Cost Benefit Analysis of Technology Improvements in Medium- and Heavy-Duty Fuel Cell Vehicles

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Overall Objectives

- Quantify the impact of system improvements on energy consumption and economic viability of light-duty fuel cell electric vehicles (FCEVs).
- Expand the analysis to medium- and heavy-duty vehicles by developing new assumptions, powertrain sizing algorithms, and U.S. standard driving cycle processes.

Fiscal Year (FY) 2019 Objectives

- Quantify the impact of technology progress on light-duty FCEVs.
- Estimate the technology progress assumptions applicable for fuel cell electric trucks (FCETs) and their impact on energy consumption and cost.

Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan[1]:

- Inconsistent data, assumptions and guidelines
- Insufficient suite of models and tools
- Unplanned studies and analysis.

Contribution to Achievement of DOE Milestones

This project will contribute to achieving the following DOE milestones from the Systems Analysis section of the FCTO Multi-Year Research, Development, and Demonstration Plan:

- Milestone 1.1: Complete an analysis of the hydrogen infrastructure and technical target progress for hydrogen fuel and vehicles.
- Milestone 1.17: Complete analysis of program technology performance and cost status, and potential to enable use of fuel cells for a portfolio of commercial applications.
- Milestone 2.2: Annual model update and validation (fourth quarter of 2011 through fourth quarter of 2020).

FY 2019 Accomplishments

The impact of FCTO technologies on medium- and heavy-duty vehicles was completed for several classes and vocations. Previous studies have highlighted the importance of fuel cell system efficiency for trucks. Because fuel costs make up a large share of the operating costs for sleeper trucks, it is important to quantify the benefits of increased system efficiency across medium- and heavy-duty applications. In a previous study, we observed that for passenger cars the cost of improving fuel cell efficiency begins to outweigh the fuel saving benefits as the peak efficiency values approach ~64%. This study demonstrated that the benefit of improving efficiency can be justified for much higher levels for trucks

INTRODUCTION

Improvements in fuel cell system efficiency and hydrogen storage density help reduce fuel consumption and cost to the end user. However, these improvements come with an initial cost penalty. This study examines

[1] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

under which conditions a higher upfront component cost resulting from a more advanced technology is justified by future cost savings. The analysis compares current fuel cell vehicles with future technologies resulting from FCTO targets, both for the fuel cell and the hydrogen storage system.

APPROACH

Some of the main research related to hydrogen storage focuses on increasing its storage density. Currently, 4.5 kg of hydrogen can be stored in a 100-kg storage system. Based on FCTO targets, the share of usable hydrogen is expected to increase to 7.8 kg. In addition to reducing the storage system weight, the fuel cell system could also be downsized as a secondary benefit; both effects would result in reductions in fuel consumption. The fuel cell system efficiency has a more direct relationship with fuel.

Table 1. Assumptions for Computing the Present Value of Fuel Savings during the Ownership Period

Assumptions	Sleeper Truck
Service period in years	3
Discount rate (%)	7
Cost of hydrogen ($/kg)	4
Annual miles travelled	120,000

Because the fuel savings are realized over multiple years of ownership, we use the total present value (TPV) by aggregating the present value of that future savings with a discount rate. TPV is the maximum justifiable additional investment for acquiring a technologically superior vehicle. TPV considers the service time of the truck because that is usually the duration of ownership for the first owner. Potential savings after that period may not influence the first owner's purchase decisions. TPV computation uses the assumptions shown in Table 1.

The previous analysis performed for passenger cars [1] was a challenging use case because the fuel mass over a car's lifetime is quite low. A car may drive less than 14,000 miles in a year and consumes approximately 220 kg of hydrogen per year, while a sleeper truck could consume as much as 13,000 kg of hydrogen per year. As a result, a more efficient fuel cell system in a truck could save more money compared to the savings from a car. For every fuel cell system efficiency to storage weight ratio considered, the powertrain components are sized for the vehicle to achieve the desired performance characteristics. The vehicle requirements are shown in Table 2.

Table 2. Performance Requirements Used for Truck Sizing

Performance Requirement	Sleeper Truck
Drive cycle for fuel consumption estimation	EPA 55 mph
Sustainable speed at 6% grade (mph)	32
Acceleration time 0–60 mph (s)	60
Cruise speed (mph)	65
Driving range between refueling (miles)	500

The FCET is sized based on the above mentioned performance requirements. The sized vehicle specifications are shown in Table 3.

