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Life-Cycle Greenhouse Gas and Non-renewable Energy Assessment of Ammonia as Fuel

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ABSTRACT

Ammonia has good fuel properties such as its high octane value, high energy density, and easier storage compared to other alternative fuels. However, it has a low flame speed which would require mixing it with a more combustible fuel, which is usually a hydrocarbon; thus greenhouse gases such as carbon dioxide are still present in the tailpipes. In this study, the global warming potential (GWP) and non-renewable energy consumption (NREC) of using different ammonia-fuel mixtures were assessed. Four fuel mixtures were considered wherein ammonia is mixed with gasoline, diesel, hydrogen, and dimethyl ether. Also, four processes of ammonia production were considered, which are the steam reforming (SR), partial oxidation (PO), and two biomass-based processes with cereal straw and cyanobacteria as raw materials. Uncertainty analyses of the environmental impacts via Monte Carlo simulation were also conducted and it showed that the standard deviations of the impacts are minor.

KEYWORDS: ammonia fuel; life-cycle assessment; global warming; non-renewable energy consumption; Monte Carlo simulation

1 INTRODUCTION

Hydrogen gas, has been a thoroughly researched alternative fuel, yet there are still many technological issues with its use. It has a low energy density and it is also risky as it could easily catch fire in case of leaks and accidents. Storage has also been an issue because high pressure is necessary (Zamfirescu & Dincer, 2008). On the other hand, ammonia, which is a non-hydrocarbon has been already been used before to power mass transit buses in Europe during the Second World War (Kroch, 1945). In contrast to hydrogen, ammonia has higher octane value and energy density and it could be stored on more moderate conditions. However, it also has disadvantages, one of which is its slow flame speed that is why it would be required to be mixed with a more combustible fuel, which in some cases is another fossil fuel (Zamfirescu & Dincer, 2008)

In this study, the greenhouse gas emissions and non-renewable energy consumption of the use of ammonia-coupled fuel system is assessed. Four ammonia-fuel mixtures were considered which are the ammonia-diesel (Reiter & Kong, 2011), ammonia-hydrogen (Frigo & Gentili, 2013), ammonia-DME (Gross & Kong, 2013), and ammonia-gasoline (Ryu, Zacharakis-Jutz, & Kong, 2014).

Ammonia produced from different modes of production were considered which includes the two aforementioned commercial methods. Two alternative biomass-based processes of ammonia production were also included. Of these two, one proposed to utilize biomass to produce hydrogen which will be used for further Haber-Bosch reaction (Ahlgren, et al., 2008), and the other one would utilize biomass as source of nitrogen and hydrogen in ammonia production (Razon, 2013).

2 METHODOLOGY

Life Cycle Assessment (LCA) is a method which determines the environmental impacts of a product or service by the inventory of relevant inputs and outputs, evaluation of the environmental impacts of those inputs and outputs, and interpreting the results of the inventory in relation to the goals/objectives of the study. Its results are important basis of decision-makings and crafting policies.

2.1 Goal and Scope Definition

The goal of the study is to assess the global warming potential (GWP) and non-renewable energy consumption (NREC) of using ammonia-fuel mixtures as fuel. The system boundary includes the different production modes of ammonia, production of the fuels that is mixed with ammonia (diesel, gasoline, hydrogen gas, and DME), plant-to-market transport, and the energy production by combustion of fuel in an internal combustion engine. The functional unit is 1 MJ of shaft work produced by the combustion engines. USA is considered as the spatial/geographical boundary which would also be the basis for inputs such as electricity and plant to market transport.

2.2 Inventory Analysis

US-based databases such as USLCI (NREL, 2012) were used as source of data. However, some data were derived from non-US based databases such as *ecoinvent 3*.01 and were adjusted to US settings by modifying variables such as transportation and electricity mix. The data for biomass-based processes were taken from the works of Ahlgren et al. (2008) and Razon (2012). Some data on NH_3-H_2, NH_3-gasoline, and NH_3-diesel were obtained via personal communication thru email to Prof. Stefano Frigo and Prof. Song Charn-Kong.

