CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 014

Digital fuel twin - a simple and consistent solution to foster drop-in and alternative fuels

Fuels - Alternative & New Fuels

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This paper has been presented and published at the 31st CIMAC World Congress 2025 in Zürich, Switzerland. The CIMAC Congress is held every three years, each time in a different member country. The Congress program centres around the presentation of Technical Papers on engine research and development, application engineering on the original equipment side and engine operation and maintenance on the end-user side. The themes of the 2025 event included Digitalization & Connectivity for different applications, System Integration & Hybridization, Electrification & Fuel Cells Development, Emission Reduction Technologies, Conventional and New Fuels, Dual Fuel Engines, Lubricants, Product Development of Gas and Diesel Engines, Components & Tribology, Turbochargers, Controls & Automation, Engine Thermondynamis, Simulation Technologies as well as Basic Research & Advanced Engineering.

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ABSTRACT

Mainly driven by local legislation, initiatives and incentives the decarbonization of the large engine segment occurs by the continuous transition from fossil to drop-in and alternative fuels. While the drop-in fuels are backwards compatible to the existing diesel technology the alternative fuels require new combustion respectively injection system technologies. Besides the technologies the fuel infrastructure starting from production until the tank is very important for the transformation speed and for the proper fuel quality.

In contrast to the ww established fossil fuel infrastructure with known quality levels, in case of the drop-in and alternative fuels the ww different feedstocks, additives and processes might lead to critical local fuel qualities, and in addition unknown mixing effects can affect functionality and lifetime of the FIE. In consequence, a consistently monitoring of the fuel from well to tank would mitigate the risks significantly.

The confirmation of the GHG intensity of the burned fuel is required for GHG regulatory, such as Fuel EU Maritime (FEUM) allowing banking and pooling to reduce or avoid penalties. Thus, a digital monitoring of the fuel supply chain fosters the implementation speed by an easy and user-friendly verification of the relevant fuel parameter. Moreover, it would mitigate the quality risk during the transition considering the drop-in and alternative fuels.

In this paper the motivation for a smart fuel monitoring along the fuel supply chain is pointed out, and the Digital Fuel Twin (DFT) as a smart solution is described.

1 INTRODUCTION

It is recognizable that the efforts to achieve climate-neutral economies are growing worldwide. In addition to binding agreements by the international community to limit global warming, such as the Paris Agreement of 2015, geopolitical developments and the resulting potential dependencies have come to play an important role in the transition to climate-neutral energy systems. Governments are providing considerable financial resources to specifically promote climate-friendly technologies. The "New Green Deal" was adopted in Europe, while the "Inflation Reduction Act" was passed in the USA in 2022 [1,2]. Similar initiatives and programs are also under way in China and India. The aim of these actions is to promote the development of new climate-friendly technologies and reduce the energy and transportation industries' reliance on imports.

Across sectors, carbon-neutral alternatives will replace the current sources of energy. If the electricity required for its production is generated from renewable sources, hydrogen as a carbon-neutral energy carrier plays an important role in this transition and is becoming increasingly important worldwide.

Bosch is convinced of the need for a global hydrogen economy and is developing key technologies along the entire hydrogen value chain [3,4]. These include electrolysers for hydrogen production, fuel cell technology for stationary and mobile applications, and components for alternative fuels like hydrogen, methanol/ethanol, and ammonia.

Mainly driven by legislation, stakeholder engagement, commercial aspects including incentives, the decarbonization of the large engine segment occurs by the continuous transition from fossil to drop-in and alternative fuels [5,6]. While the drop-in fuels are backwards compatible to the existing diesel technology, the alternative fuels require new combustion, respectively injection system technologies [7…15].

Considering certain properties of the drop-in fuels the existing diesel fuel injection equipment (FIE) may need an upgrade. The FIE for the alternative fuels are under development. Besides the technologies the fuel infrastructure starting from fuel production (refinery and accordingly reforming or synthesis) until the tank is very important for the transformation speed and for the proper fuel quality as per specification.

In contrast to the worldwide established fossil fuel infrastructure with known quality levels, in case of the drop-in and alternative fuels, the worldwide different feedstocks, additives and processes might lead to critical local fuel qualities, and in addition unknown mixing effects can affect functionality and lifetime of the FIE. In consequence, a consistent monitoring of the fuel from well to tank would mitigate the risks significantly.

