AMMONIA AS CARBON FREE FUEL FOR INTERNAL COMBUSTION ENGINE DRIVEN AGRICULTURAL VEHICLE

ACTIVATE

Work Package 5
Deliverable Report

Topic: D5.7

REPORT ON ECONOMIC PROFITABILITY OF ACTIVATENGINE BASED ON VALIDATED DEMO-SCALE DATA

Programme operated by:
National Centre for Research and Development

Project consortium:
Silesian University of Technology
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1 Executive summary

This report offers an economic assessment of ACTIVATEngine technology utilizing Life Cycle Costing (LCC) methodology. It defines the Total Cost of Ownership (TCO) and Levelized Cost of Technology (LCOT) for selected ammonia sources in comparison to conventional diesel engine. Capital costs are estimated based on market data and internal consultations, while operational costs are derived from a comprehensive review of fuel prices and annual vehicle usage detailed in Report D5.6. The analysis indicates that ammonia-fueled vehicles are approximately 3 times more expensive than their diesel equivalents, primarily due to substantial modernization and maintenance requirements. However, excluding the Common Rail system's cost from the initial investment significantly narrows this cost gap to about 2.3:1, yet a notable cost disparity persists. Delving into strategies for decreasing initial modernization expenses is crucial to enhance the economic viability of ammonia-fueled vehicle.

2 Capital cost

The ACTIVATEngine technology capitalizes on the use of ammonia in a compression ignition (CI) engine via a direct injection system. A detailed technical description of this solution is provided in other deliverables under Work Package 5 (WP5). This report offers a comparative analysis of the costs associated with potential full-scale commercialization.

The capital cost of the mini-tractor (SCOUT 15-T) for the diesel variant is reflected in its market price. The ammonia-fueled version incurs additional costs for modernization, which includes the price of components and workshop assembly fees. These costs are presented in Table 2.1. The values were determined based on market research, laboratory experience, and consultations with industry representative. However, as the costs for full commercialization are subject to various factors, the presented comparison should be viewed as an approximation rather than a definitive assessment.

The prices considered are wholesale, meaning that the listed market price for a component is discounted by taxes and retail margins, using an approximate deduction of 40%. The engine originally purchased did not have a Common Rail (CR) system installed; therefore, the cost of equipping it has been included in this analysis. In general, however, this expense might be avoided as many CI engines are typically equipped with a Common Rail system. The cost for workshop services is set at 50 EUR per hour.

Table 2.1: Capital cost increase for ammonia-fueled vehicle.

Item	**Cost, EUR (approx.)**
Purchase of diesel tractor (net)	2380
10l ammonia cylinder	310
5l nitrogen cylinder	50
Fittings - valves, connectors, etc. (solenoid valve separately)	360
High-pressure solenoid valve HP100	120
Pressure sensor	60
Siemens LOGO PLC controller	80
DN4 pipe (1.4571)	20
GDI injector	70
SCR unit	210
Workshop services	1390
Common Rail (injector, ECU, rail)	1190
Workshop services for Common Rail	750
Total - purchase of ammonia-powered tractor (excluding Common Rail)	5050
Total - purchase of ammonia-powered tractor (including Common Rail)	6990

3 Operational cost

Operational costs depend on the quantity and prices of fuels. The approach for estimating the ammonia prices follow the IEA recommendations [1]. This method follows the D4.3 report; for the purpose of this work only the input prices have been modified. To remind the approach, equation 2 presents a function to estimate the costs for ammonia produced from natural gas (steam methane reforming, grey ammonia):

$$TC = FC + VC + CCSC = FC + A \cdot NG_C + B + CCSC \tag{1}$$

where: TC - total cost, FC - fixed cost, VC - variable cost, CCSC - cost for carbon capture and storage, A,B - coefficients for empirical function describing the variable costs depending on the price of natural gas based on the [1]. All the costs are expressed in USD/tNH3.

The idea is that the price of natural gas is the most important variable determining the final cost for ammonia, all other costs are approximated and they are contained within the empirical coefficients. It is assumed that CCSC uses a fixed additional cost expressed per tonne of NH3 (blue ammonia). The values for fixed costs are estimated based on the [**?**], the coefficients for variable costs are based on [1].

