Alternative fuels and their applications on large engines

Alternative Kraftstoffe und ihre Anwendung in Großmotoren-Applikationen

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Abstract

The Paris climate goals against global warming pushes the industry and society into action. Large engines make a significant contribution of 5 -7 % of the world-wide CO_2 emissions. Consequently large engines are forced to reduce their greenhouse gas and CO_2 emissions significantly. The application areas of large engines are Construction and Industry, Power Generation, Marine and Railways. Large engines are because of several reasons difficult to replace by batteries and fuel cells. That is the reason why CO_2 neutral or even CO_2 free large engine applications are already in development to achieve the greenhouse gas emission goals for 2030, 40 and 50. Pilot applications will enter the market even by 2022 and the ramp up of new technologies will happen prior to 2030. CO_2 emission reduction can be fulfilled by improved engine and vehicle efficiency, by carbon capture and storage technologies and by bio- and e-fuel applications. This paper shows the application options for bio- and e-fuels in large engines.

Due to the fact that electrolysis based drop in fuels (e-Diesel, e-Kerosine,) have a low production efficiency, relatively high production costs and will be very likely occupied by off highway and airplane applications, alternative fuels will be required. Today hydrogen, ammonia, methane, methanol and ethanol seem to be the most promising alternative fuels for large engine applications. The physical and chemical parameters of these fuels differ a lot from Diesel and natural gas. Differences in viscosity, lubricity, density, energy density, vapor pressure, evaporation energy, flash point, flame-ability, ignition energy, cetane number, octane number and flame propagation require significant adaptions at the fuel injection/admission system as well as the combustion system.

All alternative fuels require individual mixture preparation and combustion systems for best fuel consumption and lowest exhaust emissions. The capability of retro fit and dual fuel use has to be considered in all concepts. The paper is showing the application areas and pros and cons of different mixture preparation systems for the alternative fuels of large engines.

Kurzfassung

Zur Erreichung der Klimaziele aus dem Paris Agreement ist die Industrie und die Gesellschaft zum Handel gezwungen. Großmotoren emittieren einen nicht unbeträchtlichen Anteil von 5-7% der WW CO_2 Emissionen. Sie müssen daher zwingend auch einen signifikanten Beitrag zur Reduzierung der Treibhausgase und damit der Klimaziele beitragen. Großmotoren finden in den Segmenten Marine, Eisenbahnen, Industrie, Mienenbetrieb, Gas und Ölförderung als auch in der Stromerzeugung Anwendung. Großmotoren sind aus mehreren Gründen schwierig durch Batterien und Brennstoffzellen zu ersetzen. Aus diesem Grund ist es notwendig, dass CO_2 freie, CO_2 neutrale bzw. CO_2 reduzierte

Großmotoren bereits jetzt entwickelt werden um die Treibhausgasziele 2030, 40 und 50 zu erreichen. Ab 2022 werden Pilotanwendungen und Felderprobungen mit alternativen Kraftstoffen gestartet und der Hochlauf der neuen Technologien beginnt spätestens mit 2030. CO_2 Reduktionen von Großmotoren können durch Wirkungsgradoptimierungen, durch Carbon Capture and Storage und durch e- bzw. Biokraftstoffe erreicht werden. Dieser Vortrag zeigt die Möglichkeiten der Umsetzung von e- und Biokraftstoffen und die dazu passenden Einspritztechnologien auf. Da „drop in fuels" (Diesel und Kerosin auf Basis von e- und Biokraftstoffen) einen geringen Produktionswirkungsgraf aufweisen, hohe Kosten verursachen und von der Luftfahrt und off highway Nutzfahrzeuganwendungen beansprucht werden müssen sich die Großmotoren auf die Anwendungen von e- und Biokraftstoffen mit sehr geringem Umwandlungs- bzw. Raffinierungsgrad einstellen. Aus heutiger Sicht bieten sich die Kraftstoffe Wasserstoff, Ammoniak, Ethanol, Methanol und Methan an. Die physikalischen und chemischen Parameter dieser Kraftstoffe unterscheiden sich signifikant von Diesel und Erdgas. Die Unterschiede in Viskosität, Schmierfähigkeit, Dichten, Energiedichte, Verdampfungsdruck, Verdampfungswärme, Zündfähigkeiten, Zündenergie, Cetanzahl, Oktanzahl und Flammenausbreitungsgeschwindigkeiten erfordern signifikante Anpassungen der Gemischbildungs- als auch der Verbrennungssysteme.

Aus obigen Gründen bedürfen diese Kraftstoffe zur Erreichung von hohen Wirkungsgraden und geringen Emissionen einer individuellen Optimierung der Gemischbildung und Verbrennung. Dies ist im speziellen bei Großmotoren unter dem Aspekt von Retro Fit und Dual Fuel Fähigkeit zu beurteilen. Der Vortrag zeigt analytisch die Vor- und Nachteile verschiedener Gemischbildungssysteme für alternative Kraftstoffe bei Großmotoren.

1. POWERTRAINS OF THE FUTURE - HOW WE WILL MEET OUR CLIMATE GOALS THROUGH TECHNOLOGY NEUTRALITY

Effective environmental protection requires every type of powertrain. Technology neutrality is therefore one of the most important aspects enabling us to meet our climate goals. Optimized internal combustion engines, fuel cells and electric drives are technologies, which are contributing factors. Accordingly, Bosch is constantly working on technical solution to support all technology paths. Like hybridization and FC solutions, modern injection systems ensure efficient, economical, and affordable transportation of goods.

2. DEMAND FOR TRANSPORTATION IS INCREASING

The demand for passenger and freight transport continues to increase. Biggest increase is expected for freight transport, one that is greatly disproportional to the increase in population. This is caused by increasing wealth in many parts of the world, globally distributed supply chains, and the unwavering trend of online shopping. This development offers opportunities for growth for all providers of mobility and transportations solutions (see **Figure 1**).

