Towards Low-Carbon Mobility: The Impact of Renewable Fuel Blends on Passenger Vehicles

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ABSTRACT

This study evaluates the potential of using a fuel blend of 7% synthetic gasoline and 93% anhydrous ethanol by volume for the decarbonization of the passenger vehicle transport sector in Brazil. Three synthetic gasoline production scenarios, focused on the ethanol-to-gasoline conversion process, were analyzed considering different ethanol feedstocks and their production pathways: first-generation ethanol from corn, first-generation ethanol from sugarcane, and second-generation ethanol from sugarcane bagasse. The carbon intensity (gCO_2eq/MJ) associated with the production of this renewable blend was calculated considering various typical Brazilian energy sources, including the national electricity mix and biomethane derived from sugarcane residues. The analysis incorporated critical production stages such as ethanol synthesis, electricity usage, thermal energy from biomethane, and hydrogen synthesis via electrolysis.

Results revealed significant variations in carbon intensity depending on the ethanol feedstock, with synthetic gasoline derived from second-generation sugarcane bagasse ethanol demonstrating the lowest value (6.65 gCO_2eq/MJ), followed by that from first-generation sugarcane ethanol (22.97 gCO_2eq/MJ) and from first-generation corn ethanol (25.05 gCO_2eq/MJ). Energy efficiency and carbon footprints were further assessed in terms of fuel autonomy, comparing Brazilian commercial gasoline with 27% ethanol by volume, hydrous ethanol, and the proposed renewable fuel blend. Findings indicate that the ethanol-synthetic gasoline blend offers improved energy density and vehicle range compared to hydrous ethanol, along with a significant reduction in greenhouse gas emissions relative to fossil gasoline. Specifically, the blend using 93% first-generation sugarcane ethanol and 7% synthetic gasoline produced from second-generation sugarcane bagasse ethanol reduced emissions by up to 78% compared to conventional gasoline. This comprehensive analysis emphasizes the critical role of advanced bioethanol production pathways and synthetic fuels in Brazil's transition to a low-carbon mobility system, underlining the necessity for strategic integration of renewable fuels into existing transportation infrastructure.

INTRODUCTION

The production of synthetic fuels from renewable sources has been considered a promising alternative for decarbonizing the transport sector. E-fuels can be produced independently of biomass resources, distinguishing them from biofuels. In 2022, the transport sector was responsible for 21.6% of global CO_2 emissions, totaling 7.95 gigatonnes, primarily as a result of the consumption of fossil fuels derived from petroleum [1]. Furthermore, the transformation of excess renewable energy into e-fuels offers a solution to the intermittency challenges of renewable sources, while avoiding the limitations associated with battery use in electrified systems [2]. The synthesis of liquid fuels using CO_2 derived from coal has been a well-established technology since the 20th century, though it was largely discontinued due to the historically low cost of fossil fuels. In recent years, however, growing interest has emerged in revisiting and advancing this conventional approach, driven by its potential contribution to decarbonization. Still, defining a single, standardized route for e-fuel production remains difficult, as it depends heavily on factors such as the composition of the energy matrix, the availability of green hydrogen, and the sources and methods used to obtain biogenic CO_2 [3].

Three main CO_2 capture routes are evaluated as sources for e-fuel synthesis. The first involves capturing CO_2 from high-concentration industrial streams (~45% CO_2), such as off-gases from steam methane reforming (SMR), using amine-based systems. The second route targets medium-concentration point sources (between 8 and 14% CO_2), also

using amine capture [4]. In this category, the flue gas resulting from the combustion of sugarcane bagasse in biomass plants is notable, typically containing between 10 and 14% CO_2 by volume. This gas can be treated using post-combustion capture technologies, such as amine scrubbing. Once captured, this biogenic CO_2 becomes a valuable feedstock for e-fuel synthesis, enabling negative-emission pathways when combined with renewable hydrogen [5]. The third option is Direct Air Capture (DAC), a low-temperature process that requires higher energy input. In all cases, CO_2 is treated as a waste stream with no upstream carbon burden, so only the capture and purification stages contribute to the carbon intensity of the process. A final liquefaction step may be required to ensure the necessary purity for synthesis [6].

