

IX.6 Fuel Cells as Range Extenders for Battery Electric Vehicles

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- Demonstrated the benefits of using fuel cell systems to double the range of current BEVs for medium-duty applications.



INTRODUCTION

The goal of this project is to analyze the cost–benefit tradeoffs of adding a fuel cell APU to a BEV to double its range. Doubling battery size is an option, but it comes with a considerable increase in vehicle cost. A novel approach that addresses this cost increase is to supplement the stored electrical energy of the BEV with a hydrogen fuel cell APU. The addition of a low-power APU, providing tractive power to double the range of the BEV, could be a cost-effective alternative for doubling the battery energy. This paper explores such an architecture for a Class 4 medium-duty pickup and delivery (P&D) truck using two different vehicle-level control strategies and using the levelized cost of driving (LCOD) as the basis for a cost comparison.

APPROACH

The APU power and APU fuel mass were allowed to change independently of each other. Figure 1 is a flow chart illustrating this approach.

A BEV was the starting point. This vehicle was created using future 2015 DOE assumptions for each powertrain component. The BEV was then sized to have a range twice that of the baseline BEV. This new BEV is referred to in this paper as a 2X BEV. A fuel cell APU with storage was added to this vehicle, thereby allowing the battery to then be downsized in power and in energy. Since the fuel mass was decoupled from the power, a two-dimensional parametric sweep of

Overall Objectives

- Demonstrate the cost–benefit tradeoffs of adding a fuel cell auxiliary power unit (APU) to double the range of existing battery electric vehicles (BEVs)
- Quantify the cost benefit of using a fuel cell APU for different vehicle classes based on levelized cost of driving

Fiscal Year (FY) 2013 Objectives

- Optimize the component sizing and vehicle level energy management of each individual vehicle considered
- Quantify the cost benefit of using a fuel cell APU for one compact car and one medium-duty vehicle
- Write a report summarizing the benefits of using a fuel cell APU to double the range of current BEVs

Technical Barriers

This project addresses the following technical barriers from the Market Transformation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

- (F) Inadequate user experience for many hydrogen and fuel cell applications

FY 2013 Accomplishments

- Developed vehicle-level energy management to properly evaluate the benefits of using fuel cell system power and onboard hydrogen storage.
- Quantified the trade-off between energy consumption and cost on the Urban Dynamometer Driving Schedule.

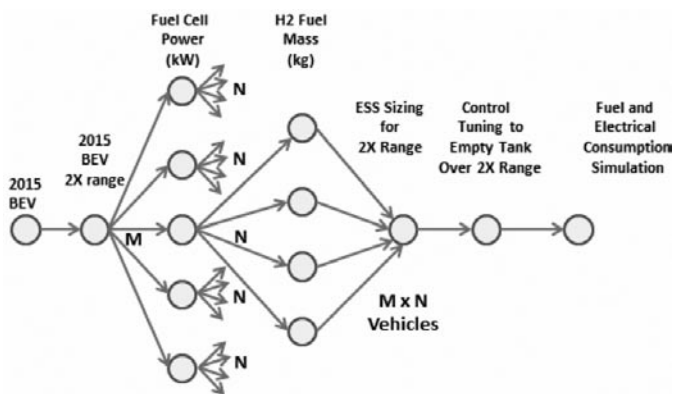


FIGURE 1. Number of Vehicles Considered – Control Strategy Based on Fuel Cell Rated Power

power versus fuel mass could be performed on the APU. The assumptions of the Class 4 P&D are similar to the Navistar EStar [1]. The cost assumptions for the fuel cell system and the hydrogen storage were provided by Strategic Analysis.

RESULTS

Two separate vehicle level control strategies were developed as part of the study. The following paragraph focuses on the control where the fuel cell system is used at its rated power. That approach has the advantage of minimizing fuel cell system cost and consequently maximize the benefits of using a fuel cell APU.