Operational costs are dependent on the quantities and prices of fuels. The methodology for estimating ammonia prices follows the recommendations by the International Energy Agency (IEA) [1]. This approach is in line with the one detailed in report D4.3; for the purposes of this analysis, only the input prices have been updated. To recap the approach, equation 2 presents a formula to estimate the costs of ammonia produced from natural gas (steam methane reforming, referred to as grey ammonia):

$$TC = FC + VC + CCSC = FC + A \cdot NG_C + B + CCSC \tag{2}$$

where TC is the total cost, FC stands for fixed cost, VC represents variable cost, and CCSC is the cost for carbon capture and storage. The coefficients A and B are empirical factors that describe the variable costs in relation to the price of natural gas, as explained in the IEA's [1]. All costs are denoted in USD per metric ton of NH3. The rationale is that the price of natural gas is the most significant variable in determining the final cost of ammonia, while all other costs are approximations included within the empirical coefficients. It is assumed that CCSC incurs a fixed additional cost per tonne of NH3, indicative of blue ammonia. Fixed terms are estimated based on [**?**], and the variable cost coefficients are dervied from the data presented in [1].

The method for estimating the cost of green ammonia is illustrated by equation 3:

$$TC = FC + VC = FC + A \cdot EL_C + B \tag{3}$$

For green ammonia, the cost is solely influenced by the price of electricity, utilizing a distinct set of coefficients A and B, which are also derived from the data presented in the IEA's report [1]. Collating all of these prices using USD / MJ (LHV) allows for obtaining the figure 3.1, where:

1. SMR (steam methane reforming) is considered low at approximately 3 USD/MMBtu and high at around 10 USD/MMBtu.
2. Diesel is considered low at 75 USD/bbl and high at 150 USD/bbl.

These values are based on spot market prices. The analysis indicates that for electrolysis to be cost-competitive with diesel at 75 USD/bbl, the price would need to fall below 18.1 USD/MWh, which is currently unlikely. However, with diesel prices hovering at the higher end (approximately 150 USD/bbl in the U.S. market in 2022), electrolysis costs below 46 USD/MWh could render green ammonia economically viable.

Figure 3.1: Break-point cost of fuels comparison.

4 Economic results

Life Cycle Cost analysis for selected scenarios was conducted based on the following assumptions:

1. The vehicle's operation within an apple orchard is informed by annual fuel consumption data derived from experimental findings and work cycle parameters discussed in report D5.6, with an economic analysis spanning a 10-year period.

2. Maintenance costs are fixed at an annual rate of 4% of the vehicle's initial purchase price, which reflects a standard approach for long-term economic assessment. For the ammonia-fueled vehicle this cost accounts for the base and modernization costs without the Common Rail.

3. Diesel pricing is averaged from the spot prices at New York Harbor, U.S. Gulf Coast, and Los Angeles, as reported by the U.S. Energy Information Administration for 2022. A 15% increment over the spot price is applied to account for the wholesale purchase, amounting to a wholesale price of 4.13 USD/gallon.

4. The retail price of biodiesel, set at 5 USD/gallon (U.S. Department of Energy, 2022), is adjusted to a wholesale figure of 4.25 USD/gallon, reflecting the typical market reduction from retail to wholesale pricing.

5. The wholesale price for natural gas is derived from the 2022 Henry Hub price, as per the U.S. Energy Information Administration, equating to 7.42 USD/MMBtu.

6. Industrial electricity rates are taken from 2022 data provided by the U.S. Energy Information Administration, resulting in a cost of 83.2 USD/MWh.

7. The cost of nitrogen is based on the prevailing market rate of 0.755 EUR/l, with the assumption that this price is stable across currency exchanges.

8. End of Life (EoL) costs are projected to be 20% of the vehicle's capital cost, an estimation aligned with industry literature [2].

This analysis assumes that the cited U.S. prices are indicative of global trends and thus applicable to the European context, with an understanding that they serve to compare relative profitability rather than to provide exact cost predictions for any specific market.