Electrolytic hydrogen (eH_2), also known as green hydrogen when produced from renewable electricity, is a key element in the energy transition and serves as a precursor for various e-fuels. This hydrogen is generated through water electrolysis, an endothermic reaction that requires 286 kJ/mol and can be conducted at low (50–80 °C) or high (700–1000 °C) temperatures [7]. Alkaline Electrolysis Cells (AEC) use KOH and nickel catalysts, operating at pressures up to 30 bar. Polymer Electrolyte Membrane (PEM) systems operate with pure water at pressures up to 100 bar but require expensive materials such as platinum [8]. High-temperature electrolysis, performed by Solid Oxide Electrolysis Cells (SOEC), co-electrolyzes steam and CO_2, reducing electricity consumption through heat integration. In this study, AEC is considered the baseline technology, with SOEC evaluated for future high-efficiency scenarios [9]. In addition, eH2 energy required to produce other fuels via Fischer-Tropsch pathway will be accessed via different Brazilian electricity sources.

eMethanol (eMeOH) can be used directly as a fuel or as an intermediate in other synthesis routes, such as the Methanol-to-Gasoline (MTG) process. It is produced by reacting CO_2 with renewable hydrogen, typically at a molar ratio of 1:2.8. The process can follow a two-step route via syngas or a direct single-step route. Key reactions include $CO + 2H_2 \rightarrow CH_3OH$ and $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$, both of which are exothermic [10]. Direct synthesis offers high methanol selectivity and is exemplified by the George Olah plant in Iceland, with a capacity of 4,000 tons per year. Energy and mass balances depend on the chosen synthesis route and operating conditions [11].

The conversion of eMethanol to gasoline via the MTG process was developed by Mobil in the 1980s [12]. This multistage process involves methanol dehydration and conversion into longer-chain hydrocarbons, operating at 300–400 °C and pressures of 15–20 bar in an overall exothermic reaction [13]. Methanol dehydration produces water and dimethyl ether (DME), which is further processed to yield a mixture consisting of gasoline (78–80%), liquefied petroleum gas – LPG (18–20%), and fuel gas (1–2%). The gasoline produced must undergo additional processing to meet road fuel specifications (CONCAWE) [14].

The Fischer-Tropsch (FT) process is a mature technology that converts syngas (a mixture of H_2 and CO) into long-chain hydrocarbons through an exothermic reaction, conducted at 190–250 °C and pressures up to 30 bar. Syngas can be produced from CO_2 via the Reverse Water-Gas Shift (RWGS) reaction using renewable hydrogen [15]. FT synthesis predominantly yields heavy hydrocarbons, which are hydrocracked to produce transportation fuels. A typical product distribution after hydrocracking includes 37% gasoline, 28% diesel, 32% kerosene, and 3% LPG [16]. The gasoline fraction requires further upgrading, such as isomerization, to meet road fuel specifications [17].

Finally, the Ethanol-to-Gasoline (ETG) process converts renewable ethanol into drop-in hydrocarbons through catalytic dehydration and oligomerization steps. In the first stage, ethanol is dehydrated to form ethylene at temperatures between 300 and 450 °C [18]. The ethylene is then oligomerized and further processed over zeolite-based catalysts to form a hydrocarbon mixture rich in gasoline-range molecules. The final product has a high-octane number and low aromatic content, making it suitable as a direct substitute for fossil gasoline [19]. This technology enables the valorization of bioethanol as a renewable feedstock for synthetic gasoline production.

The objective of this study is to evaluate different ETG production scenarios by incorporating factors that more accurately reflect the Brazilian context in the calculation of the carbon intensity of the final fuel. Additionally, the study aims to compare the use of the Brazilian Type C Gasoline, the Hydrous Ethanol Fuel (HEF) produced in Brazil, which contains approximately 7% water by volume, with a renewable fuel composed of anhydrous ethanol blended at 7% by volume with a synthetic gasoline (E93eG7), taking into account the potential operational improvements offered by the latter option.

METHODOLOGY

For the purpose of this study, a Brazilian flex fuel Large SUV PL7 vehicle was selected as the reference vehicle, with an energy efficiency of 1.83 MJ/km under the combined driving cycle, according to NBR 7024 [20]. A total vehicle lifetime of 200,000 km was also assumed for the carbon intensity calculations, based on previous studies that adopted this average value [21][22][23].

Brazilian energy matrix

The Brazilian energy matrix consists of diverse sources, each characterized by distinct levels of carbon intensity (CI). Renewable sources such as wind, hydroelectric, and solar energy present notably lower carbon intensities, highlighting their potential in sustainable energy strategies. Biomass-derived energy, including sugarcane bagasse, firewood, and black liquor, also contributes renewable

options, although their carbon intensities vary according to specific combustion technologies and processing methods. Table 1 shows the detailed values for each energy source carbon intensity based on several literatures.

