Detergents and dispersants help keep the engine clean by preventing sludge and varnish formation. Friction modifiers reduce internal friction, improving engine efficiency and performance. Taking into account the need for environmentally friendly development of lubricating oils, in the near future, the development directions of F1 lubricating oils may also include bio-based oils, and artificial intelligence may be used to optimize oil compositions, adapting them to specific engine types and operating conditions.

In accordance with FIA requirements, the oil consumption limit for any engine used was reduced in 2018 to a maximum of 0.6 L per 100 km. This reduced oil consumption limit is still in effect today. This restriction is due to the fact that the oil burned in the engine acts as additional fuel and therefore increases engine power, while fuel consumption is limited to 100 kg/h.

Considering the operating conditions of lubricating engine oil in F1 engines, the base oil is most often a fully synthetic blend of PAO (Polyalphaolefin) Group IV base oils with a viscosity of 10 W-60.

7. Increasing the F1 ICE Efficiency

Due to current F1 regulations limiting the amount of fuel delivered to the engine and its total mass consumption, power is calculated by multiplying the engine's thermal efficiency by the fuel's calorific value. Therefore, power increases by the amount of any improvement in the engine's thermal efficiency. Thermal efficiency can be improved by increasing the compression ratio or specific heat. Increasing the compression ratio leads to combustion knock. Therefore, combustion strategy development must focus on reducing the final temperature of the compressed charge in the cylinders, achieving a uniform, homogeneous fuel mixture, and increasing combustion speed and stability. Because the regulations set an upper limit for the geometric compression ratio at 18, development work aims to approach this limit. Increasing the specific heat means using a leaner-than-stoichiometric fuel-air mixture [21–23]. One way to improve knock resistance and achieve a leaner air-fuel mixture is to control the vacuum pulsation (also known as lean boost) of the air delivered to the cylinders. In the era of turbocharged engines, which use a turbocharger to deliver air to the cylinders, the mixture formation and combustion process can be influenced by

so-called negative pulsation, which allows air to be drawn into the cylinders. By using this effect, it is possible to use adiabatic expansion to lower the temperature of the inlet air to the cylinders to a lower temperature than when it leaves the intercooler. However, the negative effect is a lower mass of air delivered to the engine cylinders. To compensate for this difference, higher boost pressure is required. The Miller cycle also aids in cooling the intake air through adiabatic expansion. In general, the Miller cycle optimizes both the charge exchange volume and its thermal cycle by delaying the intake valve closure, which separates the expansion ratio from the compression ratio. This separation helps reduce combustion knock while maintaining high expansion/compression ratios, which allows for better controlled thermal efficiency. Delayed intake valve closure provides more time and space for gas expansion, which reduces the piston's lift energy. Tuning the vacuum pulsation and the Miller cycle improves knock resistance, but achieving higher boost pressures requires a larger intercooler. Furthermore, regulating the vacuum pulsation weakens the swirl flow in the cylinders, which reduces the combustion velocity. Slower combustion, in turn, increases the risk of combustion knock and makes achieving high compression ratios more difficult [21–23]. Generally, the following solutions are used to improve engine thermal efficiency [21–23,26]:

- Increasing combustion rate and stability by increasing mixture swirl in the cylinder, increasing fuel atomization pressure in the cylinder, and shaping the jet pattern.
- Improving knock resistance by reducing mixture temperature at the end of cylinder compression and optimizing valve timing.
- Improving combustion efficiency by optimizing the composition and combustion process of a lean mixture and preventing incomplete fuel combustion due to fuel spraying onto the chamber walls caused by improper fuel injection control.
- Optimizing the hydrocarbon composition and fuel additive selection to achieve higher calorific value and increased knock resistance.
- Optimizing the control of fuel atomization in the combustion chamber, combustion mixture formation, and combustion.

Reducing friction, limiting pumping losses, and optimizing thermal energy consumption also play a significant role in improving overall engine efficiency. Diamond-like carbon coatings (DLCC) used to coat piston surfaces are characterized by very low friction and high durability, significantly reducing the coefficient of friction.

New FIA regulations introduced in 2014 permitted direct fuel injection in F1 engines. This allowed engine designers to intensify their work on precisely controlling the quantity, quality, and timing of fuel injection directly into the combustion chamber to achieve more optimal combustion. At that time, Mercedes introduced a new, groundbreaking technology called Turbulent Jet Ignition (TJI) or Pre-Chamber Ignition (PCI), which played a significant role in improving the efficiency and performance of F1 engines. In TJI, 95–97% of the fuel is injected normally into the main combustion chamber, creating a lean mixture, while approximately 3–5% of the fuel is injected into a small pre-chamber with a spark plug, where a rich mixture is created. Once ignition occurs, a jet of hot gases is ejected at high pressure through holes in the small pre-chamber into the main combustion chamber, igniting the remaining, now well-prepared, homogeneous, lean mixture throughout the cylinder. This jet-like distribution of the rich mixture flame from the pre-chamber to the lean mixture in the main chamber allows for a more immediate and controlled combustion process, increasing combustion efficiency while reducing fuel consumption. A conventional combustion chamber typically ignites in the center of the cylinder, but with the Mahle Jet Ignition, ignition generally occurs from the outside in [29]. This allows for much more complete combustion of the fuel mixture. This results in more power with significantly less unburned leftover fuel. Consequently, less energy is wasted as heat and more energy

