DOE Hydrogen and Fuel Cells Program Record	
Record #: 16002	**Date:** February 9, 2016
Title: Environmental and Energy Security Benefits for APUs in Transportation Applications	
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Item

Analyses show that fuel cell auxiliary power units (APUs) for heavy duty freight vehicles and aircraft could save up to nearly 4.5 million metric tons (MT) of greenhouse gases (GHGs) per year and up to approximately 510 million gallons of petroleum per year by 2050 (if the fuel cell technology used on all freight trucks is assumed to be polymer electrolyte membrane [PEMFC]).

Data, Assumptions, and Results for Trucks

1. **In 2050, the total number of long-haul freight trucks (trip >500 miles) in the U.S. is estimated to be about 830,000.** The number of diesel Class 8 trucks forecasted in the Energy Information Administration's (EIA's) Annual Energy Outlook 2015 is 5.1 million in 2020, increasing to nearly 6.7 million in 2040. Of those, Brodrick et al. 2002 indicated that almost 460,000 travel 500 miles or more from home base—these tend to idle during rest periods. The total number of such trucks was assumed to increase slightly from the time the 2002 paper was written, to 480,000 in 2010. From there on, it was assumed that their number would grow at the same rate as the total number of Class 8 trucks projected by EIA (e.g., to nearly 760,000 in 2040). Extending the EIA projection linearly through 2050, their number would be approximately 830,000 out of 7.3 million diesel Class 8 trucks in 2050.
   Diesel consumption by idling main engine is estimated to be 0.5 gallon per hour. A typical heavy-duty truck consumes up to 1 gallon of diesel per hour when idling its main engine at 1,000 rpm engine speed, but only 0.5 gallon at 650 rpm (Cummins 2015). To be conservative in calculating fuel cell benefits, 0.5 gallon per hour with idling was assumed. A truck within the long-haul group idles approximately 1,818 hours per year (Brodrick et al. 2002).
2. **Diesel consumption by a solid oxide fuel cell (SOFC) APU is 0.32 gallon per hour**. In the 2012 report on the 21st Century Truck Partnership, the National Academies review panel cited 5 kW as the power of typical diesel APUs (National Academies 2012). In the future, it is expected that trucks and appliances on board will be more efficient, and hence a 4.5 kW fuel cell APU was assumed. This unit would consume 0.32 gallon of diesel per hour through the reforming process, based on scaling up the 0.15 gallon-per-hour estimate for a 2.1 kW load for the SOFC APU in Lutsey et al. 2005.
3. **Hydrogen consumption by a PEMFC APU is 0.2 kg per hour**. Brodrick et al. 2002 listed an estimated 0.13 GJ per hour as the hydrogen consumption rate for the PEMFC. The report did not list the fuel cell power explicitly. However, the team of Brodrick, Lutsey, and Lipman did assume 2.1 kW in their 2005 SOFC APU study. Hydrogen consumption was increased from the rate needed for 2.1 kW to match the assumed 4.5 kW basis, resulting in 0.2 kg per hour or nearly 364 kg per year (1,818 hours of operation per year to replace main engine idling).
4. **Petroleum savings associated with SOFC APUs**: Using the above results (including 1,818 hours of idling per year) and a 1.054 factor to estimate life-cycle (i.e., including upstream) petroleum, slightly larger quantity than the amount directly consumed (the 2015 GREET model [Argonne National Laboratory 2015] includes additional petroleum used, for example in shipping crude oil by tankers and transporting diesel fuel to retailers), the life-cycle petroleum consumption of an idling truck and a SOFC APU were compared.

Annual fuel savings (life-cycle) per truck with the SOFC APU:

958 gallons/year for idling – 616 gallons/year for SOFC = 342 gallons of diesel savings per year

Assuming that 20% and 40% of long-haul trucks are equipped with fuel cell APUs respectively in 2040 and 2050, the annual savings associated with 152 thousand APUs in 2040 and 332 thousand in 2050 are respectively 52 million and nearly 114 million gallons per year.

5. **GHGs emissions reduction in 2040 vs. 2050 associated with SOFC APUs**: EIA's basis for carbon emissions calculation from diesel combustion is 22.37 lb CO_2/gallon (Energy Information Administration 2008). The GREET factor for converting from diesel CO_2 emissions from a vehicle to life-cycle CO_2 diesel emissions is 1.175 to take into account upstream CO_2 emissions. Also, because GHGs include CH_4 and N_2O in addition to CO_2, the GREET factor for converting diesel CO_2 to diesel GHGs (unit: $CO_{2equivalent}$ or CO_{2e}) is 1.037. Consequently, the savings are:

   (22.37 lb CO_2/gallon)(1 MT/2,200 lb)(52 million gallons)(1.175)(1.037)= 0.64 million MT GHGs per year.