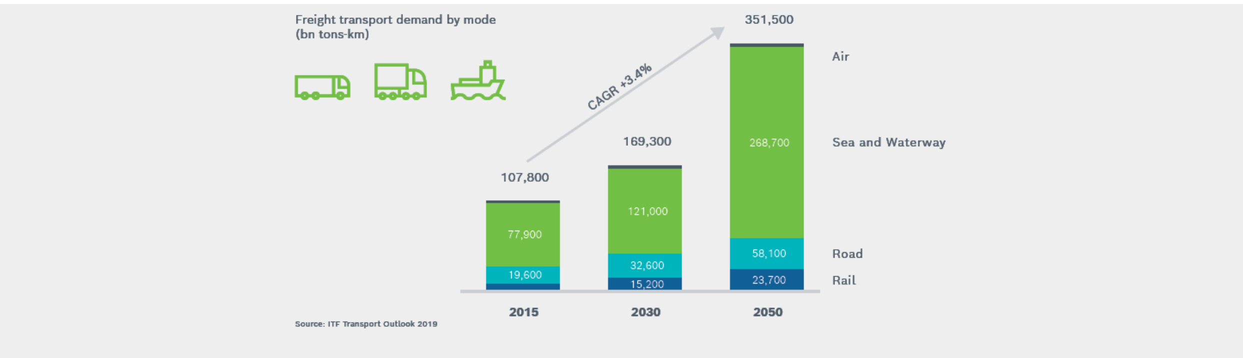


Figure 1: Increasing demand for transportation until 2050 (per segment) [1].

3. HYDROGEN IN LARGE ENGINE APPLICATIONS

The mobility sector is at the focus of the intended CO_2 reduction. In order to identify the best technical solution for each application and ensure that robust, market-compliant and last but not least, affordable technologies are quickly available on the markets, a technology-neutral approach is required. All carbon-neutral energy carriers that can reasonably be used should be integrated into that approach. For large engine applications CO_2 emissions must be assessed in a comprehensive manner over the entire life cycle, i.e. in a well-to-wheel consideration and taking into account the production and recycling of vehicles, vessels, etc… Other than, in the mobility solution in the large engines market, due to the high energy demand, Battery-electric solution represents only a niche solution for some applications, within the next decades.
Hydrogen used as a fuel will play an important role in future mobility and transportation. Apart from its direct use as a fuel, hydrogen also is the basis for the production of so-called drop-in e-fuels that can be manufactured in a carbon-neutral way and are fully compatible with current gasoline and diesel fuel standards. Renewable drop-in e-fuels and bio-fuels can be added flexibly to conventional fuels, use the existing refueling infrastructure, and are the only option to reduce the CO_2 emissions of the current global fleet of approx. 1.3 billion vehicles and 1.2 million large engines.

Drop in fuels represent a group of fuels that can immediately be used to reduce CO_2, but are very costly mid- and long term. Further alternatives like bio- and e-methanol/ethanol and ammonia need to be considered for the LE market. An additional aspect for large engine market in order to achieve best possible CO_2 reduction, is to turn fossil based fuels in “blue” fuels by carbon capture technology. Although this technology is under evaluation and not fully evaluated yet, it might be considered as part of the solution for future large engine concepts.

Figure 2 shows the evolution of the drive train for a possible H_2 path for PC/CV (passenger and commercial vehicles) as well as for large engine applications. It shows a scenario that starts with improvements on the ICE, via drop in fuels towards hydrogen engines (FC and ICE) until we reach a 100% renewable e-fuel level. **Figure 2** does not consider solution with additional alternative fuels like methane, methanol, ethanol and ammonia, which are currently considered in large engine applications. For these additional possibilities the H_2 engine would be supplemented by ICE solutions with ammonia, methane, ethanol and methanol.

100% renewable fuels includes H_2 engine and FC as well as ICE with methanol, methane, ethanol and ammonia (drop in fuels will be a niche product but are included in this consideration)

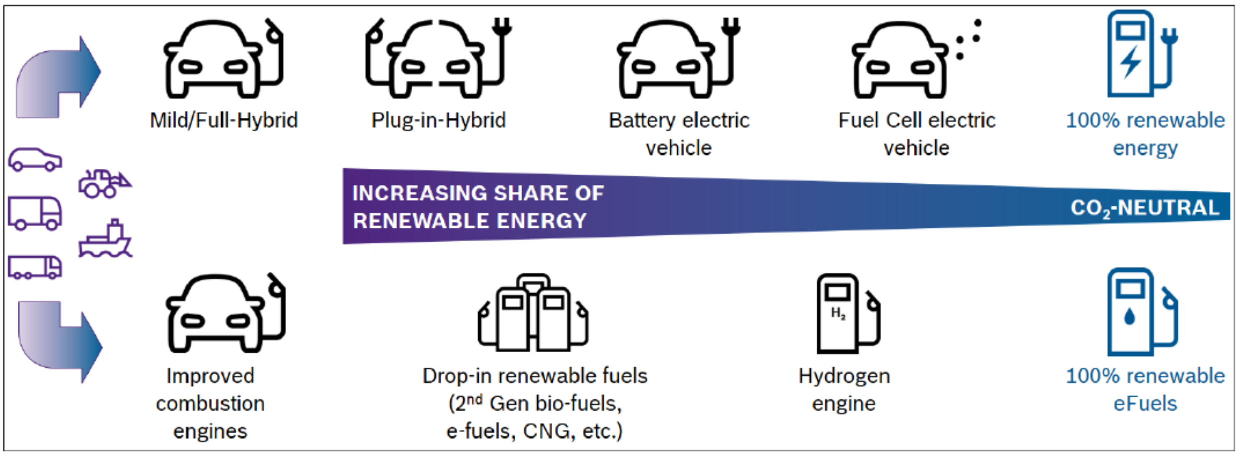


Figure 2: Path towards 100% renewable efuels [2].

4. ALTERNATIVE FUELS FOR LARGE ENGINE APPLICATIONS AND MARKET REQUIRMENTS

Figure 3 shows a possible “2030-2050 technology mix” scenario, in order to achieve the necessary Paris Agreement targets, for the mobility and transportation segment. It shows a transition from the conventional, fossil based ICE towards a mix of battery, hybrid and H_2 (FC- and IC-engine) solutions. It shows the challenge between energy density and mileage/utilization.
For large engine applications, with its even bigger energy demand, this context is even more critical. While battery solution will only work for application with a low mileage/utilization with recharge possibilities, fuel and refueling is required to cover the huge energy demand of large engine applications. In order to amortize the vessel/locomotive/truck, utilization is the key factor in order to generate a feasible business case. For the big variations of applications in the four large engine segments (Marine, Power Generation, Construction and Industry and Railways) H_2 alone, does not fulfill all market and customer requirements. Fuels with higher energy density like methanol and ammonia complete **Figure 3** in regards of even bigger applications like Railways, Marine, Construction and Industries and Power Generation.

