REPORT

GREEN TRANSPORTATION FUEL: AMMONIA

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Summary

In this brief report, some critical facts about ammonia and its utilization are discussed. The benefits of ammonia utilization compared to other conventional fuels are comparatively presented. The cost and driving range considerations for ammonia fueled vehicles are considered for comparisons. In addition, environmental impacts of various fuel driven vehicles are comparatively assessed including some energy and exergy efficiency calculations. Furthermore, the ammonia production technologies being developed by Dincer's group at University of Ontario Institute of Technology are presented for further understanding of clean energy utilization opportunities.

1. Key Facts About Ammonia

Note that ammonia (NH_3):

- consists of one nitrogen atom from air separation and three hydrogen atoms from any conventional or renewable resources.
- is the second largest synthesized industrial chemical in the world.
- is a significant hydrogen carrier and transportation fuel that does not contain any carbon atoms and has a high hydrogen ratio.
- does not emit direct greenhouse gas emission during utilization
- can be produced from various type of resources ranging from oil sands to renewables.
- is a suitable fuel to be transferred using steel pipelines with minor modifications which are currently used for natural gas and oil.
- can be used in all types of combustion engines, gas turbines, burners as a sustainable fuel with only small modifications and directly in fuel cells which is a very important advantage compared to other type of fuels.
- brings a non-centralized power generation via fuel cells, stationary generators, furnaces/boilers and enables smart grid applications.
- can be used as a refrigerant for cooling purposes in the car.

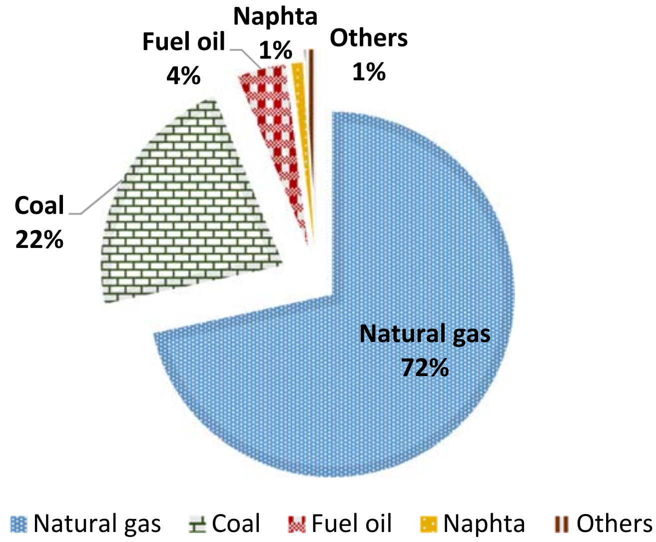

Fig.1. Sources of global ammonia production based on feedstock use (data from IEA, 2012).

Figure 1 shows a pie-chart of major sources of ammonia production based on various feedstocks world-wide. It is clearly seen that natural gas is the main source of ammonia production, accounting for 72%, respectively.

2. Ammonia as Low Cost Fuel

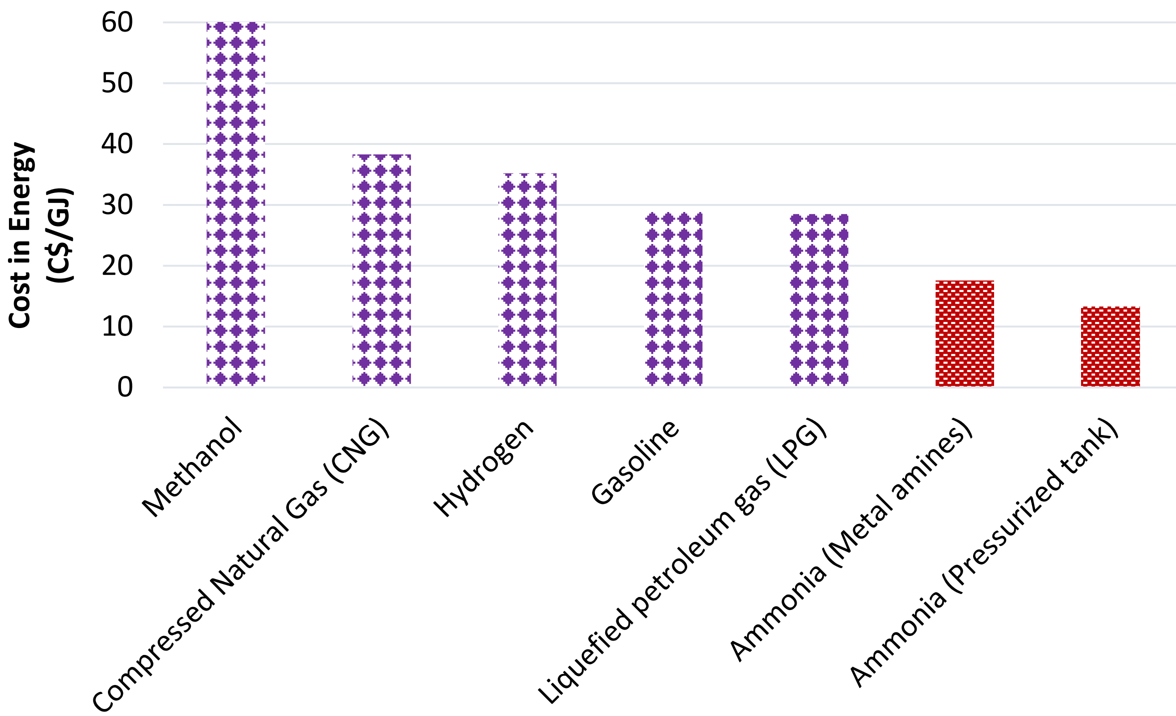

Fig. 2. Comparison of various vehicle fuels in terms of energy cost per gigajoule

Ammonia is a cost effective fuel per unit energy stored onboard compared to methanol, CNG, hydrogen, gasoline and LPG as shown in Fig. 2.

