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Premixed combustion of alternative fuels as a fast and economic path to decarbonize

Fuel Injection & Gas Admission and Engine Components

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ABSTRACT

For the decarbonization of the large engine segment, the alternative fuels hydrogen, methanol and ammonia have been selected. The relevant properties of these fuels indicate that all are more likely an Otto-cycle rather than a diesel-cycle fuel and at least lubrication and chemical resistance are more challenging for the FIE compared with diesel. Thus, the efforts and cost, respectively, for the development of new products, production processes and last but not least production tools are tremendous.

In consequence, it is very important to select the right technology considering the implementation speed, hence GHG effectivity and the economic feasibility. Although it is not the responsibility of an FIE supplier, an important factor is the time needed for the build-up of the appropriate fuel infrastructure which impacts significantly the ramp-up of the new technologies and hence the return of investment.

In this paper the selection of the right technology under the given boundary conditions and requirements followed by the Bosch engineering approach are described. Finally, an overview of the Bosch FIE portfolio to fulfill the current market demands is shown.

1 INTRODUCTION

Following the Paris Agreement of 2015, multiple initiatives and programs for the large engine segment have been started respectively and are on the way. These are for example, in the EU the emission trading system (ETS) for shipping as well as the FuelEU Maritime (FEUM), the “net zero industry act”, “fit for 55”, “repower, and in the US the “inflation reduction act”. Additional programs are the greenhouse gas (GHG) pricing and the GHG fuel intensity by the IMO. The technologies to reduce the worldwide GHG contribution of the large engine segment, which is estimated by approx. 5-7% [1, 2, 3], have been defined.

Bosch is convinced of the need for a global hydrogen economy and is developing key technologies along the entire hydrogen value chain [4,5] (see figure 1). These include electrolysers for hydrogen production, fuel cell technology for stationary, and mobile applications and components of the hydrogen engine including appropriate fuel derivates (alternative fuels), such as methanol/ethanol and ammonia.

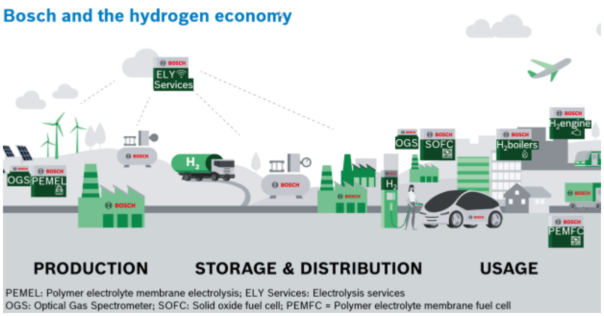


Figure 1: Bosch and the hydrogen economy

In this paper the focus is given on the alternative fuel technologies of the large engine segment. Considering the market demands and the given boundary conditions, the technology selection according to the Bosch engineering approach are described as follows. Finally, an overview of the Bosch solutions are shown.

2 MARKET TRENDS

The path towards carbon neutrality is by means of the carbonless or -neutral fuels which requires the build-up of new infrastructure. A fast penetration of the climate neutral technologies depends highly on the availability of the appropriate fuels. Both need high financial efforts and hence clear and robust boundary conditions for the required investments.

Figure 2 gives an overview of the transformation timeline. In line with the market launch certain engine OEM’s and owners started or planned demonstrator projects to validate the technologies (see rectangle with dotted line). However, the infrastructure build-up and industrialisation are comparatively delayed.

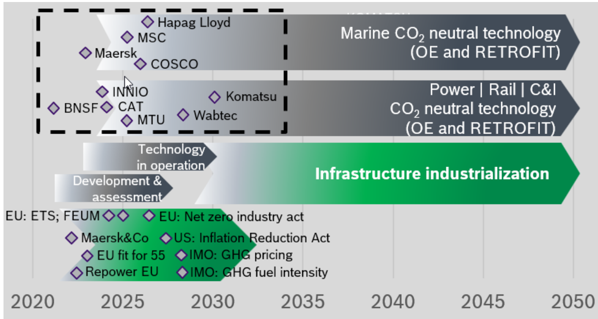


Figure 2: Transformation timeline [6,7,8,9,10,11]

In Figure 3 a base case scenario of potential maritime fuel mix transition is depicted. Two evolutionary main and one disruptive path can be identified.