The confirmation of the specification of the burned fuel with respect to e.g. greenhouse gas emissions (GHG) is required for getting incentives, respectively avoiding penalties. Thus, a proper monitoring of the fuel would foster the transition towards the drop-in and alternative fuels and increase the implementation speed by an easy documentation of the burned fuels to ensure getting the appropriate incentives.

2 LARGE ENGINE MARKET SITUATION

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.

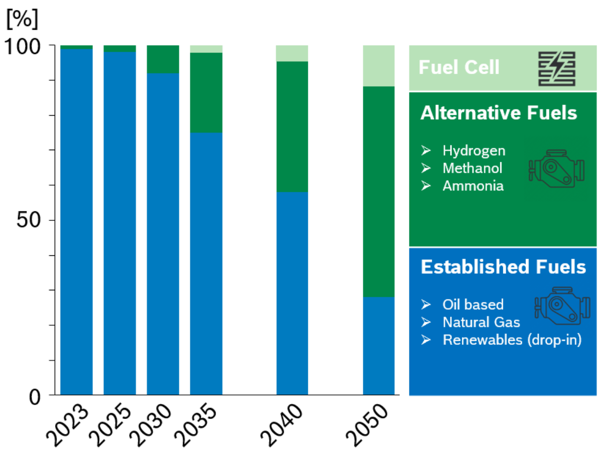

Figure 1: Fuel mix transition (HFO equivalent) [16]

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. 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 buildup, these will replace the fossil fuels together with the drop-ins beyond 2030.

The fuel cell (shown in light green) is predicted to play a recognizable role beyond 2040, but overall with a minor share until 2050. Due to 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.

In the following, the focus is given on the two main paths drop-in and alternative fuels. In contrast to the fossil fuels with well established production and supply infrastructure the launching and the critical aging behaviour of fatty acid methyl ester (FAME) may lead initially to certain risks until the maturity levels in the production are sufficient and the handling is according to the appropriate requirements.

During the critical phase it is important to mitigate the risk to avoid doubts of the engine operators and other stakeholders. Beside the elimination of potential road blocks, the most important driver for the implementation of the GHG reduction measures are an appropriate legislation to set clear guide rails for the implementation fostered by incentives.

Both, the risk mitigation, and the motivation to use the climate friendly drop-in and alternative fuels requires a certain monitoring of the real field situation.

3 DRIVER FOR FUEL MONITORING

The term “monitoring” involves tracking and overseeing various processes, systems, and interfaces to ensure correct functioning and to identify any errors or issues that may arise. The need for monitoring of a system increases the less of experience is available and the more different boundary conditions and applications/use cases are likely. Thus, the worldwide implementation of the climate neutral fuels in the large engine segment can be supported to a great extend by an adequate monitoring.

Figure 2 gives a more detailed overview of the triggers by the introduction of climate neutral fuels, related risks, and the advantages of fuel monitoring. It is separated by technology (drop-in and alternative fuels) and legislation related topics.

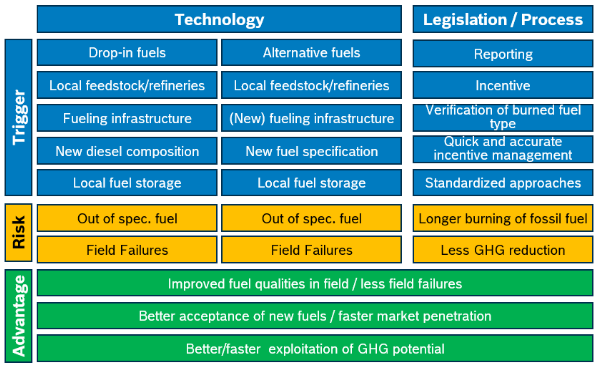

Figure 2: Demands for Fuel Monitoring triggered by Climate Neutrality

For both fuel types, the critical risk is “out of specification fuels” in the field leading to field failures. In case of the drop-in fuels, the reason for this might be the new diesel composition, the worldwide refineries with local different feedstocks and additives, as well as the local storage with potential fuel aging or contamination. Considering the alternative fuels, in addition the parallel usage of certain supply chains, for e.g. methanol as a chemical product and the worldwide adherence of the new fuel specification can be a potential root cause of failure.

