Invited Paper

LIFE-CYCLE GREENHOUSE GAS AND NON-RENEWABLE ENERGY ASSESSMENT OF AMMONIA-DIESEL MIXTURES AS TRANSPORT FUEL

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Abstract

The global warming potential (GWP) and non-renewable energy consumption (NREC) of using ammonia-diesel mix as transportation fuel were assessed. The environmental impacts in using ammonia produced from steam reforming and partial oxidation processes were considered and differentiated. The assessments were compared to the GWP and NREC of the conventional pure diesel-fueled transport. The results suggest that using the steam reforming ammonia – diesel mix would have lesser GWP compared to pure diesel. However, the partial oxidation ammonia – diesel fuel mix has higher GWP than pure diesel, also its NREC is the highest among the three fuel systems. The NRECs of steam reforming ammonia – diesel fuel and pure diesel fuel are similar. The results suggest that steam reforming ammonia – diesel fuel mixture may offer some advantages over pure diesel fuel in terms of reducing global warming potential.

Keywords: Alternative fuel, Ammonia, Global warming, Life-cycle assessment, Non-renewable energy consumption

Introduction

Hydrogen gas and ammonia are two chemical compounds that when combusted fully do not emit any greenhouse gases. The former has been studied extensively as an alternative fuel and yet up to now, full commercial implementation has not been achieved. Hydrogen fuel has a low energy density and it easily catches fire in case of leaks and accidents [1]. Storage is also an issue as high pressures are necessary. Ammonia on the other hand, has higher octane value, higher energy density, and it can be stored on moderate conditions. However, it also has disadvantages such as its low flame speed which would require coupling it with a more combustible fuel, which is usually a fossil fuel. Nitrogen oxides are also produced at higher quantities [2, 3].

Commercial ammonia is produced by the Haber-Bosch process. To produce ammonia, nitrogen gas from air is reacted with hydrogen gas by an iron catalyst at temperatures around 350 – 550°C and 10 – 25 MPa pressure range. The hydrogen for the reaction is produced by one of two processes: steam reforming of natural gas or partial oxidation of heavier feedstock.

Steam reforming is the most commonly used process in syngas production. Natural gas is used as feedstock though other heavy hydrocarbons can also be processed. The chemical reaction is endothermic and uses nickel as a catalyst. The process is performed in the temperature range 700 – 830°C and pressure of around 3.5 MPa. The second most commonly used process in syngas production is partial oxidation. Unlike steam reforming process, partial oxidation is an exothermic process and could proceed without a catalyst. Its advantage is that it could utilize a more diverse assortment of feedstock and operates at lower pressures. Both processes use considerable amounts of fossil fuels. Therefore, there is a question of whether ammonia offers any advantage over traditional fossil fuels in terms of non-renewable energy consumption and greenhouse gas emissions.

In this study, the environmental impacts of the use of ammonia produced from steam reforming (SRA) and partial oxidation processes (POA), as transportation fuel are evaluated. In the studies by Reiter and Kong [3], ammonia is mixed with diesel fuel because ammonia, by itself, will not combust spontaneously because of its low ignition temperature and flame speed. Fuel systems similar to those from Reiter and Kong [3] are compared with the use of the conventional diesel fuel.

Methodology

Life Cycle Assessment (LCA) is a method which determines the environmental impacts of a product. LCA results should only be interpreted as possibilities. Also, LCA results do not specify the time and geographical locations that these impacts will affect [4]. An LCA is essential in decision-makings, crafting policies and discriminating between two or more products or process by comparing potential environmental trade-offs/impacts [5]. LCA consists of the following components: goal and scope definition, inventory analysis, impact assessment, and interpretation.

Goal and Scope Definition

The goal of the study is to assess environmental impacts of using ammonia-diesel fuel mix as transportation fuel. The system boundary includes raw material extraction, manufacturing of diesel and ammonia, fuel transport, and final use/ consumption of the fuel. Construction and decommissioning of the industrial plants are not included in the system boundary, also the production and recycle of catalysts that are involved. The functional unit is 66 kWh which is equivalent to one hour of operation at peak power of the internal combustion engine used in the experiments of Reiter and Kong [3]. It was assumed that ammonia is transported from production facilities to the market using the existing pipe system. The distance from the diesel refinery to market was assumed to be 150 miles. The USA is considered as the spatial/geographical boundary. Sensitivity analysis was conducted to determine the effects of transportation processes and electricity mix on the environmental impacts of the systems.

Inventory Analysis

The data for diesel (100%D) and steam reforming ammonia (SRA) production are obtained from the USLCI database [6]. The data for the partial oxidation ammonia (POA) is derived from *ecoinvent 3.01* database [7-9]. The European data for the production of PO ammonia was adjusted to US setting by changing the geographical variables such as transportation and electricity mix. The emission data for the use of fuels were taken from emission tests conducted by Reiter and Kong [3]. Particularly, the fuel mixture with 60% diesel and 40% ammonia energy contribution, under constant engine power, was considered in this study because it had the most favorable fuel efficiency in the *John Deere 4045* engine [3], a model of diesel engine usually used in tractors and heavy equipment.

Impact Assessment

The impact assessment includes global warming potential and non-renewable energy consumption. The IMPACT 2002+ is used as life cycle impact assessment method [10]. Also, the Life Cycle Impact Assessment is conducted with the aid of the software SimaPro version 8.0.1 [11].