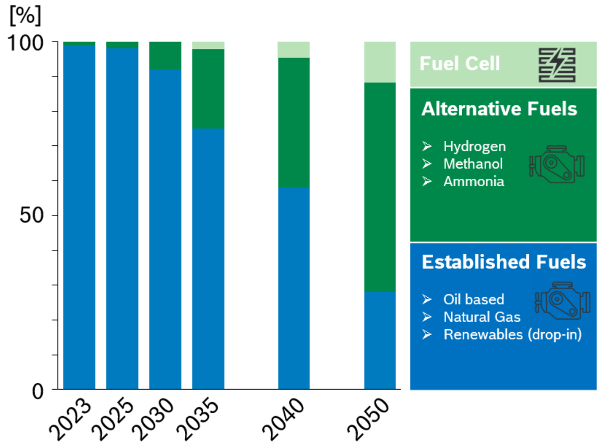


Figure 3: Fuel mix transition (HFO equivalent) [12]

The blue area indicates the established fuels, such as diesel and natural gas which will be more and more replaced by the renewable drop-in fuels (bio- and e-fuels). The penetration rate depends strongly on the local availability. Due to the backwards compatibility to the fossil diesel or natural gas (NG), the existing infrastructure and fuel injection equipment (FIE) can be used with slight modifications if needed [13]. Thus, the GHG improvement potential is effective in the existing fleet allowing a fast implementation.

Like the renewable drop-in fuels, the introduction of the alternative fuels (shown in dark green) follows an evolutionary approach but requires new infrastructure and FIE. Already defined fuels are hydrogen, alcohols (methanol, ethanol), and ammonia. Depending on the infrastructure build-up, beyond 2030 these will replace the fossil fuels together with the drop-ins.

A crucial supplement to the carbon neutrality, respectively circuit economy, is carbon capture and storage (CCS). It refers to the process of capturing carbon dioxide (CO_2) emissions from sources like power plants and industrial processes, thus preventing CO_2 from entering the atmosphere. The captured CO_2 can then be stored underground in geological formations or used in various industrial applications, such as fuel refineries to produce the carbon neutral fuels.

The powertrains of certain mobile applications, such as locomotives or ships get hybridized by a battery and an electrical motor in combination with the internal combustion engine (ICE) to improve efficiency and the maneuverability [14].

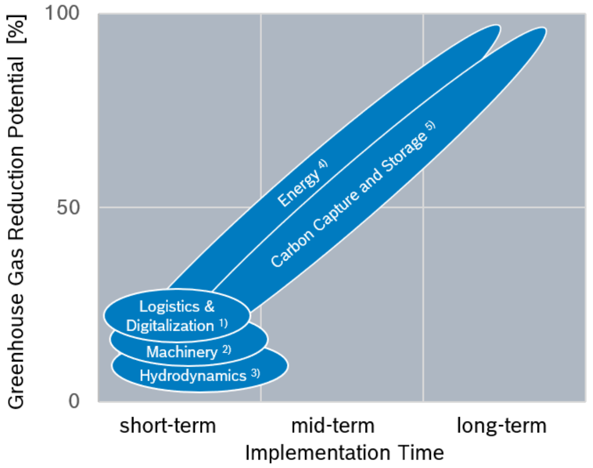
Another trend is the decentralized electrical energy supply by so called microgrids including a group of energy converter (e.g. ICE - gensets, solar panels, and wind turbines) combined with storage devices, such as batteries. These microgrids operate either connected to and synchronous with the traditional centralized grids but can also disconnect and function autonomously as physical and/or as economic conditions dictate. This capability ensures highly reliable and resilient power supply, especially in the event of a grid-wide disturbance. Microgrids are often used to enhance energy security, reduce carbon emissions, and improve energy efficiency.

As indicated in figure 3, the fuel cell (as shown in light green) is assumed to play a recognizable role beyond 2040 but overall, with a minor share until 2050. Due to its specific limits considering dynamic load adaptation (solid oxide fuel cell - SOFC) or cleanliness requirements (proton-exchange membrane fuel cell - PEMFC) and efficiency versus load characteristics, it might be a solution for a certain niche. Thus, currently the fuel cell is used in very few specific use cases and in demonstration projects only.