Aggregating capital, operational, and End of Life (EoL) costs leads to the Total Cost of Ownership (TCO) results presented in Figures 4.1 and 4.2. The ammonia-fueled vehicle is nearly three times more costly than its diesel counterpart, primarily due to substantial modernization and corresponding maintenance expenses. The analysis reveals that fuel prices have a minimal effect on the TCO which is due to moderate annual fuel consumption. If the cost of the Common Rail system is excluded from the vehicle's base price, the cost ratio between ammonia and diesel vehicles could be reduced to approximately 2.3:1, as depicted in Figure 4.2. Despite this adjustment, the cost disparity remains substantial. This finding underscores the need for targeted optimization of capital expenditures for ammonia-fueled vehicles, which should be a focal point of future research.

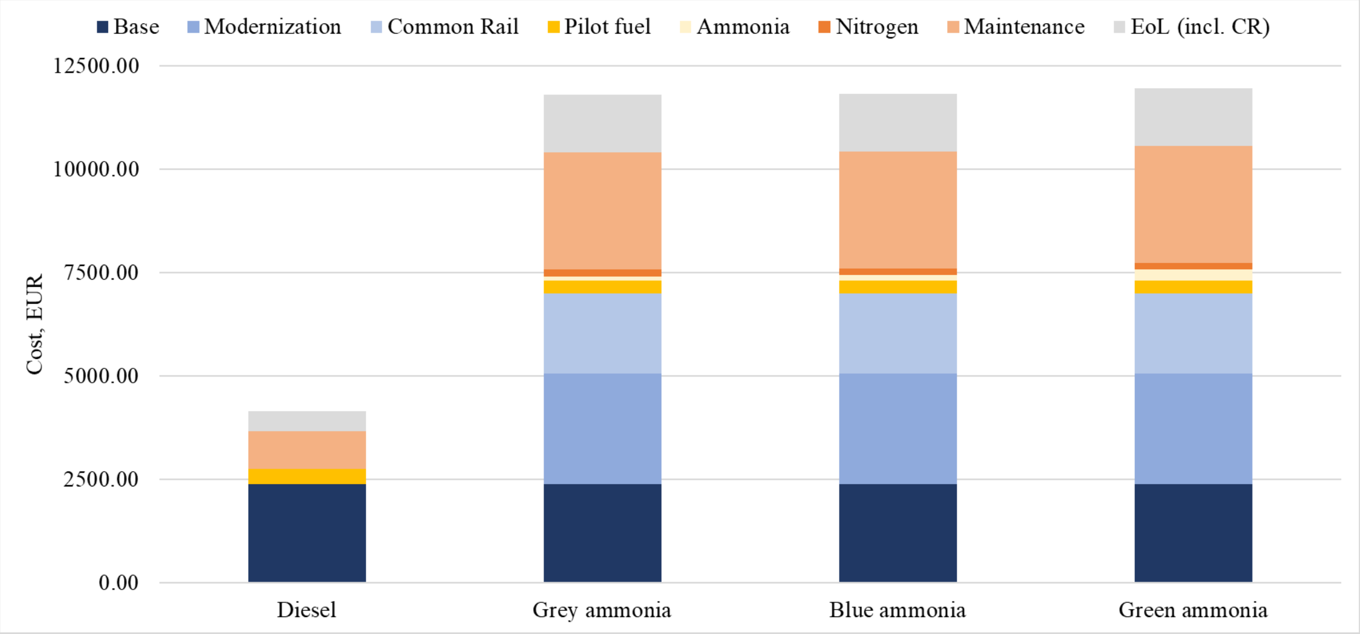

Figure 4.1: Total Cost of Ownership results (default scenario) including Common Rail.

