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Ammonia powertrain for a carbon free mobility

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Abstract: Limiting global warming to 1,5°C is the common goal of the worldwide economies. On this basis Europe has launched its Green Deal, and the European Commission has proposed its Fitfor55 Program reducing the tank to wheel CO₂ emissions from transport by 55% in 2030, and by 100% in 2035.

Meeting such Tank to Wheel (TtW) emissions requires carbon free energy carriers for all type of mobile applications.

In line with the focus of this year SIA Powertrain and Energy conference on passenger cars and all types of commercial vehicles, this paper will describe the use of ammonia as a carbon free fuel.

All aspects from production of ammonia, through its transport and its distribution to the service station are considered. Then the storage of ammonia onboard the vehicle and its use in the vehicles' powertrain are laid out and described.

The ammonia eco-system is compared with other carbon free powertrain solutions in terms of overall energy efficiency, CO₂ emissions and Total Cost of Ownership (TCO). An example of Light Commercial Vehicle (LCV) application is detailed in this article.

Keywords: Ammonia, thermal engine, zero emission, zero CO₂

1. Introduction

1.1 Tank to wheel CO₂ emission regulations evolution

Fuel economy standards are evolving and becoming more and more stringent in most of the regions of the world. The European Commission has launched its Fitfor55 program, sharpening its CO₂ requirements to a reduction of 55% compared with the 2021 value). In 2035 a CO₂ emission reduction of 100% is proposed, which will then ban all powertrains with CO₂ emissions (Figure 1).

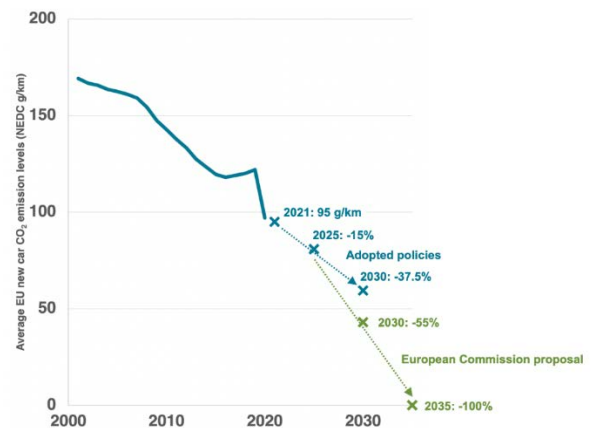


Figure 1: CO₂ emissions standard evolution for passenger cars according to EC Fitfor55 proposal [1]

On top of that, since 2020 on-board fuel efficiency measurement equipment has been installed in all vehicles sold. By this means fuel efficiency in all driving conditions can be determined and analysed. Analysis of the first set of measured fuel efficiency data is currently being analysed in Europe and the results may lead to a further evolution of the regulations.

This represents a strong challenge for all OEMs to optimize the powertrains for whatever driving conditions occur in real life.

1.2 Zero CO₂ vehicle enablers and challenges

A steep uptake of zero emission vehicles is mandatory. Latest by 2035, 100% of the vehicles in Europe are required to be Tank-to-Wheel zero CO₂ emission. For all zero emission technologies, the challenge remains to cover sufficient range, and to have a guaranteed available energy distribution network. The cost and complexity have to be kept as low as possible, to maintain vehicle affordability for most car drivers.

2. Ammonia thermal engine

Although the idea of using ammonia as a fuel dates back almost 100 years as recently summarized in the review by Mounaïm-Rousselle et al. [2,3], few studies have been carried out on engines in operation with the objective of using ammonia only. Within the framework of the H2020 project, ARENHA (<https://arenha.eu/>), several studies have been carried out on single-cylinder engines based on standard engines in order to evaluate the feasibility of an 'all' ammonia conversion [4,5]. The intrinsic properties of ammonia combustion such as its ignition resistivity and low flame speed made it necessary to choose only a spark ignition engine.