Table 3. Specifications of the Sized Vehicle

Vehicle Assumptions	Sleeper Truck
Cargo mass (lb)	38,000
Fuel cell power rating (kW)	360
Onboard hydrogen storage (kg)	90
Motor power rating (kW)	550
Battery for fuel cell dominant design (kWh)	5
Test weight (lb)	70,000
Driving range between refueling (miles)	500

This analysis uses a standard driving cycle proposed by the U.S. Environmental Protection Agency (EPA) for regulatory fuel consumption measurements (EPA55). This cycle has a steady speed target of 55 mph with varying grades. It is similar to driving conditions described in the Run On Less program conducted by the North American Council for Freight Efficiency (NACFE) [2]. NACFE's program had several fleets that were early adopters for many fuel saving technologies. Therefore, they are also expected to be among the first customers for FCETs. The hoteling loads and prolonged idling conditions that are associated with real-world operation of sleeper trucks are not considered in this evaluation.

RESULTS

We consider peak fuel cell system efficiencies ranging from 60% to 72% and storage densities ranging from 4.5 to 7.5 kg of H_2 per 100-kg tank. The resulting fuel economy (miles per kg of H_2) for a sleeper truck is shown in Figure 1. Note that the fuel cell system efficiency has a much larger impact on fuel consumption than the storage density.

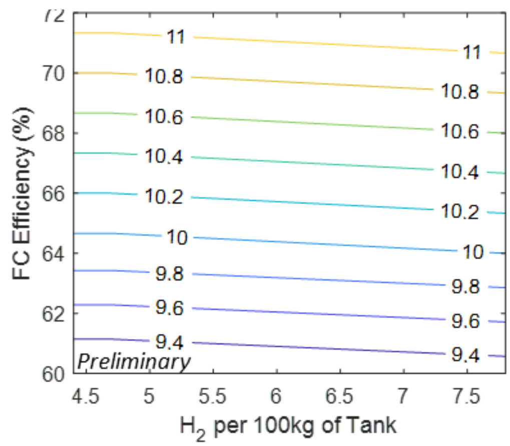

Figure 1. Variation of fuel economy in miles per kilogram with improvements in technology

Fuel cost will vary with improved fuel economy. The present value of these future fuel costs shows monetary value of technology improvements.

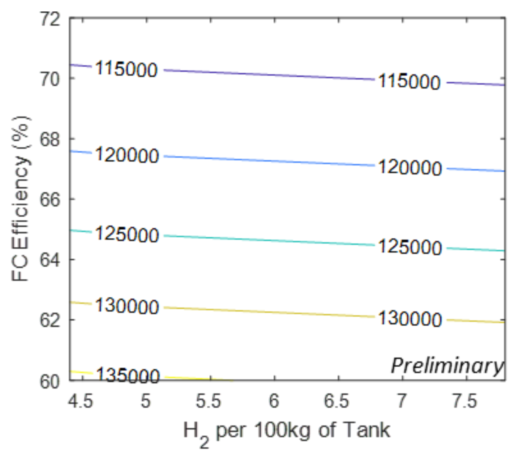

Figure 2. Present value of fuel cost in sleeper trucks over their service period

The present value of the future fuel costs is shown in Figure 2. A fuel cell powered sleeper truck of today will consume about $135,000 worth of fuel, whereas a more efficient fuel cell can reduce the fuel costs by over $20,000.

Figure 3 shows the difference in fuel cost of more advanced fuel cell trucks compared to a truck using technology available today. It represents the maximum additional investment one can justify in more efficient FCETs. It shows that the savings are more sensitive to the fuel cell efficiency in both cases. Even with aggressive reduction in the tank weight, *r*, the savings are marginal compared to those produced by fuel cell efficiency improvements.

To compare this savings to the cost of producing fuel cells, we convert both costs to dollars per kilowatt. For example, when $23,000 savings is achieved by improving the efficiency by 12 percentage points, in a truck with a 345-kW fuel cell (assuming a worst-case scenario for fuel cell system efficiency and tank weight), an additional investment of $67/kW is justifiable for improving the efficiency from 60% to 72%.