3 TECHNOLOGY TRENDS

As an example, figure 4 depicts the maritime GHG improvement measures more in detail [7]. They are clustered in 1) operational measures, 2) thermal efficiency, 3) vehicle efficiency, 4) energy (fuels), and 5) CCS.

In short term, the measures stated 1) - 3) will reduce the fuel consumption and hence also the CO_2 emissions to a certain extend while compensating partly the higher operational cost when running with the carbon neutral fuels. The operational measures (1) are characterized by low investments and operational cost, simultaneously improving the business case for implementing the efficiency measures (2, 3 which need substantial higher investment cost.



1) speed reduction; vessel utilization; vessel size; alternative routes
2) machinery efficiency improvements; waste-heat recovery; engine de-rating; battery hybridization; fuel cell
3) hull coating; hull-form optimization; air lubrication; cleaning
4) LNG/LPG; biofuels; electrification; methanol; ammonia; hydrogen; wind power; nuclear
5) CCS Captured from the exhaust gas

Figure 4: Maritime GHG reduction measures

In contrast to the measures 1) - 3), the measures 4) and 5) related to fuels and CCS allow the biggest GHG reduction until complete neutrality achieved. But they need huge investment efforts and long implementation time until the infrastructure is sufficiently installed, leading to high ramp-up cost (e.g. fuel price) and supply bottlenecks. During the transition phase the potential depends strongly on the local availability of the infrastructure.

The maritime example indicates that the need of the hour during the transition phase is a well-balanced technology selection, always considering the business case and affordability under the given boundary conditions. Due to the long lifetime of the large engines, it is worthwhile to focus not only on new builds but to consider the engines in operation by appropriate retrofits as well. This limits the acceptable complexity of a solution.

4 TECHNOLOGY SELECTION

The main criteria for the selection are as below:

- new build and retrofit capability
- single and dual fuel capability
- functionality and safety
- robustness and lifetime
- time to market (TTM)
- adequate business case

The alternative fuels are capable to burn being used by different combustion systems and appropriate air/fuel mixture formations which opens a comparatively huge solution space depicted in figure 5. For the high speed (HSE) and the smaller medium speed engines (MSE) the business case is mainly affected by the capital expenditures (CAPEX). Moreover, considering a retrofit concept, low complexity, and acceptable integration effort are strong requirements [15, 16].

The ramp up of the new technologies highly depend on the availability of the alternative fuels hence it moves comparatively slow. This leads to a long period until the return of invest (ROI), considering the development of the new technologies, including testing infrastructure for the alternative fuels, and industrialisation. Thus, the challenge to identify a business case requires a stepwise approach with clear prioritization.

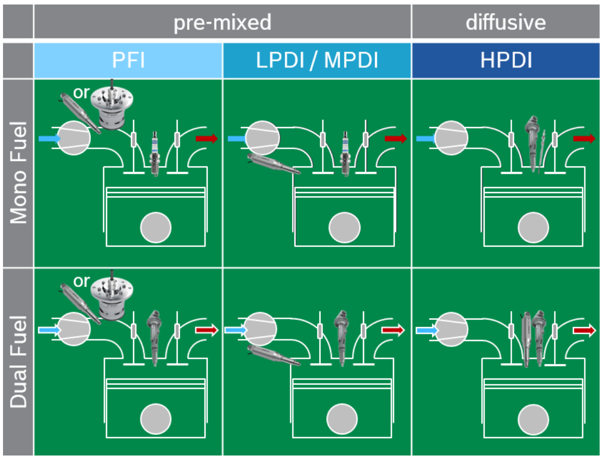


Figure 5: Combustion systems solution for alternative fuels

Figure 6 compares a PFI with a HPDI combustion system for a dual fuel motor and a liquid fuel, such as methanol. In case of a retrofit concept, the PFI approach is quite simply adaptable by an additional injector in the intake port and no additional orifice towards the combustion chamber is needed. The injector integration upstream the intake valve allows a comparatively long time for the premixing which can be further supported by optimisation of the spray layout and targeting plus certain secondary spray brake-up measures.