3 engines were selected to perform experiments and to evaluate what load with acceptable stability (%) could be reached as a function of different engine speeds to guarantee the good operating conditions and sufficient energy output. The engines characteristics, summarized in Table 1 are, overall, two spark ignition engines based on a classic design (EP6), i.e. with a tumble motion, one limited to the usual compression ratio (10.5) and the other allowing a variation of the compression ratio from 11.75 to 14 but with a long stroke (LS) and a diesel type engine (DV6) whose ignition is helped by the addition of a spark plug on the cylinder head with a compression ratio varying from 14 to 17.

Table 1. Main characteristics of 3 engines	Spark ignition Engine (EP6)	Long Stroke Spark ignition Engine (LS)	Spark assisted Diesel engine (DV6)
Displaced volume (l)	0.4	0.54	0.39
Stroke (mm)	85.8	115	88.3
Bore (mm)	77	77	75
Connected rod length (mm)	138.5	177	136.8
Compression ratio	10.5	11.75 to 14	14 to 17

An example of results as a function of the engine characteristics is presented in Figure 2 to highlight the difference between two engine architectures at 1000 rpm. With standard EP6, it is possible to run with ammonia only for medium load but impossible to select operating conditions (equivalence ratio and intake conditions) to run at low load as it can happen when restarting or slowing down a vehicle. For that, small content of hydrogen has to be added in the fuel to help ammonia combustion.

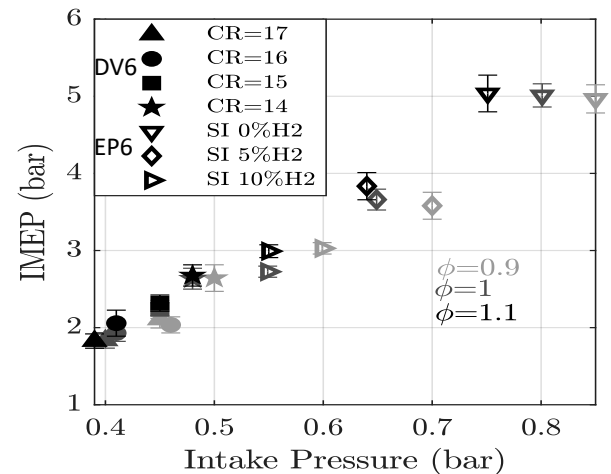


Figure 2: example of low load limits for EP6 and DV6 as a function of CR and equivalence ratio at 1000 rpm.

In the case of diesel architecture, it is evident that a good improvement of NH_3 combustion with CR increase is obtained despite of 'diesel' type flow (swirl motion), which allows to extend the low load limits (less than 2 bars of IMEP). This limit is affected slightly by the air/fuel ratio but consider a lambda of 1.1 limits a little the high ammonia consumption rate related to its low energy content compared to gasoline. The main improvement of the overall engine performances was obtained also at different engine speeds from 650 to 2000 rpm [5]. The use of a non-standard engine (LS) allows to decrease the needs of hydrogen doping but a ratio of 14 enables to reach only 3.5 bar of low load (against 2.6 bar for DV6 with the same compression ratio). It has to be noted from these studies that the indicated efficiency is in the same order than those obtained by gasoline fuelled engines.

After the flexibility of the operation of an ammonia engine, the other most important point remains the pollutant emissions, i.e. nitrogen-based ones and ammonia slip. Some examples of typical emission tendencies are shown in Figure 3. In Figure 3a the effect of engine architectures is compared for same compression ratio (CR14) : as expected due to the nitrogen-fuel route, NO_x reaches a maximum for lean mixture (between 0.8-0.9), with slightly lower emissions with diesel architecture. But from all these studies, it was concluded that the use of classical diesel bowl induces a strong drawback: a very important NH_3 slip due to NH_3 trapping, with as a function of the air/fuel mixture and the compression ratio, a parallel H_2 emission due to in-cylinder ammonia decomposition. In Figure 3b, NO , NO_2 and N_2O are plotted as a function of the equivalence ratio for the S engine at 2 different CR : NO_x emissions are composed roughly by NO , affected by the CR value. N_2O remains below 100 ppm, value reached for lean mixture. This value could not be neglected as it

corresponds to an equivalent 3% of CO₂ as warming impact.

