

Ethanol Internal Combustion Engines

HIGHLIGHTS

■ **PROCESS AND TECHNOLOGY STATUS** – The use of biofuels (e.g. bio-ethanol and biodiesel) in the transport sector can save significant amounts of fossil fuels and greenhouse gas (GHG) emissions. Internal combustion engines (ICEs) can run on bio-ethanol manufactured from biomass or waste through biochemical processes. Agricultural feedstock such as sugar beet and wheat (in Europe), corn (in the US) and sugar cane (in Brazil and other emerging countries), or even ligno-cellulosic materials such as wood, pulp fibres, papers, agriculture and industrial residues and waste can be broken down by hydrolysis to produce simple sugars, which are then fermented to produce bio-ethanol (see ETSAP TB S05). While ethanol production from primary agriculture feedstock is based on commercial technologies, the use of ligno-cellulosic materials requires technologies that are still under industrial demonstration. Gasoline-ethanol blends with 5% to 10% ethanol (called E5 and E10, respectively) can fuel conventional gasoline vehicles. Above these proportions, ethanol can cause corrosion in certain parts of conventional vehicles. However, corrosion may be avoided with relatively inexpensive engine modifications. A number of manufacturers produce flex-fuel vehicles (FFVs) that are capable to run on gasoline- ethanol blends from 0% to 85% ethanol (E85). Ethanol is mostly blended with gasoline rather than with diesel because of its low ability to ignite (i.e. low cetane rating), which is irrelevant in spark ignition (SI) ICEs, but fundamental in compression ignition (CI), or diesel engines. However, diesel-ethanol blends are also used in CI engines with some engine modifications and the use of cetane improvers.

■ **PERFORMANCE AND COSTS** – The typical efficiency (per unit energy) of vehicles running on blends of ethanol and gasoline is similar to that of pure gasoline vehicles, although further optimisation is possible. SI engines running on high blends may offer higher efficiencies (up to 9%). Potentially all future gasoline vehicles could be made compatible with all ethanol-gasoline blends from E0 to E85 (high blends require FFVs) with modest cost. This is a common practice with many vehicles in the American markets (Brazil and the US). Upgrading conventional cars for use with lower percentage blends would simply cost the sum of the parts which are at risk of corrosion – approximately €350-700. The R&D costs for manufacturers to improve the compression and timing of injection for high-blend flex fuel vehicles (to optimise their efficiency) may be passed on to consumers, but it is hard to project the extent of this with certainty. Ethanol is not as volatile as gasoline or diesel, which means there may be cold starts problems in winter or in cold climates. There are several solutions to these problems, including using additives or lowering the percentage blend. The current estimated costs for bioethanol from sugar beet, wheat, corn and sugar cane range from €0.5- €0.7 per litre of gasoline equivalent. However, costs are highly dependent on feedstock prices. Advanced biofuels from ligno-cellulosic are currently even more expensive to produce, though cost are anticipated to reduce significantly over time.

■ **POTENTIAL AND BARRIERS** – The use of biofuels can theoretically save significant amounts of GHG emissions. However, this is very sensitive to feedstock and methods of production (ETSAP TB S05). With the exception of ethanol from sugar cane, current biofuels from primary agricultural feedstock (sugar beet, wheat, corn) offer moderate CO₂ saving in comparison with second generation biofuels. Moreover, bio-ethanol production from agricultural feedstock is constrained by the competition for land use with agriculture for food production. In the mid to long term, advanced biofuels from ligno-cellulosic materials or from micro-algae (also known as second or third generation biofuels) could offer greater emissions saving and production capacity, with modest or no adverse affects on land, water and soil use. At present, in the EU, E5 can be used in regular SI engine vehicles without any modification. In Brazil, E20 is permitted in regular SI engine vehicles and E85 or pure ethanol (E100) are used with FFVs. FFVs are also widely available in the US. Technology is already well developed, so the potential for ethanol ICEs is dependent on feedstock availability. Currently, most car manufacturers focus their research work on developing engines that can make optimal use of different fuels.

PROCESSES AND PERFORMANCE - Biofuels (e.g. bio-ethanol and biodiesel) offer CO₂ reduction benefits relative to fossil fuels because their carbon was absorbed from the atmosphere as the source plants grew, rather than being released from underground storage as with fossil fuels. In theory, with high sensitivity to the production process, biofuels can offer up to a 50% greenhouse gas reduction, although the benefits of bio-ethanol from sugar cane (Brazil) are typically much greater (around 80% reduction) [18].

