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Use of NH_3 fuel to achieve deep greenhouse gas reductions from US transportation

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ABSTRACT

The transportation sector is one of the largest sources of greenhouse gases (GHGs) emissions in the United States. This study identifies scenarios for dramatically reducing future GHG emissions from the US transportation sector, specifically from light-duty vehicles (LDVs), by phasing in ammonia (NH_3)-fueled vehicles in place of vehicles using petroleum-based fuels.

Projected US LDV carbon dioxide (CO_2) emissions from the Annual Energy Outlook (AEO) 2013 reference case projections prepared by the United States Department of Energy serve as the reference case for this study. Two scenarios, in addition to the AEO reference case, have been developed in this study to illustrate the GHG emissions mitigation potential of implementing NH_3-fueled vehicles in the US LDV transportation sector through 2040. This study uses the software tool LEAP (the Long range Energy Alternatives Planning System), with which alternative scenarios can be created and evaluated by comparing their energy requirements and environmental impacts.

Aggressive implementation of NH_3-fueled vehicles replacing gasoline vehicles to account for 100% in 2040 achieves reduction of about 30% of the cumulative LDV CO_2 emissions from 2010 through 2040 produced in the reference case. It eliminates most of the annual LDV CO_2 emissions projected in the reference case in the year 2040, with a 96% reduction from reference case levels, equivalent to a reduction of approximately 718 million metric tons CO_2 equivalent in that year's emissions.

The current study demonstrates that NH_3-fueled vehicles could be a promising near-term alternative for LDV because of its significant contribution in reducing CO_2 emissions compared with vehicles of carbon based fuels.

1. Introduction

Global warming is the result of greater concentrations of greenhouse gases (GHGs), especially carbon dioxide (CO_2) building up in the atmosphere. This atmospheric build-up of GHGs is largely the result of combustion of fossil fuels and other human activities, as reaffirmed by the Intergovernmental Panel on Climate Change this past September (Intergovernmental Panel on Climate Change, 2013).

A significant portion of CO_2 emissions come from the cars and trucks we drive. Since our vehicles largely run on gasoline and diesel, as fuel is burned, CO_2 is released. The transportation sector contributed 27% of the total US greenhouse gases (GHGs) emissions in 2010. Within the transportation sector, light-duty vehicles (LDVs), including passenger cars and trucks, contributed 62% of those transportation sector emissions (US Environmental Protection Agency, 2012).

Many potential fixes to this problem have been proposed, including implementation of electric vehicles (EV). The battery technologies required by EVs, however, are relatively immature and expensive (though improving).

There is an alternative way of powering cars and trucks that has not gotten much attention to date—Ammonia (NH_3) fueled vehicles (NH_3 Fuel Association, 2015). NH_3-fueled vehicles have the potential to reduce CO_2 emissions to levels far below those achieved by some other alternative-fueled cars, such as those fueled with natural gas, or ethanol derived from corn. In the case of EV's, the CO_2 footprint of those vehicles will depend on the nature of how the electricity was produced, e.g. a coal burning power plant versus, say, a hydroelectric plant.

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This study identifies scenarios and requirements to dramatically reduce future CO_2 emissions from the US transport sector, specifically from LDV by adopting NH_3-fueled vehicles.

2. Why ammonia-fueled vehicles?

Anhydrous Ammonia (chemical formula NH_3) is composed of one nitrogen atom and three hydrogen atoms—thus there are no carbon atoms involved in the oxidation reaction when ammonia is combusted. NH_3 is a liquid fuel at room temperature and moderate pressures, nearly identical in physical properties to liquid propane. Ammonia can be used in internal combustion engine (ICE) vehicles with straightforward modifications, and is environmentally friendly, as it produces primarily only molecular nitrogen (N_2) and water vapor (H_2O) at the tailpipe, even when only low-cost emissions controls are used. Problems of unburned ammonia and NOx emissions in the engine's exhaust are removed by a selective catalyst reduction (SCR) system in NH_3-fueled vehicles (Desrochers, 2013).

Ammonia can be produced by the catalytic reaction of nitrogen from air (which is 78% N2) and hydrogen from water, usually via electrolysis (Iowa Energy Center, 2013). Currently, however, the bulk of the world's ammonia production is carried out using hydrogen produced by steam reforming of natural gas, a fossil fuel. Ammonia can be produced at an affordable cost using any energy source, including fossil fuels, such as relatively clean natural gas, as well as non-fossil fuels such as renewable wind, solar, hydro and nuclear energy (Tallaksen and Reese, 2013; Kubic, 2006).