Table.1 Fuel costs comparison supplied to compression ignition engine

	40% Ammonia/ 60% diesel	**40% Ammonia/ 60% Dimethyl ether**	**Ammonia**	**Diesel fuel**
LHV (MJ/kg)	32.6	24.5	18.6	42
Fuel rate (kg/kWh)	0.316	0.42	0.554	0.245
Fuel price (US$/kg)	$0.95	$0.70	$0.61	$1.18
Fuel energy cost (US$/kWh)	$0.30	$0.30	$0.34	$0.29

Ammonia can be used as a mixture fuel in the vehicles. Ammonia has lower cost per unit mass (kg) compared to conventional fuels. Table 1 presents the fuel energy costs for ammonia and diesel fuels including mixtures.

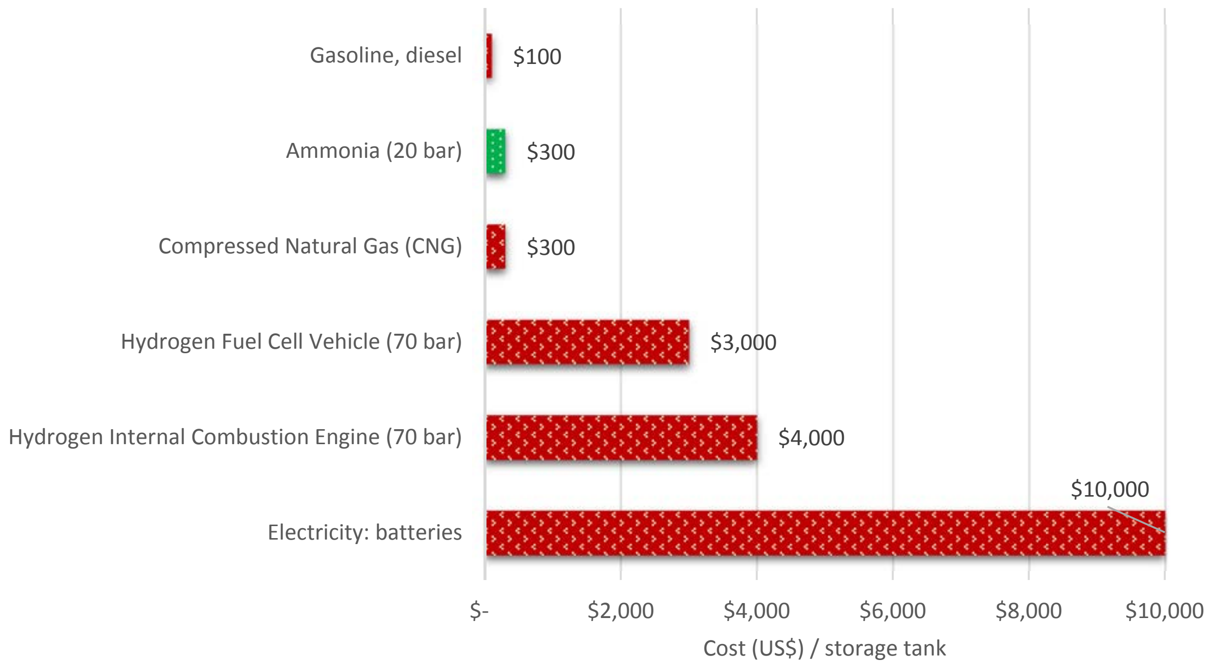

Fig. 3. On-board storage tank costs for various fueled vehicles

Fig. 3 shows that on-board storage tank for ammonia is in the same price level with compressed natural gas and gasoline vehicles.

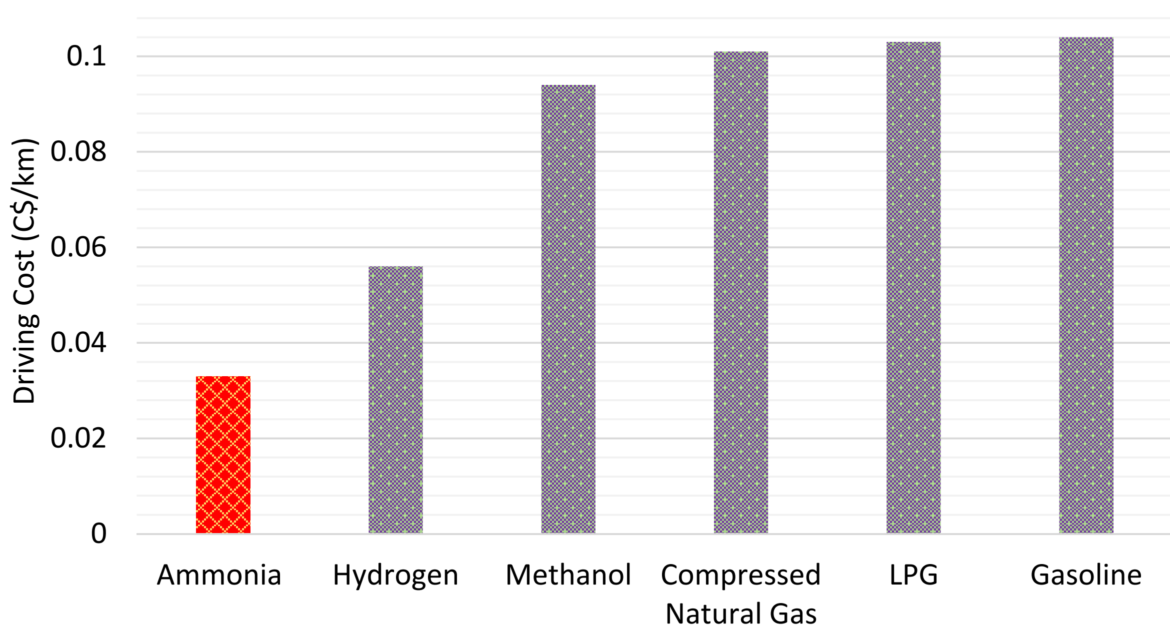

Fig. 4. Driving cost of various fuels

Ammonia yields the lowest cost per unit km traveled in comparison with other fuels as illustrated in Fig. 4.