■ **Bioethanol Production** - Bioethanol is manufactured through a biochemical reaction using hydrolysis to produce simple from sugar beet and wheat (in Europe), corn (in the US) and sugar cane (in Brazil and in other emerging countries). Sugars are then fermented to produce bio-ethanol. In the future, alternative hydrolysis methods could be used to derive ethanol from ligno-cellulosic materials such as wood, pulp fibres, papers, agriculture and industrial residues and waste. Currently, these processes are rather expensive and not yet competitive for market uptake.

Ethanol can be used in gasoline-ethanol blends with 5% to 10% ethanol (called E5 and E10, respectively) to fuel conventional gasoline vehicles. Bioethanol is often converted to bio-ethyl-ter-butyl ether (bio-ETBE) to be used as an additive to gasoline [18]. Bio-ETBE is an oxygenate ether that, similar to bioethanol, can be used as substitute for gasoline in a blend with conventional gasoline. It is produced by mixing bioethanol (47%) and isobutylene (53%) in the presence of a catalyst. Although ethanol is primarily used on the US market, ETBE is becoming more popular in the EU and Japanese markets. The reason for its growing popularity is that it shares none of the volatility concerns related to the blending of ethanol and has a higher octane content. ETBE is water insoluble and therefore can be routinely mixed into the gasoline before being shipped through conventional pipelines. There are also two further types of bioethanol, other than Bio-ETBE, which could lead to improved performance and reduced emissions and cost: a) **Butanol** (biobutanol) is a higher energy density alternative to ethanol with improved compatibility with existing petrol engines. This allows research to focus on optimising the fuel rather than optimise compatibility; b) **Bio-DMF** (2,5-Dimethylfuran) also has an energy density 40% greater than ethanol, making it comparable to petrol. However, use in vehicle engines is still at the laboratory research stage, with little known about its combustion and emission characteristics [19].

Bioethanol research is generally further forward than that for biodiesel, influenced particularly by the Brazilian market and by developments in Sweden. Efforts focus on materials compatibility because of ethanol corrosive and hygroscopic nature and on the optimisation of future gasoline technologies for use with high-blend (E85) ethanol fuels to take advantage of its high octane rating. The US Office for Transport and Air Quality has completed screening for ethanol blends up to 10% (E10). In co-ordination with the US Department of Energy, EPA is currently conducting extensive studies on the durability and emissions impacts of blends higher than E10 and up to E20. EPA has also tested and permitted E85 as an alternative fuel for flex-fuel vehicles [19]. The French government also plan to have 4000 E10 fuelling stations by the end of 2009 [20], two years ahead of EU mandatory biofuel blends.

■ **Spark Ignition Engines** – In addition to save GHG emissions, the greatest advantage of ethanol as a fuel for spark ignition (SI) engines is perhaps its high octane number and the ability to withstand high pressures and temperatures without uncontrolled ignition. As the efficiency of SI engines mainly depends on the compression ratio and high-octane fuels are particularly suitable for high compression ratios, the use of ethanol in SI engines can offer higher energy efficiency. The result is that the efficiency of engines using E85 blend can be 9% higher than that of gasoline-fuelled engines [9]. One way to obtain high compression ratio is to

configure the engine with a turbocharger (e.g. Lotus Engineering on a Toyota engine). For the Brazilian market, Ford has designed an engine for E93 (7% water), which is also able to run efficiently on E25 (gasohol). When running on E93, in addition to high compression ratio, Ford uses high precision optimized ignition timing and higher coolant temperatures to increase the efficiency. Concerns in using ethanol to fuel vehicles is associated with corrosion in the fuel system and storage facilities. The most notable compatibility problems identified in fleet tests include: a) **degradation of plastic materials** and rubber (i.e. soften and swell) caused by the solvent-like nature of ethanol [5]; b) **degradation of metals** due to the acidic or galvanic nature of ethanol. Although anhydrous ethanol is only slightly corrosive, its hygroscopic nature makes water contamination unavoidable, with metal corrosion risk increasing significantly in the presence of water contaminants such as sodium chloride and organic acids [4]. Minor problems also include clogging of fuel lines due to ethanol “stripping off” deposits [4], cold start and increased fuel emissions by evaporation [3]. The above problems are mostly associated with existing vehicles using ethanol blends E10 and beyond. Upgrading this vehicles to the use of blends with up to 20% anhydrous ethanol requires basically substitution of certain plastic parts of the fuel systems. In the common practice, low-ethanol blends E5 and E10 are already on the market all around the world and have generally shown good compatibility with existing SI engines. For high ethanol blends, Ford and others car makers are already producing flex-fuel vehicles, which can run on ethanol blends from 0 to 85% [10], with relatively inexpensive engine modifications. In both non-FFVs and FFVs, corrosion and degradation problems in the fuel system have been solved by using stainless steel substituting for aluminium, magnesium, lead, and brass among other metals. Polyvinyl chloride and some rubber parts have been replaced by materials such as high-density polyethylene, nylon, and fluorinated plastics such as Teflon [6,7]. There is no direct scientific documentation on the engine and fuel systems in Brazilian vehicles running on E100, but by all accounts the 30-year experience of car manufacturers with hydrous ethanol fuel seems to have eliminated any major compatibility problems through the correct choice of materials [8]. As to the cold-start problems, current vehicles running on high-ethanol blends use either dual-fuel systems (i.e. a small auxiliary tank with a specific volatile fuel for cold starts, that is used in Brazil) or block heaters in combination with lowering the E85 ethanol content to 70% (this approach is used in FFVs in the northern hemisphere in the wintertime). As far as the fuel transport and distribution infrastructure is concerned, low-ethanol blends can be relatively easily handled with the existing infrastructure while for high bio-ethanol blends there may be the need for investment in appropriate facilities and infrastructure.