   Using the same approach for 114 million gallons saved, the GHGs savings are 1.4 million MT/year.

6. **Petroleum savings associated with PEMFC APUs**: Hydrogen canisters are assumed to be trucked from a central steam methane reforming (SMR) plant to fueling sites where truck drivers can obtain hydrogen along with diesel fuel. In addition to the small amount of petroleum used upstream from the SMR plant for natural gas drilling and extraction, trucking hydrogen to fueling sites requires petroleum. Using GREET information, life-cycle petroleum was estimated to be 0.0014 gallon per kg hydrogen, and 0.49 gallon per year for the 364 kg hydrogen consumption.

   Annual fuel savings per truck with the PEMFC APU:

   958 gallons/year for idling (from previous calculations) – 0.49 gallon/year for PEMFC = 957.5 gallons of diesel savings per year

   Assuming that 20% and 40% of long-haul trucks are equipped with fuel cell APUs in 2040 and 2050, respectively, the annual savings associated with 152 thousand APUs in 2040 and 332 thousand in 2050 are respectively 145 million and 318 million gallons per year.

7. **GHGs emissions reduction in 2040 vs. 2050 associated with PEMFC APUs**: Using information from GREET, the GHG intensity of each kg hydrogen is 14.36 kg GHGs. For the per-truck consumption of 364 kg hydrogen vs. 958 gallons of diesel, the savings associated with each APU is 6.4 MT GHGs per year. This translates to annual savings of 0.98 million MT GHGs and 2.1 million MT GHGs for 152 thousand APUs in 2040 and 352 thousand in 2050.

<u>**Data, Assumptions, and Results for Aircrafts**</u>

1. **In 2040 and 2050, jet fuel consumption in the U.S. is estimated to be about 557 and 579 million barrels per year, respectively.** The Annual Energy Outlook 2015 projected 3.08 quads of jet fuel in 2040, or 557 million barrels, corresponding to 3.2 quads and 579 million barrels when extrapolated to 2050. With the CO_2 intensity for jet fuel at 21.1 lb per kg fuel (Energy Information Administration 2008) and GREET life-cycle factor as previously discussed for diesel, each percentage reduction would result in saving over 5 million barrels of fuel and 0.473 million MT of life-cycle CO_2.
2. **Fuel savings fraction with SOFC APU is higher for shorter range aircraft**. NASA studies conducted by United Technologies and Honeywell (Srinivasan et al. 2006, Mak and Meier 2007, Gummalla et al. 2006) show that the percentage of fuel saved depends strongly on range because very long flights are associated with much less time spent on the ground (where taxiing and engine idling during waits are responsible for much of fuel consumption on the ground as shown in Airbus 2004) and, since fuel efficiency is already high for aircraft in steady flight, the benefit of APUs is less for long-range aircraft. More recently, a leading short-haul airline announced a new project involving fuel cells for minimizing jet fuel consumption during the taxiing phase (Carrington 2016), confirming the NASA studies. Based on the NASA studies' calculated savings of 0.7% for an 8,800-mile flight (Srinivasan et al. 2006) versus 3% to 6% for trips under 1,700 miles (Mak and

Meier 2007, Gummalla et al. 2006), it was assumed that regional flights (assumed at 800 miles or less) would experience a savings of 4.5%, and longer flights (>1,400 miles) a savings of 1.8%. These distances are based on Department of Transportation 2013 showing that in 2012 the average U.S. flight is 1,400 miles in length, and the average flight stage (per plane transfer) is 850 miles.

3. **Fuel cell APUs could reduce fuel consumption by up to 2% or 4.7 million barrels of petroleum per year.** An MIT study (Babikian et al. 2002) shows that prior to 2000, regional (i.e., shorter) flights accounted for more than 40% of the number of flights, but only 7% of total jet fuel consumption. The increasing volume of regional flights over the past 10 years (Regional Airlines Association 2015) led to the assumption of current regional flights' share at 8% of jet fuel consumption versus longer flights' 92%. These data allowed the calculation of the weighted average annual fuel savings at 2% of U.S. jet fuel:

   (4.5% x 8%) + (1.8% x 92%) = 2.0%

   For 2040 and 2050, assuming that 20% and 40% of jet planes would have fuel cell APUs and multiplying 557 million and 579 million barrels in 2040 and 2050 by (2% x 20% x 1.054) and (2% x 40% x 1.054) where 1.054 is the life-cycle petroleum multiplier for diesel and similar fuels, the savings are respectively 2.2 million and 4.7 million life-cycle barrels per year in 2040 and 2050.