The mode of operation of NH_3-fueled vehicles is similar to conventional gasoline-fueled internal combustion-engine vehicles: Liquid ammonia, stored in an onboard fuel tank at moderate pressure (150 psi), is burned with air in order to move an engine's pistons, producing power which is harnessed to drive the vehicle's wheels. This familiar technology means NH_3-fueled vehicles can generally be built and maintained in the same way as the current vehicle fleet. NH_3-fueled vehicles, clearly however, unlike conventionally-fueled vehicles, do not directly release any carbon dioxide (Iowa Energy Center, 2013).

The transition to NH_3-fueled vehicles, unlike electric vehicles will be relatively simple. Most conventional cars on the road, including diesels, can run on a mixture of 90% gasoline (or diesel) and 10% liquid ammonia (nh3car, 2015), and could easily be modified to run on a mixture of up to 85% ammonia. This has already been demonstrated in spark ignited engines (Zacharakis-Jutz and Kong, 2013; HEC-TINA, 2015). The concept of the NH_3-fueled vehicles is quickly becoming a reality, and an engine that could run on 100% ammonia in a very near future is currently under development (NH_3 Fuel Association, 2013; Knight, 2011; Hollinger, 2015).

Regarding safety any safety concerns associated with ammonia fueled vehicles, studies have illustrated that ammonia would be safer than both gasoline and propane, another fuel sometimes used in LDV (Duijm et al., 2005; Quest Consultants Inc, 2009; Thomas and Parks, 2006). Ammonia has been commonly used as an industrial and agricultural chemical for over a century, and procedures have been developed to ensure NH_3 can be handled safely (Thomas and Parks, 2006). Ammonia dissipates rapidly when released because it is lighter than air. The US Department of Transportation assigns a "non-flammable liquid" designation to liquid ammonia carried in tanker trucks on highways.

The infrastructure for large-scale production and distribution of ammonia already exists worldwide, as ammonia is a major input to the chemicals industry, commercial refrigeration, NOx control, and especially agriculture as an essential nitrogen fertilizer. There are over 2000 miles of underground, low carbon steel pipelines in the United States heartland, operating 24/7 and operating at moderate pressures (e.g. compared to natural gas pipelines) and exhibiting an excellent safety and leak avoidance. NH_3 retail "filling stations" are widespread, particularly in rural areas. There is a network of approximately 800 such fueling stations in the state of Iowa alone. These "gas stations" would require reasonably modest changes to adapt to ammonia fueled cars as well, including converting them to be attendant operated. Ammonia can be easily stored in large pressurized "bullet" tanks at relatively low pressure, similar to liquefied petroleum gas (LPG) (Iowa Energy Center, 2013). At even greater volumes approaching 50,000 tons of storage, NH_3 is stored in atmospheric-pressure, self-liquified "terminals" which are located along the ammonia pipelines mentioned above.

Ammonia-fueled vehicles offer comparable range per tank of fuel as vehicles using conventional fuels partly because NH_3 combustion is more efficient (produces more horsepower for equal energy content of fuel) than gasoline or diesel (HEC-TINA 2015), making them similarly convenient to use.

$$2NH_3 + 3O_2 \rightarrow N_2 + 6H_2O.$$

The above equation shows that 1 mole of combusted NH_3 produces 3-1/2 moles of hot gas reaction products. That is better than H_2 and hydrocarbon combustion, including gasoline and diesel.

In near future, NH_3 fuel engineers would have developed direct NH_3 fuel cells, which should further increase mpg of NH_3 fuel cells LDV.

3. Reference case

Projected US LDV CO_2 emissions from Annual Energy Outlook 2013 (AEO2013) reference case projections prepared by the United States Department of Energy will serve as the reference case for this study (US Energy Information Administration, 2013). AEO 2013 provides projections of vehicle stocks, energy use, carbon dioxide emissions, and other parameters through the year 2040. US LDV stocks, average vehicle miles per gallon, vehicle miles traveled, and carbon dioxide emissions are projected in AEO 2013, shown in Table 1.