■ **Compressed Ignition Engines** – Ethanol is mostly blended with gasoline rather than with diesel because of its low ability to ignite under pressure (i.e. low cetane rating). However, diesel-ethanol blends up to 95% ethanol (E95) can be and are also used in CI engines. This is achieved through some engine modifications (e.g. Raised cylinder compression ratio) and generally with the addition of a cetane number (CN) improver to improve the engine combustion [23]. In compressed ignition (CI) engines, intense pressure is used instead of a spark plug to bring the fuel to combustion. Ethanol use in CI engines represents a more efficient ethanol application because of the higher efficiency of the combustion, which on average is about 30% higher than in SI engines. However, the efficiency of the CI engines is already the highest among commercial transportation engines and the ethanol benefits are in proportions much smaller than in SI engines, that is, a maximum increase of only about 5–10% [5]. Comprehensive fleet trials, with millions of miles driven, have been conducted with ethanol in diesel engines, in different regions and climates around the world, including Australia, Sweden, Denmark, Ireland, various states in the United States, and - not least - India [3]. Most recently, the greatest scale fleet trials is being conducted in the state of Karnataka in India, where the largest ethanol–diesel fleet in the world comprises about 5,200 buses using O₂-diesel (Energiesel), a diesel containing 7.7% ethanol and 0.5% biomass-based additive [12]. The fleet uses about 120 million liters of E-diesel per year. Energenics, the O₂-diesel producers, claim that the blending method is compatible with all diesel fuels and that Energiesel can be used in diesel engines without any modifications, while maintaining engine power output and fuel economy, comparable to that of regular diesel. The benefits of running on O₂-diesel in this case include smoke reduction and slight fuel cost reductions of about €0.0045 per litre [12]. Scania has also been producing heavy-duty engines for buses running on ethanol since the mid-1980s, with serial production since 1990. More than 600 buses have been operating in Swedish cities with significantly better emission performance than regular diesel buses. The third-generation buses are currently running on a blend of hydrous ethanol and 5% ignition improver (E95), a fuel that is utilized as efficiently as diesel fuel, with up to 44% thermal efficiency. These engines now represent a fully proven technology with no operational drawbacks. To accommodate for the ethanol fuel properties and reduce the amount of ignition-improving additive, ethanol-resistant materials are used for the fuel system and the fuel tank, and the engine compression ratio has been significantly increased [13].

Bus fleets represent the most easily-available and efficient ethanol applications in CI engines. Buses are in many cases fuelled from central stations, where it would be relatively easy to install the necessary facilities, if compared to widespread commercial applications. At

the same time, the use of ethanol in urban areas can reduce hazardous emissions. Some studies show that this benefit might be of minor importance if compared to the use of modern diesel engine equipped with diesel particle filters [14]. However, ethanol-diesel blends in CI engines have performed better than pure diesel in many trials, with higher energy efficiency and lower PM (smoke), NO_x and CO₂ emissions. In terms of drawbacks, as diesel oil has an energy content of about 36 MJ/litre and ethanol is 21 MJ/litre, relatively larger volumes of ethanol are needed, compared to diesel, to have the same power output. If the fuel injectors are not large enough to deliver the required flow of fuel, the maximum engine power output can decrease. This could limit the ethanol percentage in diesel fuel. For this reason, ethanol use in diesel engines requires larger fuel injectors, fuel pumps, and tanks. A number of R&D efforts aim to develop an ethanol engine with efficiency comparable to that of modern diesel engines while maintaining low production costs and exhaust emissions same as the gasoline engines. This has been achieved with an E30 ethanol-diesel blend that offers approximately 8% less energy per litre and some 8% lower mileage. Other studies from EPA show even better performance.