2.3 Impact Assessment

The impact assessment includes global warming potential and non-renewable energy consumption. The IMPACT 2002+ (Jolliet, et al., 2003) is used as life cycle impact assessment method. Also, the Life Cycle Impact Assessment is conducted with the aid of the software *SimaPro version 8.0.3.14 (*Goedkoop & De Schryver, 2010).

2.4 Uncertainty Analysis

Monte Carlo simulation is a widely-employed method used to determine the uncertainties of the LCA. ***SimaPro PhD*** supports advanced features in conducting this type of uncertainty analysis. For this study, 1000 runs per simulation were made and a 95%-confidence interval was set. Data on uncertainties/probability distribution such as standard deviation were taken from experimental results in published literature, databases, and representative data. For representative data, it was ensured that the estimates will be kept conservative.

3 RESULTS AND DISCUSSION

3.1 Life-cycle Greenhouse Gas Emissions

Figures 1-4 show the greenhouse gas emissions of the different process systems. "*PO"* and "*SR*" refers ammonia produced thru conventional processes which are partial oxidation (PO) and steam reforming (SR) processes while "*Anab*" refers to ammonia produced from Anabaena sp. ATCC 33047 (Razon, 2013) and "*Salix*" refers to the process proposed by Ahlgren (2008).

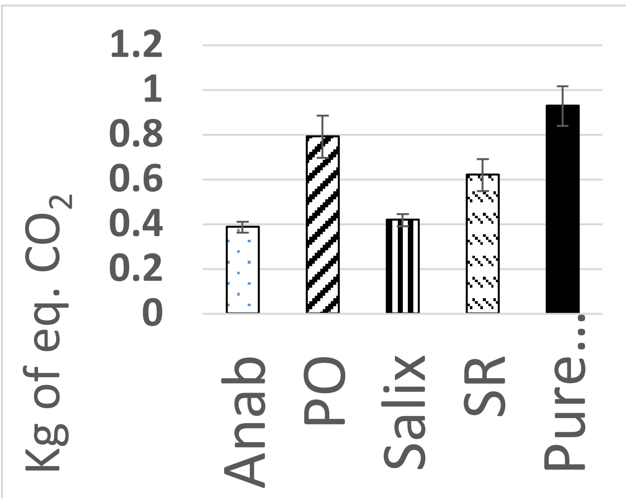

Figure 1: GWP of NH_3-Diesel Fuel Mix

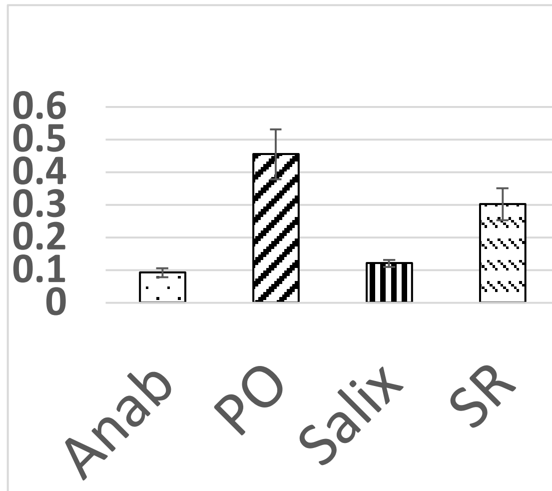

Figure 2: GWP of NH_3-H_2 Fuel Mix

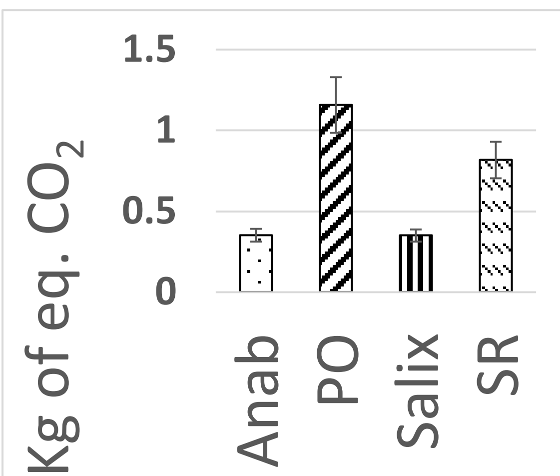

Figure 3: GWP of NH_3-DME Mixture

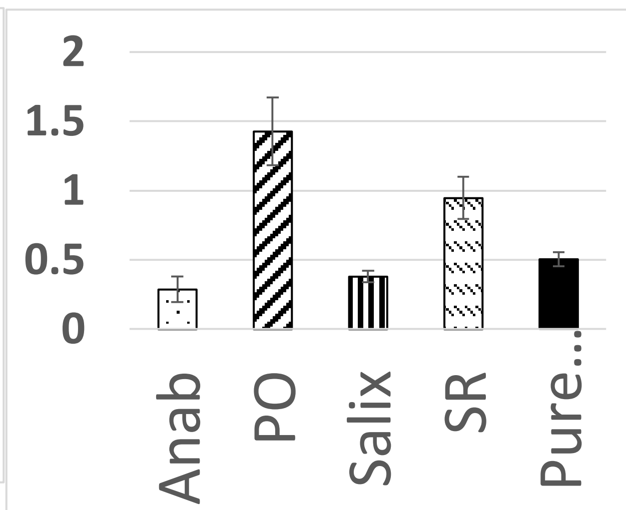

Figure 4: GWP of NH_3-Gasoline Mixture

3.2 Life-cycle Greenhouse Non-renewable Energy Consumptions

Figures 5-8 show the non-renewable energy consumption of the different process systems:

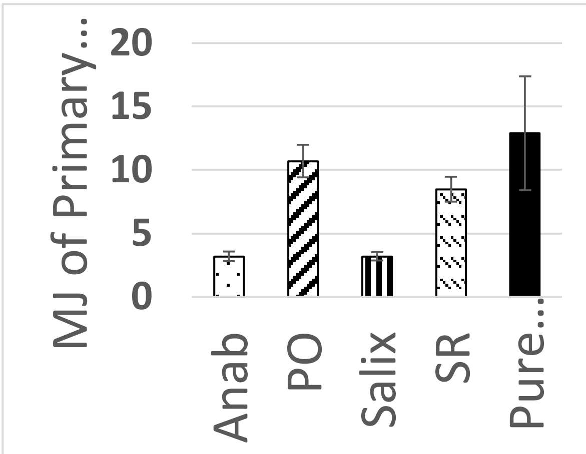

Figure 5: NRE of NH_3-Diesel Fuel Mix

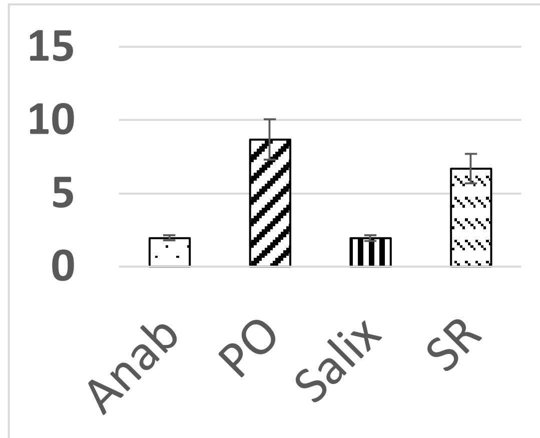

Figure 6: NRE of NH_3-H_2 Fuel Mix

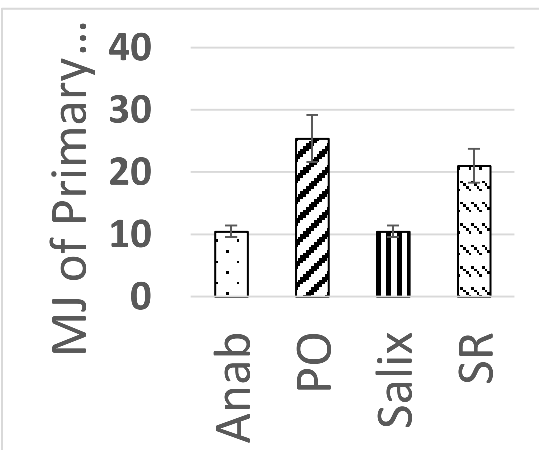

Figure 7: NRE of NH_3-DME Fuel Mix

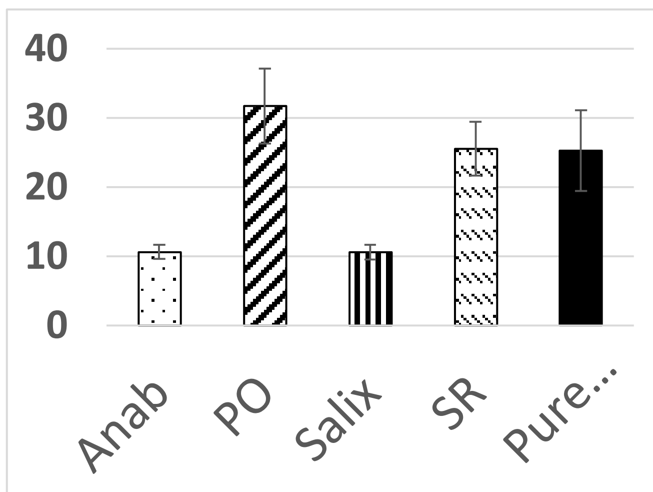

Figure 8: NRE of NH_3-Gasoline Fuel Mix

It could be observed that the systems which involves alternative ammonia from alternative sources has lower impacts compared to ammonia from conventional sources. Figures 1 and 5, shows that the global warming and non-renewable energy consumption of using ammonia-diesel fuel mixtures are lower than pure diesel. The situation in ammonia-gasoline mixtures is the reverse as the impacts of the fuel mixtures, particularly those that involve the use of conventional ammonia, are higher than pure gasoline use. The uncertainties which were computed by Monte Carlo simulation were also plotted and it is shown that the deviations are close to the mean values.

Figures 9 and 10 shows the percentage contribution of the process units to the overall life-cycle impacts. It is observed in all fuel mixture groups that the NRE consumption in systems which involves conventional ammonia that the *Production of Ammonia* phase constitutes the majority of the impact. While, in systems which involve alternative ammonia, the *Production of secondary fuels* (hydrogen, diesel, gasoline, and DME), comprise the majority of the impacts.

It is a different case with the GWP impacts. The trends are different in every fuel mix group. In NH_3-H_2 and NH_3-gasoline, the phase *Production of ammonia* has the biggest contribution. In ammonia-diesel, it is the *Combustion of fuel* phase. In the ammonia-DME, it is the production of DME.

