

Fuels Institute

LITERATURE REVIEW SUMMARY:

Future Capabilities of Combustion Engines and Liquid Fuels

NOVEMBER 2022





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Introduction

As the global community pursues lower carbon intensity in the transportation sector, many have identified electrification strategies as the most effective path to achieve these objectives. In most cases, these strategies refer to the deployment of battery electrical vehicles (BEVs) and hydrogen fuel cell vehicles (H₂FCVs), which are not equipped with internal combustion engines (ICEs); however, even under aggressive strategies to electrify the transportation system, the marketplace is expected to continue to rely for decades upon liquid fuels and internal combustion engine (ICE) vehicles, including the deployment of hybrid-electric vehicle (HEV) and plug-in hybrid electric vehicle (PHEV) technology.

This literature review covers recent, current, and pending research and development projects focused on improving the ICE efficiency and emissions. In addition, several research and development initiatives are also focused on reducing the carbon intensity of the liquid fuels that power these engines and vehicles. Understanding the objectives and potential benefits of such initiatives is important to better evaluate the potential emission contributions of the transportation sector.

Please note that different studies use different terms for engine efficiency, fuel economy, and CO₂ abatement. Efforts have been made to clarify which term is being used by each paper referenced within this report.



Internal Combustion Engines and Hybrids

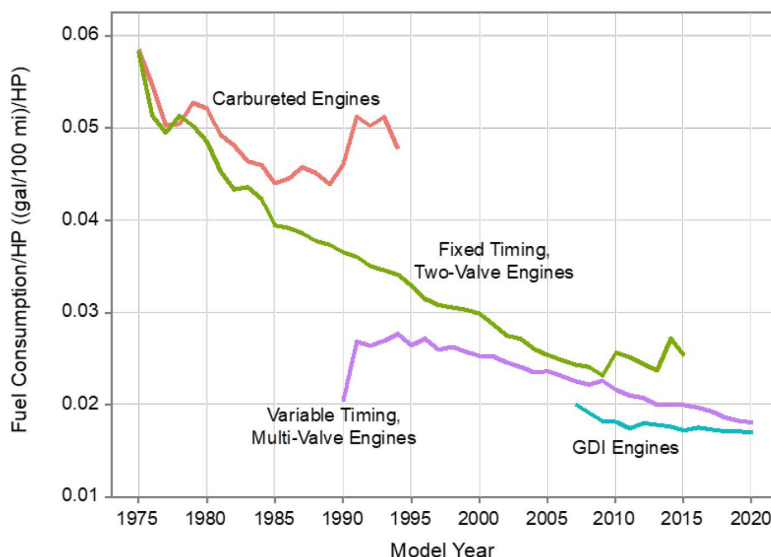
INTERNAL COMBUSTION ENGINE DESIGN, PERFORMANCE, EFFICIENCY AND EMISSION IMPROVEMENTS

Light-Duty Vehicle Gasoline Engines

Passenger car ICE design has evolved over four decades to include several fuel efficiency improvements, including variable valve timing and gasoline direct injection (GDI) (see Figure 1),

gasoline engine turbocharging (see Figure 2), and engine downsizing (i.e., number of cylinders) (see Figure 3).

FIGURE 1 : FUEL CONSUMPTION WITH DIFFERENT GASOLINE TECHNOLOGY PACKAGES



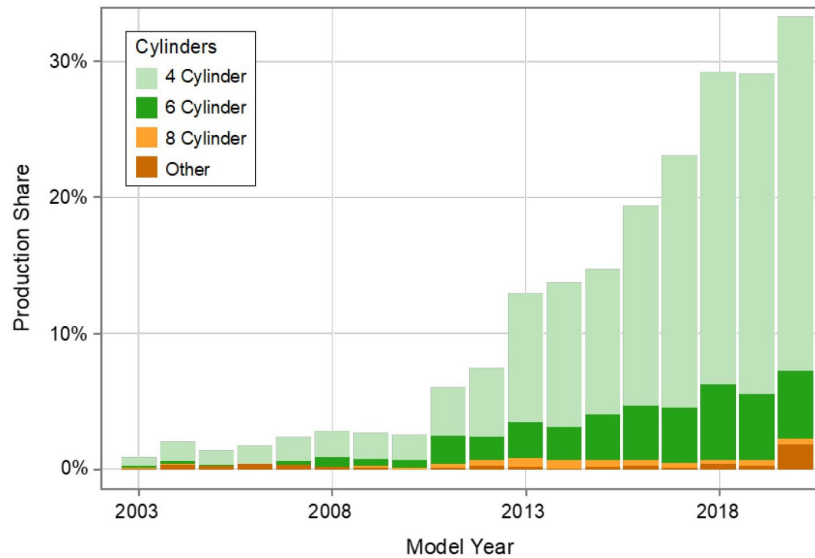
US Environmental Protection Agency, The 2020 EPA Automotive Trends Report

According to the United States Environmental Protection Agency (EPA), GDI engines were installed

in >50% of model year (MY) 2019 gasoline vehicles and are projected to continue to increase.²

² US Environmental Protection Agency, The 2020 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975, EPA-420-R-21-003, January 2021, <https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1010U68.pdf>, 46.

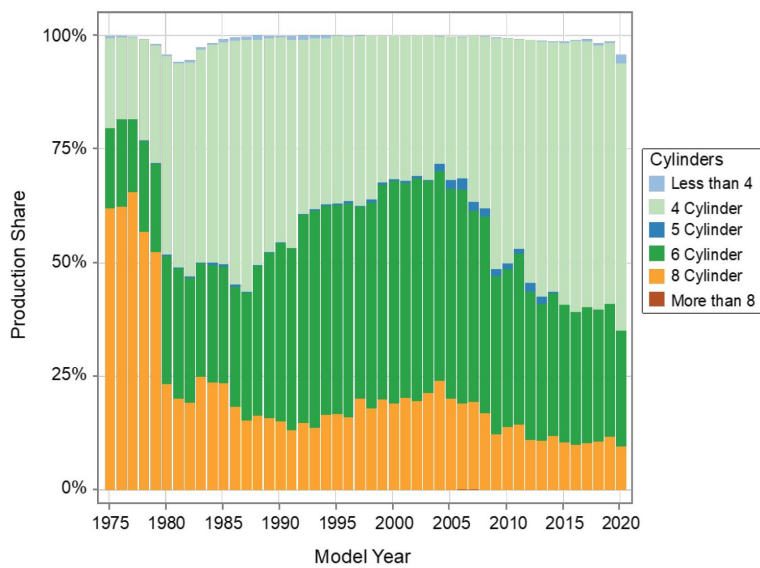
FIGURE 2: GASOLINE TURBO ENGINE PRODUCTION SHARE BY NUMBER OF CYLINDERS



US Environmental Protection Agency, The 2020 EPA Automotive Trends Report

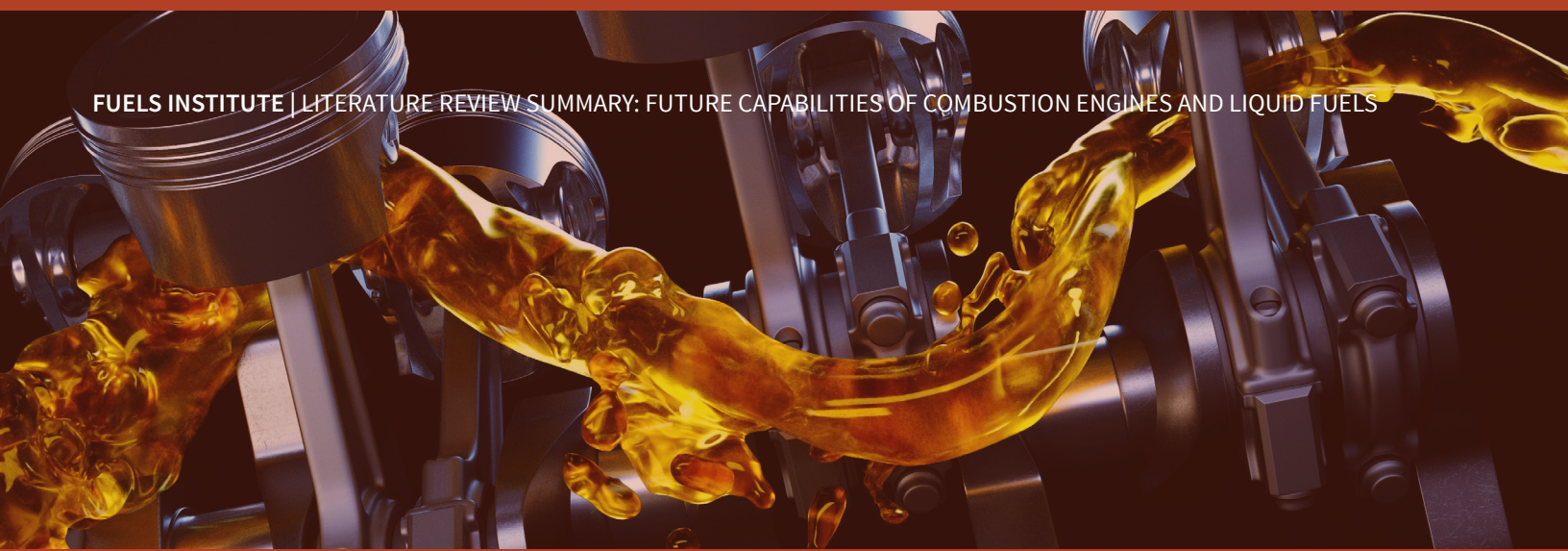
EPA also stated that vehicle engine downsizing is expected to continue with >50% of MY 2019 gasoline vehicles equipped with four cylinders or less.³

FIGURE 3: GASOLINE ENGINE PRODUCTION SHARE BY NUMBER OF CYLINDERS



US Environmental Protection Agency, The 2020 EPA Automotive Trends Report

³ US Environmental Protection Agency, The 2020 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975, EPA-420-R-21-003, January 2021, <https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1010U68.pdf>, 40.



In addition to the technology improvements listed above, cylinder deactivation and start/stop technologies have also been deployed in almost 15% and 37%, respectively, of MY2019 gasoline engines also according to the EPA.⁴ But even with this track record of steady fuel efficiency improvement,

additional ICE design improvements continue to be the subject of research efforts that include the advancements listed in Table 1 with reported improvements to fuel consumption or thermal efficiency as noted.⁵

TABLE 1: ADDITIONAL IDENTIFIED ICE DESIGN IMPROVEMENT RESEARCH EFFORTS

ICE Technology Advancement	Reported Improvement
Ceramic coatings	4.5-9% Lower Fuel Consumption
Port/direct water injection	5-15% Higher Thermal Efficiency
Exhaust gas recirculation with in-cylinder tumble flow	10% Lower Fuel Consumption

Furthermore, the National Academy of Sciences (NAS) Committee on the Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles published two reports in 2015⁶ and 2021.⁷

In the first report, the NAS Committee continued

work previously conducted by the National Research Council to provide potential ICE technology improvements that may be employed through 2030. Findings and recommendations from the first Committee Report are summarized below in Table 2, as follows:

⁴ US Environmental Protection Agency, The 2020 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975, EPA-420-R-21-003, January 2021, <https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1010U68.pdf>, 48.