3. Ammonia as the Least Expensive Fuel for Vehicles

As comparatively illustrated in Fig. 5, ammonia driven vehicle can travel 500 km with a fuel cost of 15 C$.

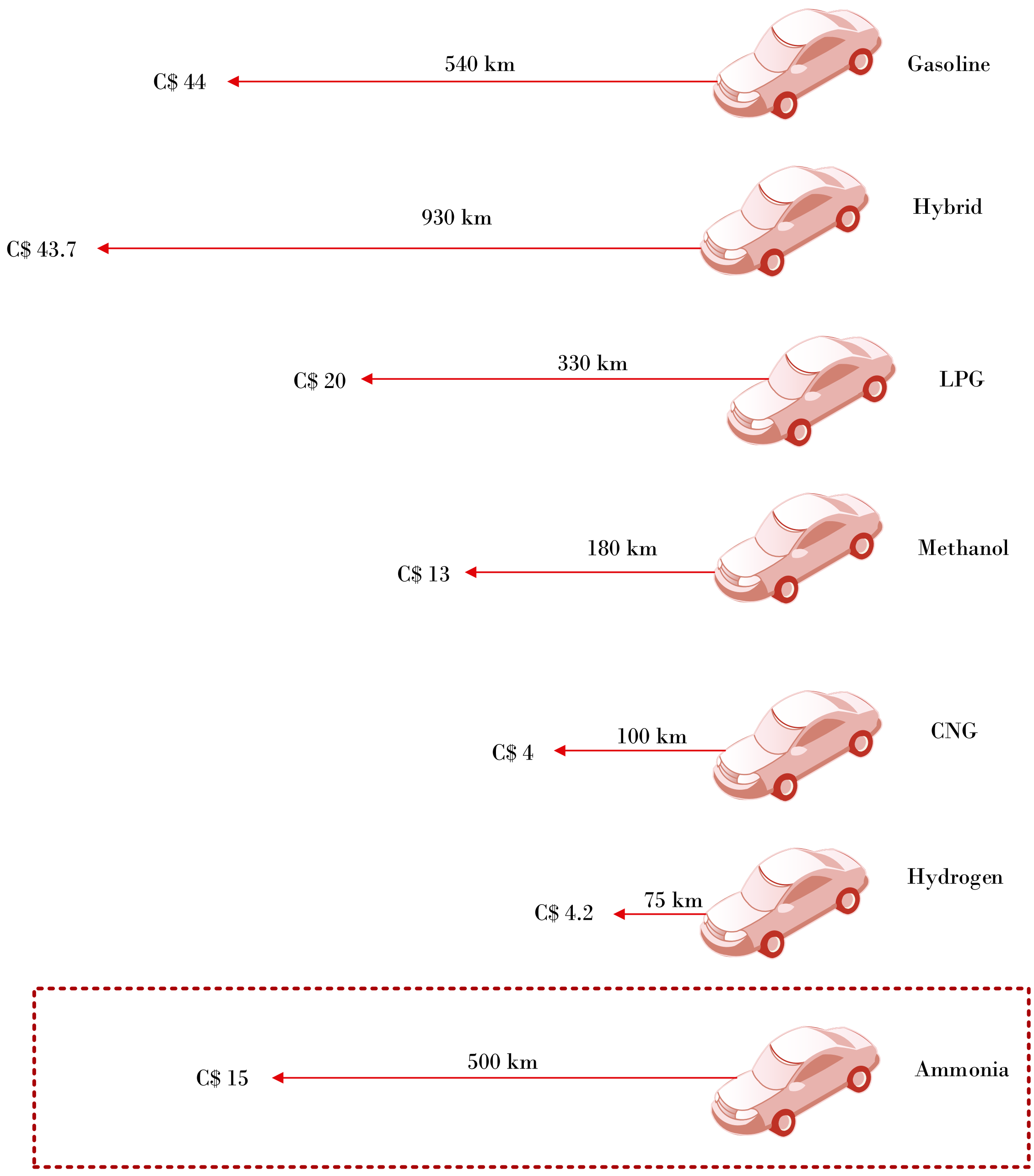

Fig. 5. Comparison of various fueled vehicles in terms of driving range per 40 L fuel

One can note the following key results:

- Ammonia is the least expensive fuel per 100 km driving range.

- There is an advantage of by-product refrigeration which reduces the costs and maintenance.
- Some additional advantages of ammonia are commercial availability and viability, global distribution network and easy handling experience.

4. Environmental Impact of Ammonia Driven Vehicles

Ammonia is still green if produced from fossil fuel based methods. The following results show the life cycle environmental impact of various fueled vehicles from raw material extraction to consumption in the vehicle per traveled km where ammonia is produced from nitrogen from air and hydrogen from hydrocarbon cracking.