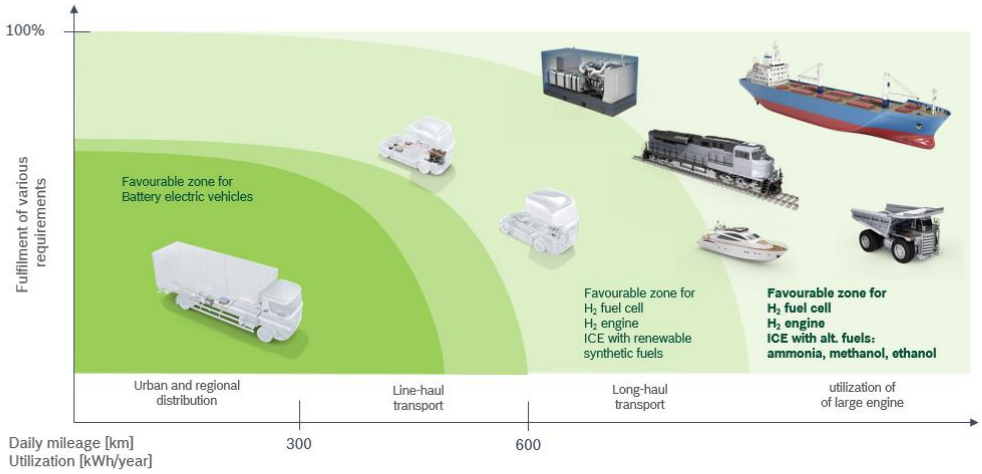
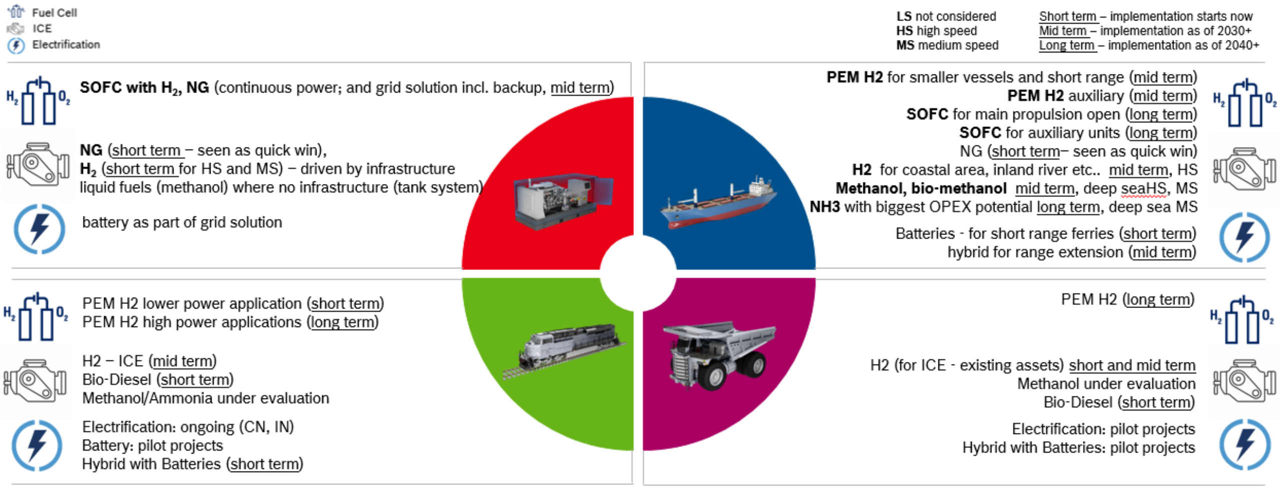


Figure 3: CO_2 neutral mobility and transportation [2].

Figure 4 shows a possible scenario of fuels in various applications short-, mid- and long-term. The fuels with its specific pros and cons will be discussed in a later chapter. Aside the ICE technology, FC and batteries are considered to establish in the Large Engine market. It also shows the expected variety in each segment. Figure 4 represents a snap shot as technology assessment is ongoing and discussion about regulatory boundary conditions are very dynamic and changing on a regular basis (IMO, EU green deal, regional H_2 strategy etc.)

- Fuel infrastructure progress is a very important part of the shown considerations. In particular, for power generation applications H_2 solutions will depend on the available H_2 distribution infrastructure in developed regions. Off grid regions will depend on fluid fuel solution which are considered easier in storage handling. FC (mainly SOFC for stationary applications) will enter the power generation market. High utilization might overcome the higher initial CAPEX.
- The segment with the highest dynamic is currently the marine segment. The variations of different applications within this segment (Deep Sea, Inland River, Costal Area etc…) lead to a big variety of possible fuels and therefore variety of different drive trains. Drive train and fuel decision are driven by OPEX and CAPEX consideration with currently lots of unknowns. Aside the commercial aspects fuel safety and fuel handling are of concern (e.g. for H_2 but even more for ammonia).



- The railway industry sees developments in different directions. While the railway grid electrifications is continuing in India and China, in particular in the urban regions, grid independent solutions are still required in extensive areas like north America, parts of China, Russia, and others. CARB in California/USA recently released their view on a possible roadmap towards CO_2 neutral drive trains for railways, lining out a H_2 based solution towards 2050. Their plan is similar to the in **Figure 3** shown path and leads from ICE improvement, hybrid solutions (ICE and Bat) towards ICE H_2 and FC long term. In the passenger segment, the trend towards FC already started in Europe with pilot projects in Germany, Austria, France and other countries.
- C&I (Construction and Industry) represents a wide range of applications itself. The end customer have started to evaluate their individual path towards a CO_2 reduced fleet. Hybridizations, electrifications and FC are seen as possible solutions. In terms of robustness ICE versions (e.g. H_2 and methanol) are still attractive options. Retrofit solutions for IC engines are necessary to utilize existing assets.

For all 4 segments (and for all applications within the segments) individual technology solution will enter the market considering different time frames.