Figure 2 shows the electrical and fuel consumption of the vehicles. In Figure 2a, one notices that as the amount of onboard hydrogen to consume increased, the electrical consumption decreased proportionally until the onboard

fuel mass reached 6 kg, at which point the electrical energy consumption was close to zero. Any additional fuel beyond 6 kg forced the range out of bounds, since the fuel energy exceeded the energy that the vehicle needed to complete the 2X range. Thus, at the 6 kg point, the vehicle transitioned from net charge-depleting to net charge-sustaining operation. Beyond 6 kg, the trip was not long enough to consume the entire mass of fuel, so the range constraint was exceeded to meet the constraint that the APU fuel tank had to be empty at the end of the trip. Figure 2b shows that, as expected, increasing the fuel mass increased the fuel consumption, because an increasingly larger mass of fuel had to be consumed over the trip distance in order to end the trip with an empty tank. Basically, fuel energy from the APU displaced electrical energy from the battery.

The top dashed line in Figure 3a shows the battery cost for a BEV, without the APU, using the baseline assumption

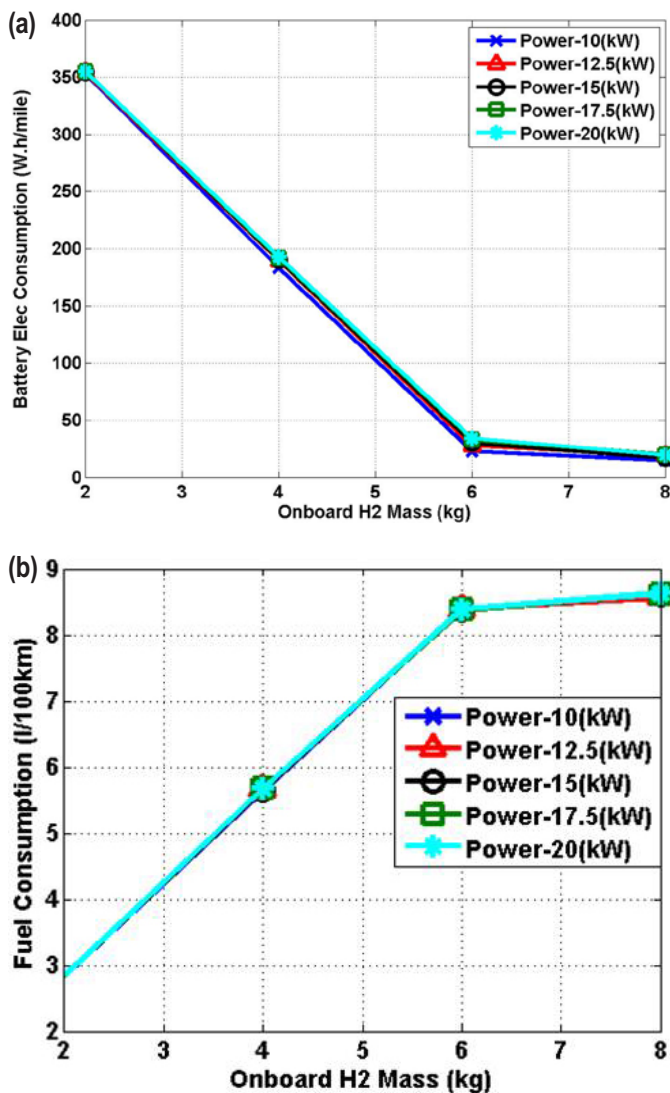


FIGURE 2. Battery Electrical Consumption (a) and Fuel Cell Fuel Consumption (b)