⁵ Eyub Canli et al., “Ceramic Coating Applications and Research Fields for Internal Combustion Engines,” Reza Golzari et al., “Impact of Intake Port Injection of Water on Boosted Downsized Gasoline Direct Injection Engine Combustion, Efficiency and Emissions,” International Journal of Engine Research 22, no. 1 (January 1, 2021): 295-315, <https://doi.org/10.1177/1468087419832791>; Augusto César Teixeira Malaquias et al., “Combined Effects of Internal Exhaust Gas Recirculation and Tumble Motion Generation in a Flex-Fuel Direct Injection Engine,” Energy Conversion and Management 217 (August 2020), 113007, <https://doi.org/10.1016/j.enconman.2020.113007>.

⁶ National Academies of Sciences, Engineering, and Medicine. 2015. Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles. Washington, DC: The National Academies Press. <https://doi.org/10.17226/21744>.

⁷ National Academies of Sciences, Engineering, and Medicine. 2021. Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy—2025-2035. Washington, DC: The National Academies Press. <https://doi.org/10.17226/26092>.

TABLE 2: OPTIONS FOR IMPROVING SPARK IGNITION ENGINE FUEL CONSUMPTION THROUGH 2030

Technology or Technology Bundle	Fuel Consumption Reduction, %
Improved lubricants, lower engine friction, variable valve timing and lift, direct injection, cooled exhaust gas recirculation and downsizing/ turbocharging.	17-18 (Combined)
Higher Compression Ratio with current regular gasoline	3
Higher Compression Ratio with higher octane regular gasoline ⁸	5
High Compression Ratio with exhaust scavenging and direct injection (Mazda-Skyactiv)	10
Electrically assisted, variable-speed supercharger	26
Lean Burn Facilitated by Low-Sulfur Fuel	5
Compressed Natural Gas-Gasoline Bi-fuel Vehicle ⁹	43
Ethanol-Boosted, Direct Injection Engines	20
Variable Compression Ratio	5
Dedicated Exhaust Gas Recirculation	10
Spark-Assisted Homogeneous Charge Compression Ignition (SI-HCCI) ¹⁰	5
Gasoline Direct Injection Compression Ignition	5
Waste Heat Recovery	3
Homogeneous Charge Compression Ignition (HCCI) (aka Low Temperature Combustion) ¹¹	5
High Octane Gasoline – 87 AKI (91 RON) Increased to 91 AKI (95 RON)	3-5

⁸ Please note that further research related to High Octane Gasoline is described in more detail in Section 2.5.

⁹ Please note that further research related to Bi-Fuel, or Duel-Fuel engines and vehicles are discussed in more detail in Section 2.4.

¹⁰ Please note that additional research related to Homogeneous Charge Compression Ignition (HCCI) is described in Section 3.0.

¹¹ Please note that further research related to HCCI is presented in Section 3.0.

In the second report, the NAS Committee continued with a similar work scope but extended the technology deployment time horizon to 2035 and focused on technology pathways (system-level

applications) instead of specific/individual technologies. Findings and recommendations from the Phase 3 Committee Report are summarized below in Table 3, as follows:

TABLE 3: OPTIONS FOR IMPROVING SPARK IGNITION ENGINE FUEL CONSUMPTION THROUGH 2035

Technology Pathways	Fuel Consumption Reduction
Downsized/Boosted Engines including, application of Miller cycle (or Atkinson cycle in the naturally aspirated case), cooled EGR, friction reduction, and cylinder deactivation	5% by 2025; With 5% More by 2030
Strong Hybrid Electric Vehicle (HEV) Configuration ¹²	35-40%
Advanced Combustion Technology (e.g. HCCI, Prechamber Combustion, Spark Controlled Compression Ignition (Mazda SkyActive-X))	Not Specified

Heavy-Duty Vehicle Diesel Compression Ignition Engines

In general, heavy-duty vehicles (Class 7-8), which carry large quantities of freight in the U.S., have relied upon diesel compression ignition (CI) engines for many reasons. Diesel engines operate at a higher efficiency than comparable spark ignition (SI) engines and have a flatter torque curve. In addition, diesel fuel has a higher energy density than gasoline.

Overall, diesel compression ignition engines have been more cost-effective, leading to a lower cost of ownership.

The following Table 4 provides a review of technology options for improving the fuel efficiency of heavy-duty CI engines.¹³

¹² Please note that Hybrid Electric Vehicle (HEV) technology is described in more detail in Section 2.2.

¹³ Characterization of Energy Distribution and Efficiency in a Modern Heavy-Duty Diesel Engine A Thiruvengadam, S Pradhan, P Thiruvengadam... - ... International Journal of ..., 2020 - sae.org

TABLE 4: TECHNOLOGY OPTIONS FOR IMPROVING DIESEL ENGINE FUEL EFFICIENCY

Compression Ignition Engine Loss Category	2020+ Compression Ignition Technology Advancement
Exhaust energy	<ul style="list-style-type: none"> ■ Increased compression ratio and increased peak in-cylinder pressures ■ Advanced turbocharger design, including two-stage and turbo-compounding ■ Two-step piston design and eight-nozzle fuel injector ■ Advanced ignition timing with actions to reduce nitrogen oxide (NO_x)
Coolant	<ul style="list-style-type: none"> ■ Thermal barrier coatings inside cylinder ■ Advancements in urea dosage and selective catalytic reduction catalyst resulting in lower exhaust gas recirculation rates and lower heat rejection
Friction	<ul style="list-style-type: none"> ■ Bearing/piston coatings and low-frictional boundary lubrication ■ Synthetic lubricants and advanced oil formulation ■ Reduced friction shaft seals ■ Reduced friction in gear train ■ In-cylinder piston components including low friction piston ring
Pumping	<ul style="list-style-type: none"> ■ Low-temperature selective catalytic reduction catalysts and partial hybridization of thermal management ■ Asymmetric turbocharger ■ Dedicated exhaust gas recirculation pump ■ High-pressure and low-pressure exhaust gas recirculation loops with smart controls ■ Thin-walled diesel particulate filter substrate (reduced back-pressure) ■ Selective-catalytic-reduction-coated diesel particulate filters
Engine accessories	<ul style="list-style-type: none"> ■ Variable flow oil and coolant pumps ■ Decoupling of the oil and water pump ■ Electric oil pumps

As follows on Table 5 below, implementing these technology improvements is expected to lead to more than 20% in fuel savings.¹⁴

European JEC research (a joint research project by the European Commission’s Joint Research Centre, EUCAR,¹⁵ and Concawe) also supports a potential improvement for heavy-duty CI engines. JEC estimated a GHG-reduction potential of 9% from

MY2016 to MY2025+ heavy-duty CI engines.¹⁶

Another research study concluded that a 5% thermal efficiency improvement (from 29.68% to 31.1%) could be attained by implementing a toroidal piston bowl with tangential grooves technology within the diesel engine combustion chamber.¹⁷

TABLE 5: EXPECTED FUEL SAVINGS PERCENTAGE BY IMPLEMENTING TECHNOLOGY IMPROVEMENTS

Category of energy loss	% Fuel In loss mechanism	% Reduction in loss mechanism	% Fuel savings
Exhaust energy	35.52	40	14.21
Coolant	10.68	25	2.67
Friction	2.32	25	0.58
Pumping	1.7	40	0.68
Engine accessories	1.3	10	0.13
Ambient heat transfer	4.3	0	0
Total			18.27
<i>Waste heat recovery</i>			<i>3.27</i>
Total			21.54

¹⁴ Characterization of Energy Distribution and Efficiency in a Modern Heavy-Duty Diesel Engine A Thiruvengadam, S Pradhan, P Thiruvengadam... - ... International Journal of ..., 2020 - sae.org J. Engines 13(4):583-599, 202

¹⁵ EUCAR is the European Council for Automotive Research & Development.

¹⁶ M. Prussi et al., JEC Well-To-Wheels Report V5 (Luxembourg: Publications Office of the European Union, 2020), doi:10.2760/100379, 95.

¹⁷ Arvind Thiruvengadam et al., “Characterization of Energy Distribution and Efficiency in a Modern Heavy-Duty Diesel Engine,” SAE International Journal of Engines 13, no. 4 (2020): 583-599, <https://doi.org/10.4271/03-13-04-0037>.

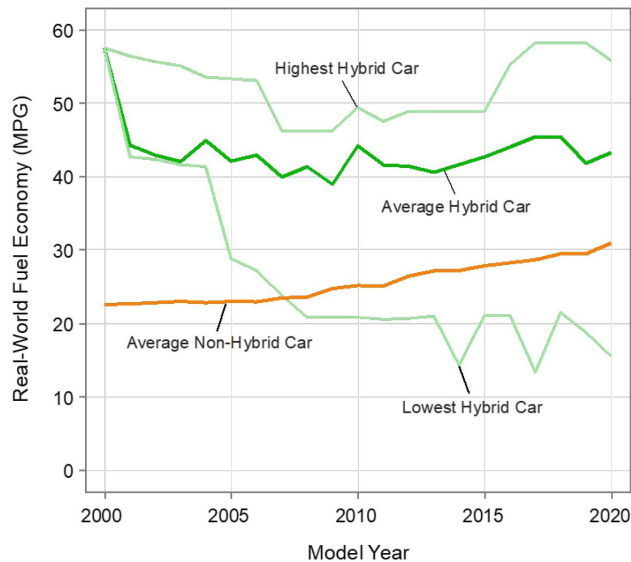


HYBRID ELECTRIC VEHICLE (HEV) DRIVETRAIN SYSTEMS

Hybrid electric vehicles (HEVs) feature an electric motor and battery that stores electrical energy to supplement the ICE, which typically allows the ICE to be downsized and operated more closely to its peak efficiency. In addition, HEVs also use

regenerative braking to capture energy from braking, which is usually lost to friction and heat. The application of HEV technology to passenger cars has yielded a real-world average fuel economy improvement of approximately 30% (see Figure 4).¹⁸

FIGURE 4: HYBRID REAL-WORLD FUEL ECONOMY DISTRIBUTION, CARS ONLY



US Environmental Protection Agency, *The 2020 EPA Automotive Trends Report*

¹⁸ US Environmental Protection Agency, *The 2020 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975*, EPA-420-R-21-003, January 2021, <https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1010U68.pdf>, 36.