A proper fuel monitoring from well to tank (WTT) would significantly mitigate the risk by confirming that the relevant fuel parameter is within the specification according to the latest analysis. This allows the engine operator to burn only fuels within the specification. Thus, the market would be cleaned up faster in case of any critical deviation along the entire fuel supply chain.

An effective implementation of the legislation requires a reporting of the actual field situation. For example, the correct payment of incentives for GHG improvements needs the verification of the burned fuel type. An accurate but simple and efficient process for verification and payment would convince even more engine operators to invest into appropriate engines to burn carbon neutral fuels. Thus, the fuel monitoring along the supply chain can significantly improve the confidence into the GHG neutral fuels, hence would foster the market penetration.

Additional potential of WTT fuel monitoring considering field quality and operation topics is shown in Figure 3. Independent from the fuel type, a verification of the fuel quality ahead of the fueling can avoid damages of the affected fuel circuit and engine components. Even if a field failure occurs it would support the identification of the root cause by exclusion of the fuel quality, hence reduces time for trouble shooting leading to reduced quality cost, yet increases operating hours.

	Field Quality	Field Operation
Potential	Verification of burned fuel quality	Knowledge of critical fuel values before combustion
	Identification / exclusion of fuel impact	Online adaptation of operating parameter
	Faster problem solving	Optimization of combustion according act. fuel parameter
Benefit	Reduced quality cost	Better exploitation of actual fuel potential
	Higher operating hours	Reduced operating cost

Figure 3: Potential of WTT Fuel Monitoring

The knowledge of critical actual fuel parameter, e.g. cetane or octane number, would allow to adjust the relevant engine operating parameter accordingly. Thus, the potential of the actual burned fuel can be better exploited, which might improve the efficiency and hence the operating cost.

Another aspect is the accurate tracking of the fuel flow along the supply chain, which can reduce or even avoid any shrinkage, therefore improves the operative cost even further.

4 REQUIREMENTS ON FUEL MONITORING

The conclusion of the previous chapter indicates a significant potential of fuel monitoring. Increasing technical confidence and better manageability of incentive payments are fostering the implementation of the carbon neutral fuels. Furthermore, the field quality and operative cost can be improved.

To enable the potentials of the fuel monitoring, certain requirements are compulsory. One tool which covers all of them is needed to make the usage as simple as possible and comfortable for all users. Figure 4 shows the four main requirements accruing from technology and legislation aspects. Considering that sensible data are tracked, the data management, including the ownership, privacy, and security of the data are decisive factors for all users and the adherence to appropriate legislation.

The integrity is a must for the acceptance by the authorities and the compatibility towards the standards is required to support all applications. An easy and fast availability in terms of WTT data access on “one button click” is a mandatory expectation of the clients.

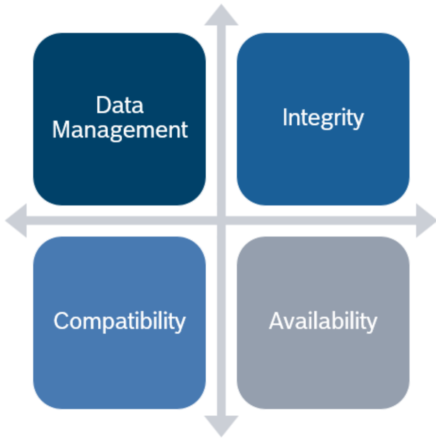

Figure 4: Main Requirements on Fuel Monitoring

A schematic overview about an effective monitoring along the fuel supply chain is depicted in figure 5. It begins at the production, moves to the distribution and storage, and finally leads to the fueling towards different applications.

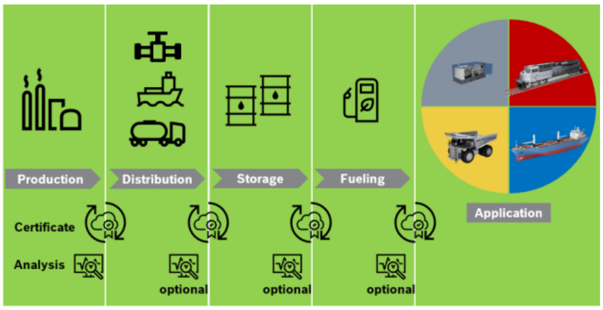

Figure 5: Fuel Monitoring along the Supply Chain

Depending on the fuel type, the application, and the local situation, the distribution can be executed per pipeline, ship or truck. The bunkering in the maritime segment might be more complex with additional distribution paths, but for the monitoring, the interfaces between the different sequences up to the fuel system of the engine are critical.