Results and Discussion

Table 1 shows the global warming potentials of the three fuel systems. The fuel system 60% diesel/40% ammonia from partial oxidation process (60%D/40%POA) has the highest global warming potential. This could be due to the lower hydrogen to carbon atom ratio of the hydrocarbons that are involved in partial oxidation process. Also, more carbon monoxide is produced in partial oxidation process than steam reforming process [12]. One unit mass of carbon monoxide is equivalent to 1.57 unit mass of carbon dioxide in terms of global warming potential. Among its main processes, the 'Production of ammonia' phase has the highest contribution to its GWP, followed by its 'Use' phase. In the 60% diesel/40% ammonia from steam reforming process (60%/40%SRA), the highest contributor to GWP is the 'Use' phase, same with the pure diesel fuel system. Tables 1 and 2 below shows that variables such as electricity and transport have minimal contributions to both impact categories evaluated.

Table 1. Individual Contributions of Systems and Processes on GWP (kg eq. of CO_2)

Main Process	Sub-process	60%D/ 40%POA	60%D/ 40%SRA	100%D
Production of Diesel	Production of Diesel	0.0072	0.0072	0.0122
	Production of other fuels	0.0120	0.012	0.0204
	Electricity (US)	0.0445	0.0445	0.0757
	Heat production	0.0607	0.0607	0.1031
	Transport (US)	0.0269	0.0269	0.0458
Production of Ammonia	Transport (US)	0.0401	0.0024	-
	Electricity (US)	0.1281	0.0606	-
	Heat production	0.0904	0.1722	-
	Production of petroleum	0.0286	0.0239	-
	Production of ammonia	1.2150	0.0502	-
Use of fuel		1.0218	1.0218	1.7362
Transportation		0.0153	0.0153	0.0260
TOTAL		**2.6907**	**1.4976**	**2.0193**

Similar to the GWPs of the systems, 60%D/40%POA has the highest non-renewable energy consumption. This could also be due to the lower hydrogen to carbon atom ratio of chemical compounds that are processed in partial oxidation reaction. More mass of these heavy hydrocarbons is needed to produce the same amount of hydrogen from that of lighter hydrocarbons used in steam reforming process. Also, its 'production of ammonia' phase consumes most of the fossil fuels.

Tables 3 and 4 below show that both impact categories are only marginally sensitive to key variable processes, which are electricity and transport. All the GWPs of the three fuel systems are sensitive to the 'Use of fuel' phase.

Table 2. Individual Contributions of Systems and Processes on NREC (MJ of primary energy)

Main Process	Sub-process	60%D/ 40%POA	60%D/ 40%SRA	100%D
Production of Diesel	Production of Diesel	-	-	-
	Production of other fuels	17.73	17.28	29.33
	Electricity (US)	-	0.460	0.783
	Heat production	-	-	-
	Transport (US)	-	-	-
Production of Ammonia	Transport (US)	-		
	Electricity (US)	1.040	-	-
	Heat production	-	-	-
	Production of petroleum	26.42	12.32	-
	Production of ammonia			
Use of fuel		-	-	-
Transportation		0.212	0.212	0.366
TOTAL		**45.41**	**30.27**	**30.48**

Table 3. Sensitivity Analyses. Percent Difference of the Impacts of the Process System to 1% Perturbation of Key Variables/Processes on GWP

Main Process	Sub-process	60%D/ 40%POA	60%D/ 40%SRA	100%D
Production of Diesel	Production of Diesel	0.00%	0.00%	0.01%
	Production of other fuels	0.00%	0.01%	0.01%
	Electricity (US)	0.02%	0.03%	0.04%
	Heat production	0.02%	0.04%	0.05%
	Transport (US)	0.01%	0.02%	0.02%
Production of Ammonia	Transport (US)	0.01%	0.00%	-
	Electricity (US)	0.05%	0.04%	-
	Heat production	0.03%	0.11%	-
	Production of petroleum	0.01%	0.02%	-
	Production of ammonia	0.45%	0.03%	-
Use of fuel		0.38%	0.68%	0.86%

Transportation		0.01%	0.01%	0.01%

Table 4. Sensitivity Analyses. Percent Difference of the Impacts of the Process System to 1% Perturbation of Key Variables/Processes on NREC

Main Process	Sub-process	60%D/ 40%POA	60%D/ 40%SRA	100%D
Production of Diesel	Production of Diesel	-	-	-
	Production of other fuels	0.39%	0.57%	0.96%
	Electricity (US)	-	0.02%	0.03%
	Heat production	-	-	-
	Transport (US)	-	-	-
Production of Ammonia	Transport (US)	-	0.00%	0.00%
	Electricity (US)	0.02%	-	-
	Heat production	-	-	-
	Production of petroleum	0.58%	0.41%	-
	Production of ammonia	0.00%	0.00%	0.00%
Use of fuel mix		-	-	-
Transportation		0.00%	0.01%	0.01%

Conclusions

The partial oxidation ammonia – diesel fuel mixture has the worst performance in the two environmental impacts that were assessed, as it has the highest GWP and NREC. The steam-reforming ammonia-diesel fuel mixture has the lowest global warming potential. The non-renewable energy consumptions of SR ammonia – diesel and pure diesel fuel are similar. The impact categories evaluated are only slightly sensitive to the transport and electricity production processes. The results show that steam reforming ammonia may be a promising transport fuel, based on potential reductions on GWP as compared to diesel fuel.

Other environmental impacts should also be considered in future studies specifically it impacts on human health. Ammonia vapors are present in the exhaust of the fuel mixture which could have damaging effects on human health [13]. There are also alternative methods in producing the hydrogen/syngas which are said to be more environmentally friendly such as through electrolysis, photolysis, hydroelectric power, etc. LCA in the use of ammonia fuel that involve these processes could also be conducted for further research. Economic analysis could also be conducted. Partial oxidation process is said to be more cost-effective than steam reforming process on some conditions [14].

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