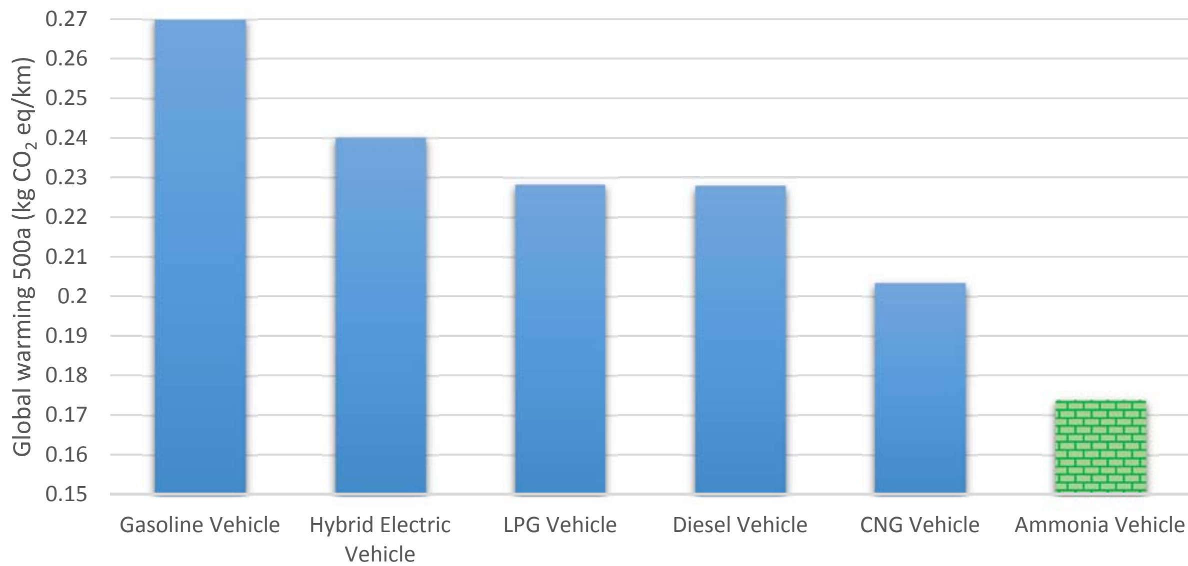

Fig. 6. Life cycle comparison of global warming results for various vehicles

Ammonia is most environmentally benign fuel in terms of greenhouse gas emissions in the vehicles as shown in Fig. 6.

Fig. 7 compares the global warming potential of ammonia driven vehicle where ammonia is either produced from solar energy or hydrocarbon cracking.

Note that global warming potential of ammonia driven vehicle is similar for solar energy and fossil hydrocarbon based options.

One should of course point out that ammonia is less toxic compared to electric and hybrid electric vehicles as illustrated in Fig 8.

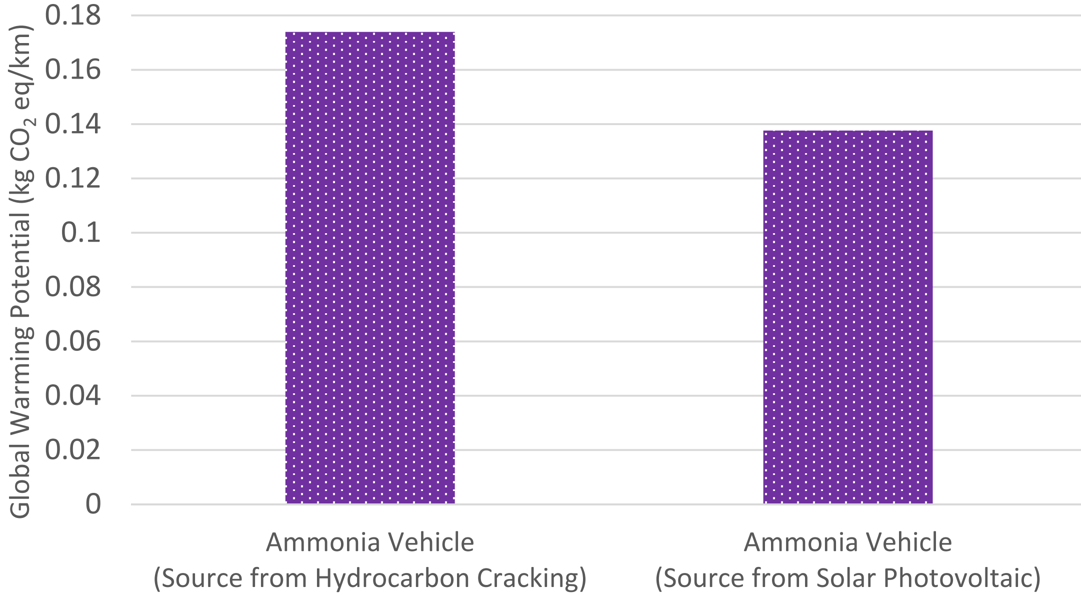

Fig. 7 Comparison of life cycle environmental impact of ammonia fueled vehicle from hydrocarbons and solar photovoltaics.

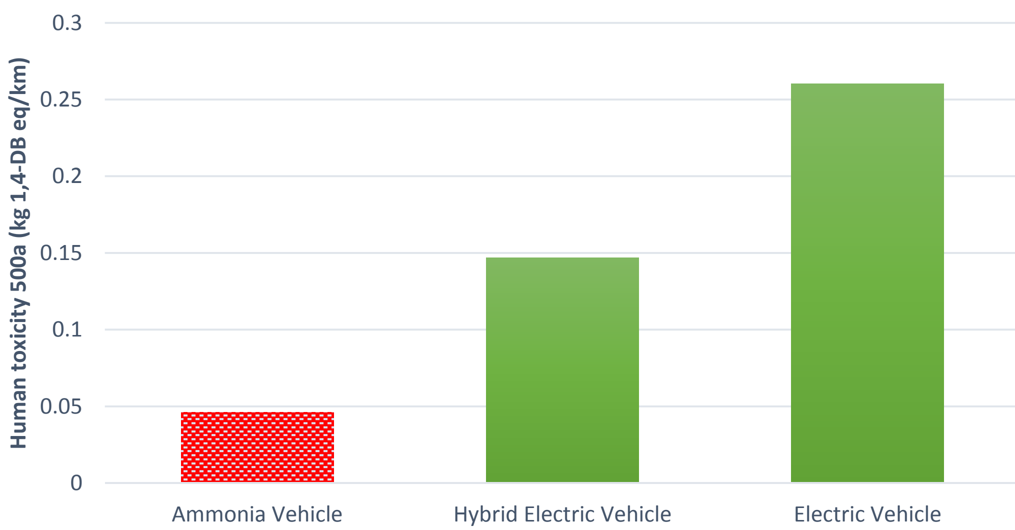

Fig. 8. Life cycle comparison of human toxicity results for various vehicles

5. Environmental Impact of Various Fuel Productions

Fig. 9 shows the comparison of ozone layer depletion values for various transportation fuels. Ammonia has lowest ozone layer depletion even if it is produced from steam methane reforming and partial oxidation of heavy oil.