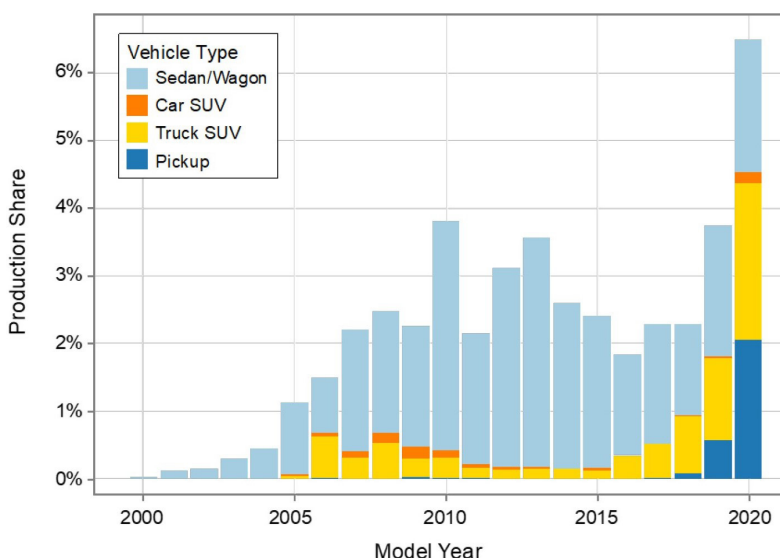
Another researcher provided a review of hybrid vehicle classifications (micro, mild, full, and plug-in), configurations (series, parallel, and mixed), and types of engine cycles (Otto¹⁹, Atkinson²⁰, and Miller²¹). This review indicated a fuel consumption reduction of 5% to 8%, 20% to 25%, and 45% for micro, mild, and full/plug-in HEVs, respectively.²²

European JEC research also supported the potential improvement through use of HEV technology in

passenger cars. JEC estimated that non plug-in hybridization of ICEs reduces fuel consumption by 25%.²³

Furthermore, hybrid vehicle technology could be potentially applied to additional future light-duty vehicles depending on economic feasibility, since the production share of HEVs composed only 6% to 7% of MY2020 light-duty vehicles (see Figure 5).²⁴

FIGURE 5: GASOLINE HYBRID ENGINE PRODUCTION SHARE BY VEHICLE TYPE



US Environmental Protection Agency, The 2020 EPA Automotive Trends Report

¹⁹ Otto Engine Cycle consists of a four-stroke cycle for internal-combustion engines of the type used in automobiles where the first stroke consists of the suction into the cylinder of the explosive charge (as gas and air), the second stroke consists of the compression, ignition, and explosion of the charge, the third stroke consists of the expansion of the gases, and the fourth stroke consists of the expulsion of the products of combustion from the cylinder

²⁰ Atkinson Cycle, as a modification to the four-stroke Otto Cycle, is designed to be more efficient at the expense of some torque at low engine speeds. The main difference occurs during the second stroke when the rising of the piston compresses the mixture of fuel and air (charge) in the combustion chamber. On the Atkinson engine, the intake valve is still open and some of the fuel and air mixture exits this valve so that the volume is compressed while the remaining mixture of fuel and air re-enters the next cylinder.

²¹ Miller Cycle is a modification to the Atkinson Cycle, where the intake valve is also left open longer than it would be in an Otto-cycle engine. This loss of charge air would typically result in a loss of power; however, in the Miller cycle, this is compensated for by the use of a supercharger.

²² Juan P. Torreglosa et al., "Analyzing the Improvements of Energy Management Systems for Hybrid Electric Vehicles Using a Systematic Literature Review: How Far Are These Controls from Rule-Based Controls Used in Commercial Vehicles?" Applied Sciences 10, no. 23 (2020): 8744, <https://doi.org/10.3390/app10238744>.

²³ Prussi et al., JEC Well-To-Wheels Report V5, 10.

²⁴ US Environmental Protection Agency, The 2020 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975, EPA-420-R-21-003, January 2021, <https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1010U68.pdf>, 49.

Research projects also continue to seek ways to improve HEV efficiency, as shown in Table 6.²⁵

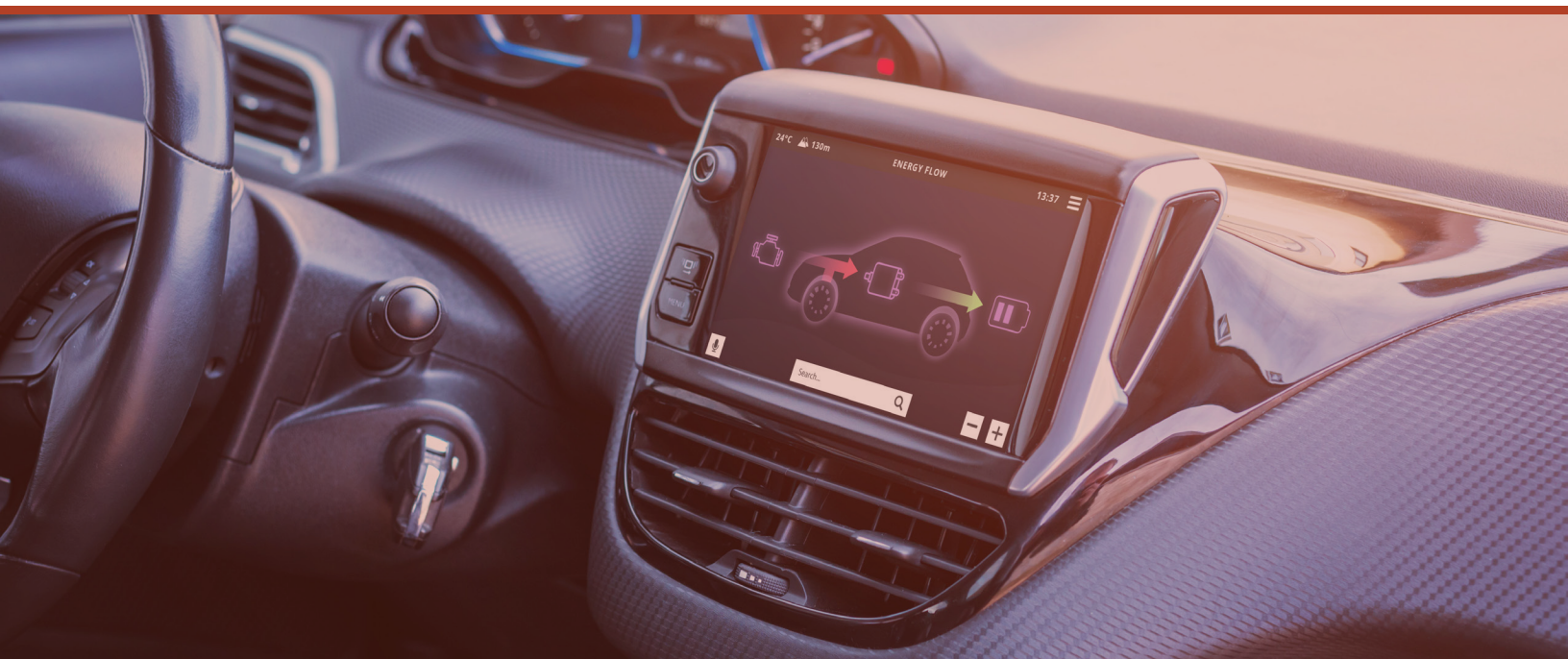
Research investigating the conversion of the gasoline ICE portion of a HEV from SI to CI has found that gasoline compression ignition (GCI) hybrids reduce well-to-wheels (WTW) GHG emissions by 7% to 43% versus unhybridized GCI and 26% to 55%

versus conventional SI.²⁶

European JEC research also supports a potential opportunity to use hybrid technology within heavy-duty vehicles; however, JEC estimates that heavy-duty HEVs are only approximately 7% more efficient than stand-alone CI diesel fuel engines.²⁷

TABLE 6: POTENTIAL FUTURE HEV ADVANCEMENTS

HEV Technology Advancement	Reported Efficiency Improvement
Improved energy management systems versus rule-based control systems	5-10%
Thermoelectric generator waste heat recovery	1.7%



²⁵ Andrew Smallbone et al., “Realization of a Novel Free-Piston Engine Generator for Hybrid-Electric Vehicle Applications,” *Energy Fuels* 34, no. 10 (September 2020): 12926–12939, <https://doi.org/10.1021/acs.energyfuels.0c01647>; Amir F.N. Abdul-Manan et al., “Bridging the Gap in a Resource and Climate-Constrained World with Advanced Gasoline Compression-Ignition Hybrids,” *Applied Energy* 267 (June 2020), 114936, <https://doi.org/10.1016/j.apenergy.2020.114936>.

²⁶ AFN Abdul-Manan, et al., “Bridging the gap in a resource and climate-constrained world with advanced gasoline compression-ignition hybrids”, *Applied Energy*, 2020 - Elsevier

²⁷ Prussi et al., JEC Well-To-Wheels Report V5, 17.

INTERNAL COMBUSTION ENGINE EMISSION CONTROL SYSTEMS AND AFTERTREATMENT IMPROVEMENTS

Except for technology advancements tested to reduce engine back-pressure, recent research projects did not indicate a corresponding gasoline or

diesel engine performance or efficiency improvement (see Table 7).²⁸

TABLE 7: EMISSION CONTROL SYSTEM TECHNOLOGY IMPROVEMENTS

HEV Technology Advancement	Reported Efficiency Improvement
Three-way catalytic converter with perovskite-based metallurgy	Maintained emissions reduction performance after hydrothermal aging versus activity loss for standard catalyst
Catalytic converter cone angles	Allows exhaust to flow more freely and limits back-pressure (engine performance benefits not quantified)
Cold-start optimal control	NO _x emission reduced 35% versus traditional engine-controller
Diesel engine selective catalytic reduction DeNO _x optimization—cell density constant with increased diameter and decreased catalyst length	Better catalyst performance and reduced back pressure (engine performance benefits not quantified)

²⁸Ch. Indira Priyadarsini et al., “Effect of Cone Angle on Performance of Catalytic Converter,” Journal of Information and Computational Science 13, no. 12 (2020): 73-80, doi:16.10090.JOICS.2020.V13I12.287391.4132; Jonathan Lock et al., “Cold-Start Modeling and On-Line Optimal Control of the Three-Way Catalyst,” arXiv:2104.12390, Cornell University, <https://arxiv.org/pdf/2104.12390.pdf>; Pelsu Pelen, “Modeling the Effect of SCR Denox Unit on Diesel Engine Performance,” (master’s thesis, Middle East Technical University, January 2020), <https://open.metu.edu.tr/bitstream/handle/11511/45645/index.pdf>; Brian Robert Matias Hutchison, “Investigating the Influence of Fuel Volatility on Particle Emissions Phenomena in a Production Gasoline Direct Injection Engine,” (master’s thesis, University of Toronto, 2021), partial available at: <https://www.proquest.com/openview/c1d4f97023b661b5e42a34bb9254cf97/1?pq-origsite=gscholar&cbl=18750&diss=y>.