4.1 Trends in the Large Engine Market/ FIE requirements

- In order to develop the best fuel injection technology for upcoming ICE generations it is essential to understand the trends and drivers as well as the requirements of the market. CO_2 reducing efforts is the biggest driver in the large engine market right now, as described in the previous chapter. Within this scope of future technology development, additional market requirements, trends and drivers are evident.
- Regulations for different segments and/or specific applications would be binding targets that need to be applied. Such binding regulations are more and more under discussion, and would accelerate the transition maybe at the expense of technology variety. Prediction of when regulation will be applied in which segment, region etc. is difficult as the political landscape is currently very dynamic. Bosch expects a trend towards binding regulation and an acceleration of the transition.
- Bio-Diesel blends (20-100%) is an immediate possibility to offer CO_2 reducing technology to the market. Engine OEMs have to offer such solution immediately. Current and future FIE needs to support this trend.
- NG for gas engines is one of the most controversial discussed solution (short term). As NG is seen as a quick win in regards of CO_2, the methane slip is seen critical and unresolved. NG solution is currently a trend in the LE market short term (2030). Possible methane slip limitations will decide the NG trend beyond 2030. Technical solution of possible after treatment as well as combustion optimization are additional aspects in this discussion.
- In particular in the marine market dual fuel applications are currently an established FIE technology.

NG/Diesel combination, in order to apply to IMO ECA zones and optimize OPEX. As the future alt. fuel market is difficult to predict there is a strong interest to continue with dual fuel applications on applications where this concept is already established and therefore have a Diesel fallback solution, in order to minimize commercial risk.

- For Single Fuel applications, a pilot injection in particular for carbon free alt. fuels, like H_2 but even more ammonia is seen critical. Although a small pilot quantity could be ensured with bio-diesel the whish is to avoid any carbons in a carbon-free fuel path. Whether or not such a combustion system will be available in the market is currently open and has to be investigated further.
- Bosch sees a broader industrialization of alt fuel technology into the large engine market prior to 2030, ramping up with ICE with alt. fuels as well as FC (PEM and SOFC) entering the market on a broader scale. In a growing large engine market the number of new engines applied to the market is considered to be between 60 and 80k/year in the next 20 years. Combined with a life cycle of around 30 years for most LE applications, a share of market for alt. fuels (ICE and FC) bigger than 50% in 2050 is difficult to achieve. In order to increase the SoM with alt fuels, future FIE concepts have to support retrofit on existing engines. Dual fuel and single fuel retrofit solutions have to become part of future fleet considerations, in order to achieve best possible progress towards de-fossilization.
- Customer expectations is that, FIE robustness and reliability remains on the current established level. The concepts that are currently being developed is based on existing technology and/or existing Bosch know how. As new fuels will cause new challenges for large engine components Bosch strategic approach is to implements only technical elements where know how is already available.

5. ALTERNATIVE FUELS FOR LARGE ENGNINE APPLICATIONS

Robert Bosch is supporting various technologies to fulfill the climate goals of the Paris agreement. All these technologies aim for reduced CO_2 and GHG emissions. Electrified battery electric vehicles, PEM fuel cells for on highway vehicles, Sulfur Oxide fuel cells for electricity production, hydrogen in combustion engines, PtX fuels in combustion engines and bio fuels in combustion engines. The Bosch position is clearly explained in chapter one [1].

Bosch is actively supporting the implementation of CO_2 reduced fuels. In [1] an example for the general Bosch activities is given.

An option for reducing CO_2 that is still typically underestimated today is liquid synthetic fuels from renewable energy sources. The focus here is on “drop-in renewable fuels,” meaning the fuel mixture must conform to the EN228 (gasoline) or EN590 (diesel) standard. These can then be used directly, and take their effect, in the existing vehicles and off highway applications. The CO_2 improvement varies depending on the production method and admixture components and can be 100 %, when the CO_2 emitted by the vehicle running with e-fuels is fully neutralized by the CO_2 captured from the atmosphere for the production with renewable electricity. In concrete terms, this means that R33, for example, is already available today at some filling stations and is approved for all diesel engines, and enables an immediate CO_2 reduction of 20% compared to conventional fuel. This is also possible for gasoline. Bosch is working with Shell and an OEM on a drop-in Blue Gasoline with a 20% potential reduction in CO_2 and plans to introduce this fuel at Bosch plant filling stations starting in 2021. The specification for this fuel will be freely available to all market participants. Results are shown in **Figure 5**.

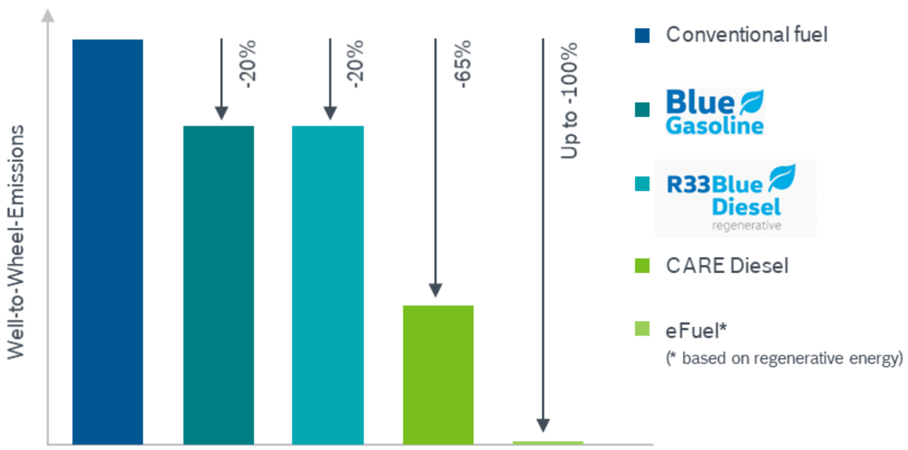


Figure 5: CO_2 reduction potential with drop in fuels [1].

Alternative CO_2 neutral or CO_2 free fuels will play a major role in the field a large power trains and large engines. They can be either H_2 based or bio based. **Figure 6** shows the prime paths for the production of PtX fuels as well as the prime paths for the production of bio fuels.