Even in 2040, 81% of LDV, in the AEO 2013 reference case projection, will still be fueled with gasoline. Interestingly, although LDV stocks increase by 26% in 2040 relative to 2010, and vehicle miles traveled increases 11% in 2040 over 2010, LDVs consume less fuel in 2040 than in 2010 because the average vehicle efficiency (expressed as miles per gallon) increases by 72% between 2010 and 2040. The net result of these changes is that overall CO_2 emissions from LDVs decrease through 2040, and by 2040 are more than 20% lower than 2010 emissions.

4. Mitigation strategies

4.1. Mitigation scenarios

Two scenarios, in addition to the AEO reference case, have been developed in this study to illustrate the CO_2 emissions mitigation potential of implementation of NH_3-fueled vehicles in the US LDV transportation sector through 2040. Table 2 shows the assumptions regarding phasing in NH_3-fueled vehicles in the US through 2040 for each scenario. The reference case of AEO projection does not exclude electric vehicles and fuel cell hydrogen vehicles, which are expected to have a similar effect on reducing CO_2 emissions.

4.2. Software tool to be used for analysis

To calculate CO_2 emissions reductions of emissions mitigation strategies, this study uses the software tool LEAP (the Long range Energy Alternatives Planning System), with which alternative

Table 1
US LDV stocks, average vehicle miles per gallon, vehicle miles traveled, and CO_2 emissions (2010–2040) (US Energy Information Administration, 2013).

Item	2010	2020	2030	2040
Total LDV stock (million)	225	239	262	284
Average vehicle miles per gallon	21.0	24.1	31.3	36.1
Vehicle miles traveled (VMT)	11,803	11,992	12,662	13,111
CO_2 emissions (million metric tons CO_2 equivalent per year)	1060	929	825	804

Table 2
Scenario assumptions for LDV in the US through 2040.

Reference case	Reference case of AEO 2013
Alternative 1 case	NH_3-fueled vehicles replacing gasoline vehicles to account for 10% of the vehicle fleet in 2020, 30% in 2030, and 50% in 2040, respectively
Alternative 2 case	NH_3-fueled vehicles replacing gasoline vehicles to account for 10% of the vehicle fleet in 2020, 50% in 2030, and 100% in 2040, respectively

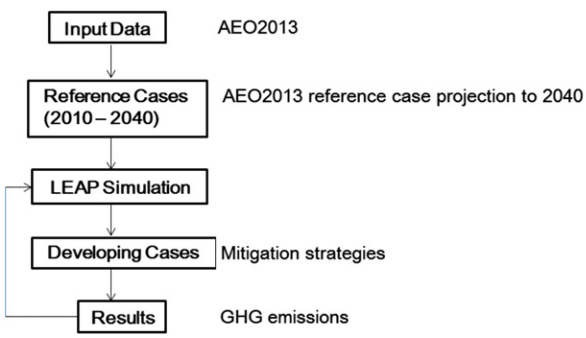

Fig. 1. Schematic of analytical approach.

scenarios can be created and evaluated by comparing their energy requirements, costs, and environmental impacts. LEAP is a software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute—United States (Stockholm Environment Institute, 2013).

4.3. Analysis approach

Fig. 1 illustrates the analytical approach used in the study to estimate potential reductions of CO_2 emissions in the US transportation sector through 2040 through development and application of the mitigation strategies considered, with future transportation sector activity as described in AEO2013 serving as the basis for analysis.

5. Results

5.1. Mitigation effects

Table 3 and Fig. 2 show US LDV CO_2 emissions through 2040 for each mitigation scenario using LEAP program. The estimated reference case LDV CO_2 emissions calculated using the LEAP model in this study are between one and seven percent, depending on the year, different than those in the AEO 2013 reference case. The discrepancies in LDV CO_2 emissions results between this study and AEO 2013 arise from the different assumptions used in the calculation of CO_2 emissions in both cases. These differences, however, do not affect the overall analytical conclusions reached by this study.

The Alternative 1 case could reduce cumulative LDV CO_2 emissions from 2010 through 2040 by about 20%, while the Alternative 2 case achieves reduction of about 30% of the cumulative LDV CO_2 emissions from 2010 through 2040 produced in the reference case. The Alternative 2 case eliminates most of the annual LDV CO_2 emissions in 2040 projected in the reference case, with a 96% reduction from reference case levels, equivalent to approximately 718 million metric tons CO_2 equivalent for a year.