INTERNAL COMBUSTION ENGINE CONFIGURED FOR DUAL FUELS AND BLENDS

Traditional dual-fuel engines operate on a primary fuel such as natural gas while utilizing a small amount of diesel as the pilot ignition fuel. Commercial stationary dual-fuel engines are an established technology, but dual-fuel engines in transportation are under research and development while various fuel combinations and engine designs are being tested. Future developments such as dual-fuel injectors and optimized nozzle designs are expected to provide higher overall efficiency. Research on fuel combinations has focused on the primary fuel and finding alternatives with lower carbon levels than natural gas such as hydrogen, syngas (synthetic gas composed of hydrogen, carbon monoxide and carbon dioxide produced from the gasification of carbon-containing fuels), renewable natural gas (natural gas produced from renewable sources such as landfills, manure digesters and wastewater treatment plants), and others.

One research paper reviewed the use of liquefied petroleum gas (LPG) and dimethyl ether (DME) with diesel fuel. Using LPG and DME with diesel fuel provided for a brake thermal efficiency (BTE)²⁹ improvement of 3.5% to 14% when compared to the diesel-fuel-only mode, and the combination of LPG, DME, and diesel fuel provided for a BTE improvement approximately 24% higher than the LPG/diesel

dual-fuel result.³⁰

Several recent research studies have also focused on gasoline-ethanol blends.³¹ These studies have included 10% gasoline-ethanol blends (E10), 15% gasoline-ethanol blends (E15), mid-level gasoline blends (E16-50), and ethanol flex fuel (E51-83). Conversion kits are being manufactured to convert a conventional E10 gasoline vehicle to a flex-fuel vehicle. Each kit, designed for certain makes and models, requires EPA certificates of conformity. Those that have received such certificates are available for approximately \$300-1,000, not including installation. Because ethanol flex fuel (a.k.a. E85) has about 29% less energy content per unit volume than conventional gasoline, the flex-fuel conversion requires increased volumetric fuel delivery rates at increased ethanol levels to produce the same power (i.e., more gallons per miles), and as expected, fuel efficiency (measured in miles per gallon) is approximately 29% lower depending on the ethanol percentage (51% to 83%); however, based on an interpolation of the European JEC study of carbon-intensity results for E10 gasoline (128 gCO₂/km) and E100 (91 gCO₂/km), GHG emissions reduce by 15% to 23% by converting from E10 to ethanol flex fuel (E51-83).³²

²⁹ Brake Thermal Efficiency is defined as break power of an engine as a function of the thermal input from the fuel and is represented as Brake thermal efficiency = Power/Energy Required.

³⁰ Wittison Kamei, Experimental Investigation of a Dual-Fuel Compression Ignition Engine for Improvement of Emissions and Thermal Efficiency, (Guwahati, India: Indian Institute of Technology Guwahati, Lakshminath Bezbaroa Central Library (14.139.196.25), July 1, 2021), abstract available at <http://gyan.iitg.ernet.in/handle/123456789/1897?show=full>.

³¹ Additional work is being developed by the Fuels Institute is intended to provide the history related to gasoline-ethanol blends, including past and present ethanol volumes and blend percentages, as well as the types of vehicles that can use various gasoline-ethanol blend percentages, as further described in this paragraph.

³² John F. Thomas, Shean P. Huff, and Brian H. West, Fuel Economy and Emissions of a Vehicle Equipped with an Aftermarket Flexible-Fuel Conversion Kit (Washington, DC: US Department of Energy Office of Scientific and Technical Information, April 1, 2012), <https://doi.org/10.2172/1038474>; Ryan B. Wicker et al., Practical Considerations for an E85-Fueled Vehicle Conversion, SAE Technical Paper 1999-01-3517, 1999, <https://doi.org/10.4271/1999-01-3517>; György Budik, "Conversion of Internal Combustion Engine from Gasoline to E85 Fuel," Periodica Polytechnica Transportation Engineering 38, no. 1 (2010):19-23, <https://doi.org/10.3311/pp.tr.2010-1.04>; "Gen5DIY Flex Fuel Kits," Gen5DIY, no date, https://www.gen5diy.com/collections/gen5diy-flex-fuel-kits?gclid=EAlaIqObChM17fv-i4f78wIVwXvBB3w_gdsEAAAYASAAEgKHT_D_BwE; Sebastian Blanco, "EPA Approves Flex-Box Smart Kit, the First Certified Ethanol Conversion Kit," Autoblog, October 11, 2007, <https://www.autoblog.com/2007/10/11/epa-approves-first-ethanol-conversion-kit-for-some-fleet-vehicle/>; "Compare EflexFuel Products," FlexFuel Technology, StepOne Tech America Inc., no date, <https://eflexfuel.com/us/auto-products>; "Flex Fuel Conversion Kits," Autosales Inc. dba Summit Racing Equipment, no date, <https://www.summitracing.com/search/part-type/flex-fuel-conversion-kits>.



Several other recent research studies focus on biomass-based diesel fuel, namely biodiesel and renewable diesel. Although renewable diesel (a.k.a. hydrotreated vegetable oil (HVO)) has been considered a “drop-in” fuel that can be used as a diesel fuel substitute up to 100% in existing CI engines, biodiesel blending has been generally limited to 20%, as warranted by original equipment manufacturers. This research review did not reveal

any recent research efforts related to biodiesel and renewable diesel or after-market conversion/adaptation opportunities for increasing biodiesel blend percentages.

See Section 3.0 Engine and Fuels Viewed as a Holistic System below for more information on other dual-fuel/engine combinations.

INTERNAL COMBUSTION ENGINE OPTIMIZED FOR HIGH-OCTANE FUELS

In a report published in 2012, Ford Motor Company engineers determined that blending additional ethanol above 10% increases the minimum research octane number (RON) of regular-grade gasoline blendstock by four to seven points (approximately 92.5 RON E10 to 94.3 RON E15 and 98.6 RON E30).³³ Ford engineers also determined that the use of the “higher RON would enable greater thermal efficiency in future engines through higher compression ratio (CR) and/or more aggressive turbocharging and downsizing, and in current engines on the road today through more aggressive

spark timing under some driving conditions.”³⁴ Ford engineers estimated the improvement to be within one to three CR-units.³⁵

In June 2020, CONCAWE also released a report investigating the fuel consumption improvements with running high-octane gasoline (from 95 to 102 RON) on an adapted engine with a compression ratio 2 CR-units higher (12.2:1 than the comparison engine 10.2:1).³⁶ The results indicated a fuel consumption improvement of 1.75% to 3.72%, depending on the driving-cycle (see Table 8).

³³ J.E. Anderson et al., “High Octane Number Ethanol–Gasoline Blends: Quantifying the Potential Benefits in the United States,” *Fuel* 97 (July 2012): 585-594, <https://doi.org/10.1016/j.fuel.2012.03.017>.

³⁴ Anderson et al., “High Octane Number Ethanol–Gasoline Blends.”

³⁵ The compression ratio is the ratio between the volume of the cylinder and combustion chamber at their maximum and minimum values.

³⁶ Heather Hamje, “Running High-Octane Petrol in a Suitably Adapted Engine,” *Concawe Review* 29, no. 1 (June 2020): 4-11, <https://www.concawe.eu/wp-content/uploads/HOP.pdf>.

TABLE 8: FUEL CONSUMPTION IMPROVEMENT WITH HIGH-OCTANE GASOLINE

	95 RON	98 RON	100 RON	102 RON	95 RON	98 RON	100 RON	102 RON
Drive Cycle	litres/100 km				% improvement vs 95 RON			
NEDC	7.078	7.062	7.019	6.954	-	0.22	0.83	1.75
WLTC	7.663	7.640	7.552	7.486	-	0.29	1.44	2.3
RDE	8.129	8.022	7.927	7.827	-	1.32	2.48	3.72
Artemis	8.34	8.245	8.168	8.075	-	1.14	2.06	3.17

European JEC research further supports the potential opportunity for GHG emissions improvement for higher-octane fuels (102 RON with 10% ethanol), which enable engines to be deployed with higher compression ratios. The JEC report states: “For gasoline engines, the combination of high compression rates with a high-octane gasoline (102 RON) offers a similar GHG performance [as] Direct Injection Compression Ignition (DICI)

vehicles when approaching 2025+.”³⁷ The researchers used the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) to estimate direct injection spark ignition (DISI) gasoline engine GHG emissions at 128 gCO₂e/km Well-To-Wheels (WTW). When optimized for high-octane fuel, the GHG emissions decreased approximately 8% to approximately 118 gCO₂e/km WTW.³⁸



³⁷ Prussi et al., JEC Well-To-Wheels Report V5.

³⁸ Prussi et al., JEC Well-To-Wheels Report V5, 10 and 50.

Engine and Fuels Viewed as a Holistic System

Several research projects were identified that reviewed changes to engines and fuels holistically to improve vehicle performance and efficiency.³⁹ Table 9 summarizes these projects.