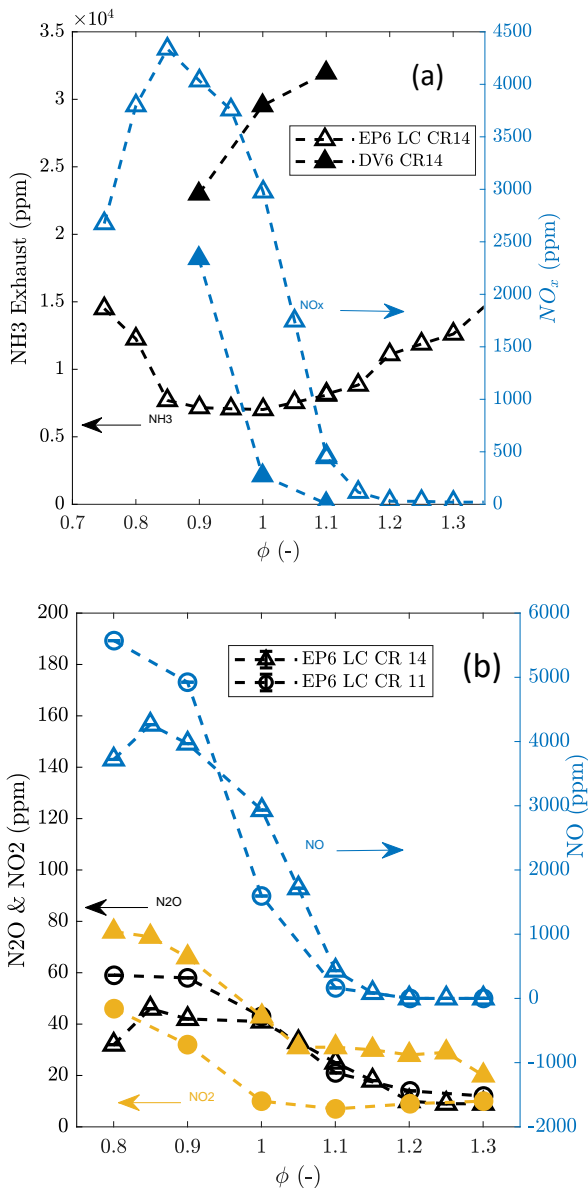


Figure 3. Example of exhaust emissions as a function of equivalence ratio for different engine architecture and compression ratio. (a) unburnt NH₃ and NO_x, (b) nitrogen species.

In conclusion, it is possible to run with ammonia as fuel in standard engines: in SI architectures, it is necessary either to add hydrogen (by onboard cracker) to the engine during the various starting phases [6] or to increase the compression ratio considerably, in Diesel architectures, spark igniter has to be added and optimisation of combustion chamber is required to avoid too strong ammonia slip before the post-treatment system. The indicated efficiency is the best around an equivalence ratio of 0.9 which reduces the fuel consumption but induces

higher NO_x emissions (even N₂O). Therefore, the best compromise for operating conditions has to be defined and selected as a function of exhaust post-treatment technology.

3. Ammonia Storage System and autonomy

3.1 Energy density

The energy density of carbon free fuels is quite different from the energy density of conventional fuels. Additionally, the powertrain efficiency of a battery electric vehicle is more than 2 times higher than the efficiency of a powertrain based on a combustion engine on WLTC. This has a significant effect on the quantity of energy to store onboard the vehicle.

Therefore, it is crucial to include the powertrain efficiency factor in the energy storage system design and base the vehicle concept on a desired autonomy.

Underneath a comparison chart of various energy storage volumes required for a vehicle autonomy of 100 km.