On the other hand, fossil-based and other non-renewable sources, such as steam coal, coke oven gas, fuel oil, diesel oil, and natural gas, have significantly higher carbon intensities. Nuclear power, despite being non-renewable, stands out with a relatively low carbon intensity compared to other conventional sources. Analyzing these varying carbon intensities is crucial for informed decision-making and strategic planning aimed at mitigating carbon emissions across Brazil's energy sector.

For the purpose of the scenario analyses in this study, the carbon intensity attributed to electricity consumption will be based on the Brazilian average energy mix, which reflects the proportional contribution of each source listed in Table 1 to the national electricity matrix. This approach ensures that the results incorporate the typical environmental impact associated with electricity use across Brazil. Additionally, for specific scenarios involving ethanol production from sugarcane, the electricity demand will also consider localized generation from the combustion of sugarcane bagasse, a common practice in agro-industrial facilities that enhances energy self-sufficiency while influencing the overall carbon footprint.

Table 1 - Carbon intensity (gCO_2eq/MJ) associated with different energy generation sources in Brazil

Energy Source	CI (gCO_2eq/MJ)	Reference
Hydroelectric	6.67	[24]
Wind	3.06	[24]
Solar	11.39	[24]
Sugarcane Bagasse	13.68	[25]
Firewood	12.67	[25]
Black Liquor	36.42	[25]
Other Renewable Sources	7.72	[25][26]
Nuclear	3.31	[25]
Steam Coal	227.78	[26]
Natural Gas	136.11	[26]
Coke Oven Gas	234	[25]
Fuel Oil	294.59	[25]
Diesel Oil	200.11	[25]
Other Non-Renewable Sources	146.44	[25][26]
Brazil Average	15.3	[27]

Ethanol production scenarios

Three distinct ethanol production scenarios were considered: two first-generation ethanol scenarios, derived from corn and sugarcane processing, respectively, and one second-generation scenario, utilizing sugarcane bagasse. The carbon intensity for each scenario will be calculated based on the Brazilian mixed electricity energy pathway or by burning sugarcane bagasse in specific scenarios, as referenced in Table 1.

First-generation ethanol from corn is produced via direct fermentation of starch, whereas sugarcane ethanol utilizes juice extracted directly from the plant. In contrast, second-generation ethanol derived from sugarcane bagasse involves cellulosic conversion, exploiting plant residues. Comparing these three feedstocks is essential to assess environmental impacts, energy efficiency, and sustainability, thus identifying the most advantageous routes for reducing carbon emissions.

Table 2 - Carbon intensity (gCO_2eq/MJ) associated with ethanol production from different feedstocks

Ethanol Feedstock	Generation	CI (gCO_2eq/MJ)	Reference
Corn	1st	26.13	[28]
Sugarcane	1st	20.51	[28]
Sugarcane Bagasse	2nd	4.41	[28]

Comparing these three feedstocks is essential to assess environmental impacts, energy efficiency, and sustainability, thus identifying the most advantageous routes for reducing carbon emissions.

Synthetic gasoline production scenarios

This study evaluates the Ethanol-to-Gasoline (ETG) pathway for synthetic gasoline production, representing a viable route for the integration of renewable carbon and hydrogen sources.

In the ETG route, renewable ethanol is catalytically dehydrated to ethylene and subsequently converted into gasoline-range hydrocarbons. Traditionally, this transformation involves sequential dehydration and oligomerization steps; however, recent technological advancements have enabled a direct single-step conversion via the CADO-ETH process. This innovative route employs Ni/HZSM-5-based catalysts to convert wet ethanol directly into liquid hydrocarbons, eliminating the need for external hydrogen input or prior ethanol dehydration. As a result, the overall energy efficiency of the process is significantly enhanced, reaching values above 93%. Given its high efficiency and compatibility with existing ethanol

infrastructure, particularly in countries like Brazil, the CADO-ETH process stands out as a highly promising pathway for the sustainable production of drop-in synthetic gasoline [29].