TABLE 9: EFFICIENCY IMPROVEMENT FROM VARIOIUS FUEL AND ENGINE COMBINATIONS

Engine and Fuel Combination	Efficiency Improvement
Turbocharged internal combustion engine with compressed natural gas	Fuel consumption reduced 10.1% versus naturally aspirated internal combustion engine
Reactivity controlled compression ignition (RCCI) engine with biofuels	Unquantified
Reactivity controlled compression ignition (RCCI) with diesel fuel and gasoline	Unquantified lower emissions and higher brake thermal efficiency compared to spark ignition internal combustion engine
Reactivity controlled compression ignition (RCCI) with methanol and dimethyl ether	Gas injection thermal efficiency improvement 1.3% versus convention diesel engine with dimethyl ether
Homogeneous charged compression ignition (HCCI) with hydrogen-enriched 80% diesel/20% algal oil and graphite oxide nanoparticles	Similar performance to compression ignition engine with NO _x and smoke reduction of 75% and 53%, respectively

³⁹ Jim Alexander and E. Porpatham, “Numerical And Experimental Analysis on the Effects of Turbocharged Compressed Bio-Methane-Fueled Automotive Spark-Ignition Engine,” Clean Technologies and Environmental Policy (2021), <https://doi.org/10.1007/s10098-021-02161-5>, prepublished version available at https://assets.researchsquare.com/files/rs-193776/v1_covered.pdf?c=1631854641; Amin Paykani et al., “Reactivity Controlled Compression Ignition Engine: Pathways Towards Commercial Viability,” Applied Energy 282, part A, (January 15, 2021): 116174, <https://doi.org/10.1016/j.apenergy.2020.116174>; Akhilendra Pratap Singh, Vikram Kumar, and Avinash Kumar Agarwal, “Evaluation of Reactivity Controlled Compression Ignition Mode Combustion Engine Using Mineral Diesel/Gasoline Fuel Pair,” Fuel 301 (October 1, 2021): 120986, <https://doi.org/10.1016/j.fuel.2021.120986>; Arun Kumar, “A CFD Study on DME/Methanol Fuelled Unconventional RCCI,” (master’s thesis, Eindhoven University of Technology, January 2021), https://pure.tue.nl/ws/portalfiles/portal/168501063/1279807_Arun_Kumar.pdf; Parthasarathy Murugesan et al., “Role of Hydrogen in Improving Performance and Emission Characteristics of Homogeneous Charge Compression Ignition Engine Fueled with Graphite Oxide Nanoparticle-Added Microalgae Biodiesel/Diesel Blends,” International Journal of Hydrogen Energy (in press, corrected proof available September 2021), <https://doi.org/10.1016/j.ijhydene.2021.08.107>.

TABLE 10: OPTIONS FOR FUTURE POWERTRAIN-FUEL COMBINATIONS

Energy Carrier	Drive System	Conversion Technology	Infrastructure	TRL	Remark
NG (SNG, BNG, LNG)	ICE	none	To be extended	TRL 8-9	Focus on methane slip
DME	ICE	none	To be built-up	TRL 7-8	Focus on production chain
Hydrogen	ICE	none	To be extended	TRL 5-6	Focus on renewable electricity and H ₂ infrastructure
PTF	ICE	none	Existing	TRL 7-9	Focus on renewable production chain
Electricity (catenary)	Hybrid ⁽¹⁾	none	To be built-up	TRL 7-8	Focus on renewable electricity
Battery	E-motor	none	To be extended	TRL 9	Focus on renewable electricity and infrastructure for charging
Hydrogen	E-motor	fuel cell	To be extended	TRL 7-8	Focus on renewable electricity and H ₂ infrastructure
NG (SNG, BNG, LNG)	E-motor	fuel cell and fuel processing	To be extended	TRL 5-6	Complex system technology
PTF	E-motor	fuel cell and fuel processing	Existing	TRL 4-5	Complex system technology

⁽¹⁾ Hybrid system of catenary-based electric powertrains and an internal combustion engine or fuel cell system. (Peters et al., "Future Power Train Solutions for Long-Haul Trucks.")

An additional research project involved a review of different heavy-duty powertrain and fuel combinations with technical readiness level⁴⁰, as detailed in Table 10.⁴¹

As previously cited within this report, the European JEC also conducted a comprehensive WTW analysis of more than 1,500 different automotive fuels and powertrain combinations. After screening the combinations with a technical readiness level of six or greater -

- Passenger car fuel/engine combinations with the lowest GHG emission rates (gCO₂e/km) include:⁴²
 - Compressed biomethane (CBM) in an SI engine
 - with mild-hybrid technology; and
 - HVO from used cooking oil in a DICI Engine with hybrid technology.

- Heavy-duty vehicle (Type 5 tractor-trailer combinations aka Category 7-8) fuel/engine combinations with the lowest GHG emission rates include:⁴³
 - HVO from used cooking oil in a DICI engine; and
 - CBM in a positive ignition (PI) engine with hybrid technology.

Tables 11 and 12 list some of the fuel/powertrain pathways for passenger cars and heavy-duty (Type 5 aka Category 7-8) vehicles with estimated GHG-reduction potentials for MY2025+.⁴⁴

⁴⁰ Technology readiness levels (TRLs) are a method for estimating the maturity of technologies during the acquisition phase of a program. TRL is determined during a technology readiness assessment (TRA) that examines program concepts, technology requirements, and demonstrated technology capabilities. TRLs are based on a scale from 1 to 9 with 9 being the most mature technology.

⁴¹ Ralf Peters, Janos Lucian Breuer, Maximilian Decker, Thomas Grube, Martin Robinius, Remzi Can Samsun, and Detlef Stolten, "Future Power Train Solutions for Long-Haul Trucks," Sustainability 13, no. 4 (February 19, 2021): 2225, <https://doi.org/10.3390/su13042225>.

⁴² Prussi et al., JEC Well-To-Wheels Report V5, 11.

⁴³ Prussi et al., JEC Well-To-Wheels Report V5, 14.

⁴⁴ Prussi et al., JEC Well-To-Wheels Report V5, 12 and 15.

TABLE 11: WORLDWIDE HARMONIZED LIGHT VEHICLE TEST PROCEDURE, PASSENGER CARS MODEL YEAR 2025 AND BEYOND

Fuel/Powertrain Combination	gCO ₂ e/km Well-to-wheel	Greenhouse Gas Reduction Potential
Gasoline direct injection spark ignition	128	-
With Hybrid Technology	94	28%
High-octane fuel (102 RON) gasoline direct injection spark ignition	118	8%
With Hybrid Technology	88	31%
Ethanol (E100) gasoline direct injection spark ignition—ethanol from wheat	91	29%
With Hybrid Technology	67	47%
Ethanol (E100) gasoline direct injection spark ignition—ethanol from wheat straw	28	78%
With Hybrid Technology	20	84%
Diesel fuel direct injection compression ignition	120	6%
With Hybrid Technology	101	21%
Synthetic diesel fuel direct injection compression ignition	34	73%
With Hybrid Technology	28	78%
Hydrotreated vegetable (used cooking oil) direct injection compression ignition	15	88%
With Hybrid Technology	13	90%
Compressed biomethane direct injection spark ignition	15	88%
With Mild-Hybrid Technology	13	90%

TABLE 12: HEAVY-DUTY TYPE 5 MODEL YEAR 2025 AND BEYOND

Fuel/Powertrain Combination	gCO ₂ e/tkm Well-to-wheel	Greenhouse Gas Reduction Potential
Diesel fuel compression ignition	63	-
With Hybrid Technology	58	8%
Ethanol-based fuel for diesel engines (ED95) compression ignition—ethanol from straw	22	65%
Synthetic diesel fuel compression ignition	19	70%
Biodiesel (B100 canola) compression ignition	34	46%
Hydrotreated vegetable oil (used cooking oil) compression ignition	10	84%
Liquefied natural gas high-pressure direct injection	59	6%
Compressed biomethane positive ignition	8	87%



Liquid Fuels Production

Industry efforts to decarbonize and reduce GHG emissions along the fuels production value chain have been in motion for years. As an example, industry reductions in flaring fugitive natural gas through improved maintenance routines, vapor recovery units, and sophisticated leak detection systems and repair systems have all been instrumental in reducing emissions. In addition, increased efficiency improvements have allowed companies to lower their fuel consumption, reduce costs, and reduce their carbon emissions. A set of new options are on the horizon to further cut emissions and help industry efforts toward achieving net-zero emissions: carbon capture, low-carbon fuel substitution, and low-carbon feedstocks substitution.

CARBON CAPTURE

The CO₂ emissions from refineries originate from four main sources: process heaters (30-60%), fluid catalytic cracking (FCC) unit (20-50%), hydrogen production (5-20%), and utilities (20-50%).⁴⁵ The three main technologies for capturing CO₂ are:

1. Pre-combustion - CO₂ in a hydrocarbon fuel stream is removed prior to use as a process fuel at the refinery by converting the fuel into syngas (H₂, CO) through gasification and then H₂ and CO₂ via a shift reaction;
2. Post-combustion - The capture of CO₂ in the flue/exhaust gas stream that is generated by a process unit using solvent absorption, membrane separation, or adsorption; and

3. Oxygen-combustion - An air separation unit separates oxygen from nitrogen before the combustion process to promote a flue/exhaust gas composed of only H₂O and CO₂.

Concawe's technology review shows that commercially available technology exists to allow for the capture of 85% to 90% of carbon emissions, but few projects have been implemented at refineries.

Over the next couple of decades, advancements and research in carbon-capture technology will look to increase the percentage of emissions captured while reducing overall costs (see Table 13).⁴⁶

⁴⁵Ashish Bhadola et al., Technology Scouting—Carbon Capture: From Today's to Novel Technologies, (Brussels, Belgium: Concawe, September 15, 2020), https://www.concawe.eu/wp-content/uploads/Rpt_20-18.pdf, 72.

⁴⁶Bhadola et al., Technology Scouting—Carbon Capture: From Today's to Novel Technologies, pg. v.

TABLE 13: CONCAWE CARBON CAPTURE TECHNOLOGY REVIEW

Technology*	Technology readiness level	Characteristics
Commercial		<ul style="list-style-type: none"> ■ First generation technology ■ 85-90% CO₂ capture rate with 95% CO₂ purity ■ Average cost of CO₂ capture is US \$50-75 per tonne
Near-term commercial		<ul style="list-style-type: none"> ■ Second generation technology ■ 90% CO₂ capture rate with 95% CO₂ purity ■ Reduce cost of electricity (COE) by 20-30% ■ Average cost of CO₂ capture is US \$40 per tonne
Emerging		<ul style="list-style-type: none"> ■ Early stages of research and development ■ 95% CO₂ capture rate with 95% CO₂ purity ■ Reduce COE by 30-40% ■ Average cost of CO₂ capture is US \$30 per tonne

(Bhadola et al., *Technology Scouting—Carbon Capture: From Today’s to Novel Technologies.*)

*A list of potential technologies that fall within each of these categories is available in the executive summary of the source report.