5.2. Cost–benefit results

Besides emitting zero greenhouse gases from vehicles, NH_3 fuel could provide additional environmental benefits from the reduction of well-to-tank carbon emissions associated with the production and delivery of conventional fuels. Assuming around 21 g of CO_2 are emitted per megajoule of gasoline produced (Bandivadekar, 2008), an estimated well-to-tank CO_2 emission for a gasoline vehicle in America is approximately 1.5 metric tons of CO_2 per year, based on an average fuel economy of about 21 miles per gallon for the gasoline vehicle on the road in America and an average annual distance traveled per vehicle of 12,000 miles (US Environmental Protection Agency, 2011). Table 4 shows well-to-tank CO_2 emissions of LDV under the AEO 2013 reference case. The cumulative well-to-tank CO_2 emissions for gasoline engine LDV from 2010 through 2040 are approximately 7781 million metric tons CO_2 equivalent.

Compared to gasoline vehicles, NH_3-fueled vehicles do not produce carbon dioxide during operation. Although CO_2 would be emitted during, mostly truck delivered, NH_3 fuel delivery, it would be less than a few percent than that of the well-to-tank CO_2 emissions associated with gasoline fuel production and delivery in America shown in Table 4 (Bandivadekar, 2008).

Current industrial ammonia production plants, which run on fossil fuels, produce approximately 1.2–1.8 metric tons of CO_2 per ton of ammonia produced (Ganley et al., 2007; Wood and Annette Cowie, 2004). Assuming that NH_3-fueled vehicles have equivalent fuel energy input per mile of gasoline vehicles, one NH_3-fueled vehicle, if fueled with conventionally-produced NH_3, will cause emissions by ammonia-producing factories of somewhere between 4.2 and 6.1 metric tons CO_2 per year, which is 7%–36% less than that emitted by a similar gasoline vehicle. However, once advanced ammonia production methods (e.g. solid state ammonia synthesis, Ganley et al., 2007) that are now working at the lab scale are commercialized in the very near future, if non-fossil sources of electricity are used, no CO_2 emissions will be emitted during ammonia production process. This is also true with the electrolyzer and Haber–Bosch approach.

The retail price of gasoline on February 6, 2015 was $2.17 per gallon, according to US Energy Information Administration (2015). The average bulk ammonia price in 2014 was estimated at about $584 per metric ton (Apodaca, 2015). The estimated retail price of ammonia by comparing the wholesale price of gasoline with the retail price of gasoline is $2.13 per gallon. Advanced ammonia production methods would be expected to decrease ammonia production costs, and thus prices (Ganley et al., 2007; Yoon, 2013).

Table 5 shows required amount of ammonia in selected years to fuel each of the LDV NH_3-fueled vehicles penetration scenarios outlined above, plus estimates of the amount of electricity required to make ammonia in each scenario, assuming a commercially mature solid state ammonia synthesis method. This study assumes

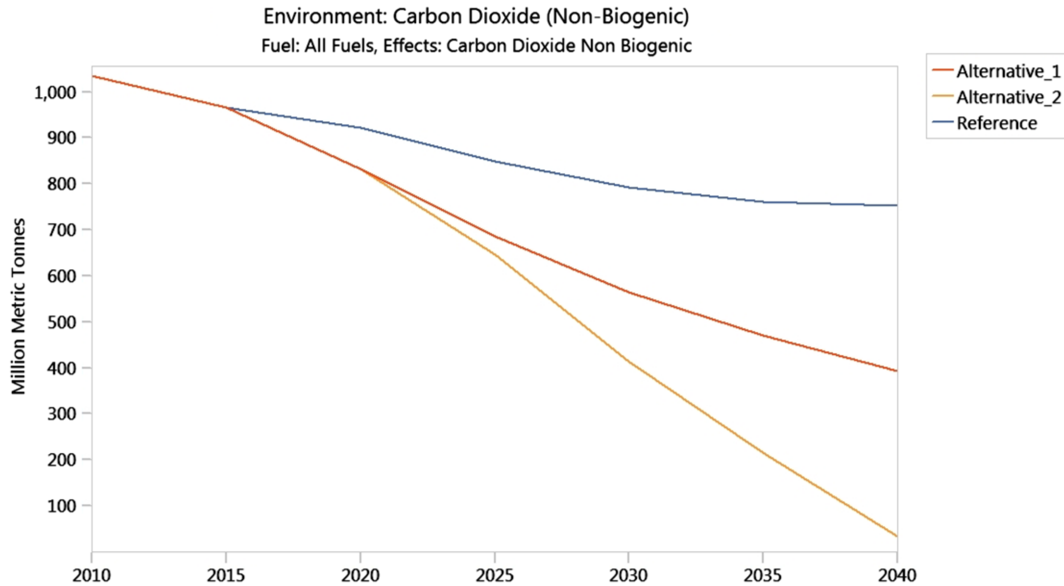

Fig. 2. US LDV CO_2 emissions through 2040 under scenarios including implementation of NH_3 as a fuel.