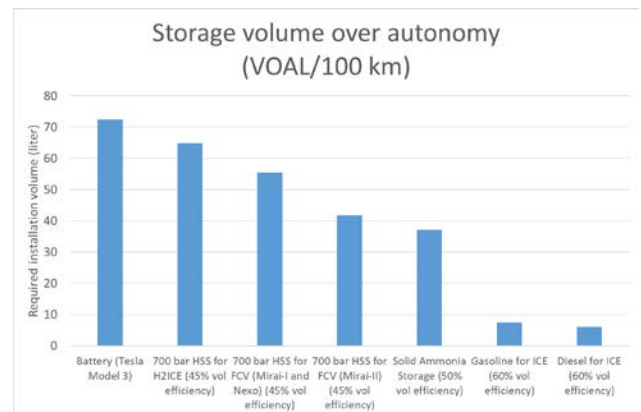


Figure 4: Required car body volume over vehicle autonomy on WLTC [7]

The chart in Figure 4 takes into account that the volume available in a car body is never exactly the optimal shape for the energy storage system. On batteries a distance is to be kept to adapted and fit standard cell modules. 700 bar hydrogen vessels have a cylindrical shape and can therefore not go in all corners on a vehicle. Conventional gasoline and diesel tanks have a rounded shape as well.

The battery takes up the largest space for a given autonomy. Using hydrogen as a fuel and this in combination with the most efficient fuel cell technology can almost halve the required energy storage space compared to a battery.

Storing Ammonia on a solid structure in combination with a conventional combustion engine further reduced the required volume for 100 km autonomy.

3.2 Autonomy on highway

Vehicle integration of batteries and 700 bar H₂ compressed tanks in terms of mass and volume is one of the main challenges to ensure reasonable vehicle ranges to these technologies.

In Figure 5, an assessment of the volumetric energies between solid NH₃ and 700 bar H₂ storages in the vehicle tanks is performed, but also the residual available energies at the wheels considering the losses for highway conditions. For comparison, NMC batteries are also included.

We can notice that the solid NH₃ storage is quite competitive compared to the other solutions:

- at the tank location, volumetric energy equals for NH₃ 1.5 kWh/L, 0.72 kWh/L for 700bar H₂ and 0.3 kWh/L for NMC battery.
- at the wheels, NH₃ keeps a margin over the other solutions with 0.54 kWh/L vs 0.25 kWh/L for the other solutions.

It makes the NH₃ solid storage a competitive candidate in terms of vehicle volume integration versus the achievable range, that could reach more than double the range with the same storage volume.

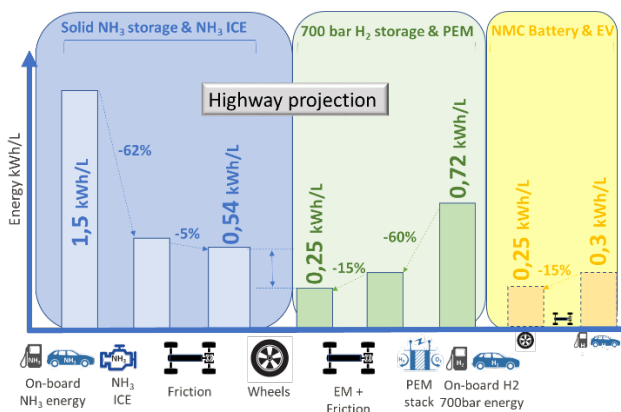


Figure 5: Volumetric energies in kWh/L for solid NH₃ and 700 bar H₂ storages

4. Ammonia retail cost

With an annual production of 180 million tons and 120 ports already equipped with ammonia trading facilities [8], ammonia is a widely used and traded commodity, which, in its liquid form, at 20 bar and ambient temperature or atmospheric pressure and - 33°C, has a 50% higher volumetric energy density than liquid hydrogen, making ammonia a convenient hydrogen carrier but also an alternative decarbonated fuel to hydrogen. Ammonia is produced from the combination of hydrogen and nitrogen, through the century-old Haber Bosch process, and its production cost depends significantly on the hydrogen cost production, making low-cost green hydrogen producing regions potential cost competitive green ammonia exporters. In MENA (Middle-East-North Africa) countries, green ammonia production cost is

anticipated to be 400USD/ton by 2030 [9], and its shipping transportation cost to EU can be assumed to be 50USD/ton [10].