As government incentives increase and costs decrease, more projects will start to develop over the coming years. A few of the most notable carbon-capture projects at refineries in the last decade include:

- Petrobras Refinery, Brazil (2012): Petrobras in collaboration with other oil majors conducted a successful pilot-scale test on a 33 bpd FCC unit that utilized oxygen-combustion to capture CO₂ emissions;
- Valero Refinery, Port Arthur, Texas (2013): the steam methane reforming (SMR) plant utilizes pre-combustion carbon-capture technology;

- NWR Sturgeon Refinery, Alberta Canada (2020): operates a pre-combustion carbon-capture unit by converting heavy bottoms into syngas where the hydrogen is further used in refinery operations; and
- Aramco implemented a demonstration project at the Hawiyah Gas Plant with the “capability to capture and process 45 million standard cubic feet of CO₂ at our plant in Hawiyah. The captured CO₂ is piped 85 kilometers and pumped into the Uth Maniyah oil reservoir, sequestering the gas while also helping to maintain pressure in the reservoir and recover more oil.”⁴⁷

⁴⁷ Aramco, “Managing Our Footprint; Carbon Capture Utilization and Storage”, <https://www.aramco.com/en/sustainability/climate-change/managing-our-footprint/carbon-capture-utilization-and-storage>

FUEL SUBSTITUTION

Electrification

Electrification is already widely used across various manufacturing industries and becoming an option for the oil and gas sector. Electrification of energy-intensive equipment such as furnaces and

boilers will allow companies to reduce GHG emissions through electricity derived from renewable sources such as solar or wind (see Table 14).⁴⁸

TABLE 14: ELECTRIFICATION OPTIONS

Technology	TRL	Category	Process system and electrification option
Electric steam boiler	9	Power-to-Heat	Utility system: Replacing conventional (natural gas-driven) boilers
Industrial heat pumps	8-9	Power-to-Heat	Utility system: Heating (low to medium temperatures)
	9		Heat recovery system: High-grade steam production by mechanical vapour recompression of excess, low-pressure steam and thus reduction of steam boiler load
Electric drives	9	Power-to-Mechanical drive	Utility system: Reducing steam demand by replacing steam turbines to provide mechanical drive for pumps and compressors
Electrolysis	6-9	Power-to-Hydrogen	Reactor system: Replacing conventionally produced hydrogen for hydrotreater and hydrocracker with hydrogen from water electrolysis
Heat pump-assisted distillation	Low	Power-for-Separation	Separation system: Reducing heat demand for the crude oil separation process
Membrane-assisted distillation	Low	Power-for-Separation	Separation system: Reducing heat demand for the crude oil separation process

(Schuwer and Schneider, "Electrification of Industrial Process Heat: Long-Term Applications, Potentials and Impacts," 415)

⁴⁸ Dietmar Schüwer and Clemens Schneider, "Electrification of Industrial Process Heat: Long-Term Applications, Potentials and Impacts," in ECEEE Industrial Summer Study Proceedings, ed. Therese Laitinen Lindström, Ylva Blume, and Nina Hampus (Stockholm, Sweden: European Council for an Energy Efficient Economy, 2018), 411-422, available at https://epub.wupperinst.org/frontdoor/deliver/index/docId/7037/file/7037_Schuwer.pdf.

Also, a 2017 electrification project at the Marathon Refinery in Martinez, California, replaced a gas-fired turbine with an electric motor that drives the refrigeration compressor at the alkylation unit. Even though electrification technology is ready for

commercialization, retrofitting a complex integrated facility such as a refinery is challenging. Future research and demonstration plants are expected to focus on application-specific technical implementation and evaluate costs.

Hydrogen as a Fuel

Hydrogen at a production facility can also act as a fuel substitute for fossil-based furnaces and boilers, but modifications to the equipment are necessary. The technology has yet to be commercialized, but companies have deployed pilot projects with hydrogen-ready boilers that can run on either natural gas or 100% hydrogen. Utilizing hydrogen produced from renewable sources as the fuel means the equipment would have zero carbon dioxide emissions. In 2021, HyNet North West in Manchester, UK, did a live demonstration of a 1MW

industrial hydrogen boiler.

Future research and work are focused on scaling the technology to major industrial-size applications such as refineries. For example, Hydrogen Technologies Inc. headquartered in Stockton, California, is developing a boiler with 30% greater efficiency than traditional hydrocarbon boilers with 97% boiler thermal efficiency that requires no smokestack, lowering both capital and operating expenses.⁴⁹

FEEDSTOCK SUBSTITUTION

Low-Carbon Crude Oil

Upstream of refiners, similar options are available to reduce fuel life-cycle carbon emissions by lowering the carbon intensity of the crude oil feedstocks.

- Electrification: Upstream crude oil producers can electrify equipment used in the field to lower their emissions profile.
- CO₂-Enhanced Oil Recovery (CO₂-EOR): This oil-extraction method increases overall pressure in the oil well, allowing for increased production while a portion of the injected CO₂ remains trapped underground. Any CO₂ that is not initially stored can be collected and injected back into the well permanently.

Under the California Low Carbon Fuel Standard, five projects have been implemented to install solar arrays in various oil fields across California to lower the carbon intensity of crude oils; similar projects have been implemented in other parts of North America as well:

- Poso Creek Oil Field Solar Electricity Project, Kern County, California (2020): an estimated emissions reduction of 23,605 MT CO₂e per year from supplying solar electricity directly to the oil field.

⁴⁹Hydrogen Technologies, "Dynamic Combustion Chamber," https://hydrogentechnologiesinc.com/wp-content/uploads/sites/2/2021/07/Hydrogen-Technologies-Inc-Corporate-Presentation_Final-08.pdf

- Valero Refinery, Port Arthur, Texas (2013): the SMR plant in Texas referenced in the section on “Carbon Capture” sends the CO₂ for use in EOR at the West Hastings Unit oil field in southeast Texas.
- Husky Energy, Lashburn, Saskatchewan, Canada (2019): a 30-ton-per-day carbon-capture pilot plant, “the project is the world’s first pilot-scale plant using structured adsorbents to capture carbon from a once-through steam generator for use in heavy oil recovery”.
- Shell Quest Facility, Edmonton, Alberta, Canada (2020): captures and stores CO₂ from their hydrogen production for bitumen upgrading.

Biomass

Production of liquid fuels from biomass-based feedstocks occurs through two general pathways:

- Stand-alone processing converts a biomass-based feedstock into fuel
- Co-processing simultaneously processes a biomass-based feedstock with a petroleum feedstock to produce a product made up of both renewable and petroleum products

In all cases, the introduction of biomass-based feedstocks lowers GHG due to biogenic emissions. This refers to the fact that plants absorb CO₂ from the atmosphere through photosynthesis as they grow and release it back into the atmosphere when they are burned for energy, keeping the carbon balance neutral.



Hydrogen

Earlier, hydrogen was mentioned as a fuel substitute for furnaces and boilers, but it could also be used as a feedstock for hydrogen-consuming process units such as hydrocrackers and hydrotreaters. As shown in Figure 6, a key component in reducing emissions would be tied to the production pathways used to produce the hydrogen: Steam Methane Reforming of Natural Gas (SMR of NG) (gray hydrogen), SMR with carbon capture (blue hydrogen), SMR of Renewable Natural Gas (SMR of RNG), electrolysis via renewable electricity (green hydrogen), and thermal decomposition of methane.⁵⁰

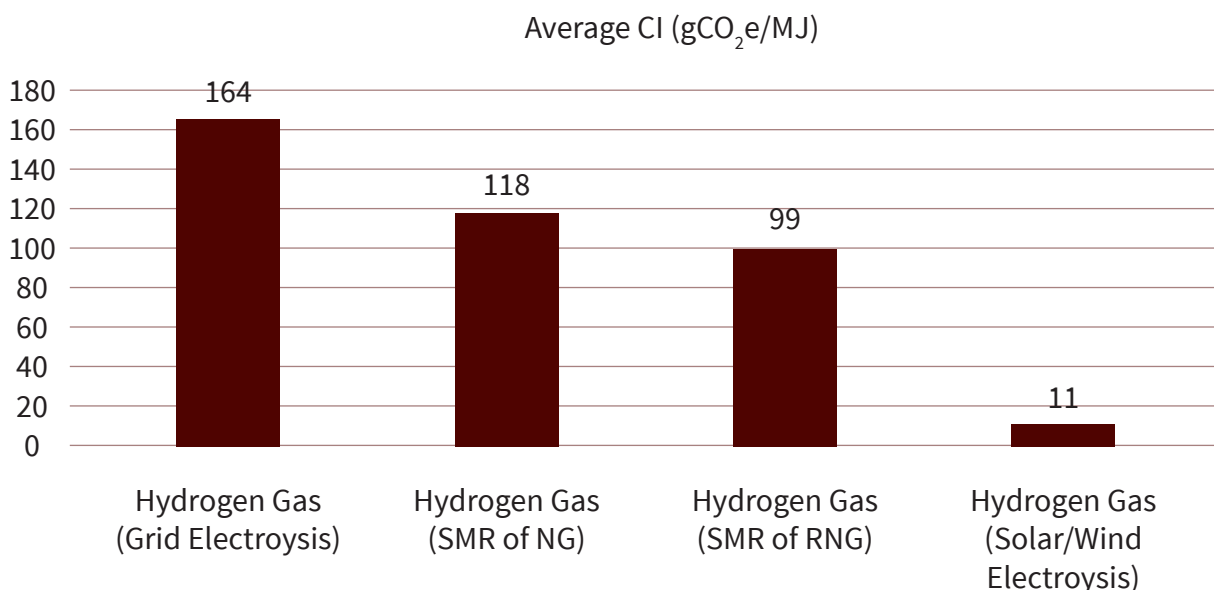
- BP Lingen Refinery, Germany (2024): 60MW electrolyzer unit to produce green hydrogen;
- Grangemouth Refinery, Scotland (2027): SMR with carbon capture, utilization, and storage to produce blue hydrogen

Saudi Aramco, Saudi Arabia (2020) and the Institute of Energy Economics, Japan (IEEJ) successfully demonstrated the production and shipment of forty tons of high-grade blue ammonia from Saudi Arabia to Japan for use in zero-carbon power generation.⁵¹

Green/blue hydrogen production projects in development at refineries include:

- Shell Rheinland Refinery, Germany (2021): 10MW electrolyzer unit to produce green hydrogen;

FIGURE 6: HYDROGEN CARBON INTENSITY FROM VARIOUS PRODUCTION PATHWAYS



(California Air Resources Board, “LCFS Pathway Certified Carbon Intensities”)

⁵⁰ “LCFS Pathway Certified Carbon Intensities,” California Air Resources Board, no date, <https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities>.