From combustion point of view the premixed combustion is characterized by low NOx but higher unburned products (HC, CO) in comparison to the diffusive combustion (HPDI). However, the exhaust gas aftertreatment (EGT) for CO and HC reduction are significantly less complex compared to a NOx-catalyst (selective catalytic reduction (SCR)) system. In case of HPDI the need of a second high pressure system and the high integration and application efforts are unfavorable. Remaining advantage for the HPDI is the higher potential for power and the achievable substitution rate.

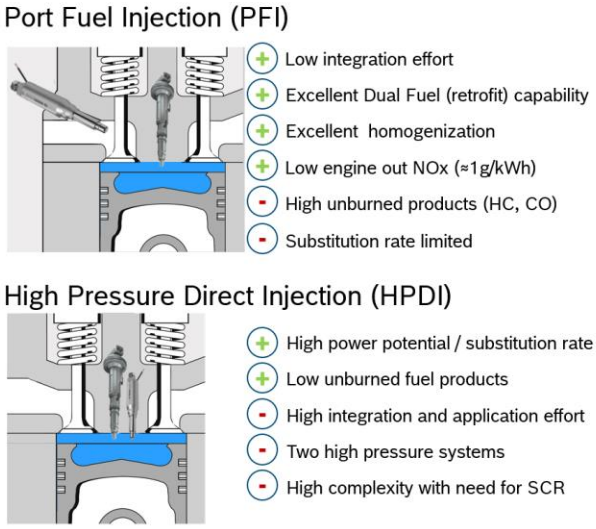


Figure 6: Comparison of PFI vs. HPDI for methanol

In comparison to the PFI the LPDI combustion system (see figure 7) has further potentials with respect to power density, which is caused by higher cylinder charges using the cooling effect of the evaporation in case of liquid fuels, like methanol and the avoidance of the suppression of charge air by gaseous fuels, such as hydrogen. Moreover, it avoids the risk of backfiring with hydrogen and the feasibility of increasing the exhaust gas enthalpy upstream the turbine by demand via a post injection allows better load response.

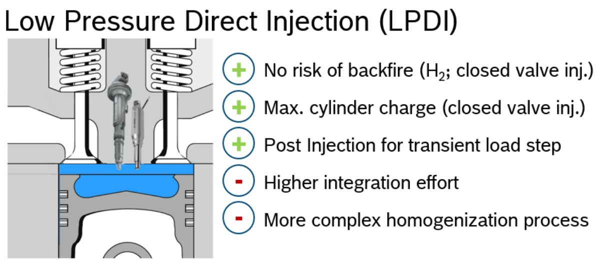


Figure 7: Assessment of LPDI

In contrast, the integration effort is higher (borehole towards combustion chamber) and due to the limited mixture formation period during the compression stroke the homogenization is more complex. For stationary applications, such as gensets, which get the hydrogen supplied out of a distribution network, the maximum available gas pressure can be an additional challenge.

Taking all relevant criteria into account, the premixed combustion systems are the best answer towards the current market demands [17, 18, 19, 20]. Limiting the scope accordingly, the matrix of potential combustion systems is reduced by one third. Hence, 4 remaining concepts still need to be covered by the FIE (see figure 8). Considering the business case, the number of variants need to be extremely limited and therefore the solution is a modularity with a strong focus on function, robustness, packaging, and finally cost.