Even then ETG route from [29] is quite promising, in this study, a more conservative approach based on [30] (ETOH to SAF] was used. In addition to the carbon intensity of electricity used during synthesis and the upstream emissions from ethanol production, the overall carbon footprint of the ETG route would also account for the contributions from natural gas and hydrogen, both of which are required in the process. For natural gas, a carbon intensity of 78.1 gCO_2e/MJ is reported [27]. In this study, natural gas was replaced by biomethane produced from sugarcane, with a carbon intensity of 4.84 gCO_2e/MJ, while the renewable hydrogen used in the process has a carbon intensity equal to the carbon intensity of the Brazilian electricity mix divided by the efficiency of the electrolysis process, which is on average 71% [8]. The use of biomethane in replacement of natural gas resulted in a process gCO2e/MJ reduction from 18,90 to 2,05.

To complement the evaluation of synthetic gasoline production scenarios, it is essential to outline the methodology used to calculate the final carbon intensity (CI) of the Ethanol-to-Gasoline (ETG) process. This calculation integrates the cumulative carbon emissions from all energy-consuming stages involved in the production of eGasoline. Specifically, the CI is determined by summing the products of the energy consumption per megajoule of eGasoline produced ($MJ/MJ_{eGasoline}$) and the respective carbon intensity (gCO_2eq/MJ) of each input. The stages considered include: ethanol synthesis (1.02 $MJ/MJ_{eGasoline}$), electricity usage (0.02 $MJ/MJ_{eGasoline}$), biomethane consumption for thermal energy (0.23 $MJ/MJ_{eGasoline}$), and hydrogen synthesis (0.03 $MJ/MJ_{eGasoline}$).

Each of these stages contributes to the overall CI according to the carbon intensity of its energy source. For instance, ethanol production carries a variable CI depending on the biomass feedstock—ranging from corn to sugarcane or cellulosic materials—while electricity reflects the average carbon intensity of the Brazilian power grid. Natural gas and renewable hydrogen each have established emission factors based on their source and production route.

Finaly, the eGas fuels IC from different ethanol crops and generations were calculated for scenarios: first-generation ethanol produced from corn (1G C EtOH), first-generation ethanol derived from sugarcane juice (1G S EtOH), and second-generation ethanol produced from sugarcane bagasse (2G S EtOH).

RESULTS

With the foundational data and methodological framework previously discussed, Table 4 presents the calculated results for the carbon intensity associated with eGasoline production via the Ethanol-to-Gasoline (ETG) pathway. These results are derived from three distinct ethanol supply scenarios, each evaluated under the assumption that the Brazilian electricity mix—characterized by the values in Table 1—provides the energy inputs required throughout the conversion process.

Table 4 - Calculated Carbon Intensity (gCO2eq/MJ) for e-gasoline production according to three different ethanol production scenarios

eGas	Inputs		
	Energy-consuming stage	MJ/ $MJ_{eGasoline}$	IC (gCO2/ $MJ_{eGasoline}$)
eGC (eGasoline from 1G corn ethanol)	1G C ETOH	1.02	26.65
	Electricity	0.02	0.32
	Biomethane	0.23	1.11
	H2	0.03	0.65
	Total	28.74	
eGS1 (eGasoline from 1G sugarcane ethanol)	1G S ETOH	1.02	20.92
	Electricity	0.02	0.32
	Biomethane	0.23	1.11
	H2	0.03	0.65
	Total	23.00	
eGS2 (eGasoline from 2G sugarcane ethanol)	2G S ETOH	1.02	4.50
	Electricity	0.02	0.32
	Biomethane	0.23	1.11
	H2	0.03	0.65
	Total	6.58	

Among the evaluated scenarios, the use of first-generation corn ethanol (EtOH C-1G) resulted in the highest total carbon intensity, reaching 25.05 gCO_2eq/MJ of eGasoline. The scenario using sugarcane ethanol (1G S EtOH) showed a lower impact, with 23.00 gCO_2eq/MJ, due to the lower upstream emissions associated with sugarcane cultivation and processing. The lowest carbon intensity was observed in the second-generation sugarcane bagasse ethanol scenario (2G S EtOH), with a total of 6.65 gCO_2eq/MJ, representing a reduction of over 40% compared to corn-based ethanol.

The significant advantage of the second-generation pathway is linked to the lower carbon burden of its feedstock, as sugarcane bagasse is a lignocellulosic residue with minimal associated emissions. This allows for a more efficient use of biomass resources and results in a lower overall environmental impact in synthetic gasoline production.

Table 5 presents the fuel blend compositions accessed. For E93eG7-C fuel blend, first generation corn ethanol was used as ethanol base fuel and as feedstock for eGas production; For E93eG7-S1 fuel blend, first generation sugarcane ethanol was used as ethanol base fuel and as feedstock for eGas production. For E93eG7-S2, first generation sugarcane ethanol was used as ethanol base fuel

and second generation sugarcane ethanol was used as feedstock for eGas production. The last composition was used to provide a coherent scenario, once at this time, only one second generation sugarcane ethanol plant is fully operational).