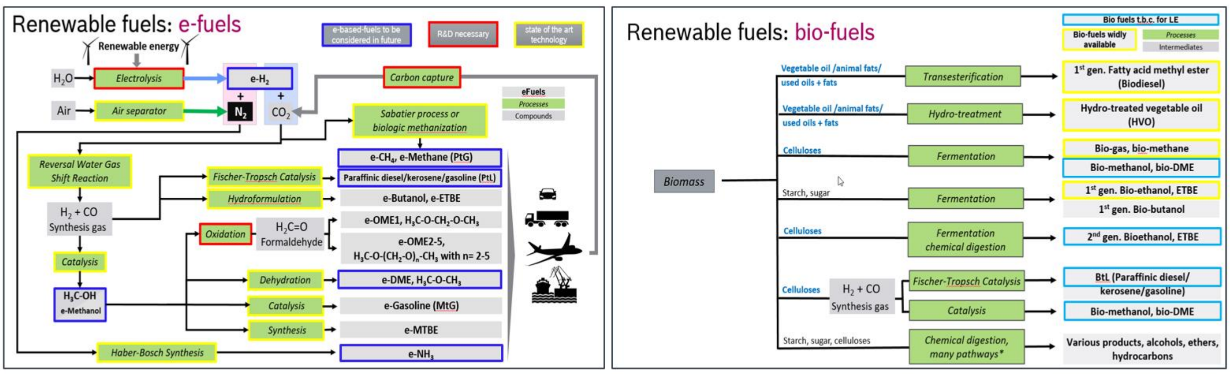


Figure 6: e- and bio- fuel production

Analyzing the e-fuel production path leads to the conclusion that hydrogen, ammonia, methane and methanol are showing the highest e-fuel production efficiency. All other e-fuels are more complex in production which leads to a loss of efficiency in production. That is also valid for the Fischer-Tropsch catalysis which enables even the production of e-Diesel.

The bio-fuels production can be based on different sources. Starch and sugar are critical resources. They can also be used in food production and can be questioned as long as humans are starving. Ethanol is the first grade product out of starch and sugar.

Vegetable oil, fats and used oils can be utilized for bio fuel production. Vegetable oil must not lead to land grabbing and the destruction of forests. Hydrogenated Vegetable Oil (HVO) and Fatty Acid Methyl Ester (FAME) are already available at the market. They can be applied in Diesel engines if they comply with the already existing fuel standards (e.g. EN 590, EN 16734, EN 16709, EN 14214 and EN 15940).

The most promising bio fuel production is based on celluloses production. Methanol and Ethanol are by products of the celluloses fiber production. Celluloses fiber mills could optimize their production processes for methanol and ethanol if prices would become attractive for them. This partly already is given for the production of ethanol. Bio-methane (bio-gas) can also be produced in a very efficient way but the methane slip in production (around 2%) is seen as very critical as methane is a very strong GHG (20 to 100 times stronger than CO_2). The utilization of bio-methane on large scale will require a significant reduction of the methane slip in methane production.

Bio-fuels have significant production volume limitations. It is worldwide not enough feed stock available to replace fossil based fuels by bio fuels.

Looking at the overall availability and efficiency of e- and bio-fuels the following fuels are attractive in principle:

- Paraffinic Diesel, HVO and FAME: They can be applied on diesel engines if they fulfill diesel fuel standards
- DME, OME: Can be applied on Diesel engines with adaptions on the injection system.
- Methane: Can be applied on gas engines.
- The most promising CO_2 free e-fuels for large engines are hydrogen and ammonia and the most promising CO_2 neutral e-and bio-fuel is methanol and in some regions ethanol. A blend of lignin and ethanol could also become of interest in future. All these fuels require significant adaptions in the combustion and mixture preparation systems to enable best fuel consumption and lowest emissions.

Figure 7 shows the main parameters for the application of hydrogen, ammonia, methanol and ethanol.

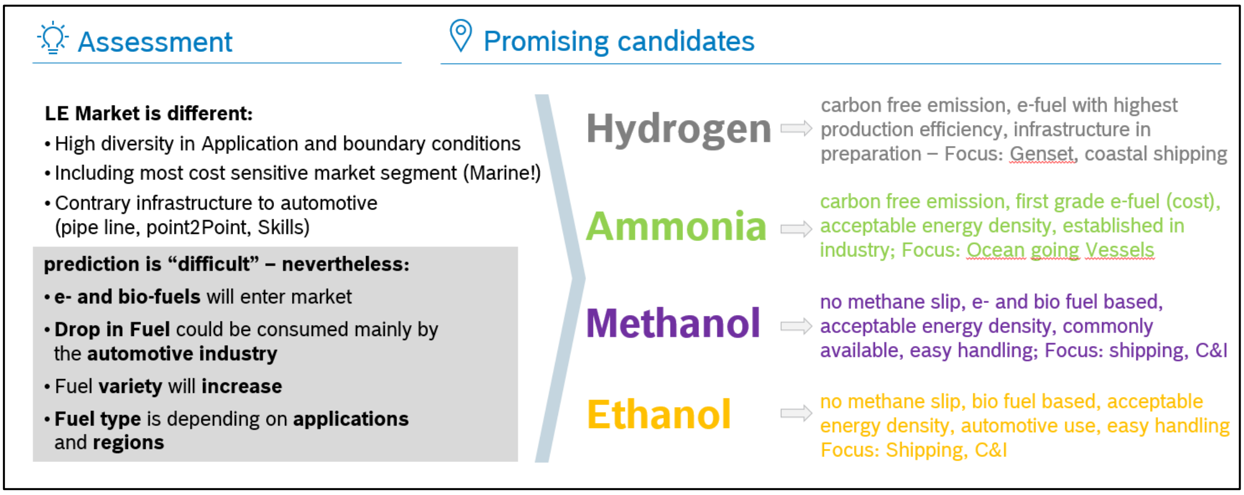


Figure 7: Alternative fuel – assessment

The physical and chemical parameters of these fuels differ a lot from Diesel and natural gas. Differences in viscosity, lubricity, density, energy density, vapor pressure, evaporation energy, flash point, flame-ability, ignition energy, cetane number, octane number and flame propagation require significant adaptions at the fuel injection/admission system as well as the combustion system.

Hydrogen has an extremely low density of 0,09 g/m3 in combination with very low ignition energy of 0.017 mJ, a very wide ignitable air fuel ratio from 0.13 till 10 and a very high flame propagation speed of 230 cm/s.

Methanol and Ethanol have a very high Octane number (107) and compared to Diesel a very low viscosity (< 1,2 cSt). The energy density of methanol (20 MJ/kg) is 50% and of ethanol (27 MJ/kg) is 30% below the energy density of Diesel. The evaporation energy of ethanol (841 kJ/kg) and methanol (1089 kJ/kg) are very high compared to Diesel (250 kJ/kg). Formaldehyde emissions have to be considered.