Figure 6 shows the retail cost breakdown of green ammonia imported from MENA region to France, assuming distribution cost equivalent to gasoline and Diesel fuels of 0.2EUR/L [11], an energy-based energy tax (TICPE) equivalent to the tax on ED95 [12], the greenest available road fuel [13], and 20% VAT. With a cost of 175EUR/kWh, equivalent to 0.9EUR/kgNH₃, ammonia retail cost is potentially comparable to hydrogen at 6EUR/kgH₂, home charging [14] and Diesel fuel.

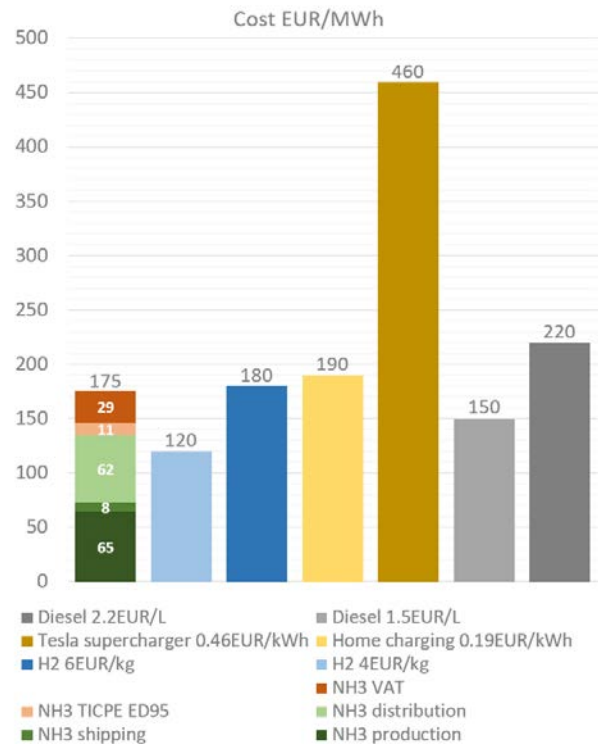


Figure 6: 2030 energy retail cost

5. TCO evaluation

We present in this section a first assessment of the Total Cost of Ownership of the NH₃ ICE technology versus the current Diesel ICE but also versus a Battery Electric Vehicle (BEV) and a Plug-In Fuel Cell Electric Vehicle (FCEV) for a Light Commercial Vehicle (LCV) type.

Indeed, for commercial vehicle application, the TCO is one of the main purchasing driver for the customer. Nonetheless, TCO estimation is a complex exercise because of all the prices that will have a major impact on the results and are not well known for 2030 as the future energy prices (H₂, fast charging, etc.), the future battery ones, the maintenance costs (battery of fuel cell replacement mandatory), the vehicle residual values, ... The calculations are done with the current

estimations and will be continuously refined with the carrier and technology maturity improvement.

We opt for a 500 km WLTC range hypothesis for the NH₃ ICE, BEV and FCEV. Diesel will not really be impacted by the range because of the low-cost storage system compared to the other technologies.

We also proceed to some energy cost swaps.

In Figure 7 & Figure 8 we compare the TCO for WLTC and highway usages, for 120 000 km on 4 years leasing base.

We can notice that the NH₃ ICE stays competitive compare to the Diesel reference @2.5€/L for all the usages.

Because of their high efficiencies on WLTC, BEV and FCEV have the lowest energy costs except for BEV if we assume a fast charge @0.5€/kWh.