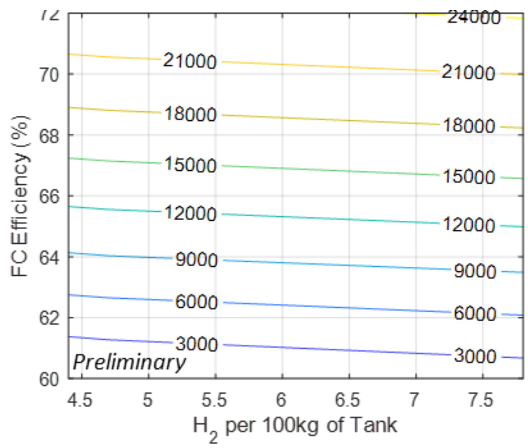

Figure 3. Present value of fuel savings in sleeper trucks achieved over the service period

Impact of Hydrogen Cost on Savings

The cost of hydrogen has a significant impact on the maximum acceptable incremental component cost. In this study, we consider hydrogen costs that range from $4/kg to $16/kg to estimate uncertainty. The TPV of fuel savings is plotted against the efficiency improvement that resulted in those savings in Figure 4.

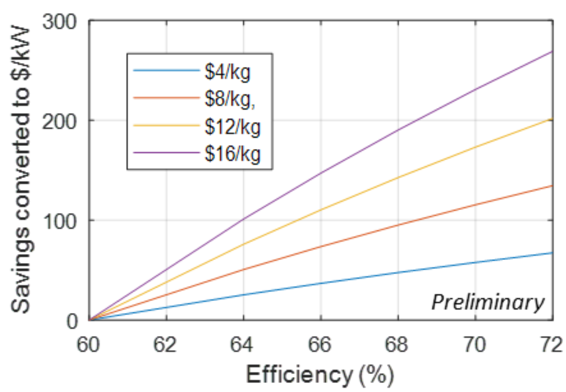

Figure 4. TPV of savings for varying levels of efficiency improvements

Cost of Improving Fuel Cell Efficiency

The analysis of light-duty fuel cells showed various design solutions for efficiencies ranging from 60% to 64%, and their cost of production was expressed as $/kW. The solutions shown in Figure 5 were developed using GCTool, for various platinum loading and thermal design conditions, by fuel cell experts at Argonne [3].

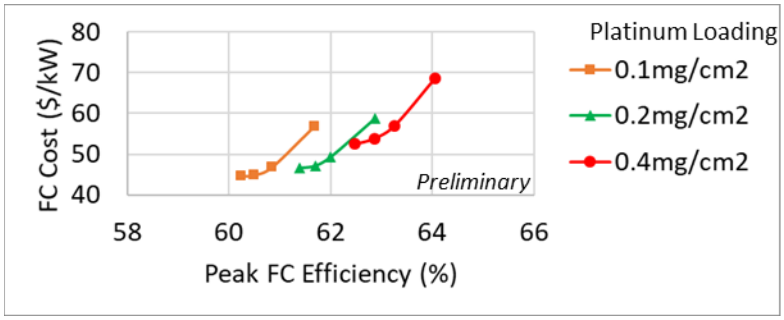

Figure 5. Cost of improving the efficiency of fuel cells

This analysis covered the improvement up to 64% peak efficiency for the fuel cell. If we compare the incremental cost of fuel cells from Figure 5, we notice that the 64% efficient fuel cell system design is $25/kW more expensive than the 60% efficient solution. This is similar to the savings observed for the $4/kg scenario in Figure 4.

Based on the FCTO target-setting documents for medium- and heavy-duty vehicles, the targeted cost of a 72% efficient fuel cell is expected to decrease under $80/kW, as the production volumes increase. In a scenario where those FCTO cost targets are met, the savings shown in Figure 4 will outweigh the cost.

To evaluate a worst-case scenario where the design changes produce incremental increases in cost and efficiency, the data from GCTool (up to 64% efficiency) is extrapolated to produce low- and high-cost estimates for higher efficiency fuel cells. This is an approximate assumption based on design solutions from GCTool and FCTO cost targets, and fuel cell experts have reviewed it. Figure 6 shows the assumed incremental cost of improving the efficiency of the fuel cell.