Note that production of fuel ammonia yields lower greenhouse gas emissions compared to petrol and propane production as shown in Fig. 10.

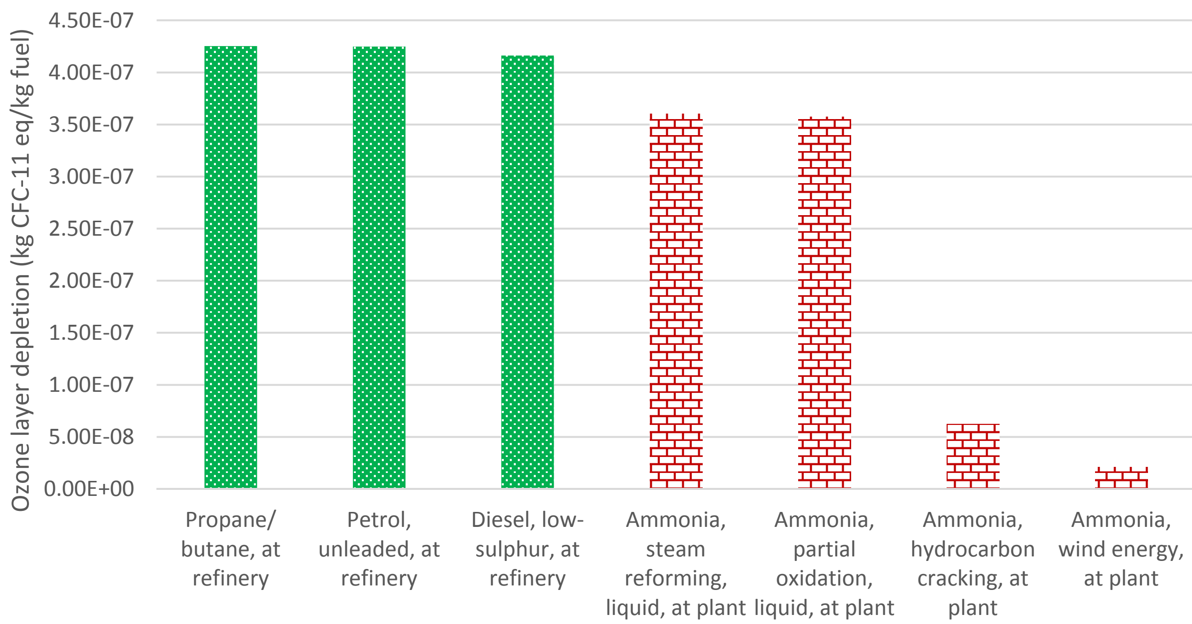

Fig. 9. Ozone layer depletion during productions of various fuels

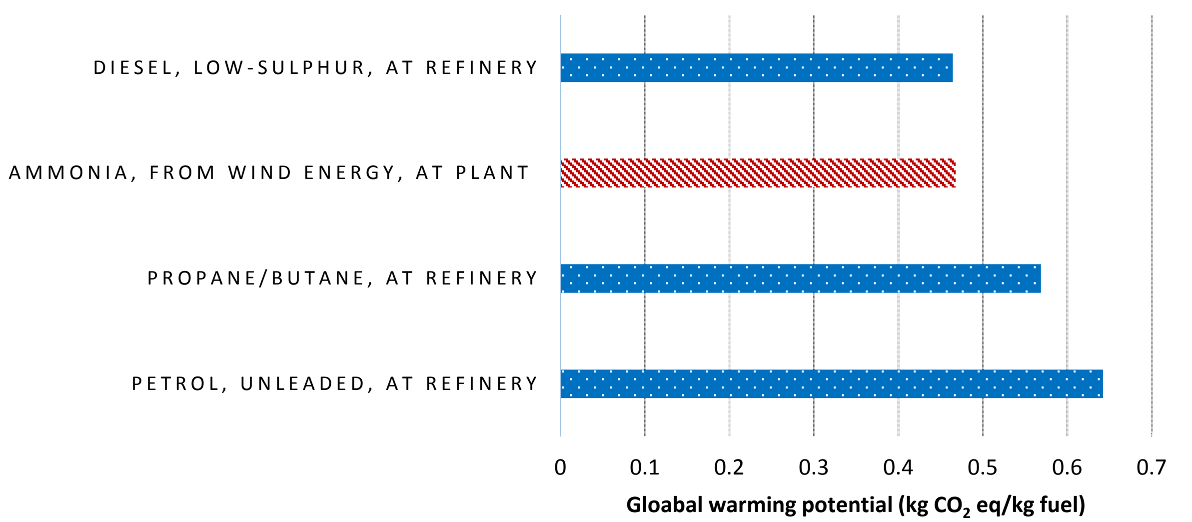

Fig. 10. Greenhouse gas emissions during production of various fuels

6. Environmental Impact of Ammonia Production

There are multiple pathways for ammonia production. Ammonia is cleaner when produced from renewable resources. Fig. 11 compares the environmental impacts of various ammonia production pathways.

- Ammonia from renewable resources has the least environmental impact.
- Ammonia from hydrocarbon cracking and underground coal gasification is most environmentally benign option among conventional methods.