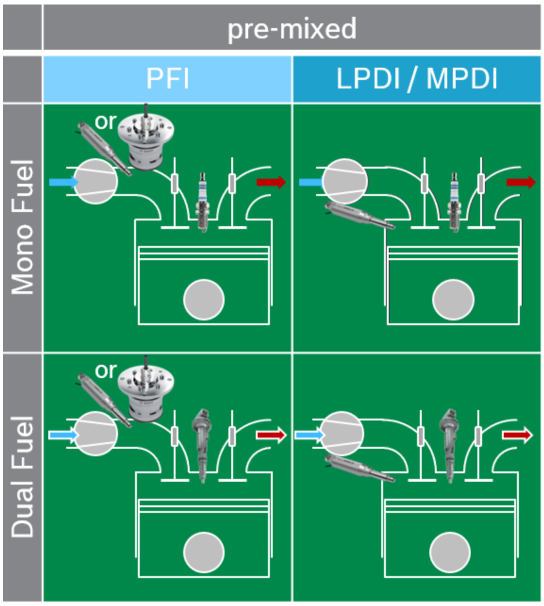


Figure 8: Combustion systems in scope

5 ALTERNATIVE FUEL INJECTOR AFI-LP

Following the Bosch product engineering approach the main requirements on the injector modularity have been identified followed by a systematic concept competition to each define the best solutions. The result is shown by the overview in figure 9. The inner pitch circle areas (yellow lettering) list the requirements, whereas the corresponding outer pitch circle areas (white lettering) depict the dedicated measures.

A key feature is the layout of the modularity itself. The valuable core modules, such as the solenoid drive, the dampening, and the nozzle module have been standardized to a great extend. To cover the fuel types three nozzle modules with different seat diameter and needle lift combinations are included in the core. For the fine tuning and the customer specific spray targeting the highly flexible spray forming cap (SFC) on top of the nozzle is foreseen.

Beside the load, adequate material and coating selection play an important role for the robustness, lifetime, and reproducibility of the injection behaviour. Fluid separation prevents the sensible injector areas from getting in touch with the aggressive low viscosity fuels. The internal and external sealing over lifetime is ensured by a laser welding of the crucial connections which supports the safety combined with a double wall capability. For excellent functional performance (e.g. multiple

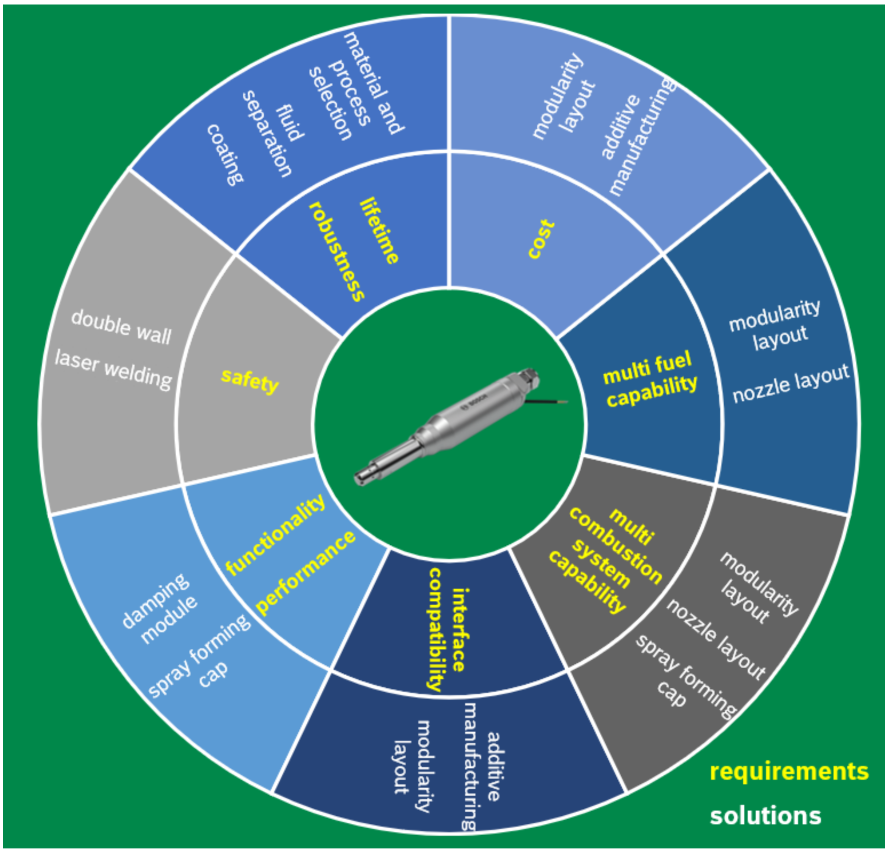


Figure 9: AFI-LP modularity overview

injection) over the lifetime a damping module is available as an option.