Initially, after the production, the data of the analysis of the fuel are documented in a certificate. Beside the characteristic parameter it can include further data which are worthwhile to monitor. At each interface point the certificate is handed over along with the fuel. An update of the previous document with an actual fuel analysis or additional data is optional and possible at each interface point.

As a result, all relevant fuel data are available at the final handover before burning in the engine. Thus, the reporting of the technical and the legal related information of each fuel batch are available for the engine fleet operator.

5 DIGITAL FUEL TWIN

The Bosch Digital Fuel Twin cloud solution (DFT) delivers specific fuel parameters together with the fuels distributed along the fuel supply chains [17]. As specific result, CO_2 footprint usage certificates are issued to the end-customer, considering mixed usage of fossil and renewable fuels. These certificates can be utilized by a variety of different stakeholders, e.g. in the area of fleet operators and logistics customers. Figure 6 depicts schematically the cloud-based fuel supply chain monitoring by the DFT in the automotive environment. Following, the ecosystem and working principle are explained by the automotive segment which can be a blueprint for the large engine segment.

Figure 6: Key stakeholders connected via the DFT

- DFT consists of an orchestrated data lake with private, encrypted data rooms for individual stakeholders who can upload their specific data via a standard interface while remaining the solely data owners of their private data.

- Based on a data sharing agreement between Bosch and single stakeholders, the DFT algorithm gets access to specific data points granted by each single stakeholder in order to generate logic delivery links throughout the fuel supply chain.

- Additionally, DFT performs plausibility monitoring checks, considering blending or mixing of different fuels along the fuel supply chain as well as in the vehicle's tank.

- Next to defining and operating the infra-structure, together with external certifying authorities, Bosch is orchestrating the entire process guaranteeing the state-of-the-art data privacy and security, application of corresponding calculations methods, and standards to bridge the regulation domains of fuel producers on the one side and commercial end users on the other side.

- As a result, DFT provides the end customer with a CO_2 footprint certificate which can be utilized for sustainability reporting, as a proof of compliance with contractual CO_2 reductions or as an instrument in marketing and advertising.

5.1 Working principle

The digital fuel twin digitalizes the entire fuel supply chain from production to end consumer, with the aim of providing an accurate, certified proof of the CO_2 footprint of the fuel quantities consumed (see figure 7). Additionally, fuel relevant parameters, such as length of stay at single locations or along the supply chain can also be provided.

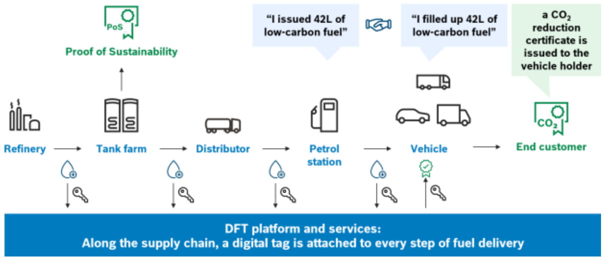

Figure 7: Working principle of DFT

The individual market participants along the supply chain store their specific data in their private data rooms on DFT. Bosch specifies standard interfaces, configures data formats, and provides the infrastructure. The stakeholders uploading data remain data owners at all time and they have solely access.

In line with the data sharing agreement signed between Bosch (as the DFT operator) and the individual market participants, the DFT algorithm gets access to specific data points, so that DFT as a service can represent a logical, secure end-to-end chain link from manufacturer to consumer. Such a trace is anonymized, not disclosing any private data, and still allowing delayed data provision throughout the system. This way it is considered that not all stakeholders have all data available in real-time, but the end customers still get all data relevant for their reporting.