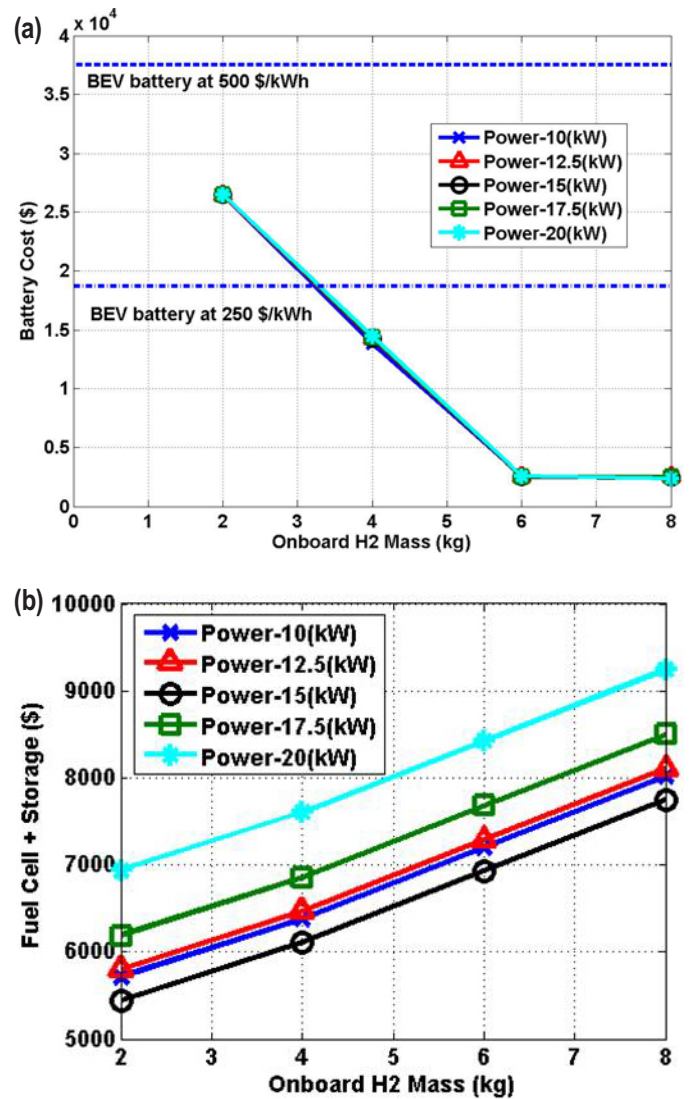


FIGURE 3. Battery Cost (a) and Fuel Cell System with Hydrogen Storage Cost (b)

of \$500/kWh. For comparison, the bottom dashed line shows the battery cost for a 2X BEV if an assumption of \$250/kWh is used for the battery's specific cost. Halving the specific cost for a BEV halves the battery cost. The fuel cell APU cost equation had two terms: one dependent on APU power, and the second dependent on hydrogen storage fuel mass. The APU cost linearly increased by \$2,500 when the hydrogen mass increased from 2 to 8 kg. The cost overall increased by \$1,500 when the power increased from 10 to 20 kW, but the relationship was nonlinear, and a local minimum was reached at 15 kW, as shown in Figure 3b.

The total manufacturing cost savings over the BEV for the Class 4 P&D truck is close to \$30,000 for a 15-kW APU with 6 kg of onboard storage. Figure 4 shows this result. Four other interesting vehicle cost cases are also shown in Figure 4 for comparison to the APU option. Case A is the manufacturing cost for a 2X BEV assuming the base specific battery is \$500/kWh. Case B is the manufacturing cost of a 2X BEV, assuming the specific battery cost is \$250/kWh instead of \$500/kWh. Case C is the manufacturing cost of a fuel cell hybrid electric vehicle (HEV) using the same production numbers as the APU of 10,000 units/year. Case D is the manufacturing cost of a fuel cell HEV using a production number of 500,000 units/year. This figure indicates that adding a fuel cell APU is always a viable option when the battery cost is \$500/kWh. Even if the battery cost matches the DOE cost targets, the APU still adds some benefit to reducing the cost of the BEV when supplying 6 kg of onboard storage. However, if the production numbers were to increase significantly by a factor of 50, the fuel cell HEV would become the most cost-effective option.

The LCOD is shown in Figure 5; it decreased by 38% compared to that of a 2X BEV, when using 6 kg of hydrogen. This figure uses the following assumptions: 5-year vehicle