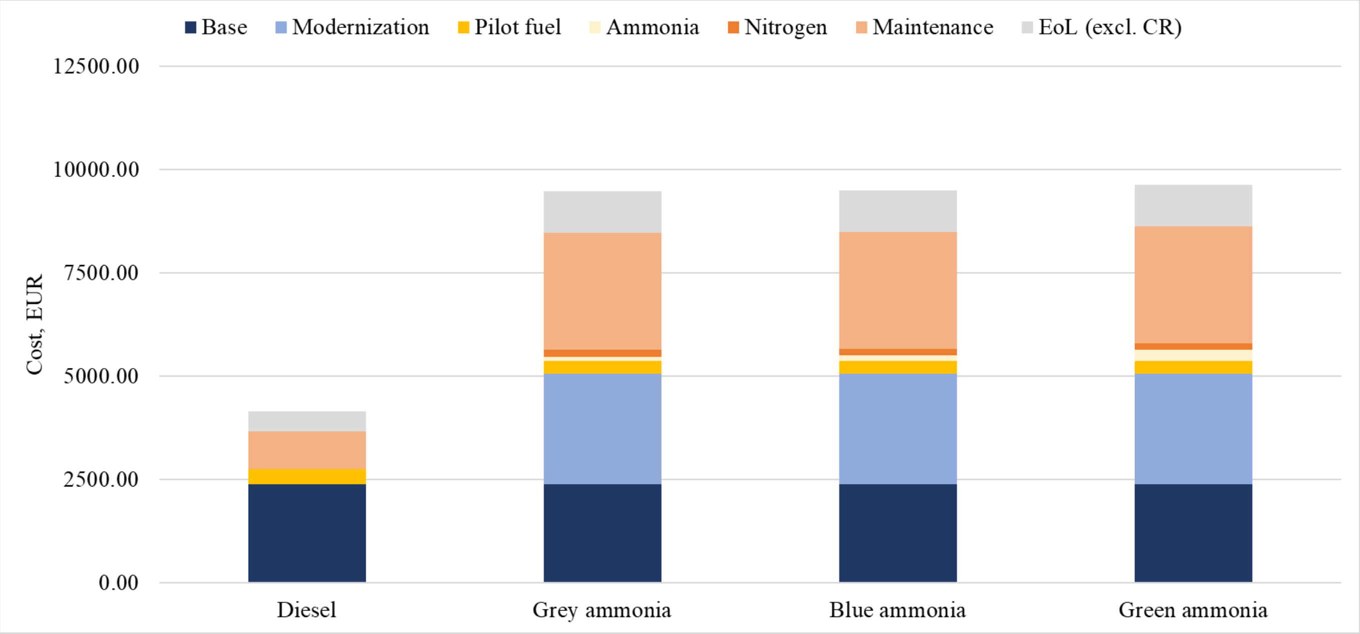

Figure 4.2: Total Cost of Ownership results (default scenario) excluding Common Rail.

Given the inherent uncertainties in estimating the full commercialization costs of ammonia-fueled vehicles, including market and technological variabilities, two additional scenarios are analyzed: optimistic and conservative. The assumptions for these scenarios are summarized as follows:

1. Optimistic scenario: It is assumed that modernization cost is 25% lower than in the baseline scenario. Furthermore, the annual diesel cost is projected to increase by 3%, while the annual cost of green ammonia and biodiesel decreases by 2%. The cost of grey and blue ammonia, nitrogen, and maintenance remain constant throughout the analysis period.
2. Conservative scenario: In this scenario, the modernization cost is 25% higher than in the baseline. The cost of green ammonia and biodiesel increases by 3% annually. The costs of diesel, grey and blue ammonia, nitrogen, and maintenance remain constant.

The results for the optimistic scenario are shown in Figures 4.3 and 4.4. Accounting for annual fuel price fluctuations does not change the trend: capital costs followed by maintenance dominate the vehicle's price. The ammonia-fueled vehicle is 2.5 times more expensive, which can be reduced to approximately 2:1 ratio by excluding the Common Rail system. Plotting the results for the conservative scenario, as presented in Figures 4.5 and 4.6, leads to similar conclusions, with the ammonia-fueled vehicle being approximately 3.2 times more expensive, a difference that can be reduced to 2.5:1 without the Common Rail system.