Each DFT participant is free to choose between different suppliers in the fuel supply chain. Likewise, DFT supports mixed refueling of renewable or fossil fuels in fleet operation. However, the default value of fuel consumed is considered as fossil (worst case assumption) and only when the robust, trustful delivery chain link is created, the CO_2 footprint value is updated with respect to the real fuel properties. This way DFT supports real-time data applications as well as reports with delayed data provision.

With the so-called "digital handshake" fuel data is provided from the fueling station to the single vehicles when registered on DFT. This way there is no additional hardware retrofit needed but a robust, hundred percent digital pairing between single vehicles to single refueling events of a fueling station is realized. For this digital pairing, solely existing data already defined by corresponding standards applicable for fuel retail on the one side and vehicles on the other side is reused.

Data provision to DFT is typically implemented via the payment systems of fueling stations and via fleet management systems which consolidate the vehicle data. In case of logistics operators, the DFT interfaces foresee, next to mixed fueling also mixed loading, when a trip is delivering goods to several end customers. Based on corresponding logistics standards each customer gets just accounted the own portion of the CO_2 footprint per trip.

5.2 Real-life application of the DFT

The CO_2 footprint certificate provided by DFT can be utilized as follows:

- for sustainability reporting
- as a proof of complying with contractual CO_2 reductions, or
- as an instrument in marketing and advertising for climate-friendly products and services (cf. figure 8)

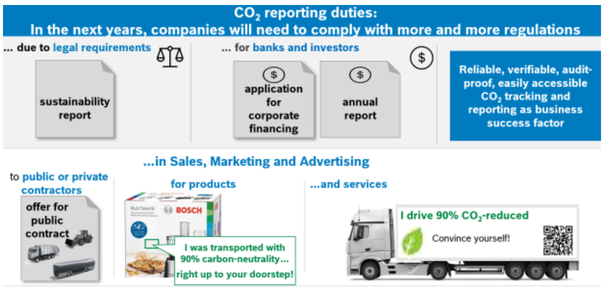

Figure 8: Possible uses of DFT certificates

All these possible applications require reliable, verifiable, transparent, audit-proof, and, above all, easily accessible evidence with just a click of a button.

In the following example from the automotive domain the commercial impacts of DFT in real life usage are explained. However, this can also be applied to the large engine domains as well.

In case of logistics and fleet operators the DFT provides additional flexibility and service for their end customers.

Depending on the logistic routes and customer willingness to pay for de-fossilization by means of usually more expensive renewable fuels, the logistics operator can flexibly utilize different CO_2 strategies for different customers. By means of mixed fueling, the operator can contract in year average e.g. -30% CO_2 reduction compared to fossil trips for customer A, and -60% for customer B.

To support the implementation strategy of the logistics operator, the CO_2-live-ticker dashboard provides clear overview of real-time data per customer, trip, and vehicle. Figure 9 (top) highlights the real CO_2 emissions in comparison to substituted fossil ones as example for a fleet of 13 vehicles. With mixed fueling the companies' individual target for real emissions can be monitored and aimed for flexibly. As a result of the year all fillings show that the fleet ran on average 20% HVO in 2024 (figure 9, middle). Also, more detailed evaluation of the data is possible c.f. CO_2 reduction weekly view in figure 9 (bottom). The dashboard enables transparent steering towards the contracted year average value.