⁵¹ Aramco, “World’s first blue ammonia shipment opens new route to a sustainable future”, Sept 27, 2020, <https://www.aramco.com/en/news-media/news/2020/first-blue-ammonia-shipment>

Alternative Internal Combustion Engine Fuels

NATURAL GAS

There are already more than 175,000 natural gas vehicles in the U.S. with millions more worldwide. “The advantages of natural gas as a transportation fuel include its domestic availability, widespread

distribution infrastructure, and reduced greenhouse gas emissions” over conventional gasoline and diesel fuels, especially when using renewable natural gas (RNG).⁵²

BIOFUELS

Biofuels have been successfully used in the transportation market for more than 20 years by blending with traditional petroleum fuels. “Liquid biofuels require little change in fuel distribution

infrastructure or the transport fleet and can therefore be rapidly deployed, leading to much-needed reductions in [GHG] emissions.”⁵³

Conventional/First Generation Biofuels

Conventional biofuel production technologies have established fuel carbon intensity pathways and have well established commercially viable operations. Such technologies include fermentation for corn ethanol production, transesterification for biodiesel production, hydrotreating for renewable

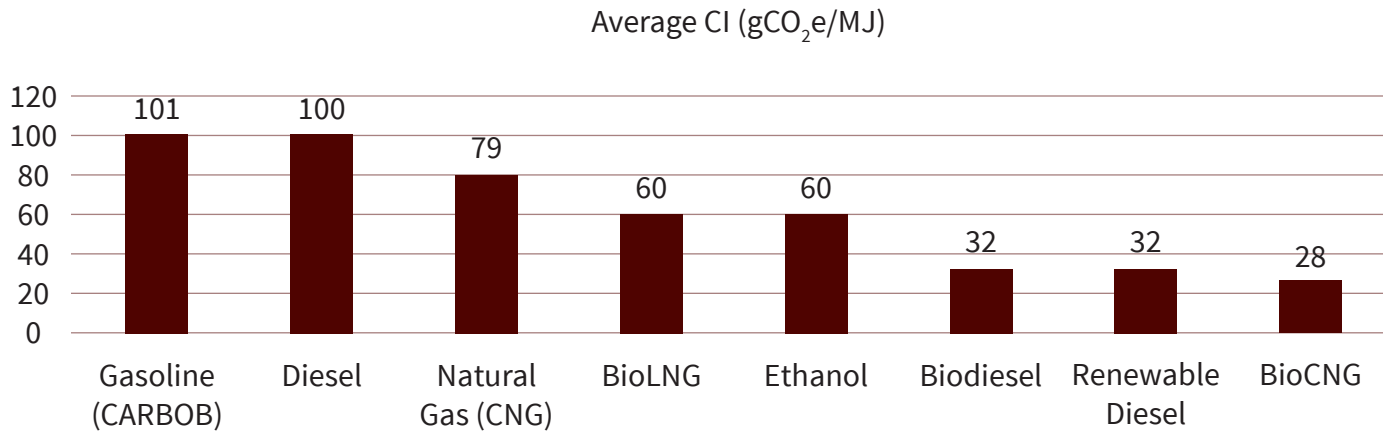
diesel production, and methane capture/purification for biomethane (biogas or renewable natural gas) production. Each conventional/first generation biofuel reduces GHG emissions by at least 20% compared to the petroleum fuel they replace, as shown in Figure 7 below.⁵⁴

⁵² “Natural Gas Benefits and Considerations,” Alternative Fuels Data Center, US Department of Energy, no date, https://afdc.energy.gov/fuels/natural_gas_benefits.html.

⁵³ Sakari Oksanen et al., Advanced Biofuels: What Holds Them Back? (Abu Dhabi, UAE: International Renewable Energy Agency, November 2019), https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Advanced-biofuels_2019.pdf, 7.

⁵⁴ “LCFS Pathway Certified Carbon Intensities,” California Air Resources Board.

FIGURE 7: COMPARATIVE CARBON INTENSITIES OF PETROLEUM FUELS AND CONVENTIONAL BIOFUELS



(California Air Resources Board, "LCFS Pathway Certified Carbon Intensities")

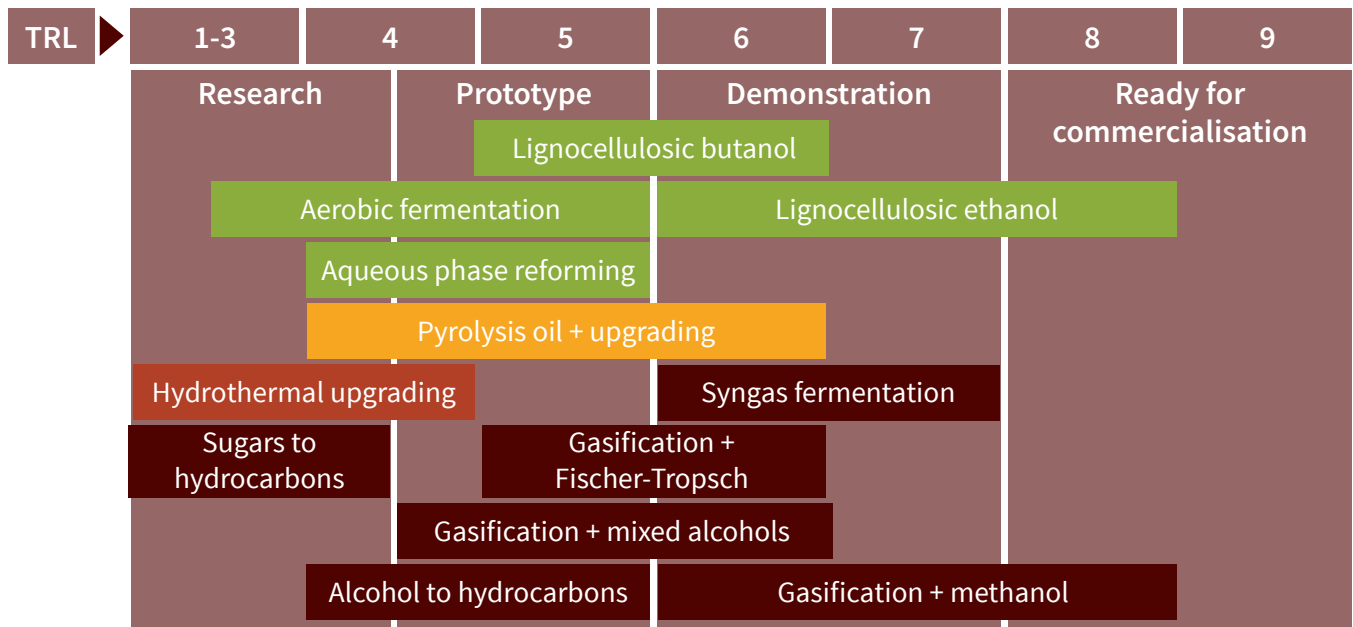
Advanced/Second Generation Biofuels

Emerging technologies and resulting fuel pathways are still in the development stages and not ready for commercialization. These include fuels similar to conventional/first generation biofuels but with different feedstocks and production processes. Such technologies include gasification and

Fischer-Tropsch process, hydrothermal liquefaction, pyrolysis, lignocellulosic ethanol/butanol, and many others. Figures 8 and 9 show various advanced/second generation biofuel production pathways in development and their respective carbon intensities.⁵⁵

⁵⁵ Genevieve Alberts et al., Innovation Outlook: Advanced Liquid Biofuels (Abu Dhabi, UAE: International Renewable Energy Agency, 2016), Pages 26 and 64. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Innovation_Outlook_Advanced_Liquid_Biofuels_2016.pdf.

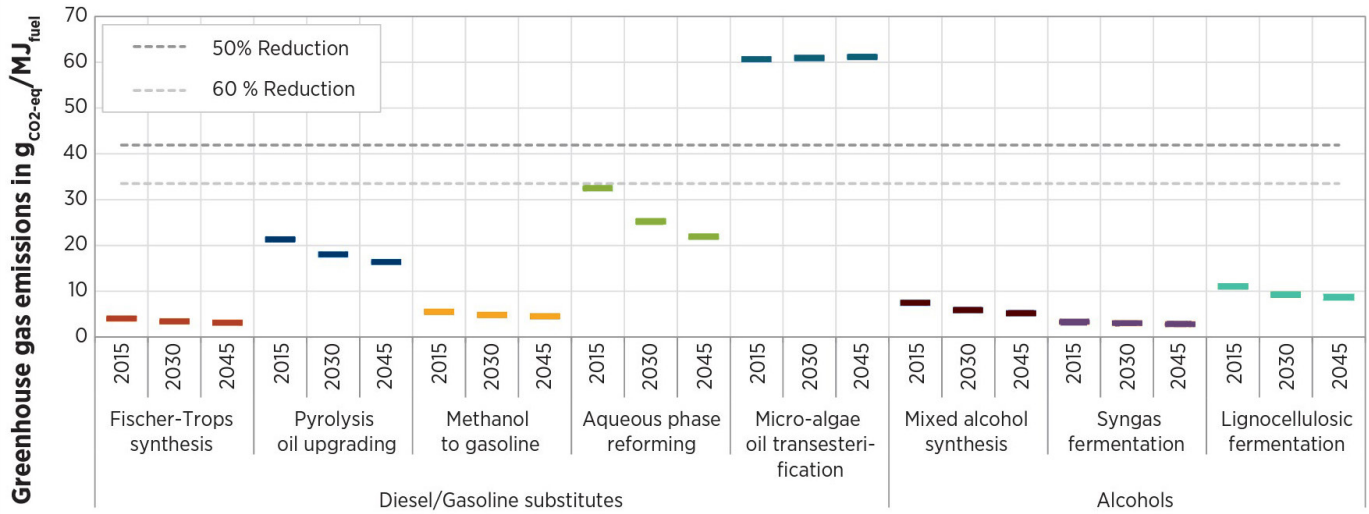
FIGURE 8: SECOND GENERATION BIOFUELS DEVELOPMENT STATUS



(Alberts et al., Innovation Outlook: Advanced Liquid Biofuels)



FIGURE 9: SECOND GENERATION BIOFUELS CARBON INTENSITIES



(Alberts et al., Innovation Outlook: Advanced Liquid Biofuels)

Based on a survey, the International Renewable Energy Agency found that the most important barriers for advanced biofuels are:⁵⁶

1. Regulation
2. Production Economy
3. Feedstock Related
4. Technology Risk
5. Financing related
6. Public perceptions

Current advanced/second generation biofuels

projects include:

- Sierra BioFuels Plant, Fulcrum BioEnergy, Storey County, Nevada (2022): Converting municipal solid waste through gasification and Fischer-Tropsch process to produce transportation fuels
- Red Rock Biofuels, Lakeview, Oregon (2022): Converting waste woody biomass through gasification and Fischer-Tropsch process to produce transportation fuels

⁵⁶ Oksanen et al., "Advanced Biofuels: What Holds Them Back?" P. 74.