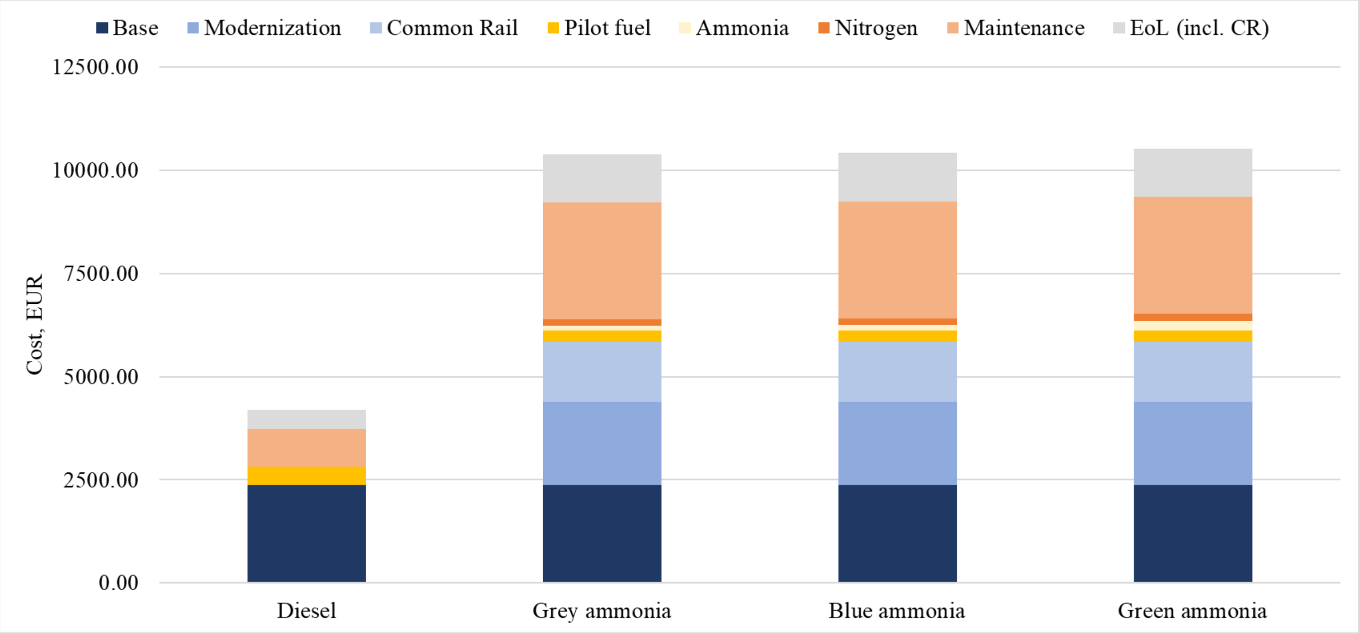

Figure 4.3: Total Cost of Ownership results for optimistic scenario including Common Rail.