Ethanol's high-octane number – an advantage in SI engines - is a disadvantage for use in CI engines. Ethanol is unlikely to auto-ignite under the conditions existing in standard diesel engines. In short, when using ethanol ignition starts later than with pure diesel, but the combustion time does not change. This results in a more violent combustion. To solve the problem, a common practice in standard diesel engines running on ethanol is the addition of ignition improvers. Also, using ethanol fuel in CI engines can result in poor cold-starting, rough idling, and excessive NO_x emissions. Possible solutions include the use of lubrication additives or other materials to prevent problems with fuel pumps and injectors. Scania buses currently operate on a daily basis on 95% ethanol and 5% additive, and need no more maintenance than Scania's regular diesel buses.

The near future of the CI engines is the homogeneous charge compression ignition (HCCI), which is a combination of the best features of SI and CI engine principles, i.e. CI engine high fuel efficiency and SI engine clean emissions. At present, major technical issues for HCCI engine commercialization are combustion control and the operating range. Thus, HCCI engines are currently best suited for stationary, rather than automotive, applications. HCCI engines fuelled by all percentages ethanol–diesel blends have been investigated using both anhydrous and hydrated ethanol. Outcomes show that ethanol reduces emissions, high ethanol blends minimise smoke and NO_x emissions, and highly "wet" ethanol (60%–70% water) in HCCI engines may result in a very significant

reduction in life-cycle energy use. However, many of these potential advantages require significant additional R&D efforts.

CURRENT COSTS AND COST PROJECTIONS

■ **Bioethanol** - Current estimated costs of ethanol range from €0.5 to €0.7 per litre of gasoline equivalent. The costs of biofuels are dominated in most cases by the cost of feedstock. Current biofuels are produced at a roughly 50% more relative to conventional fuels, though this is highly variable depending on the particular feedstock and production pathway. For the cheaper biofuel options (i.e. ethanol from sugar cane in Brazil and corn in the US) the cost of CO₂ avoided falls to around zero on the assumption of oil price of €50/bbl, but more expensive European biofuels continue to have a cost premium, primarily due to diseconomies of scale. The price of second generation biofuels from cellulosic-based materials and crops is currently buoyed by process costs, but it is anticipated to fall in the longer term. Forecourt prices for biofuels may vary in competitiveness depending on government support.

■ **Flex-Fuel Ethanol ICE Vehicles** - All new vehicles can run on at least E5 without problems and usually under the manufacturer's warranty. E5 or E10 use is not always recommended by manufacturers. Potentially all future gasoline vehicles could be made compatible with all ethanol blends from E0 to E85, with modest or no extra cost on the vehicle. The use of high ethanol blend (E85) requires specific Flex-Fuel Vehicles (FFVs) as is done with many vehicles in the American markets (U.S. and Brazil). All the major car manufacturers are capable of making vehicles compatible even with hydrated ethanol (E100), since they all produce cars for the Brazilian market [3]. Because the technology is not new and requires only the substitution of some components and materials in the fuel line to withstand slightly more corrosive fluids, the future costs for flex-fuel cars are not likely to vary too far from the costs of conventional vehicles. R&D costs of manufacturers to improve the compression and timing of injection for high blend flex fuel vehicles (to optimise their efficiency) may be passed on to consumers. While it is difficult to project the extent of this with certainty, this additional costs are expected to be modest. Upgrading existing cars for use with lower percentage blends would simply cost the sum of the parts which are at risk of corrosion – approximately €350-700.

POTENTIAL & BARRIERS - The use of biofuels can theoretically save significant amounts of GHG emissions. However, this is very sensitive to feedstock and methods of production (ETSAP TB S05). With the exception of ethanol from sugar cane, current biofuels from primary agricultural feedstock (sugar beet, wheat, corn) offer moderate CO₂ saving in comparison with second generation biofuels. Moreover, bio-ethanol

production from primary agricultural feedstock is constrained by the competition for land use with food production. This encompasses land availability and ownership, land use change and the effect on food and feedstock commodity prices. The wider uptake of biofuels could also divert resources from other bioenergy applications for example electricity generation and heating, that may have greater life-cycle greenhouse gas benefits. In the future there may also be additional/increasing competition for biomass resource for bio-materials and textiles, and for bio-chemicals. In the mid to long term, advanced biofuels from ligno-cellulosic materials or from micro-algae (also known as second or third generation biofuels) could offer greater emissions saving and production capacity, with modest or no adverse affects on land, water and soil use.