Bioblendstocks

The US Department of Energy’s Co-Optimization of Fuels & Engines initiative released a study in 2021 that screened thousands of blendstocks for medium- and heavy-duty ground transportation and identified 13 that have the potential to be produced commercially while reducing GHG emissions by at least 60%. “The 13 blendstocks comprise 6 hydrocarbons, 3 esters and 4 ethers;” among these,

“the hydrocarbons, fatty acid methyl esters and fatty acid fusel esters present minimal barriers to adoption.” The study did not involve an economic feasibility or availability assessment of the 13 blendstocks. As a result, there could be significant issues prior to implementation related to blendstock production and economic viability.⁵⁷

E-FUELS

Electro-fuels (E-fuels), or power-to-liquids, are produced through the combination of CO₂ and H₂. CO₂ can come from carbon-capture sources such as flue gas at a refinery or from the atmosphere using direct air capture, while H₂ can be produced via electrolysis using renewable electricity. The primary e-fuels are e-methane, e-hydrogen, e-ammonia, e-methanol, e-DME and e-OME (oxymethylene ether), e-gasoline, and e-diesel. These synthetic fuels can be used in ICE vehicles, though in some cases with modifications.

According to Concawe, “most e-fuels conversion routes (except from e-hydrogen or e-ammonia)

consist of e-hydrogen reacting with captured CO₂ to produce clean syngas consisting of hydrogen and carbon monoxide. Syngas can further be processed to produce several types of fuels.”⁵⁸ There are two main pathways to convert the syngas into fuels: methanol synthesis and the Fischer-Tropsch process.

The e-fuel technologies are yet to be commercialized, but a few demonstration plants are being developed. Many e-fuels technologies are in the later stages of development, as indicated by a Technical Readiness Level (TRL) of nine (9) shown within Table 15 below.



⁵⁷ Daniel J. Gaspar et al., Top 13 Blendstocks Derived from Biomass for Mixing-Controlled Compression-Ignition (Diesel) Engines: Bioblendstocks with Potential for Decreased Emissions and Improved Operability (Washington, D.C.: US Department of Energy, July 2021), <https://doi.org/10.2172/1806564>, <https://www.osti.gov/servlets/purl/1806564>, xiv, 30 (see figure captions).

⁵⁸ A. Soler, Role of e-Fuels in the European Transport System: Literature Review (Brussels, Belgium: Concawe, January 2020), https://www.concawe.eu/wp-content/uploads/Rpt_19-14.pdf, 23.

TABLE 15: TECHNICAL READINESS LEVEL OF E-FUELS TECHNOLOGIES

Technology	TRL (today)
Water electrolysis	
Alkaline electrolyser	9
Polymer-electrolyte membrane electrolyser (PEM)	8
High-temperature electrolyser cell (SOEC)	5
CO ₂ supply	
CO ₂ extraction	
CO ₂ from biogas upgrading, ethanol production, beer brewing,...	9
CO ₂ exhaust gas	
Scrubber with MEA	9
Scrubber with 'next generation solvent'	8
Absorption/electro-dialysis	6
Pressure-swing absorption (PSA)/Temperature-swing absorption (TSA)	6
CO ₂ from air	
Absorption/electro-dialysis	6
Absorption/desorption (TSA)	6
CO ₂ conditioning (liquefaction and storage)	9
Synthesis	
H ₂ storage (stationary)	9
Fischer-Tropsch pathway	
Fischer-Tropsch synthesis	9
Reverse water gas shift (RWGS)	6
Hydrocracking, isomerization	9
Methanol pathway	
Methanol synthesis	9
DME synthesis	9
Olefin synthesis	9
Oligomerization	9
Hydrotreating	9

(Soler, Role of e-Fuels in the European Transport System: Literature Review)

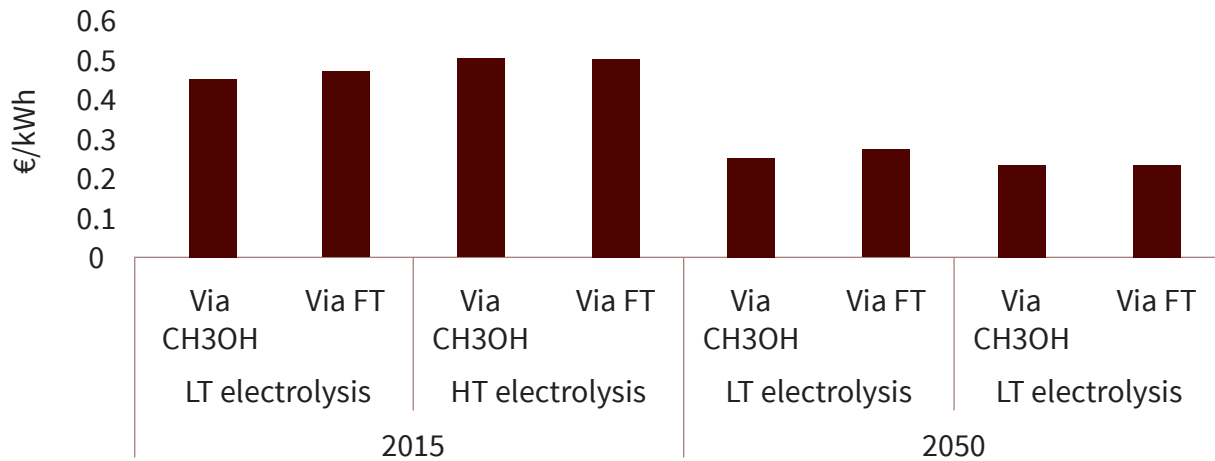
The total production cost will continue to reduce as the various technologies involved with the production of e-fuels continue to develop and renewable electricity becomes cheaper. Figure 10 shows the cost of production in 2015 versus 2050 for the two major routes (methanol synthesis/ Fischer-Tropsch process) and whether high- or low-temperature electrolysis is used.

Current projects in e-fuels include:

- Siemens Energy, Magallanes region, Chile (2022): e-fuel production using wind energy and direct air carbon capture followed by methanol synthesis

- Nordic Blue Crude, Nordic Electrofuel AS, Porsgrunn, Norway (2022): e-fuel production using wind energy and captured CO₂ from industrial emission followed by Fischer-Tropsch process
- Repsol, Bilbao, Spain (2024): e-fuel production using renewable electricity and captured CO₂ from the co-located Petronor refinery followed by Fischer-Tropsch synthesis
- Shell Rheinland Refinery, Germany (2025): e-gasoline production using green hydrogen generated in an electrolyzer

FIGURE 10: COST OF E-LIQUID FUELS BY TYPE OF TECHNOLOGY



(Soler, Role of e-Fuels in the European Transport System: Literature Review)

Internal Combustion Engine Zero-Emission Pathways

In general, most research papers to date do not describe pathways to achieve carbon neutrality from a WTW GHG perspective when using liquid or gaseous fuels within ICE vehicles. Studies by the European JEC consortium and McKinsey & Company postulate possible carbon-neutral or near-carbon-neutral combinations, but these combinations are not yet commercially available.

SYNTHETIC DIESEL PATHWAYS

Two synthetic diesel pathways either approach zero WTW GHG emissions or provide for negative WTW GHG emissions when using the Fischer-Tropsch process using residual feedstock (waste wood, black liquor, or pyrolysis oil derived from waste wood) or via power-to-liquid using renewable electricity. The

e-fuel (power-to-liquid) route combined with DICI vehicles approach zero WTW GHG emissions when using renewable electricity and negative WTW GHG emissions when using wood residue coupled with carbon capture and sequestration.⁵⁹

DIMETHYL ETHER PATHWAY

DME produced from renewable electricity via methanol synthesis and DME synthesis from CO₂ flue

gas used in a compression ignition engine can approach zero WTW GHG emissions.⁶⁰

COMPRESSED BIOMETHANE (CBM) PATHWAY

CBM produced from manure digesters and used within DISI and performance improved (PI) engines can provide for negative WTW GHG emissions due to a significant credit for avoided methane emissions

from untreated manure storage. Please note that the negative GHG emissions for biomethane from manure can only be considered if there are farms where untreated manure is stored.

⁵⁹ Prussi et al., JEC Well-To-Wheels Report V5, 58 and 99.

⁶⁰ Prussi et al., JEC Well-To-Wheels Report V5, 60 and 105.

LIQUEFIED BIOMETHANE AND LIQUEFIED SYNTHETIC NATURAL GAS PATHWAY

Like CBM, liquefied biomethane and liquefied synthetic natural gas sourced from manure digesters and used in high-pressure direct injection engines can provide negative WTW GHG emissions,

significantly due to avoiding methane emissions. The negative GHG emissions for biomethane from manure can only be considered, however, if there is farm application of untreated manure.⁶¹

HYDROGEN PATHWAY

Hydrogen ICE vehicles with hydrogen sourced from renewable sources can potentially approach zero WTW GHG emissions.⁶² Hydrogen fuel cells have received a lot of attention, but H₂-ICE could also be a

viable alternative with necessary engine modifications. Toyota has invested considerable resources to develop hydrogen vehicles and has successfully converted a Toyota Corolla to an H₂-ICE.



⁶¹ Prussi et al., JEC Well-To-Wheels Report V5, 102.

⁶² Bernd Heid, Christopher Martens, and Anna Orthofer, "How Hydrogen Combustion Engines Can Contribute to Zero Emissions," McKinsey & Company, June 25, 2021, <https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-hydrogen-combustion-engines-can-contribute-to-zero-emissions>.

Conclusion

In summary, the authors of this report identified approximately 17,000 research articles published within the past two years focused on improving ICEs or lowering their carbon footprint. An observer could conclude that this abundance of research projects indicates not only a continuing interest in improving the ICE but also supports a point-of-view that the ICE will continue to power motor vehicles well into the future. This point-of-view is succinctly captured by the following quotation from the 2021 NAS report:

“Internal combustion engines (ICEs) will continue to play a significant role in the new vehicle fleet in MY 2025–2035 in ICE-only vehicles, as well as in hybrid electric vehicles (HEVs) from mild hybrids to plug-in hybrids, but will decrease in number with increasing battery electric vehicle (BEV) and fuel cell electric vehicle penetration. In this period, manufacturers will continue to develop and deploy technologies to further improve the efficiency of conventional powertrains, for ICE-only vehicles and as implemented in HEVs. Developments in the ICE for hybrids will advance toward engines optimized for a limited range of engine operating conditions, with associated efficiency benefits. Major automakers are on differing paths, with some focusing their research and development and advanced technology deployment more squarely on BEVs, and others more focused on advanced HEVs to maximize ICE efficiency.”⁶³

⁶³ National Academies of Sciences, Engineering, and Medicine. 2021. Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy—2025-2035. Washington, DC: The National Academies Press. p. 369. <https://doi.org/10.17226/26092>.

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