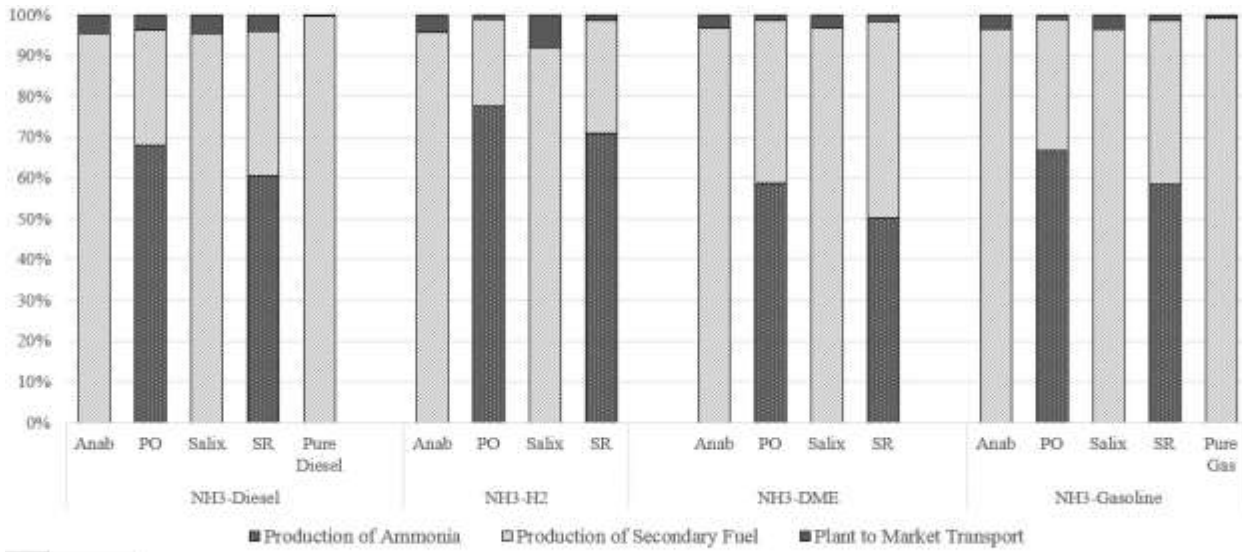

Figure 9. Percentage NRE of Processes in Different Fuel Systems

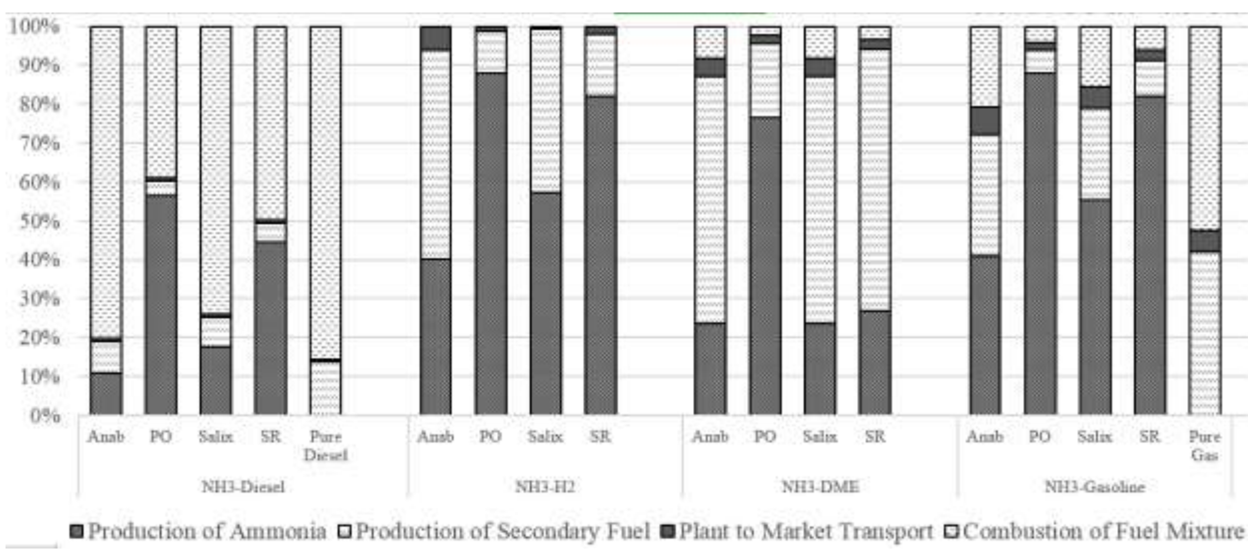

Figure 10. Percentage GWP of Processes in Processes in Different Fuel Systems

4 CONCLUSION

The study showed that the *Production of Ammonia* phase in the life-cycle of ammonia fuel systems, contributes to a large percentage in many of the environmental impacts. As of the moment, only the systems which utilizes alternative ammonia would result to a lower GWP and NREC compared to pure diesel and pure gasoline fuelling systems. The uncertainty analyses that were conducted also add integrity to the results as deviations are close to the mean values.

For further studies, other alternative processes on ammonia production could be explored such as ammonia produced utilizing the wind and solar energy. Other impacts could also be assessed, particularly, the eutrophication and acidification, as these two are linked with the nitrogen cycle. Impacts on land and water use could also be investigated. It is also recommended that improvement should be made on probability data, especially on alternative ammonia production as only representative data where used.

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