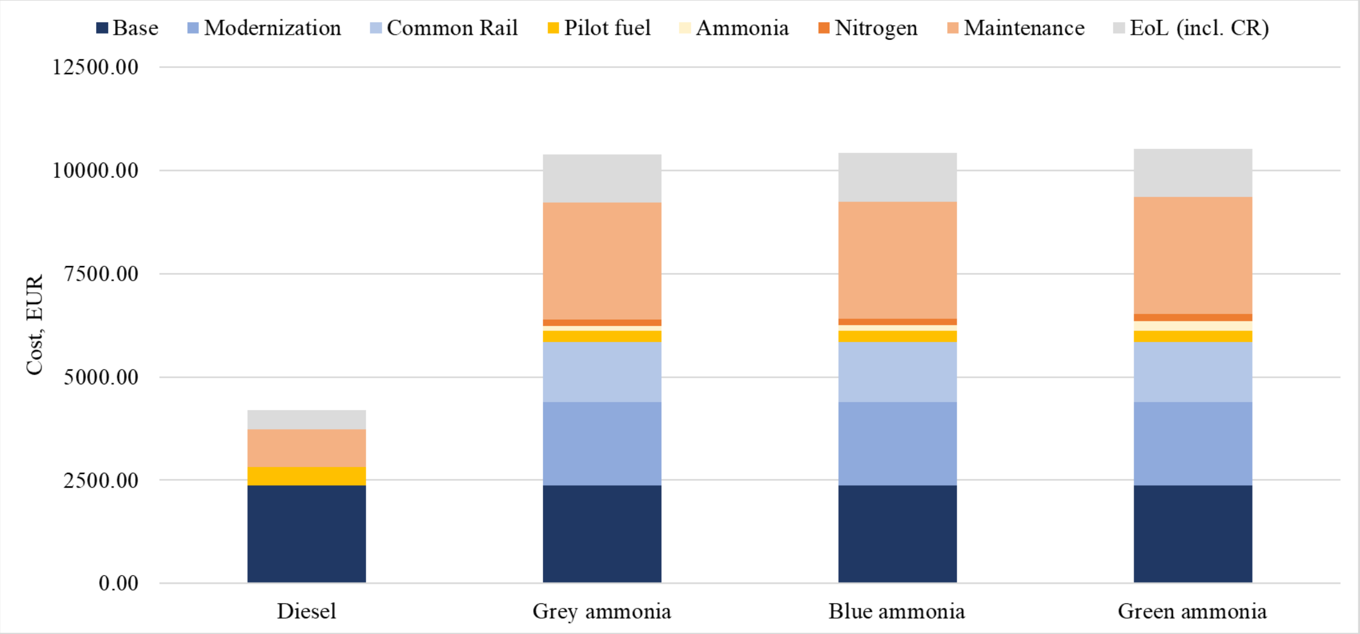

Figure 4.4: Total Cost of Ownership results for optimistic scenario excluding Common Rail.

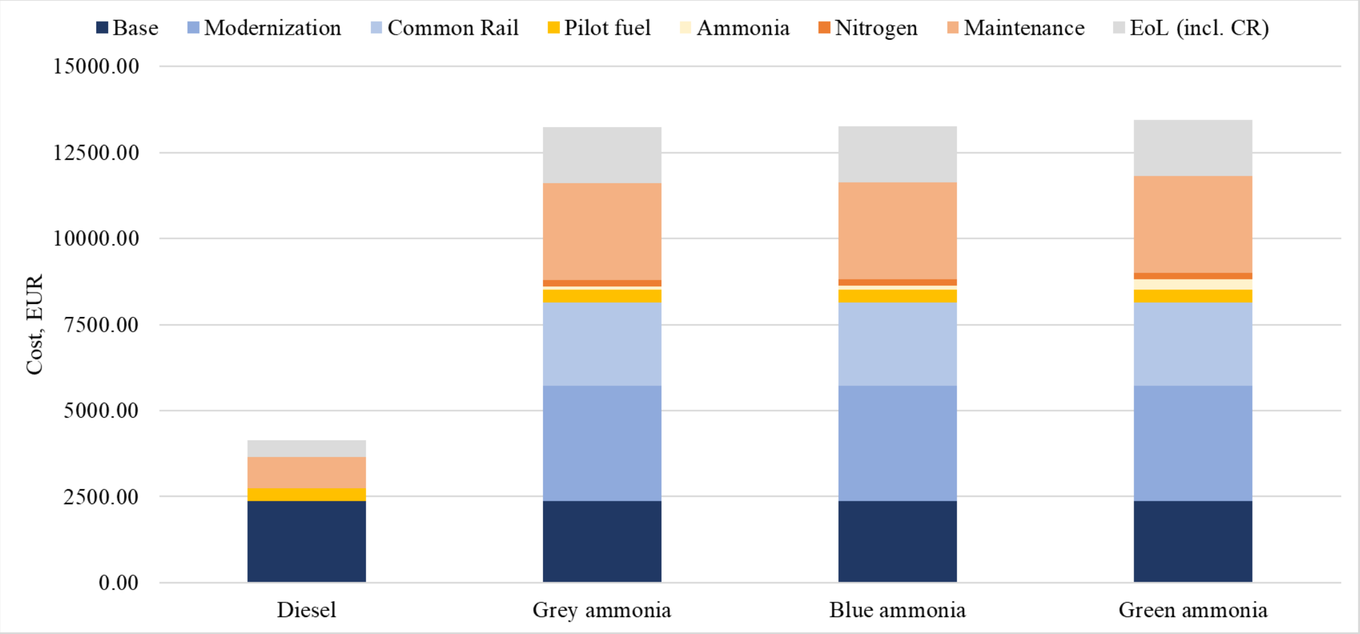

Figure 4.5: Total Cost of Ownership results for conservative scenario including Common Rail.