To fulfill the different combustion system related requirements on the injector position, a side and a top feed design are available. The additive manufacturing of the injector body allows a customer specific adaptation towards the cylinder head interface. Finally, the scalable platform modularity of the AFI-LP supports the alternative fuel types burned via the premixed combustion systems and fits to the specific customer interfaces.

5.1 Functional layout

To define the required pressure level range without having initially testing results from the engine, a characteristic parameter has been used which allows to consider the experience of air/fuel mixture formation optimisation with gasoline engines.

The Sauter Mean Diameter (SMD) refers to a specific measurement used in fluid mechanics and particle technology. It is defined as a diameter that would represent a droplet's size if it were assumed to be spherical, allowing for the calculation of flow properties and behavior of a mixture of different-sized droplets.

The mean SMD is defined by the following formular:

$$d_{\text{sauter}} = \frac{\sum(d_i^3 * n_i)}{\sum(d_i^2 * n_i)}$$

Where:

- d_i is the diameter of the individual droplets
- n_i is the number of the droplets with the diameter di

This measurement is particularly useful in applications involving sprays, as it provides a way to characterize the average size of droplets in a non-spherical context.

For a proper air/fuel mixture formation the droplet size plays an important role with respect to the evaporation of a liquid fuel such as methanol. Hence the SMD value gives a good indication to assess the spray quality of an injector. The SMD itself depends on spray parameter, like injection pressure and certain spray interactions, which is described by the primary and secondary droplet collapse.

In Figure 10 the SMD versus the pressure is depicted based on multiple measurements with gasoline injectors. To verify that the results with gasoline are representative for methanol, the characteristic numbers like Reynolds, Ohnesorge, and Weber have been considered. This allows to identify the relevant fuel properties such as viscosity, density, and surface tension. The appropriate values of gasoline and methanol are in the same order of magnitude, hence confirming the relevance of the results for methanol.

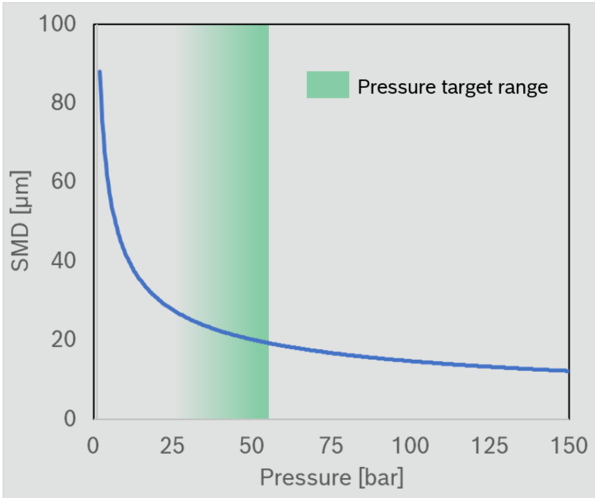


Figure 10: SMD versus pressure

The correlation between the SMD versus pressure (figure 10) indicates a steep gradient below approx. 10 bar and a saturation above approx. 50 bar. The conclusion for the air/fuel mixture formation is to avoid pressure below 10 bar and to allow a maximum pressure of 50 to 60 bar for an optimal evaporation support. The evaporation is affected by engine specific parameter, e.g. intake air temperature, -motion, and spray targeting as well. Thus, the individual pressure demand needs to be evaluated finally by engine tests. However, based on the SMD versus pressure curve a recommendation of a reasonable maximum injection pressure for methanol PFI is in between 10 to 60 bar.

The functional features allow a reproducible injection pattern over lifetime thanks to the fluid separation and needle dampening. The direct needle control allows a closed loop control of the injection and hence helps furthermore to exploit the combustion limits such as knocking or misfiring. Within the AFI-LP platform the customer can select the injector which fits best to the project demands allowing to achieve a sustainable high engine performance.

Individually and flexible, the SFC allows a precise adaptation of the injection spray layout by e.g. number of holes and selectable geometries. Bosch supports the adaptation of the injector fostering a fast TTM by using verified and sophisticated development tools (see figure 11), optimized by multiple projects with different engine layouts.