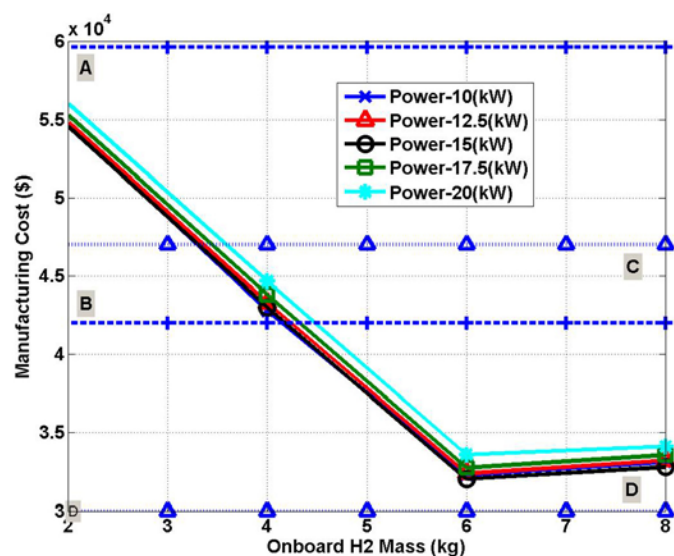


FIGURE 4. Manufacturing Cost for APU Vehicles

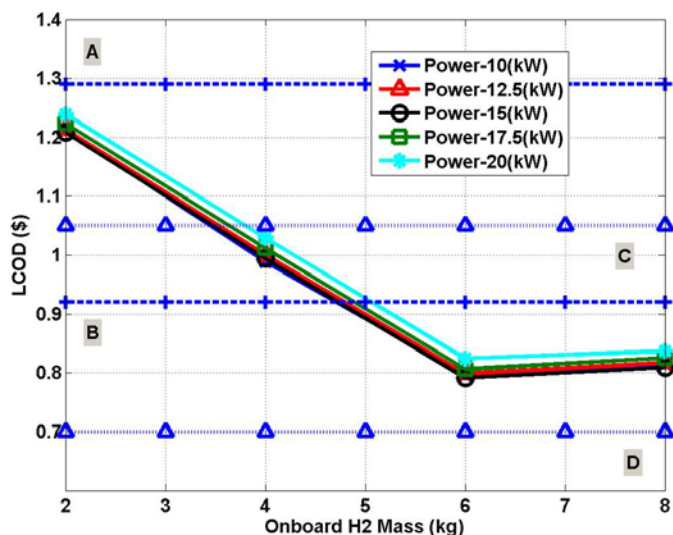


FIGURE 5. LCOD for APU Vehicles

life with 15,000 miles traveled per year. For comparison, line A shows the 2X BEV LCOD. Line B shows the 2X BEV assuming \$250/kWh. Line C shows the fuel cell HEV case assuming 10,000 units/year. Line D shows the fuel cell HEV case assuming 500,000 units/year.

CONCLUSIONS AND FUTURE DIRECTIONS

On the basis of the cost assumptions and drive cycles considered in this project, the following statements can be made regarding this specific combination of assumptions for a Class 4 P&D truck:

- Using a fuel cell system and storage is cheaper than using a battery to store energy.
- However, a Li-ion battery is cheaper than a fuel cell system for delivering power.
- Using a fuel cell that is close to its rated power (i.e., maximum power control) provides the lowest LCOD.
- For the Heavy-duty Hybrid Utility Trucks drive cycle considered and when the default LCOD assumptions in this paper are used, a 10-kW fuel cell system with 6 kg of onboard hydrogen would provide an optimum solution.
- Increasing vehicle lifetime, annual miles traveled, and fuel cost did not significantly change the relative benefit comparison between the maximum power strategy and the maximum efficiency strategy.
- The optimum onboard mass dropped to 2 kg for both the maximum power strategy and the maximum efficiency strategy when the fuel cost was \$8/gasoline gallon equivalent (in 2010 \$).
- The results are affected by the cost of hydrogen, vehicle lifetime, driving distance, and cost of the battery.

However, the fuel cell APU option consistently reached a lower LCOD when compared with a BEV with twice the original electric range when the cost of the fuel cell was considered at a production level of 10,000 units.

- When the production level was increased to greater numbers (e.g., 500,000), the fuel cell as a system was cheaper overall than the battery. At 500,000 units, it appears that it would be more cost effective to produce the fuel cell vehicle than a BEV and APU combination that has a 2X range

FY 2013 PUBLICATIONS/PRESENTATIONS

1. P. Sharer, A. Rousseau, “Benefits of Fuel Cell Range Extender for Medium-Duty Vehicle Applications”, EVS27, Barcelona, Nov 17–20 2013.

REFERENCES

1. Navistar, *eSTAR*TM, <http://www.estar-ev.com> accessed April 2012.