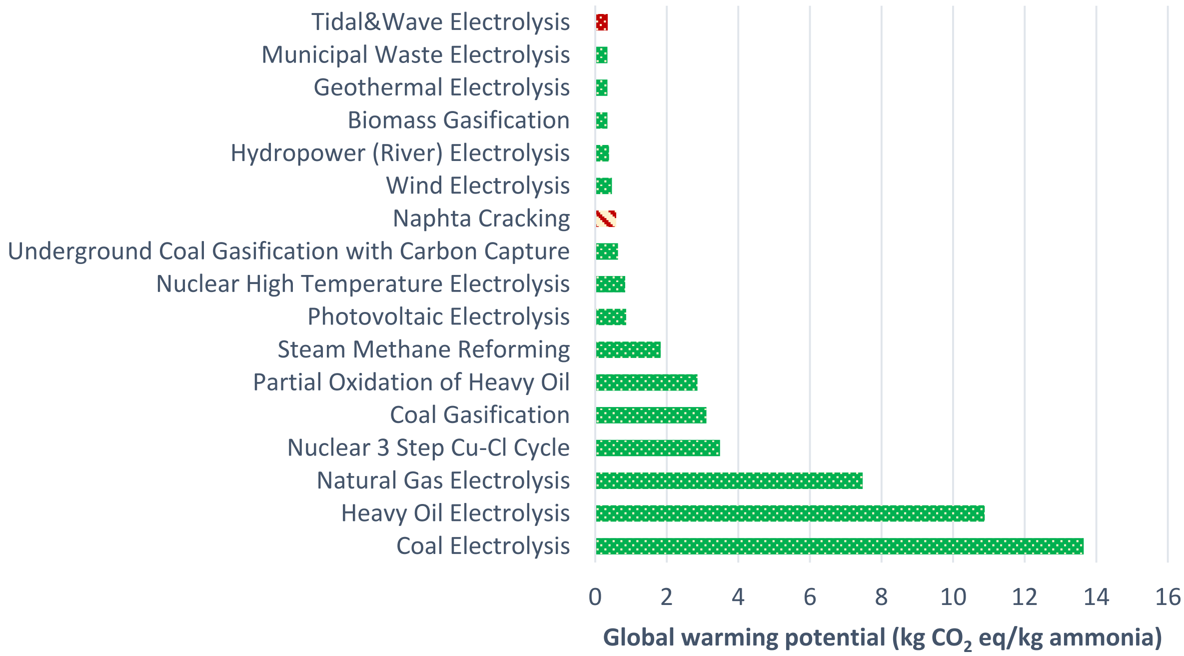

Fig. 11. Global warming values of all ammonia production methods

7. Ammonia Production by Various Methods

Here, comparative illustration of energy and exergy efficiencies for various ammonia production options are shown in Figs. 12 and 13.

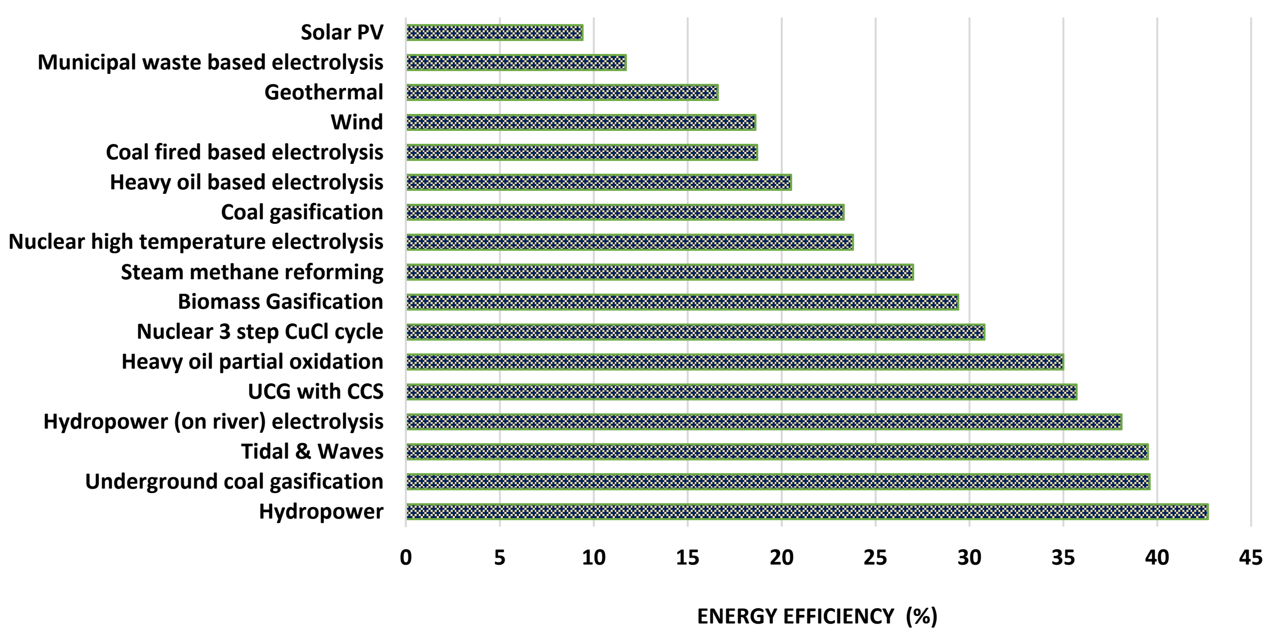

Fig. 12. Comparison of energy efficiency values for various ammonia production methods

Note that hydropower and underground coal gasification based ammonia production has the highest energy and exergy efficiencies.