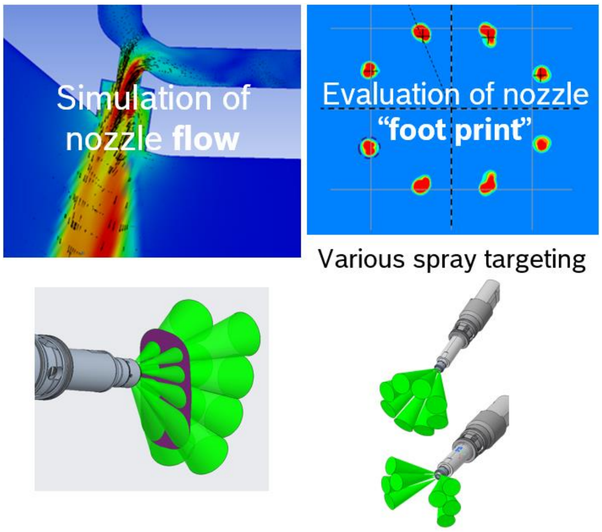


Figure 11: Tool chains for spray optimization

6 ELECTRONIC CONTROL UNIT (ECU)

For the actuation of the FIE (diesel and alternative fuels) and engine management functions the MD1CE200 control unit is foreseen. The compact ECU (see figure 12) is derived from the Bosch automotive ECU platform for commercial vehicles and is extended with special features for large engine applications. Using the existing high-volume series proven automotive ECU, the MD1CE200 ensures a high robustness with long lifetime.

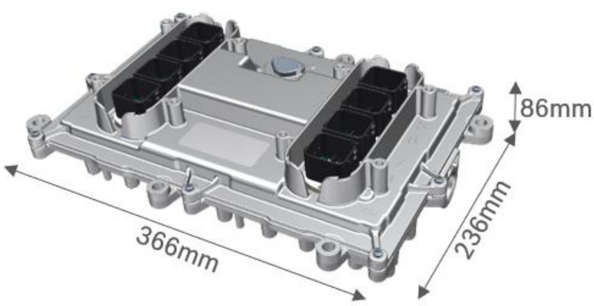


Figure 12: Dimensions of the ECU MD1CE200

The powerful ECU can operate as full engine controller for 12-cylinder engines with a single unit and for higher cylinder variants with a multi controller concept in a parents-child configuration. For integration in an existing engine control system the ECU can also be used as modular, intelligent driver for the fuel injectors or gas valves.

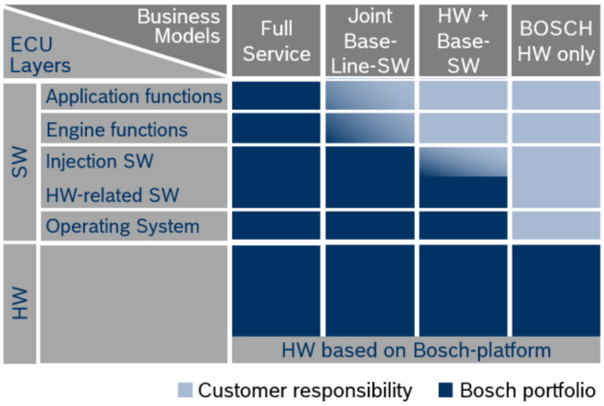


Figure 13: SW flexibility according to demands

With the available SW sharing concepts (see figure 13) customers can individually use and integrate their own functionalities within the provided HW and SW platform to adapt to the specific demands.

7 FIE PORTFOLIO

Figure 14 shows an overview of the Bosch portfolio for the established diesel and natural gas like fuels (see blue area) and the alternative fuels hydrogen, methanol, and ammonia (see green area). The entire diesel FIE portfolio is ready for the use of drop-in fuels (specified bio- and paraffinic diesel).

Depending on the different applications and use cases, the field experience to be gathered in the future must confirm that the fuel-quality requirements are met in the global markets. For the admission of gaseous fuels into the intake port (PFI), the large engine gas valve (LEGV) is foreseen. It can be used for natural gas, hydrogen, and ammonia.

