

Abstract

Ammonia may be considered a practical hydrogen carrier and diesel substitute for decarbonization in a CI engine used in a mini tractor intended for orchard operations. Environmental and economic assessments of such a solution are evaluated through life cycle assessment and life cycle costing methods. Life cycle assessment, performed using LCA for Experts software (formerly GaBi), accounts for multiple ammonia production pathways: ammonia based on hydrogen from steam methane reforming (grey), ammonia based on steam methane reforming with carbon capture and storage (blue), and ammonia based on hydrogen from electrolysis with electrical energy supplied by PV (green PV), wind (green wind), and a nuclear plant (pink). The analysis is based on experimentally gathered emissions data of the engine, where ammonia is utilized via a port injection setup, with rapeseed-based biodiesel serving as a pilot fuel. A mini tractor-specific working cycle of vehicle operation is considered, and the results are reported per hectare-year of the vehicle's operation (functional unit). For impact assessment, three midpoint ReCiPe categories are used – climate change, fossil depletion, and freshwater consumption – and two endpoint categories: human health and ecosystem quality.

First, an LCA of ammonia production methods compared to diesel is presented. The study shows that nuclear- and wind-based NH_3 minimize greenhouse gas emissions; however, pink ammonia increases fossil depletion and freshwater use due to uranium and cooling water burdens. Second, engine tests of a dual-fuel CI engine indicate slightly lower average efficiency than diesel, with the gap narrowing at high loads. However, partial load operation reveals elevated NO_x , N_2O , and NH_3 slip.

Complete LCA of the ammonia-fueled mini tractor shows that at the operational stage greenhouse gas emissions are reduced from approximately 88 kg CO_2 eq. for the diesel-fueled engine to approximately 72 CO_2 eq. for the ammonia-fueled one (–18 %), which can be assessed as a moderate reduction. This is due to the presence of N_2O emissions, a potent greenhouse gas, and the CO_2 from the pilot fuel for the ammonia-fueled engine. When the full life cycle is considered, climate reductions of 42–44 % are achieved when NH_3 is produced by wind or nuclear and the biodiesel carbon footprint is included. On a full life cycle basis, the results on fossil depletion show that green solar/wind ammonia allows for a 43–45 % reduction, whereas pink ammonia results in an impact increase of 78 % compared to the diesel-fueled engine. Full life cycle freshwater consumption rises 40–50 % for all NH_3 cases (apart from the nuclear route that rises to approximately twice that of diesel). Compared with the diesel scenario, full life cycle endpoint results show that the ammonia-fueled tractor causes about 47 % higher impact on human health and roughly double the impact on ecosystem quality, regardless of the ammonia source. When an SCR system using residual ammonia in the exhaust is considered to reduce NO_x and NH_3 emissions

from the operational phase, these impacts are reduced, but the human health impact still remains around 19 % higher and the ecosystem quality impact about 1.6–2 times higher than for diesel.

Life cycle costing employs a bottom-up approach, sourcing acquisition, operational, and end of life costs from laboratory and literature inputs, considering the same ammonia production pathways as in the environmental assessment. First, a price comparison of fuels on an energy basis is presented; ammonia is found to be economically competitive with diesel at a low natural gas price (below 6 \$/MMBtu for the natural gas with carbon capture and storage pathway) or an electricity price below 38 \$/MWh for electrolysis-based ammonia under a 1 \$/l diesel price. Complete life cycle costing case study results indicate that the required upfront investment for an ammonia-fueled vehicle – which is about three times higher than a diesel vehicle – is the main challenge preventing overall economic competitiveness.

Considering uncertainty in the estimation of capital expenditure and volatile fuel markets, the estimated range of results shows that an ammonia-fueled tractor is 2–4 times more costly in total than that of a diesel mini tractor. To shift profitability in favor of ammonia from the orchard owner's perspective, policymakers could implement a direct purchase incentive for a carbon-free vehicle, offsetting the high acquisition cost for orchard owners (a suggested range is 3000–8000 \$, with 6000 \$ being the default estimate), and include the cost of carbon emissions compliance for diesel to promote low carbon technologies.