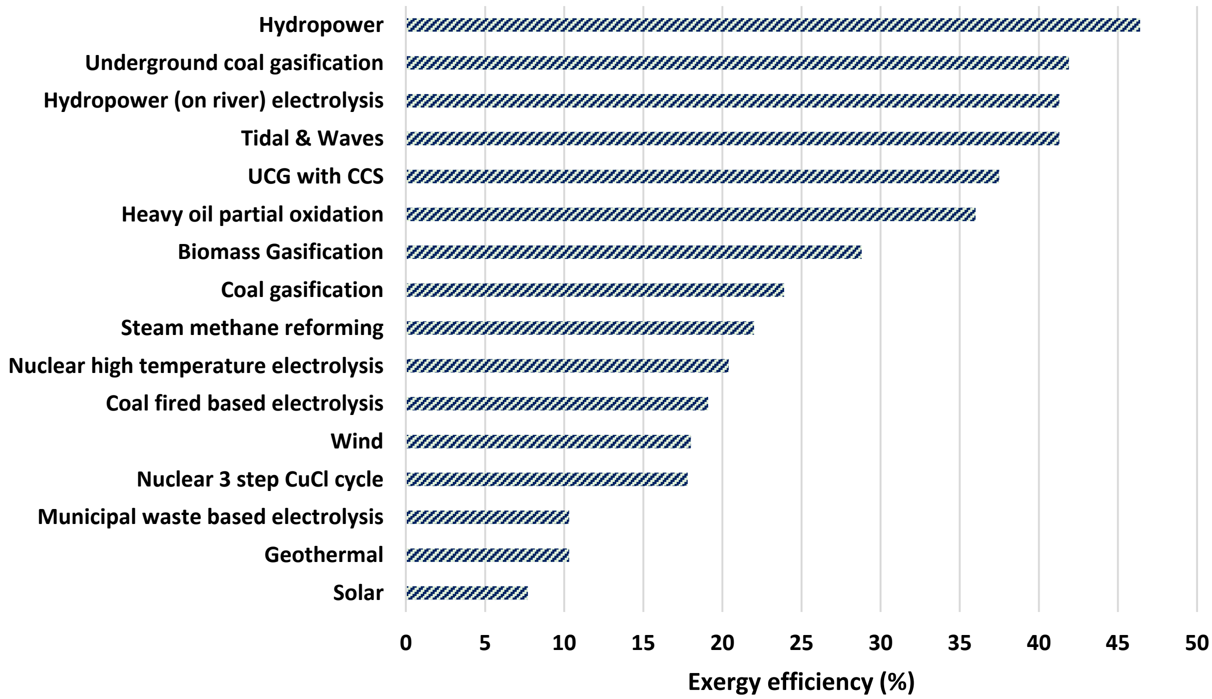

Fig. 13. Comparison of exergy efficiency values for various ammonia production methods

8. Research, Development and Innovation at University of Ontario Institute of Technology

8.1 Ammonia from Hydrocarbons

Ammonia can be produced from any hydrogen including hydrocarbons using cracking of hydrocarbons into hydrogen and carbon. Methane is a favored option for hydrogen production from a hydrocarbon because of its high H to C ratio, availability and low cost. Furthermore, the carbon produced can be sold as a co-product into the carbon black market which could be utilized in inks, paints, tires, batteries, etc. or sequestered, stored, and used as a clean fuel for electricity production. The sequestering or storing of solid carbon requires much less development than sequestering gaseous CO_2. Bitumen which can be obtained from oil sands in Alberta can also be a possible source of hydrocarbons for ammonia production. UOIT is in the progress of developing new methods for hydrocarbon cracking using microwaves and thermal plasma disassociation technique as shown in Fig. 14.

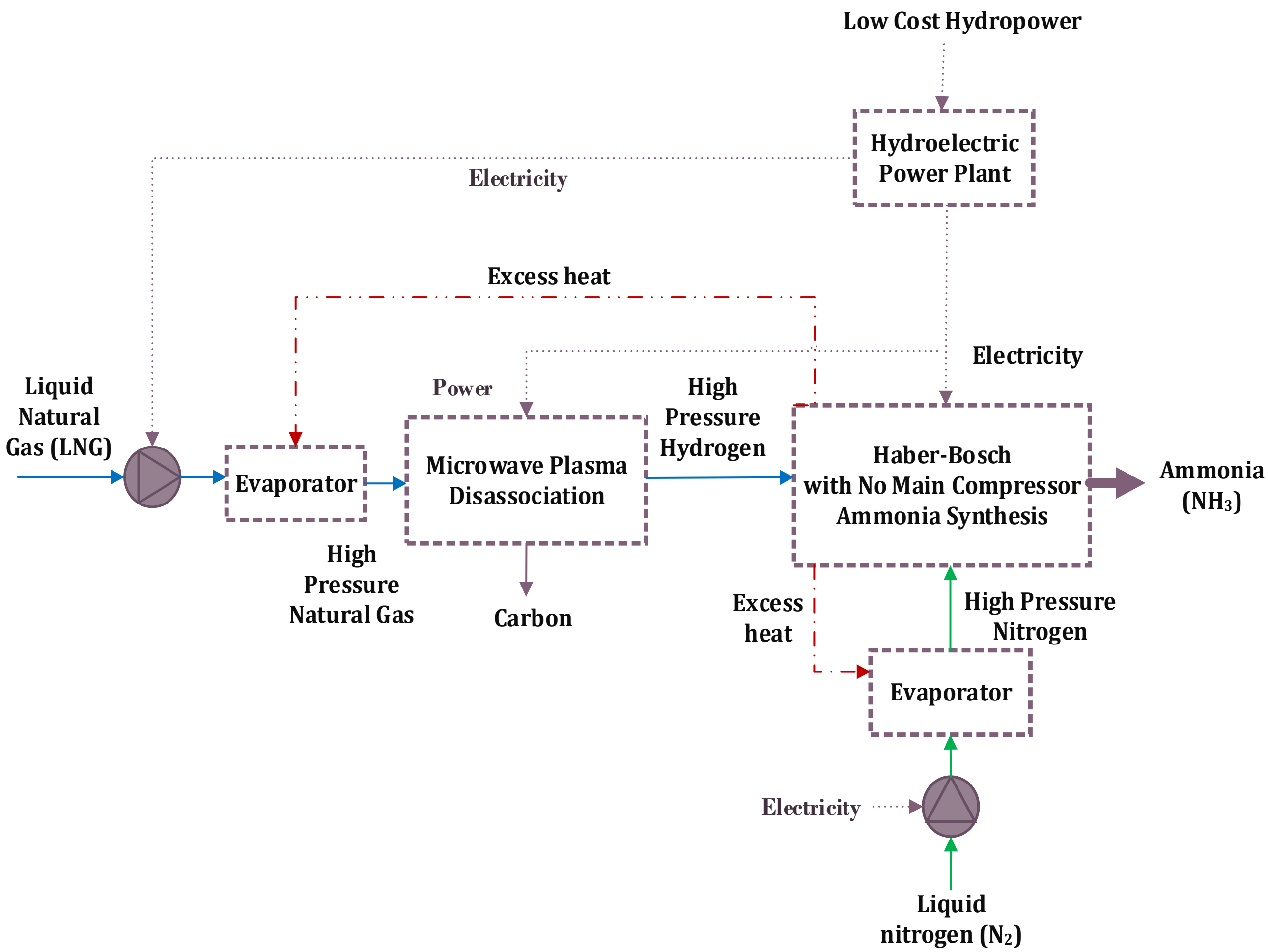

Fig. 14. Schematic diagram of hydrocarbon cracking based ammonia production being developed at UOIT