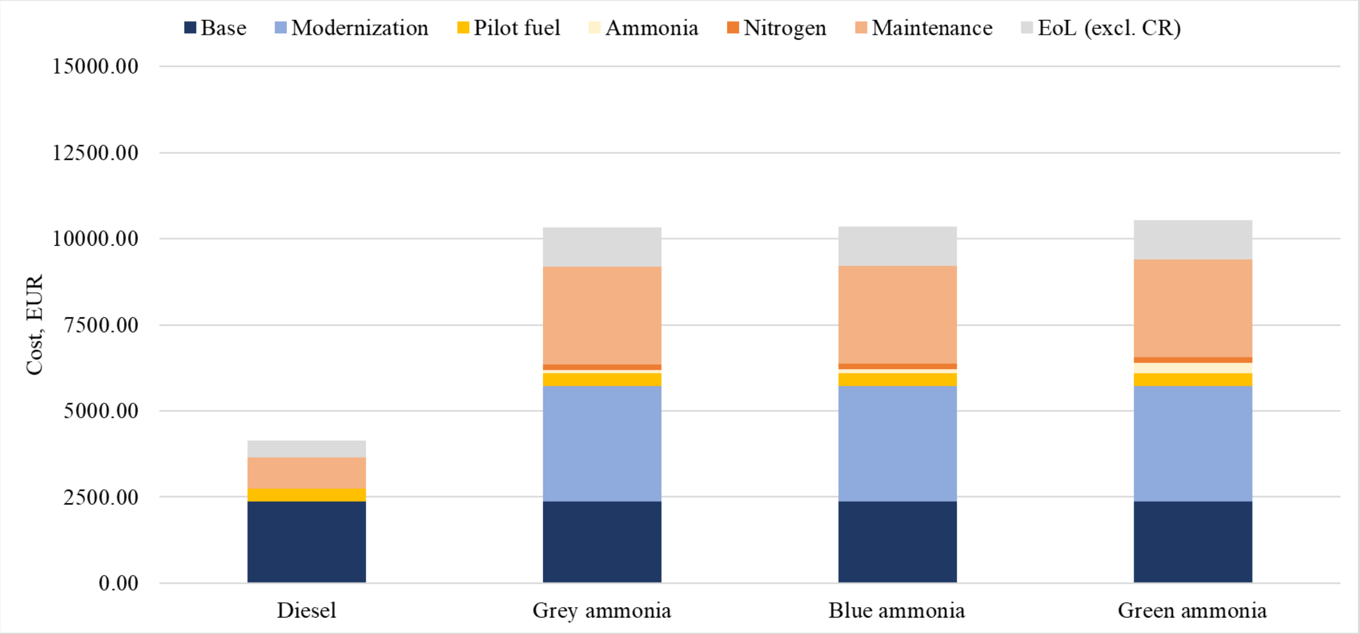

Figure 4.6: Total Cost of Ownership results for conservative scenario excluding Common Rail.

Based on the Total Cost of Ownership (TCO), the Levelized Cost of Technology (LCOT) can be calculated by dividing the TCO's monetary value by the total work performed by the tractor over its lifetime, expressed in kWh. For the case study considered, the LCOT results are depicted in Figure 4.7. The capital cost calculation includes the cost of the Common Rail system. The trends observed in the LCOT mirror those seen in the TCO analysis; the ammonia-fueled vehicle is approximately 3 times more expensive.