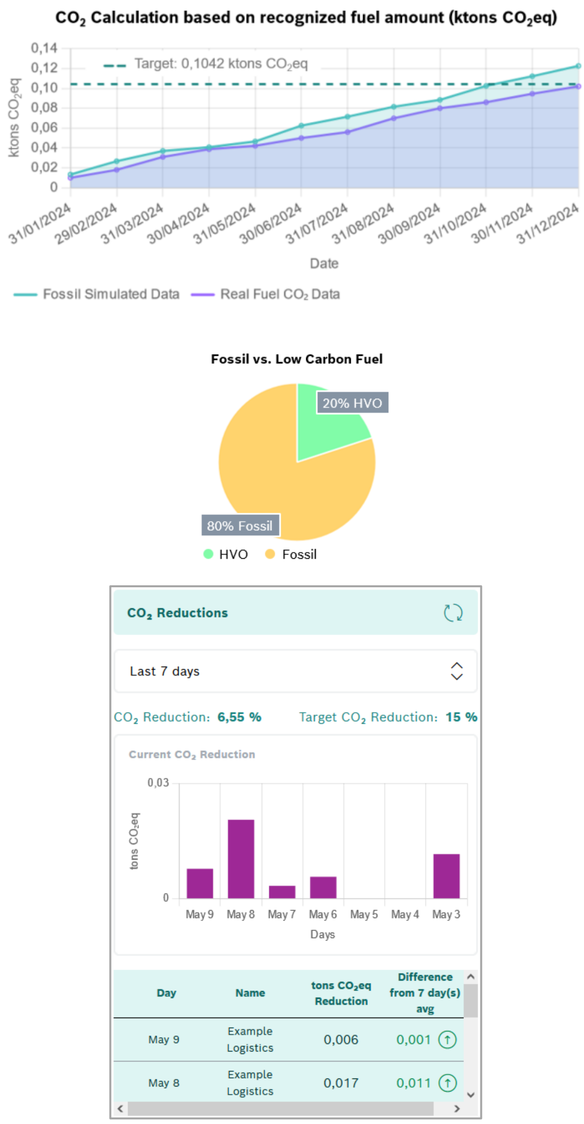

Figure 9: Example DFT CO_2-live-ticker dashboard

For a specific period (e.g. a year relevant for environmental reporting), the total CO_2 footprint certificate per end customer is issued towards the fleet operator to forward the same to their corresponding customers (cf. figure 10).

Similar usage certificates can also be generated for the fleet operator itself for own environmental reporting, but also for other stakeholders upstream the fuel supply chain, such as a fuel retail network.

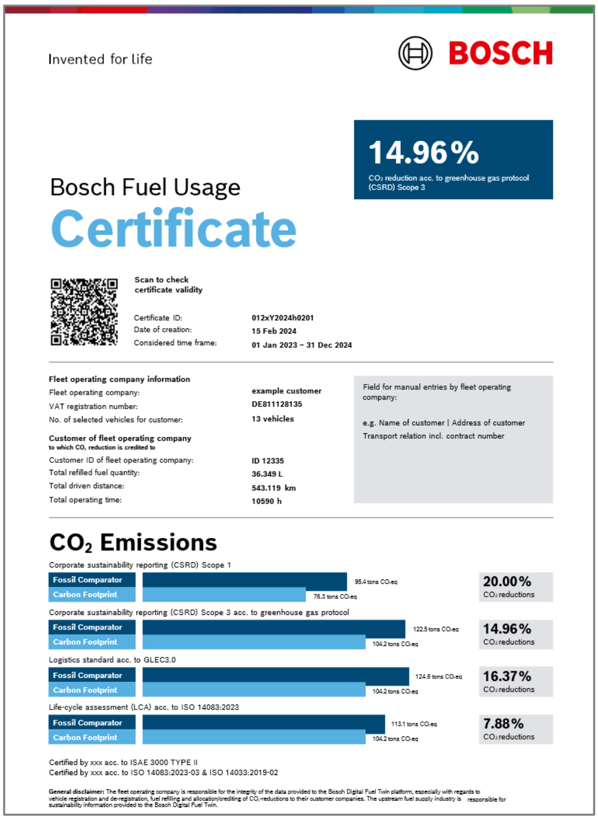

Figure 10: Example Bosch Fleet Fuel Usage Certificate

Considering usually higher costs for renewable fuels, these cost adders of using CO_2-reduced fuels can be passed on transparently and creating added value for the customer.

The mechanism is illustrated in Figure 11 (top, middle) using the example of a company car. Assuming exclusive usage of HVO100 fuels and a total monthly vehicle operational cost of over 1300 Euro (leasing + fuel costs), the estimated additional costs of 18 Euro (<2% cost adder) are only marginal, but a significant CO_2 footprint reduction of 90% can be reached. Figure 11 (bottom) shows that by mixed fueling of fossil diesel and HVO100 a CO_2 reduction of 58% is also possible. With mixed fueling also lower portions at lower cost adders can contribute to de-fossilization.

As a result, a maximum flexible pay-per-use climate protection can be realized by investing only a few cents extra – scalable for every budget.