On highway, because of the BEV/FCEV decreased efficiencies compared to WLTC, the NH₃ ICE appears to be a quite competitive solution compared to the other candidates.

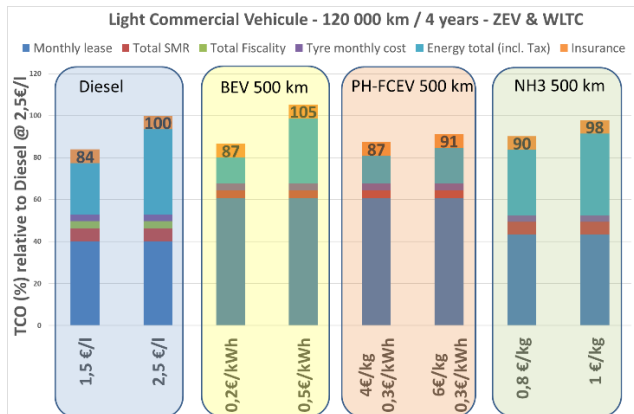


Figure 7: TCO evaluation for ZEV & WLTC usage

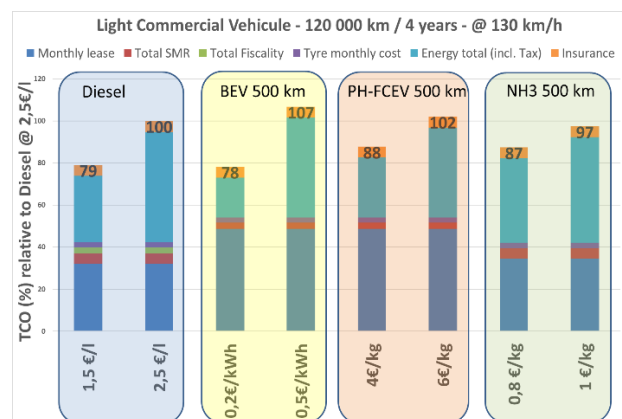


Figure 8: TCO evaluation for highway @ 130 km/h

6. Conclusion

European Commission and European countries adopted politics mitigating greenhouse gases promoting electrified and hydrogen powertrains. Nevertheless, in future, other decarbonized energies

and powertrains could be used beside BEV and FCEV. We demonstrated in this article that ammonia as a fuel presents some benefits in energy density and TCO compared to conventional decarbonized powertrains.

Moreover, ammonia could be used directly in well-known ICE and hybridized powertrains. Those technologies are robust and cheap compared to BEV and FCEV.

Authors also expect some benefits in Life Cycle Assessment of this ammonia and ICE powertrain compared to other decarbonized powertrains, lowering the needed amount of rare metals. This point will be assessed in the coming months.

Further research and innovation work remain to make this ammonia fuel a concrete alternative:

- the combustion processes in engine must be further studied to be sure to cover all driving conditions,
- the aftertreatment system (NO_x, N₂O & NH₃) must be designed and validated,
- the on-board ammonia storage system using salt and adsorption, must be safe in any using case.

Major thresholds for this technology development will be to see ammonia becoming a worldwide green energy carrier and decarbonized fuel for shipping industry. In those conditions, local retailing will become realistic also for road transport.

7. Acknowledgement



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SI: Spark Ignition
TCO: Total Cost of Ownership
TtW: Tank to Wheel
VAT: Value-Added Tax
WLTC: Worldwide Harmonised Light vehicles Test Cycle
WLTP: Worldwide Harmonised Light vehicles Test Procedure
ZEV: Zero Emission Vehicle

9. Glossary

BEV: Battery Electric Vehicle
CR: Compression Ratio
FCEV: Fuel-Cell Electric Vehicle
ICE: Internal Combustion Engine
IMEP: Indicated Mean Effective Pressure
LCV: Light Commercial Vehicle
MENA: Middle East and North Africa
NH3: Ammonia
RPM: Rotation per Minute