Ammonia is very toxic and requires specific safety procedures. It has an energy density slightly below of methanol (18,6 MJ/kg), has low flame-ability and very low flame propagation (6,7 cm/s). N_2O and NOx emissions have to be considered. From the production costs point of view H_2 and NH_3 seem to be the most promising fuels.

Coming from the current applied combustion systems in large engines, Diesel and homogenous lean burn, some changes will be required. [2], [3], [4], [5] and [6] show that H_2 combustion requires some adaption to ensure stable combustion and to prevent auto ignition. Most applications are based on homogenous mixture but some work on diffusion flame based combustion.

[7] shows the pros and cons of the methanol based combustion with either homogenous mixture or high pressure injection diffusion flame combustion. [8] describes the achieved results on a medium speed engine with high pressure methanol injection and diffusion flame based combustion. They claim even a fuel consumption improvement beyond Diesel combustion. [9] shows the requirements for ammonia combustion on a two stroke engine which is based on diffusion flame combustion. The flame-ability of ammonia is poor and the flame propagation rate low. That is why ammonia either is requiring a pilot injection for ignition or a prechamber ignition with high prechamber flame penetration into the main combustion chamber.

All above mentioned boundary conditions lead to a very wide spread of requirements for the fuel injection/admission system for the alternative fuels. The fuel, the combustion system and the injection system are directly coupled to each other. By theory a huge number of variations is possible [5, 7] but not practical for industrialization. An evaluation of the pros and cons of different injection systems is necessary to determine the main technology paths.

Figure 8 is giving an overview of the alternative fuels versus the reasonable injection/admission systems. It is considering market requirements, customer feedback and the recommendations of the thermodynamic experts. Methane is not considered in this chart as it can be handled in the admission system and combustion system like natural gas. Ethanol is not separately considered as it can be handled like methanol. LEO (lignin ethanol blend) is not considered as it is currently no mainstream.

Figure 8 is showing the preferred fuel systems versus the type of combustion (single or dual fuel) and the type of alternative fuel. A clear market trend is seen. Single fuel concepts even try to avoid Diesel pilot injection to enable complete CO_2 free combustion. Dual fuel concepts prefer the utilization of the already existing Diesel injection system.

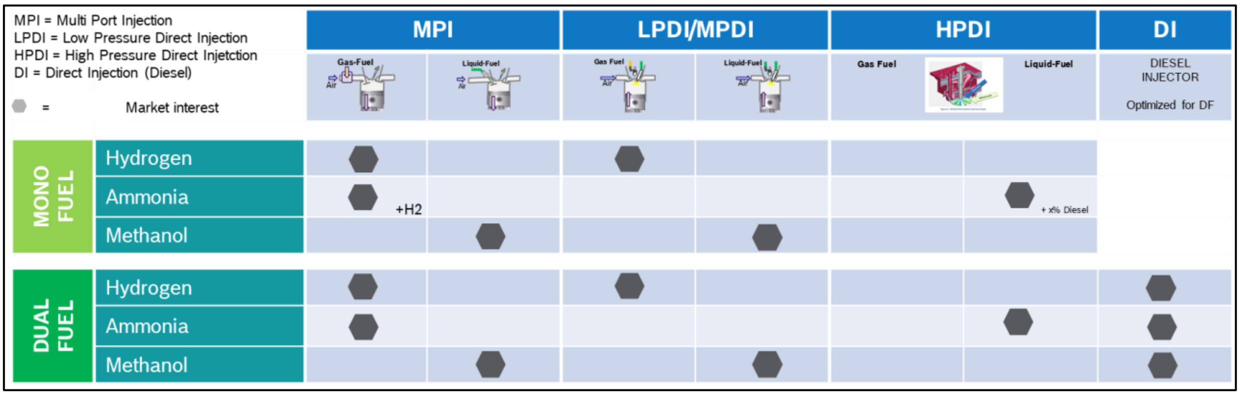


Figure 8: Market requirements on fuel injection systems for alternative fuels.

Hydrogen can either be injected into the intake manifold or directly into the combustion chamber. Low pressure admission is preferred as tank and pipe line systems do have pressure limitations and a cryogen H_2 pump is a very challenging and cost intensive solution. For H_2 gas admission into the manifold slightly modified large engine gas valves (LEGV) can be used. They are a robust and simple solution for dual fuel engines. Due to extreme low density and large volume of H_2 the H_2 admission into the manifold is significantly reducing the filling of the combustion chamber (-350 mbar manifold pressure [2]) and hence leading to reduced engine power. Additionally is a homogenous H_2 air mixture difficult to achieve with manifold admission. The low pressure direct admission of H_2 is preventing from these drawbacks. The separate path of air and H_2 enable best filling of the combustion chamber. The optimization of the H_2 stream directly into the combustion chamber enable good mixing of H_2 and air resulting in significantly reduced nocking conditions [2]. The direct admission of H_2 prevents in addition the risk of back firing into the intake manifold.

Ammonia is gaseous under atmospheric conditions. The fuel admission can be performed with a large engine gas valve into the intake manifold. This is a simple solution for fuel admission. Ammonia is difficult to ignite requiring an ignition stream with high temperature and strong penetration into the combustion chamber. This can be achieved either with pre-chamber ignition or with a diesel pilot injection. The pros and cons of manifold admission (MPI) versus direct injection (HPDI) are not fully verified so far.
Methanol can either be injected into the intake manifold (MPI) or directly into the combustion chamber (LPDI/MPDI). The pros and cons of these technologies are shown in [7]. Methanol allows homogenous lean burn combustion, stratified charge combustion and diffusion flame combustion.