Table 3
US LDV CO_2 emissions through 2040 under scenarios compared with AEO 2013 reference case (Unit: million metric tons CO_2 equivalent per year).

Case	2010	2020	2030	2040	Cumulative (2010–2040)
Reference case (AEO2013)	1060	929	825	804	27,552
Reference case in this study	1035	921	792	752	26,817
Alternative 1 case	1035	832	565	393	21,879
Alternative 2 case	1035	832	413	34	18,556

Table 4
Well-to-tank CO_2 emissions for US gasoline engine LDV through 2040 for AEO 2013 reference case (Unit: million metric tons CO_2 equivalent per year).

Case	2010	2020	2030	2040	Cumulative (2010–2040)
Reference case (AEO2013)	308	268	227	215	7781

Table 5
Required ammonia and electricity to make ammonia through 2040 for each mitigation scenario.

Case	2010	2020	2030	2040
Alternative 1 case				
Ammonia (million metric tons)	0	61	156	247
Electricity (TWh)	0	430	1095	1731
Alternative 2 case				
Ammonia (million metric tons)	0	61	261	495
Electricity (TWh)	0	430	1825	3462

7000 kWh of electricity to produce one metric ton of ammonia, based on reports that the solid state ammonia synthesis method consumes around 6000–8000 kWh of electricity to produce one metric ton of ammonia (Ganley et al., 2007; Yoon, 2013). For the same energy content, liquid ammonia has 2.3 times the mass of gasoline (Grannel, 2008).

Projected in the AEO 2013 reference case, electric power capacities and electricity generation in America through 2040 are given in Table 6 (US Energy Information Administration, 2013). To implement the Alternative 2 case, additional electricity generation of 11% in 2020, 42% in 2030 and 74% in 2040, respectively, than those of AEO 2013 reference case, while electricity increases of 11% in 2020, 25% in 2030 and 37% in 2040, respectively, for the Alternative 1 case. Installation of additional electric power generation capacity sufficient to produce the ammonia required, particularly CO_2-free electricity, would be a major challenge in aggressive deployment of NH_3-fueled vehicles.

Table 6
Projections of power capacities and electricity generation in America through 2040 in AEO 2013 reference case.

Case	2010	2020	2030	2040
Fossil fuel (Coal, gas and oil)				
Power generation capacity (GWe)	720	699	756	835
Electricity output (TWh)	2608	2579	2836	3028
Nuclear energy				
Power generation capacity (GWe)	101	111	114	113
Electricity output (TWh)	807	885	908	903
Renewable energy				
Power generation capacity (GWe)	148	175	182	229
Electricity output (TWh)	394	557	601	753
Total				
Power generation capacity (GWe)	969	985	1051	1178
Electricity output (TWh)	3809	4021	4345	4684

If ammonia for NH_3-fueled vehicles was produced with nuclear energy and renewable energy, the GHG emissions produced would be near-zero. However, if ammonia for NH_3-fueled vehicles were produced with electricity generated by fossil energy, significant GHG emissions during power generation would result. The same problems would occur with electric vehicles and fuel cell hydrogen vehicles.

Gasoline vehicles can be retrofitted to run on mostly ammonia at a cost of between $1000 and $5000 (Yoon, 2013; Proefrock, 2007). Only LDVs already on the road would need to be converted at those prices. "New" NH_3 LDV's would cost the same as petroleum LDVs. Governmental subsides could encourage the public to adopt NH_3-fueled vehicles until automakers can produce NH_3-fueled vehicles on a large scale.

6. Conclusion

This study demonstrates that NH_3-fueled vehicles could be a promising alternative for LDV public/commercial conversion to fossil-free fuels because of its significant contribution in reducing CO_2 emissions compared with vehicles of carbon-based fuels.