In the US and Brazil, flex-fuel versions of many models have been widely available for a number of years and these countries are also the two largest producers of bioethanol. In Brazil, over half of the fuel consumption in the gasoline vehicle market is ethanol, with vehicles using up to 100% pure ethanol. In the US, production of ethanol is continuing to ramp up due to future targets to significantly increase the quantity of biofuel used. This is despite production of ethanol from corn (typical in the US) being 5 to 6 times less efficient than producing it from sugarcane (in Brazil). However, this is expected to improve with the introduction of second generation production processes and new strategies are being designed to bolster biofuel production while guarding against potential environmental damage.

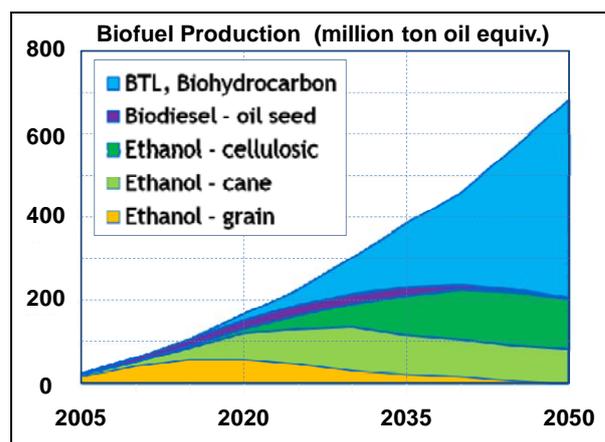


Fig. 1 – Projected volume and composition of future biofuel production to 2050 (IEA [21])

In the European Union, the Renewable Energy Directive is a major driver for uptake of biofuels within the Member States. The Directive defines a 20% target for the use of renewable energy in the EU energy mix by 2020, with 10% to be met mainly through the use of biofuels. While first generation biofuels are currently limited to an average 5% blends for bioethanol and 7%

blends for biodiesel, there is a lot of pressure for raising these percentages to get the chances of achieving the 10% Directive's target. Second generation biofuels offer a greater potential but are not yet ready to enter the

market [19]. According to IEA projections, the production of biofuels could take the route outlined in Figure 1. Costs are also forecast to reduce by around 30% in the long term [21].

Table 1 – Summary Table: Key Data and Figures for E85 Flex-Fuel Ethanol Vehicles [1, 9, 16, 22]

Flex-Fuel Ethanol Vehicles [1, 9, 16, 22]			
Technical Performance	Small Cars	Medium Cars	Large Cars
Energy Input	Bioethanol E85 (85% Ethanol, 15% Gasoline)		
Base Energy Consumption (l/km)	0.091	0.105	0.161
Base Energy Consumption (MJ/km)	1.96	2.28	3.48
Technical Lifetime, yrs	12	12	12
Environmental Impact			
CO ₂ and other GHG emissions, g/km (TTW)	20.6	23.9	36.6
CO ₂ and other GHG emissions, g/km (WTW)	93.1	108.1	165.3
Costs			
Capital Cost, overnight, Euro/unit	10,279	16,643	25,505
O&M cost (fixed and variable), Euro/km	0.031	0.044	0.054
Economic Lifetime, yrs	12	12	12
Baseline Gasoline Vehicles [16]			
Technical Performance	Small Cars	Medium Cars	Large Cars
Energy Input	Gasoline		
Base Energy Consumption (l/km)	0.062	0.072	0.111
Base Energy Consumption (MJ/km)	2.05	2.38	3.64
Technical Lifetime, yrs	12	12	12
Environmental Impact			
CO ₂ and other GHG emissions, g/km (TTW)	143.5	166.7	255.0
CO ₂ and other GHG emissions, g/km (WTW)	169.1	196.4	300.5
Costs			
Capital Cost, overnight, Euro/unit	10,279	16,643	25,505
O&M cost (fixed and variable), Euro/km	0.03	0.04	0.05
Economic Lifetime, yrs	12	12	12

Notes: CO₂ emissions for E85 estimated on the basis of 50% reduction in lifecycle emissions for bioethanol versus gasoline on an energy basis. TTW = direct emissions from the tailpipe (taken to be zero for biofuels, as the CO₂ emitted is the same as that absorbed during the growth of the biomass feedstock). WTW = full lifecycle emissions from production, distribution and use of a fuel. Dataset is for current (2010) performance and costs.

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