6. ADMISSION CONCEPTS – A COMPREHENSIVE APPROACH

As stated above, future fuels will, especially for the LE market, require new fuel injection equipment and technologies. Many different aspects have to be considered which significantly increase the variety of concepts and designs. CAPEX and OPEX play an important but varying role in different market segments and in different regions. The complexity of the injection system as well as the ability for retrofit solutions for the huge numbers of engines remaining in the field for decades is important as well. Concepts have to serve high and medium speed engines similar.
To address all these requirements, a comprehensive development concept is needed to keep costs and development time within reasonable limits.
Thus, the admission technology has to be split into three sections **(Figure 9):**

a) Port fuel admission for gaseous fuels in general
b) Low/medium pressure direct injection for gases and liquids as well as for liquid port fuel injection into the intake path
c) High pressure direct injection for diffusion combustion

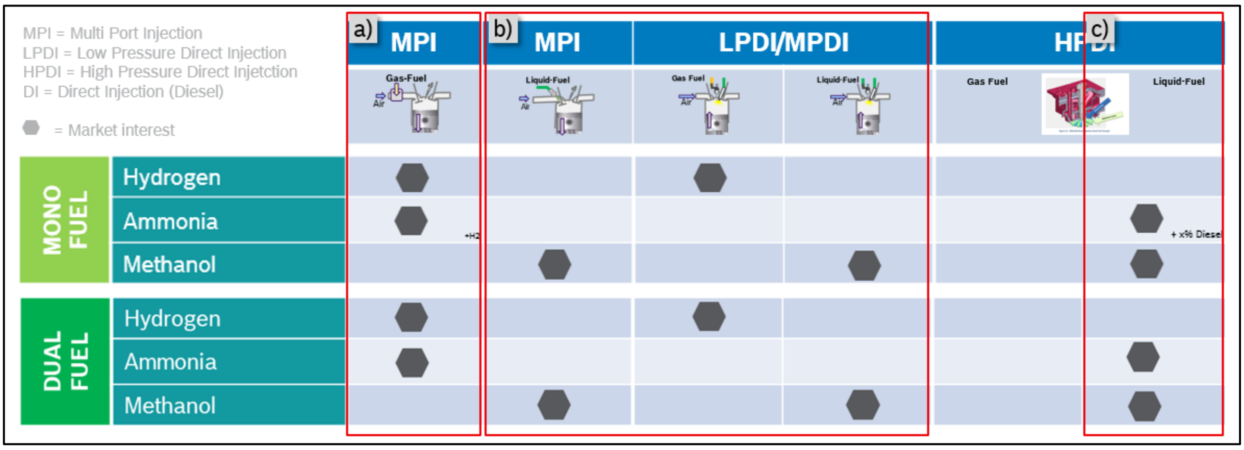


Figure 9: Split of fuel admission/injection technologies.

Ad a) Gases port fuel admission into the intake path is a well-known technology. It is the simplest cylinder individual way for mixture forming in general. The Bosch LEGV (Large Engine Gas Valve) is the appropriate product for sequential gas admission close to the intake valve and can be applied with methane and H_2 without major changes. Several H_2 applications are running with the LEGV and attest the valve an excellent performance. These are mono fuel as well as dual fuel engines and high and medium speed engines.
With small modifications, the LEGV is also capable for ammonia use. Engine tests are scheduled for the near future investigating different ignition concepts. The Bosch LEGV has confirmed a high maturity level. Especially the low leakage rate, the small cycle to cycle variations and the low wear rate make the LEGV attractive for H_2 and ammonia applications. The LEGV is available for high and medium speed engines and has different design versions for genset and marine applications, **Figure 10**.

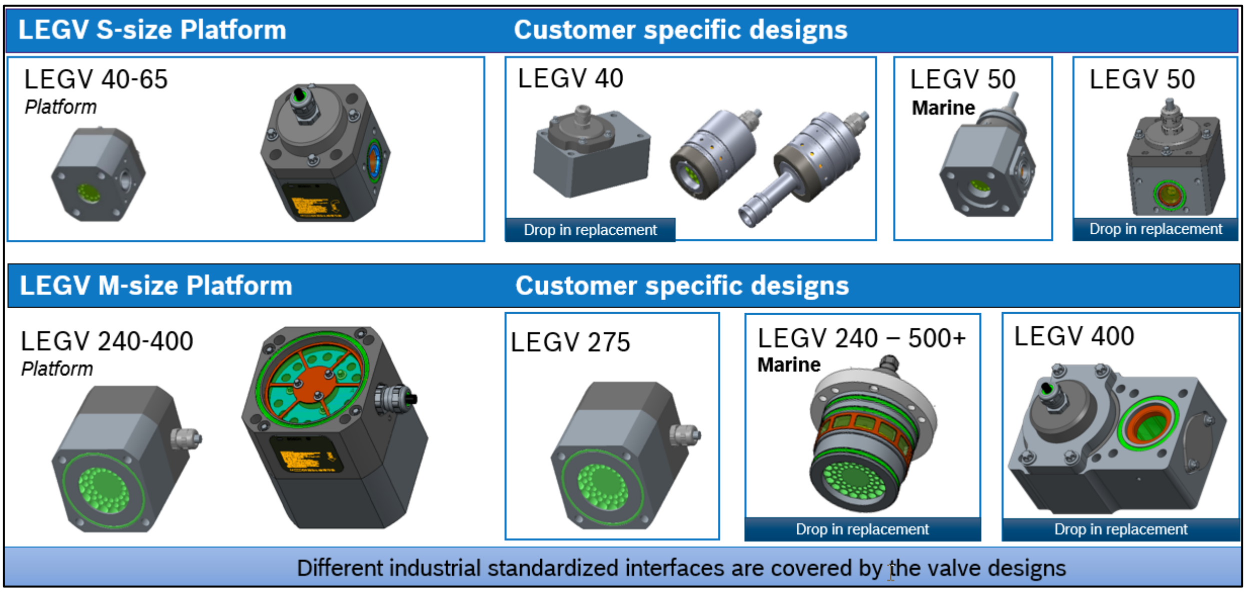
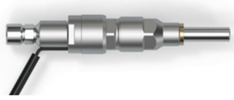


Figure 10: Design variations of the LEGV for natural gas, hydrogen and ammonia applications.

Ad b) A low/medium pressure injection equipment is needed for gaseous and liquid fuels for direct injection as well as for liquid port fuel injection. For H_2 this is the most promising technology to ensure best filling of the combustion chamber and to avoid back firing into the intake manifold. The low pressure direct injection (<30 bar) can support stable injection even at low tank pressure and avoid expensive cryogen pump technology. [2] shows that that the switch from MPI to DI admission enables an improvement of 350mbar in the intake charge pressure. The forming of the injection jet allows additionally the optimization of the H_2 distribution in the combustion chamber. This is with manifold port admission only to achieve with additional measures. The homogenous H_2 distribution improves the running stability and avoids local hot spots, consequently leading to a significantly reduced knocking behavior and improved efficiency and engine performance. The H_2 engine has a different behavior than a gasoline or Diesel engine and has still a significant potential for improvement. That potential can only be utilized with optimized mixture preparation and charging conditions. Table 1 from [2] is showing the pros and cons of different H_2 mixture preparation concepts.