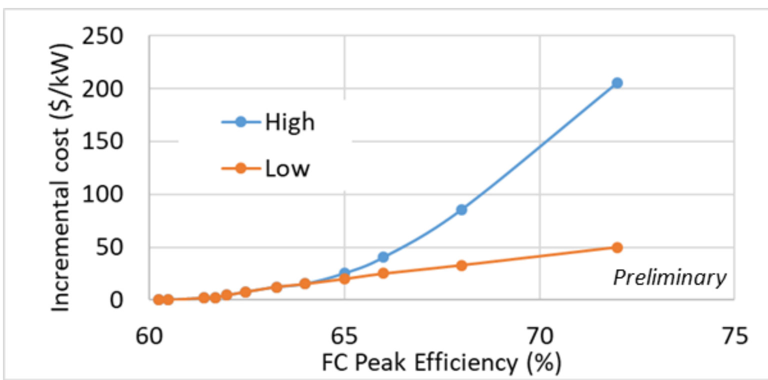

Figure 6. Assumed incremental cost in achieving higher efficiency for fuel cells

Net Savings

We then compute the net savings by deducting the cost from the present value of future savings (Figure 7). The left panel shows that the low cost estimates result in net savings irrespective of efficiency. This shows that even if the incremental cost of improving efficiency is as high as $50/kW for a 72% efficient fuel cell, it will result in savings for the consumer. On the other hand, if we assume a more pessimistic cost for the high-efficiency fuel cells, for hydrogen cost at $4/kg, the cost starts to outweigh the savings as we approach 66% peak efficiency.

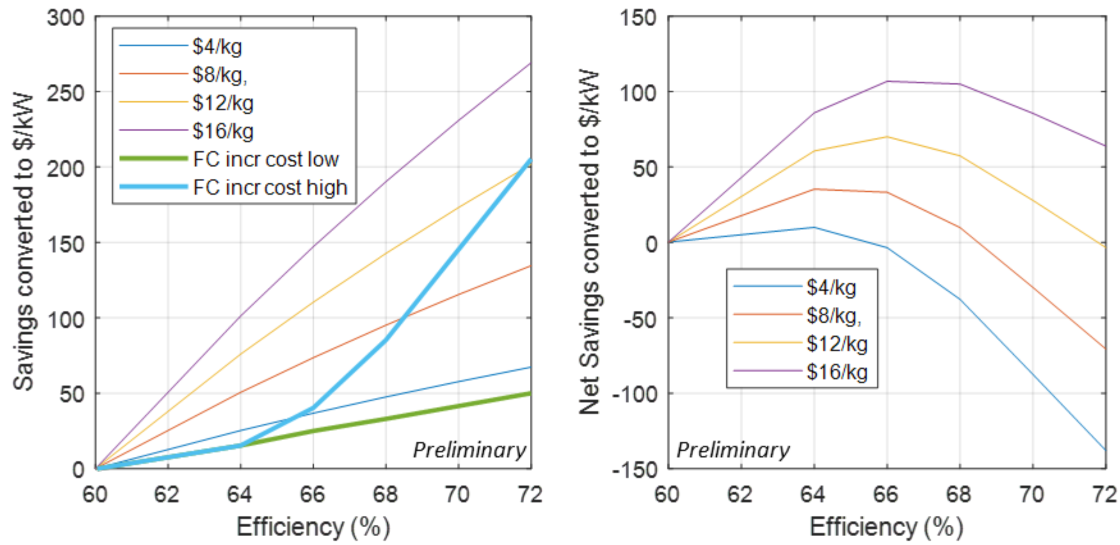

Figure 7. Savings, initial cost, and net monetary benefits

CONCLUSIONS AND UPCOMING ACTIVITIES

This study quantifies the value of fuel cell system efficiency improvement for a present-day sleeper truck on fuel consumption and TPV. The TPV of future fuel savings is compared to the additional cost of producing higher efficiency fuel cells. Multiple hydrogen costs were considered to evaluate short-term as well as long-term scenarios. The amount of fuel savings provides an upper limit for the justifiable incremental cost in improving the efficiency of fuel cells for this particular application.

Depending on the hydrogen cost, the maximum fuel cell system efficiency that would be economically attractive for present-day line-haul trucks will be as low as 66% ($4/kg) and as high as 72% ($12/kg). Those values are higher than those previously estimated for passenger car vehicles.

REFERENCES

1. R. Vijayagopal et al., "Cost Benefits Analysis of Technology Improvement in Light Duty Fuel Cell Vehicles," DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, 2018.
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