Calculation example:
add-on cost for renewable fuel PC & HD

CO_2 reduction	Passenger Car	Truck
	7L / 100 km	30L / 100 km
-20%	+0,2 Cent / km	+0,8 Cent / km
-50%	+0,5 Cent / km	+2,1 Cent / km
>-90%	+1,0 Cent / km	+4,2 Cent / km

Assumption: 0,14 €/L price add-on for HVO compared to classic Diesel

Calculation example:
leasing contract for a business passenger car and exclusive usage of HVO100 with 90% CO_2 reduction:

Extra cost for carbon-reduced fuel:	+0,14 € / Liter (HVO100)
Average consumption	Ø 7,0 Liter / 100km
Mileage per month	1.800 km
Additional cost:	18 € / month
For comparison: monthly operational costs (incl. leasing and fuel)	1.300 € / month

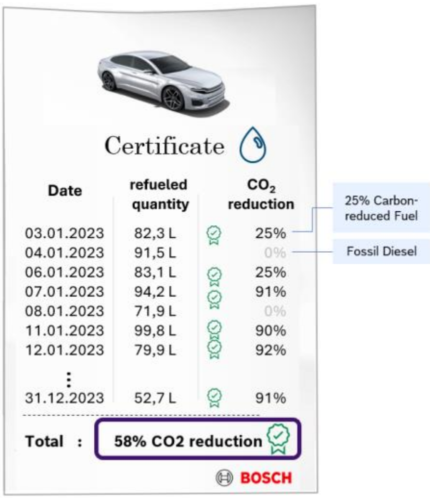

Figure 11: CO_2 reduction is affordable with DFT

6 DFT POTENTIAL FOR THE LARGE ENGINE SEGMENT

The example from the automotive segment illustrates the high flexibility of the smart DFT monitoring with respect to the customer behavior and market situation. Due to the digital nature, it matches to the multiple use cases and different boundary conditions within the large engine segment. This allows the users a maximum flexibility to enable mixed fueling and to adapt the fueling to the specific demands while optimizing the operating expenses.

With the introduction of the maritime decarbonization regulatory from EU and International Maritime Organization (IMO) such as

Emission Trading System (ETS), Fuel EU Maritime (FEUM), and Carbon Intensity Indicator (CII), a commercial motivation is given to meet the appropriate GHG intensity targets. For example, the FEUM focus on the energy consumption related to the geographical scope of the voyage. The targets are applicable for 50% of energy consumed on voyage to Europe (EU)/European economic areas (EEA) or out of EU/EEA and on voyages to/from EU outermost regions, and for 100% of energy consumed on voyage within EEA and in EEA ports. To achieve the GHG intensity target of a ship selected fuels with lower well to wake (WtW) GHG intensity can be assigned.

As depicted by figure 12 the FEUM compliance scheme allows a banking and pooling approach in case of a compliance surplus but a penalty if the GHG intensity target is not met (compliance deficit). It is possible for a single ship to borrow compliance surplus from next or to use banked surplus from last year. Moreover, a pooling with other ships is allowed. In the critical case of a compliance deficit and neither borrow nor pooling would be applied a penalty has to be paid to close the gap to the GHG intensity target. The appropriate price per ton of very low sulfur fuel oil (VLSFO) equivalent GHG is 2400 €. For a typical container ship with approx. 68.000 Deadweight Tonnage (DWT) this can lead to a penalty of 12 mio.€ which might be reduced by approx. 13% if 100% bio fuel would be considered [18].

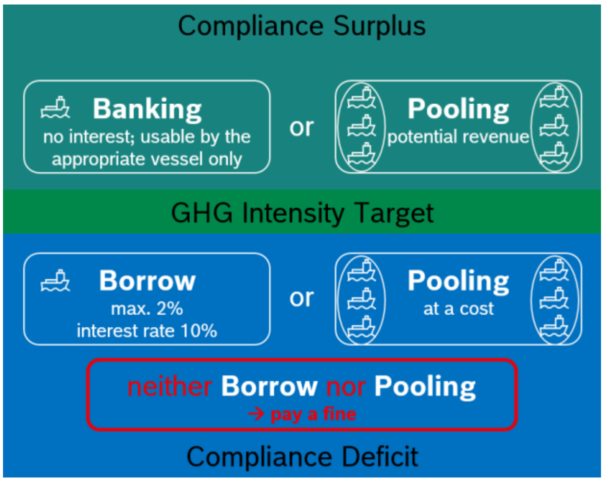

Figure 12: Compliance Scheme for FEUM [18]

The fuel supply chains for alternative fuels such as methanol (see figure 13) vary at the beginning in the feedstock and production process, but the distribution infrastructure is quite comparable with the same number of interfaces. Depending on the production pathways (grey, blue, and green) the GHG footprint differs significantly [19] depending on feedstock and CCS percentages (blue methanol). The GHG intensity range even within one alternative fuel type, and the multiple interface points along the fuel supply chain indicate the challenges for the proper implementation of the GHG regulatory.