Table 1: Comparison of different H_2 injection concepts [2]

H_2 injection	Port Fuel Injection		Direct Injection		
Timing	single point	multi point open valve	intake stroke & beginning of compression stroke	Near TDC (Top Dead Center)	
System costs	moderate		medium	costly H_2 injection system	like Hp DI + Diesel system
Power density	**about -30%** compared to Diesel		comparable to Diesel / moderate deviation (0 up to -20%)		
Efficiency	slightly below Diesel		**close to Diesel**		
Additional aspects	**High risk of backfire**	**Risk of backfire**	**Synergy with FCEV**, comparable H_2 LP-system	H_2 compression pump required, **possible higher NO_x emissions** due to lack of homogenization	Like Hp DI + **CO_2 emission from Diesel pilot**
Evaluation Result	Possible solution for lower functional / power requirements		No backfiring **Best cost / benefit trade-off**	**Higher system cost, complex system layout**	Higher system cost, complex system layout, CO_2 aspects
Bosch view	Path for **lower requirements** 		**Prime path** 	No activities due to: Poor cost/benefit	Poor cost/benefit + no path down to "zero" CO_2

LPDI may also have advantages for ammonia injection. It can prevent from back streaming of ammonia into the intake manifold and minimize quenching losses. For injection of liquid ammonia a fuel pressure of 100 bar is required. All this needs to be proven by engine verification.

Methanol has different boundary conditions. [7] shows clearly the difference if MPI (homogenous mixture) and HPDI (diffusion flame) based combustion is applied. Both systems lead to good results. LPDI has compared to MPI, the additional advantage that the very high evaporation energy of methanol can fully be utilized for in cylinder cooling. A further increase of the injection pressure from LPDI to MPDI can enable stratified charged operation. This principle potential requires engine confirmation.

All the above mentioned boundary conditions and requirements need to be addressed in one concept. Within Bosch a lot of experiences from Otto MPI (EV) and DI (HDEV) injection, from Gas (NGI and LEGV) admission and from Diesel injection (CR) is available. Based on these technology platforms a modular and uniform MPI, LPDI and MPDI injection technology is in development for large engines covering the power range of high and medium speed engines.

Port fuel admission (a) and low/medium pressure direct injection (b) are technologies for pre-mixed combustion.

Ad c) High pressure direct injection is supporting Diesel like diffusion combustion. Since the future fuels discussed above are not self-igniting by standard compression ignition (low cetane number), an additional effort is required. Various concepts are feasible for addressing this purpose. Ignition improver, surface ignition and the use of a Diesel pilot injection ignition are options. All these solutions require a high pressure injector, capable to handle the future fuels.

A low viscosity injector based on Common Rail technology (MCRS) is a high performance option for diesel like combustion with alternative fuels. It offers full fuel flexibility, high performance and high flexibility in terms of system solutions and retrofit options with a moderate degree of complexity.

All three technologies are illustrated in **Figure 11**.

Figure 11: Concept to meet requirements for future fuel admission

A, b and c can support single fuel as well as dual fuel applications where single fuel can be completely Diesel free and dual fuel utilizes the existing Diesel injection. This seems to be the preferred direction of the OEMs to be either completely CO_2 free or to have a save Diesel backup solution. Robustness of new injection systems have to fulfill the same requirements as existing FIE. With our product portfolio approach Bosch is supporting these requirements.

7. SUMMARY AND OUTLOOK

Large engines will continue to operate in the next decades and support the fulfillment of the global worming targets of the Paris agreement. They will be in competition with other powertrain concepts, but they can't be eliminated by batteries and fuel cells due to several reasons.

E- and bio-fuel based hydrogen, ammonia, methane, methanol and ethanol seem to be the most promising fuels to significantly reduce the CO_2, particulate and greenhouse gas emissions of large engines. Their attractiveness varies by application, region and engine size. Fuel availability, costs and infrastructure as well as safety requirements are main drivers for the use cases. Pilot applications will be installed in 2022 and a ramp up is expected prior to 2030.

For methane, hydrogen and ammonia applications already today the LEGV can be applied. Within Bosch a lot of experiences from Otto MPI (EV) and DI (HDEV) injection, from gas (NGI and LEGV) admission and from Diesel injection (CR) is available. Based on these technology platforms a modular and uniform MPI, LPDI and MPDI injection technology for hydrogen, ammonia and methanol is in development for large engines, covering the power range of high and medium speed engines. Development priorities are set by market trends and customer requests within the platform.

For high pressure injection of methanol and ammonia is a CR injector based concept available. Currently hydrogen engine based activities show the strongest interest, leading to the highest priority for large engine hydrogen low pressure direct injection systems. Our modular uniform concept will also support methanol and ammonia applications.

We will face a fast learning curve with all alternative fuels which will accelerate the development of the required injection systems. That must consider service solutions to enable fast retro-fit of existing engines. The utilization of existing large engines with alternative fuels is the fastest way to reduce greenhouse gas emissions in large power trains.

8. NOMENCLATURE

BEV	Battery electric Vehicle
C&I	Construction and Industry
CAPEX	Capital Expenditure
CARB	California Air Resource Board
COP	Conference of the Parties - Paris Agreement
CR	Common Rail
CV	Commercial Vehicle
DI	Direct Injection
DME	Dimethylether - synthetic Diesel fuel
ECA	Emission Control Areas
EEXI	Energy Efficiency Existing Ship Index
eFuel	Fuels made from renewable electricity
FAME	Fatty Acid Methyl Ester
FC	Fuel Cell
FIE	Fuel Injection Equipment
GHG	Green House Gas
HPDI	High Pressure Direct Injection
HVO	Hydrogenated Vegetable Oil
ICE	Internal Combustion Engine
IMO	International Marine Organization
LE	Large Engines
LEGV	Large Engines Gas Valve
LEO	lignin ethanol blend
LPDI	Low Pressure Direct Injection
MeOH	Methanol
MPDI	Medium Pressure Direct Injection

MPI	Multiport Injection
NG	Natural Gas
OME	Oxymethylenether - synthetic Diesel fuel
OPEX	Operational Expenditure
PC	Passenger Care
PEM FC	Polymer Electrolyte Membrane Fuel Cell
PtX	"Power-to-X" – Electricity based fuels
SOFC	Sulfur Oxide fuel cells
SoM	Share of Market

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