Table 5 – Fuel blend composition

Fuel blend	Composition	
	Ethanol for blend	Ethanol for eGas production
E93eG7-C	1G C ETOH	1G C ETOH
E93eG7-S1	1G S ETOH	1G S ETOH
E93eG7-S2	1G S ETOH	2G S ETOH

To complement the carbon intensity analysis, Table 6 presents a comparative assessment of the energy range offered by four different fuels: Brazilian Type C Gasoline (E27), Hydrous Ethanol Fuel (HEF), anhydrous ethanol (E100, composed as mix of 50% 1G sugarcane ethanol and 50% 1G corn ethanol), and the proposed renewable blend designated as E97eG7. For IC calculations, HEF IC was calculated as the average IC of the first generation corn and sugarcane ICs. This evaluation considers the lower heating value (LHV) of each fuel, based on data provided in reference [27] in order to estimate the total energy delivered per unit of volume. For this comparison, the LHV of eGasoline was assumed to be equivalent to that of conventional Type C Gasoline, enabling a consistent analysis. The HEF value reflects the reduced energy density due to its water content, while the E97eG7 blend combines 93% synthetic gasoline with 7% anhydrous ethanol by volume, aiming to balance high energy density with renewable content.

Table 6 – Fuel consumption comparison considering a Brazilian flex fuel Large SUV Energy Range between Brazilian Type C Gasoline, HEF and E97eG7

Fuel	Energy Range (MJ/km)	LHV (MJ/l) [27]	Fuel Consumption (km/l)	Vehicle Range Gain compared to HEF (%)
E27	1.83	32.0	17.49	61.7%
HEF	1.83	19,6	10.71	-
E100	1.83	21,1	11.53	7.7%
E93eG7	1.83	21.9	11.95	11.5%

The results show a clear variation in fuel consumption depending on the energy density of each fuel. Brazilian Type C Gasoline, with the highest LHV (32 MJ/l), achieves the lowest fuel consumption rate at 14.1 km/l. Hydrous Ethanol Fuel (HEF), due to its lower LHV of 21.1 MJ/l, presents a substantially higher fuel consumption of 9.81 km/l. The E93eG7 blends—regardless of the ethanol feedstock used—achieve an intermediate fuel consumption of 10.17 km/l, reflecting their higher energy density compared to HEF. Also, the proposed E93eG7 fuel offers 11,5% additional range relative to HEF, while maintaining a high renewable content. The improved performance results from the higher LHV of the synthetic gasoline component in the blend, which enhances energy delivery per unit volume and extends vehicle range without compromising compatibility with existing powertrains. Additionally, if E100 was compared to HEF, a theoretical 7.7% vehicle range gain would be found, which is highly correlated to previous tests comparing HEF and E100 BSFC in a VW engine presented in 2024 SIMEA edition [31]. Figure 1 shows a graphical comparison for the carbon intensity of each fuel production, considering Well-To-Tank values according to [27] for Brazilian Type C Gasoline and HEF, and the values calculated for the proposed E93eG7.

The carbon intensity values shown in the Figure 1 reveal a considerable variation between ethanol-based fuels. E27 exhibits the highest well-to-tank carbon intensity, close to 90 gCO_2e/MJ due to its fossil origin. HEF shows a considerably lower impact, around 23.3 gCO_2e/MJ, due to its renewable origin. The E93eG7 blends present intermediate values that vary according to the ethanol feedstock used: approximately 28.55 gCO_2e/MJ for corn-based ethanol, 22.83 gCO_2e/MJ for sugarcane ethanol, and 19.54 gCO_2e/MJ for second-generation sugarcane bagasse ethanol. By combining these carbon intensities with the fuel consumption (km/l) values listed from Table 6, it is possible to estimate the emissions per kilometer driven for each fuel. The results are shown in Figure 2.