Furthermore, NH_3-fueled vehicles could be quickly deployed in large scale since the infrastructure for large-scale production and distribution of ammonia already exists worldwide and gasoline vehicles can be retrofitted to run on mostly ammonia at a modest cost.

References

Apodaca, L.E., 2015. Nitrogen (Fixed)—Ammonia. US Geological Survey, Mineral Commodity Summaries, January.

Bandivadekar, A.P., 2008. Evaluating the impact of advanced vehicle and fuel technologies in US light-duty vehicle fleet (Ph.D. thesis), MIT.

Desrochers, Patrick, 2013. Making and treating NOx formed in NH_3 engines. In: 2013 NH_3 Fuel Conference, Sacramento, CA, September 22–25.

Duijm, N.J., Markert, F., Paulsen, J.L., 2005. Safety assessment of ammonia as a transportation fuel. Riso National Laboratory, Denmark, February.

Ganley, J.C., Holbrook, J.H., McKinley, D.E., 2007. Solid state ammonia synthesis. In: 2007 Annual NH_3 Fuel Conference, San Francisco, CA, October 15–16.

Grannel, S., 2008. The operating features of a stoichiometric, ammonia and gasoline dual fueled spark ignition engine (Ph.D. thesis), University of Michigan.

HEC-TINA web site. 2015. http://www.cleangreenengines.com/product/anhydrous-ammonia/.

Hollinger, T., 2015. Internal combustion Engines and Ammonia. Available from: https://nh3fuel.files.wordpress.com/2012/05/ted-hollinger.pdf.

Intergovernmental Panel on Climate Change, 27 September 2013. IPCC Fifth Assessment Report (WGI AR5).

Iowa Energy Center, 2013. NH_3—The Other Hydrogen report. Available from: http://www.iowaenergycenter.org/grant-and-research-library/nh3-the-other-hydrogen-report.

Knight, H., 2011. Portable ammonia factories could fuel clean cars. New Scientist, 1 September.

Kubic, W.L., 2006. Nuclear-Power Ammonia Production. Los Alamos National Laboratory, 9 October.

nh3car.com web site. 2015.

NH_3 Fuel Association web site. 2015. www.nh3fuelassociation.org.

NH_3 Fuel Association, 25 April 2013. Ammonia fueled sports car: Marangoni Toyota GT86 Eco Explorer. Available from: http://nh3fuelassociation.org/2013/04/25/ammonia-fuel-marangoni-eco-explorer/.

Proefrock, P., 2007. New Vehicle Burns Ammonia! Emissions: N2 and H2O, 8 August. Available from: http://www.ecogeek.org/component/content/article/861.

Quest Consultants Inc., June 2009. Comparative Quantitative Risk Assessment of Motor Gasoline, LPG and Anhydrous Ammonia as an Automotive Fuel.

Stockholm Environment Institute, 2013. An Introduction to LEAP. Available from: http://www.energycommunity.org/default.asp?action=47.

Tallaksen, J., Reese, M., 2013. Ammonia production using wind energy: An early calculation of life cycle carbon emissions and fossil energy consumption. In: 2013 NH_3 Fuel Conference, Sacramento, CA, September 22–25.

Thomas, G., Parks, G., 2006. Potential roles of ammonia in a hydrogen economy: A study of issues related to the use ammonia for on-board vehicular hydrogen storage. US Department of Energy, February.

US Energy Information Administration, April 2013. Annual Energy Outlook 2013 with Projections to 2040.

US Energy Information Administration, 6 February 2015, Today in Energy—Daily Prices. Available from: http://www.eia.gov/todayinenergy/prices.cfm.

US Environmental Protection Agency, December 2011. Greenhouse Gas Emissions from a Typical Passenger Vehicle.

US Environmental Protection Agency, 2012. Fast Facts: US Transportation Sector Greenhouse Gas Emissions 1990–2010.

Wood, S., Annette Cowie, A., 2004. A review of greenhouse gas emission factors for fertiliser production. Cooperative Research Centre for Greenhouse Accounting, June.

Yoon, H.C., 2013. Private communication. Korea Institute of Energy Research, June.

Zacharakis-Jutz, G.E., Kong, S.C., 2013. Characteristics of a spark ignition engine using direct ammonia injection. In: 2013 NH_3 Fuel Conference, Sacramento, CA, September 22–25.