4. **Fuel cell APUs could reduce GHGs emissions by up to 2.3 million MTs per year.** Using the CO_2 intensity for jet fuel at 21.1 lb per kg fuel and GREET's factors 1.175 and 1.037 from the previous diesel calculations to calculate life-cycle GHGs from engine CO_2 emissions, the 2.2 million and 4.7 million barrel savings would result in 1.1 million and 2.3 million MTs of annual GHGs savings in 2040 and 2050.

Independent Review

This analysis was reviewed by Dave Andress, DA and Associates, and Peter Devlin, DOE Fuel Cell Technologies Office.

References

Airbus. *Getting to Grips with Fuel Economy*. Issue 4, October 2004. http://www.smartcockpit.com/aircraft-ressources/Getting_To_Grips_With_Fuel_Economy.html

Argonne National Laboratory. Greenhouse Gases, Regulated Emissions and Energy use in Transportation (GREET) Model (2015). https://greet.es.anl.gov/

Babikian, R., Lukachko, L., Waitz, I. *The Historical Fuel Efficiency Characteristics of Regional Aircraft from Technological, Operational, and Cost Perspectives*. Massachusetts Institute of Technology, 2002.

Brodrick, C.J., Farshchi, M., Lutsey, N., Lipman, T., Dwyer, H., Sperling, D., Gouse III, S.W., Harris, D.B., King Jr., F.G. *Evaluation of Fuel Cell Auxiliary Power Units for Heavy-Duty Diesel Trucks*. Transportation Research Part D. 2002. Transportation Research Board. http://www.sciencedirect.com/science/article/pii/S1361920901000268

Carrington, D. *Easyjet Unveils Plan for "Hybrid Planes" Using Hydrogen Fuel Cell*s. February 2, 2016. http://edition.cnn.com/2016/02/02/aviation/easyjet-hybrid-plane-hydrogen-fuel-cell/index.html?eref=rss_topstories

Cummins Corporation. *Secrets of Better Fuel Economy*. 2015. http://cumminsengines.com/uploads/docs/Secrets%20of%20Better%20Fuel%20Economy_whitepaper.pdf

Department of Transportation. *Total Passengers on U.S. Airlines and Foreign Airlines U.S. Flights Increased 1.3% in 2012 from 2011*. April 4, 2013. http://www.rita.dot.gov/bts/press_releases/bts016_13

Energy Information Administration, Annual Energy Outlook 2015. http://www.eia.gov/forecasts/aeo/

Energy Information Administration. 2008. www.eia.gov/survey/form/eia_1605/excel/Fuel_Emission_Factors.xls

Gummalla, M., Pandy, A., Braun, R., Carriere, T., Yamanis, J., Vanderspurt, T., Hardin, L. *Fuel Cell Airframe Integration Study for Short-Range Aircraft*. September 2006 (United Technologies Research Center for NASA). http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060051725.pdf

Lutsey, N., Lipman, T., Brodrick, C.J. *Analysis of Potential Fuel Consumption and Emissions Reduction from Fuel Cell Auxiliary Power Units (APUs) in Long Haul Trucks*, Elsevier Science Direct, Energy 32 (2005) 2428-2438.

Mak, A, Meier, J. *Fuel Cell Auxiliary Power Study*. February 2007 (Honeywell Engines, Systems & Services for NASA). http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070014605.pdf

National Academies of Science and Engineering. *Review of the 21st Century Truck Partnership, 2012.* Finding 6.3. http://www.nap.edu/catalog/13288/review-of-the-21st-century-truck-partnership-second-report

Regional Airlines Association. http://www.raa.org/resource/resmgr/AR2014/RAA2014_MajorsRegionalsShare.jpg

Srinivasan, H., Yamanis, J., Welch, R., Tulyani, S., Hardin, L. *Solid Oxide Fuel Cell APU Feasibility Study for a Long Range Commercial Aircraft Using UTC ITAPS Approach*. December 2006 (United Technologies Research Center for NASA). http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070004892.pdf