For the alternative fuels, be it liquified or gaseous, the alternative fuel injector - low-pressure (AFI-LP) platform is foreseen for LPDI and PFI combustion systems. Samples are available for customer investigations.

HPDI combustion systems will be supported by the alternative fuel injector – high-pressure (AFI-HP) which is currently in prototype stage. An alternative fuel pump (AFP) is in the development and the final concept will be the result of a concept competition.

The ECU MD1CE200 with a highly flexible software controls the entire FIE portfolio and engine management functions.

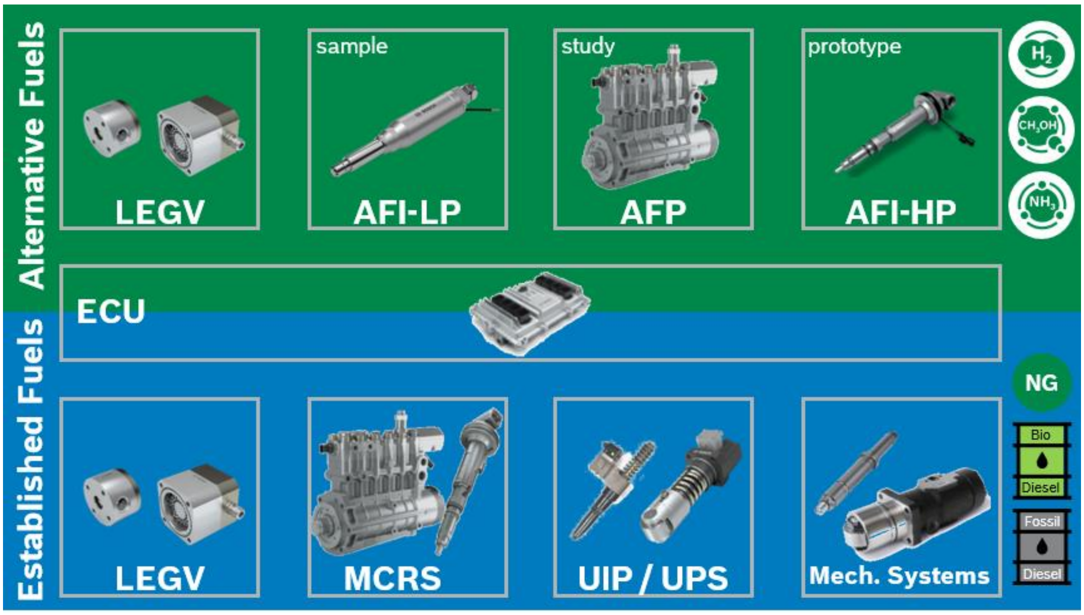


Figure 14: FIE portfolio

8 SUMMARY AND CONCLUSION

The path towards carbon neutrality of the large engine segment is by means of carbonless or -neutral fuels. This requires the build-up of new infrastructure. A fast penetration of the climate neutral technologies depends highly on the availability of the appropriate fuels. Both need high financial efforts and hence clear and robust boundary conditions for the required investments.

The alternative fuels (hydrogen, methanol, and ammonia) are selected sub segment and use case specific, depending on energy content, storage efforts, and last, but not least, local availabilities. The build-up of the infrastructure for the alternative fuels needs huge efforts in investment and time to get ready for upscaling.

Consequently, during the transition phase a well-balanced technology selection always considering the business case and affordability under the given boundary conditions is needed. For HSE and the smaller MSE the premixed combustion systems are the best answer towards the current market demands considering new builds and retrofits.

Following the Bosch product engineering approach the requirements on the injector modularity have been identified, followed by a systematic concept competition to define the best solution. As a result, the AFI-LP platform modularity has been defined, which is scalable, supporting the premixed combustion systems, useable with gaseous or liquid fuels. Within the AFI-LP platform the customer can select the injector which fits best to the project demands allowing to achieve a sustainable high engine performance. Bosch supports the adaptation of the injector, fostering a fast TTM by using verified and sophisticated development tools.

For the actuation of the FIE and engine management functions the powerful and compact MD1CE200 control unit is available with a highly flexible SW sharing model. It can also be used as modular, intelligent driver for the fuel injectors or gas valves.

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