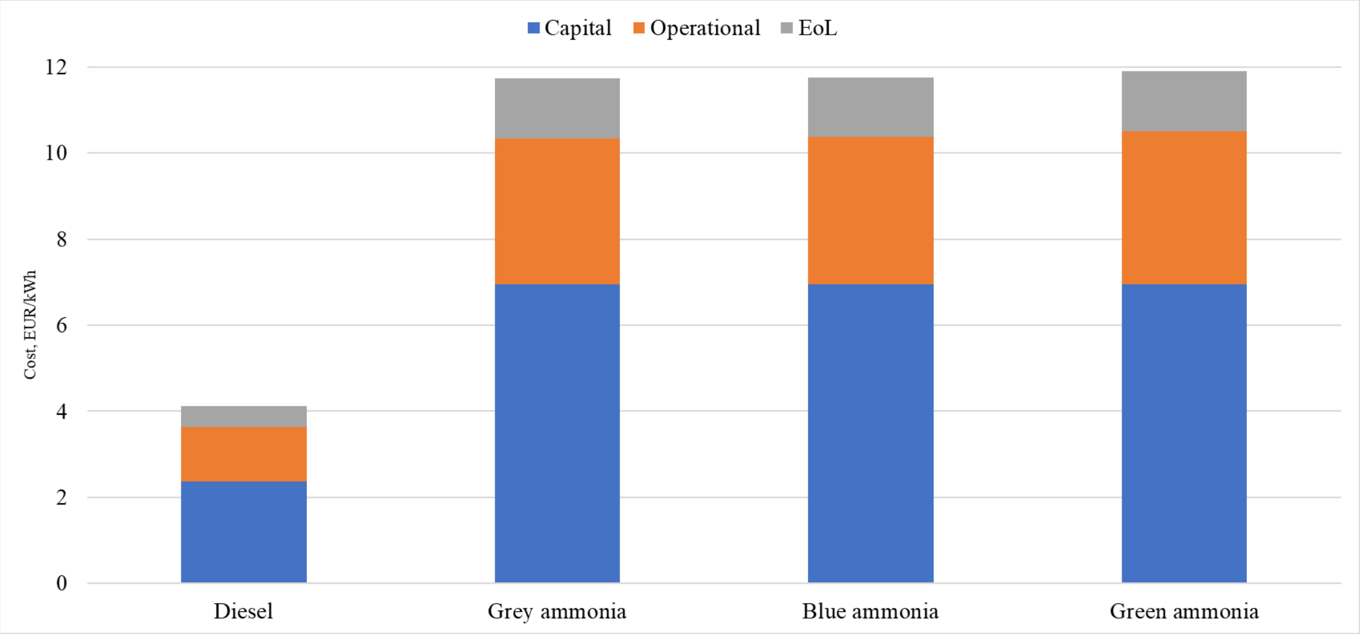

Figure 4.7: Levelized Cost of Technology results.

5 Summary

Total Cost of Ownership and the Levelized Cost of Technology have been calculated for the case study of a mini tractor fueled by a modified ammonia engine based on direct injection system and compared to the standard diesel case. The analysis indicates that vehicles powered by ammonia are around 3 times more expensive than their diesel equivalents, mainly due to significant modernization needs and related maintenance costs. It was observed that the overall Total Cost of Ownership (TCO) is marginally impacted by fuel prices, attributed to the vehicle's moderate fuel usage per year. By removing the cost of the Common Rail system from the initial price of the vehicle, the cost difference between ammonia and diesel-powered vehicles could drop to about 2.3 to 1. However, even with this adjustment, there's still a considerable gap in costs. These results highlight the importance of focusing future research on reducing the upfront costs of ammonia vehicles, aiming for more cost-effective capital investment strategies. This finding underscores the need for targeted optimization of capital expenditures for ammonia-fueled vehicles, which should be a focal point of future research. Exploring ways to reduce the initial modernization costs or enhance operational efficiency could make ammonia-fueled vehicles more economically competitive.

References

[1] Future of hydrogen. *Seizing today's opportunities, Report prepared by the IEA for the G20, Japan.*, page 107, 2019.

[2] J. Ally and T. Pryor. Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems: An Australian case study. *Energy Policy*, 94:285–294, 2016. URL: `http://dx.doi.org/10.1016/j.enpol.2016.03.039`, `doi:10.1016/j.enpol.2016.03.039`.