is converted into work, significantly increasing the engine's thermal efficiency, allowing the engine to produce more power while using less fuel (Figure 6) [4,20,30,31]. Mahle, the inventor of this technology, claims that it improves fuel efficiency and thermal efficiency by 10–25%. Current designs of F1 combustion engines tend to achieve a thermal efficiency of 54–56%.

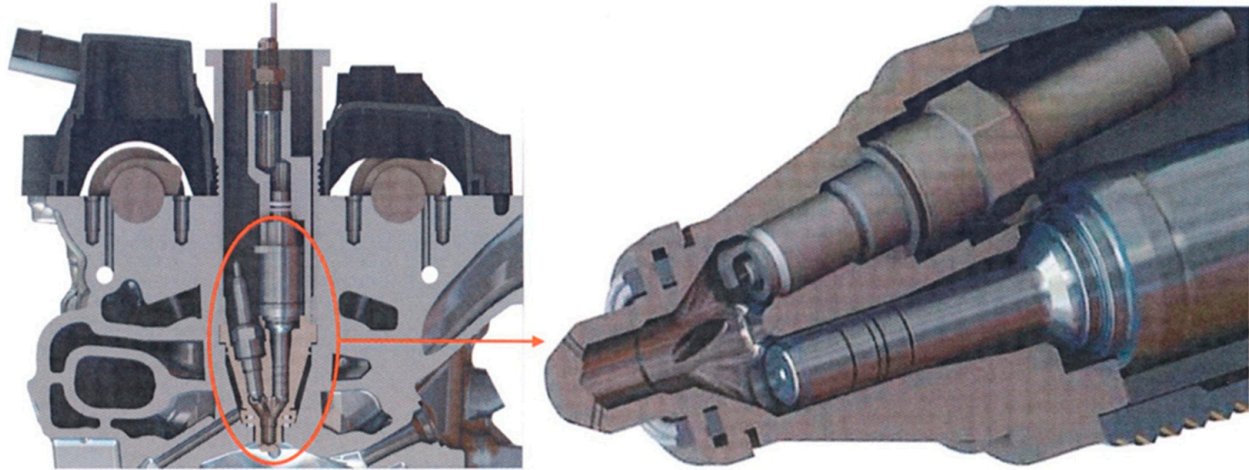


Figure 6. Turbulent Jet Ignition (TJI) [Mahle].

As indicated in Table 2, the maximum permissible fuel flow to the engine will be replaced in 2026 by a limit on the fuel's energy content, rather than its mass. Combined with the new fuel composition, this change could cause the combustion characteristics of the 2026 F1 engines to differ from those of the 2025 F1 engines. The calorific value of biofuel compliant with the 2026 FIA requirements, Table 3, will likely be slightly lower than that of traditional gasoline. As a result, to obtain similar energy delivered by the fuel, more fuel would need to be fed to the ICE cylinders, which still have a displacement of 1600 cm³. This will lead to a richer combustion mixture and, therefore, a lower combustion temperature.

This will result in a reduction in NO_x emissions, which is the main pollutant for all combustion engines, as well as a decrease in power [30–32]. However, since the calorific value of the fuel is no longer important, this change implies the possibility of using oxygen solutions to further increase the amount of oxidant introduced into the cylinders of the combustion engine and thus being a way to increase the maximum power [29,30,33–35]. Furthermore, switching from hydrocarbon fuel to biofuel will lead directly to lower carbon dioxide emissions.

8. Conclusions

Formula 1 (F1) represents the pinnacle of achievement in the development of technology in the broadest sense and progress in motorsports. The groundbreaking technical solutions developed and used in F1 push the boundaries of engineering and performance far into the future. At the same time, with the growing emphasis on sustainability, F1 is adapting to global carbon neutrality requirements. As a result, in the near future, F1 will have to strike a balance between technical innovation and environmental responsibility imposed by new regulations concerning both the development of powertrains and environmentally friendly fuel technologies. Starting in 2026, the electric part of the drive system will be responsible for generating almost half of the power unit's power (power breakdown (ICE–53%/Hybrid 47%)). Also, from 2026, only 100% sustainable (synthetic) fuel will be used to power F1 engines, and the possibility of using hydrogen as an emission-free fuel is already being explored. Therefore, the pro-ecological evolution of powertrains and fuels in Formula 1 is a fact and will be a key direction for the future development of F1.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the author.

Conflicts of Interest: The author declares no conflicts of interest.

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