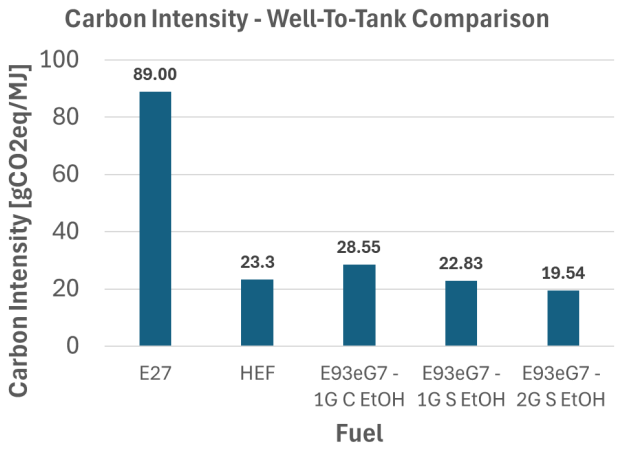

Figure 1 – Well-to-tank carbon intensity (gCO2e/MJ) comparison between Type C Gasoline, HEF and E93eG7.

The CO_2eq emissions per kilometer driven, as shown in Figure 2, highlight a substantial reduction, from 22,1 up to 25.4 tCO_2eq by the end of 200,000 km in greenhouse gas

output when using renewable fuel alternatives. Again, E27 registered the highest emission level at approximately 162 gCO_2e/km. HEF shows a notable decrease, with emissions around 42.7 gCO_2e/km, owing to its renewable origin. Among the E93eG7 blends, values range from 41.8 to 52.3 gCO_2e/km when first-generation corn or sugarcane ethanol is used. The most significant improvement is observed in the E93eG7-S2 blend using second-generation sugarcane bagasse ethanol (EtOH S-2G), which lowers emissions to approximately 35.7 gCO_2e/km. This represents a reduction of 16.2% compared to HEF and almost 78% relative to fossil gasoline, emphasizing the environmental benefit of integrating low-carbon ethanol sources into synthetic fuel formulations.

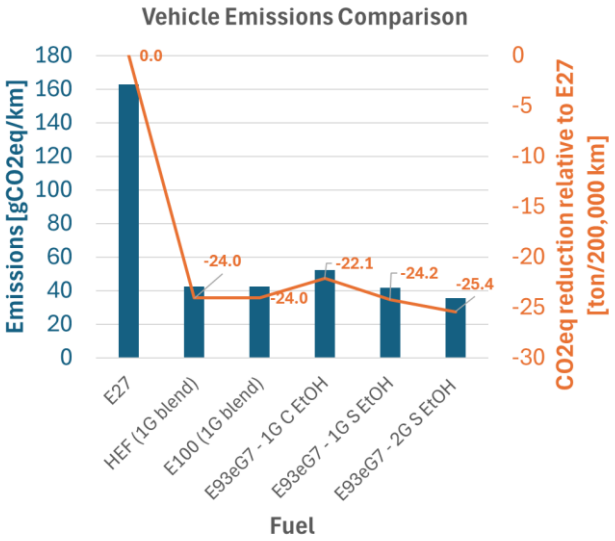

Figure 2 – Vehicle emissions comparison in gCO2e/km and ton of CO2e reduction during the vehicle lifespan of 200.000 km.

CONCLUSION

The evaluation of different production and application scenarios for the renewable fuel blend E93eG7, composed of 93% anhydrous ethanol and 7% synthetic gasoline (eGas) produced via the Ethanol-to-Gasoline (ETG) process, revealed significant environmental benefits. The analysis of three ethanol supply pathways—1G C EtOH, 1G S EtOH, and 2G S EtOH—demonstrated substantial variation in the carbon intensity (CI) of the resulting eGas, with the lowest CI observed for eGas derived from 2G S EtOH (6.65 gCO_2eq/MJ), compared to 22.97 gCO_2eq/MJ and 25.05 gCO_2eq/MJ for 1G S EtOH and 1G C EtOH, respectively. Among the fuel blends assessed, E93eG7-S2—comprising 1G S EtOH as base fuel and eGas produced from 2G S EtOH—exhibited the lowest overall carbon footprint, with emissions of 35.7 gCO_2eq/km. Over a typical vehicle lifetime of 200,000 km, this corresponds to a cumulative emission of just 7.1 tons of CO_2eq, representing a 78% reduction compared to the 32.4 tons emitted by fossil gasoline (E27). In addition to its substantial greenhouse gas mitigation potential, the E93eG7-S2 blend also delivered an 11.5% increase in vehicle range per liter relative to Hydrous Ethanol Fuel (HEF), driven by the higher energy density of its eGas component. These findings position E93eG7-S2 as a high-impact, environmentally superior fuel option for Brazil's light-duty transportation sector, leveraging existing ethanol infrastructure while enhancing emissions efficiency in the transition to low-carbon mobility.

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