8.2 Ammonia from Solar Energy

Solar energy based hydrogen and ammonia production arises as one of the most sustainable solutions of today's critical energy, environmental and sustainability issues. Since solar energy cannot be directly stored or continuously supplied, it is required to convert solar energy to a storable type of energy. Ammonia is a significant candidate as a sustainable energy carrier. The main objective of studies at UOIT is to develop novel solar based ammonia production systems. In one of the proposed technique as shown in Fig. , the hybrid system maximizes the utilized solar spectrum by combining photochemical and electrochemical hydrogen production in a photo-electrochemical system and by integrating generated hydrogen as a reactant in the electrolytic ammonia synthesis processes such as molten salt based systems. Current studies in molten salt based electrochemical processes have made some novel developments. Using hydrogen and atmospheric air, combining them into a molten salt of NaOH-KOH with nano-Fe_2O_3 as the catalyst to produce ammonia is the developing technology at the moment.

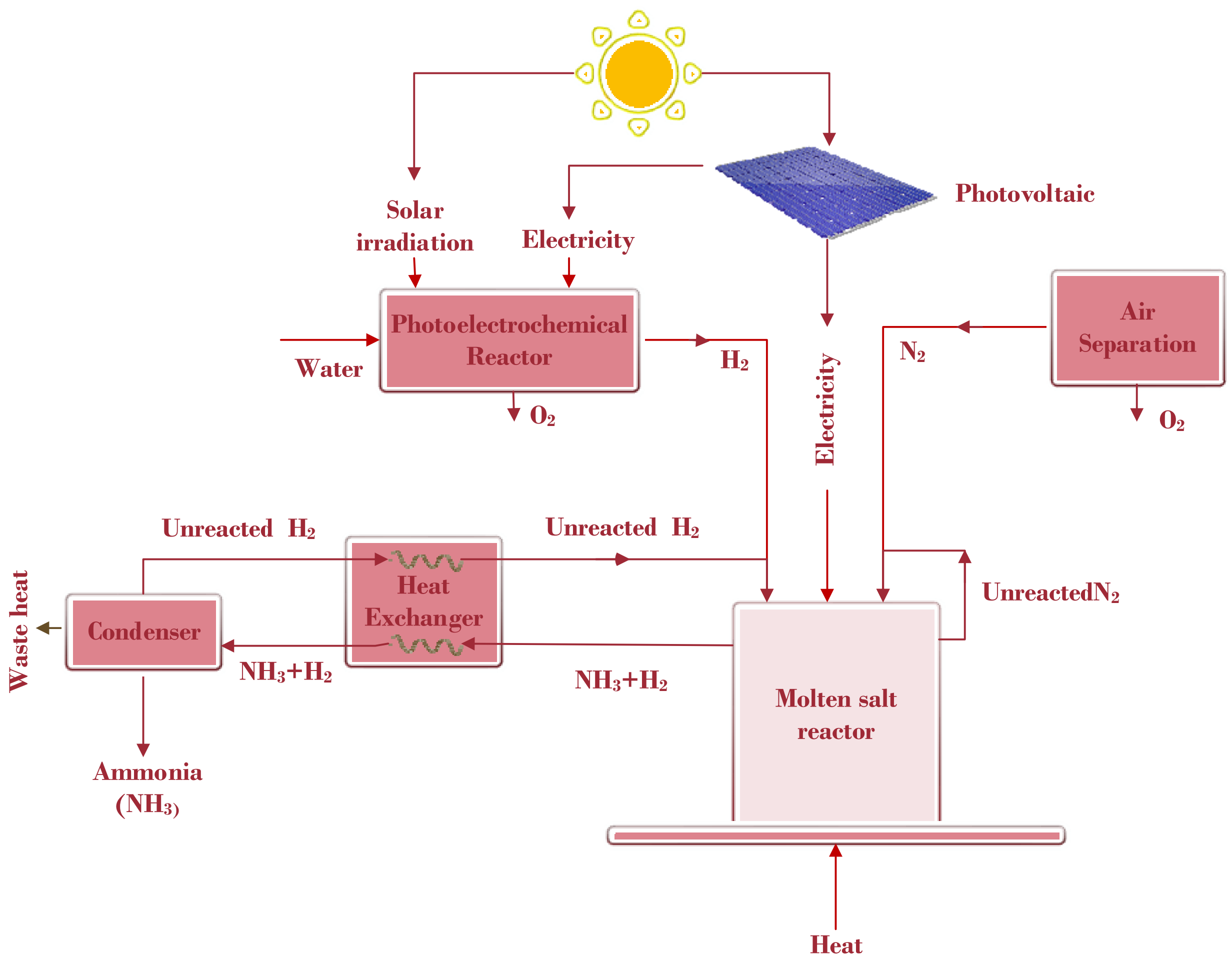

Fig. 15. Schematic diagram of solar energy based ammonia production being developed at UOIT

9. Closing Remarks

In this brief report, it is concluded that ammonia, as a clean and sustainable transportation fuel, emerges as the most environmentally benign option compared to commonly used traditional fuels. The life cycle greenhouse gas emissions from production of ammonia is much lower than the emissions coming out of other fuels during their lice cycles. Furthermore, ammonia does not emit direct greenhouse gas emissions during utilization in the vehicles because of the fact that it is a carbon-free fuel. The driving range of ammonia driven vehicles is higher, and the cost per unit km traveled becomes much less. Furthermore, ammonia usage in the transportation sector can significantly decrease the amounts of greenhouse gas emissions in the world. Dr. Dincer's group at the University of Ontario Institute of Technology is developing various innovative ammonia production technologies using traditional and renewable sources.

Further Sources

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