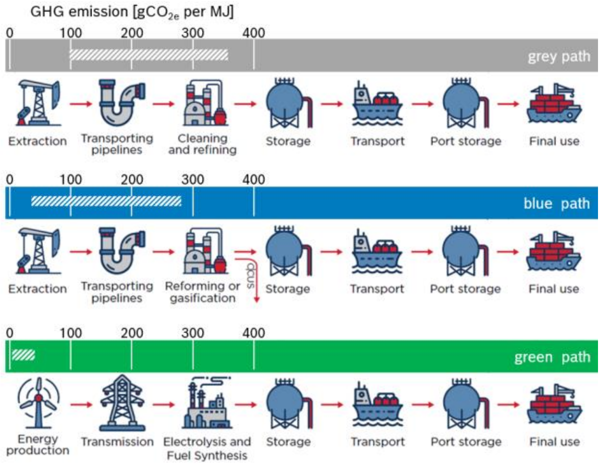

Figure 13: Alternative fuel pathways [16, 19]

Moreover, the different boundary conditions in the ports around the globe including legal aspects is a challenge, too. However, the availability and the access to consistent and verified data about the burned fuel during all voyages of a ship is from utmost importance for a compliance scheme such as FEUM. Thus, a smart DFT monitoring is an excellent solution not even for the maritime but for all mobile and stationary applications (railway, mining, etc.) with complex fuel supply chains and GHG regulatory.

Expected challenges are mainly the worldwide availability of a standardized handling of the PoS (Proof of Sustainability) whereas the fuel production certification is standardized available e.g. as by the ISCC (International Sustainability & Carbon Certification). Once the standards are agreed and the data are handed over into the DFT monitoring all stakeholders and partners can be supported properly ensuring a user-friendly usage of the GHG regulatory. Bosch is ready to set-up first proof of concept with ecosystem partners in the LE domain.

7 SUMMARY AND CONCLUSION

The CO_2 neutrality of the large engine segment will be achieved by the continuous transition towards more carbon neutral fuels. During the transition phase an application specific verification of the actual fuel burned is needed to define the appropriate greenhouse gas reduction. The new fuels and the different mixture lead to certain risks considering quality, and in case of FAME, potentially aging.

The knowledge regarding the relevant fuel parameter before combustion can mitigate the risk by avoidance of out of specification fuel, flowing into the fuel system of the engine. A certificate of the burned fuel allows to get incentives and improves the field quality respectively the root cause analysis in case of a failure.

Further opportunities are given by the adaptation of the operating parameter according to the actual fuel type. All these benefits support the market penetration of the carbon neutral fuels, hence ensure a faster greenhouse gas reduction.

This demand can be covered by an online monitoring of the fuel supply chain direct after the production to the engine fuel system (tank), allowing the data access to all relevant stakeholders and end users. The Bosch Digital Fuel Twin (DFT) is an adequate “one button click” solution, allowing a transparent and save data management with easy accessibility for eligible users.

The DFT is already launched within the automotive segment and adapted towards the multiple requirements from the authorities, the fuel suppliers, and the end consumers. Even the existing base is an excellent blueprint for further segments. Due to its high flexibility, it can be optimized towards the specific demands of the large engine segment.

Focusing on the GHG reduction, the Bosch large engine FIE portfolio covers the demands around the established and the alternative fuels entirely. Enabling smart digital monitoring of the fuel supply chain, the DFT is a perfect supplement to foster a faster penetration of the GHG friendly technologies into the market.

To conclude, Bosch is ready to set-up first DFT proof of concept with ecosystem partners in the LE domain. With this, higher costs for alternative fuels with less GHG intensity may be transferred as added-value for the end-customer.

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