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Benefits of Fuel Cell Range Extender for Medium-Duty Vehicle Applications

P. Sharer[1], A. Rousseau [1]

[1]*Argonne National Laborator, 9700 S. Cass Ave., Argonne, IL, 60439 USA, arousseau@anl.gov*

Abstract

Hydrogen-powered vehicles have long shown great potential to displace fuel. However, due to the lack of infrastructure and the high cost of the components, the technology has not yet been introduced in the market. On the other hand, current battery electric vehicles (BEVs) also hold great promise, but their market penetration is limited due to their range. This study seeks to address the limitations of both technologies with regard to the medium-duty vehicle market by assessing the fuel displacement and cost–benefit potential of adding fuel cell systems to double the current range of BEVs. The addition of a fuel cell system will address drivers' anxiety over the range of BEVs while minimizing the powertrain cost through optimized component sizing.

Keywords: commercial, truck, EV, EREV, fuel cell, hydrogen, lithium battery

1 Introduction

The goal of this study is to analyze the cost–benefit tradeoffs of adding a fuel cell auxiliary power unit (APU) to a battery electric vehicle (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.

2 Methodology

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

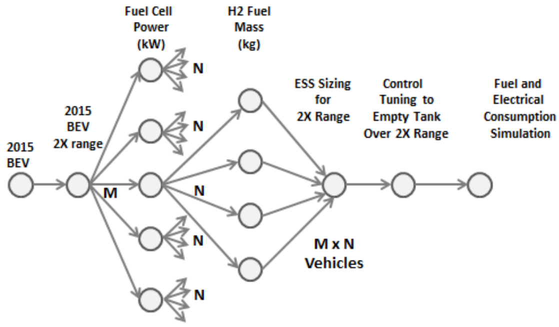

Figure 1: Number of Vehicles Considered – Control Strategy Based on Fuel Cell Rated Power

A BEV was the starting point. This vehicle was created using future 2015 U.S. Department of Energy (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 power versus fuel mass could be performed on the APU. Figure 2 shows an example grid that was swept. Not all combinations of power and fuel mass were admissible. Some fuel masses were too large to be completely consumed by a given APU power over the doubled range. For the points in this region of the grid, dropping the on power threshold to zero would not be enough to ensure that the vehicle completed its doubled range with an empty tank.

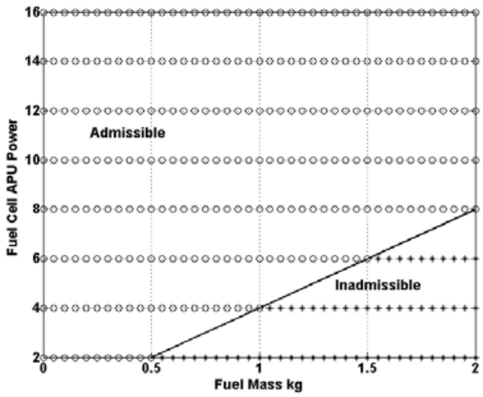

Figure 2: Number of Vehicles Considered – Admissible Vehicle

2.1 Modeling Software

All simulations discussed in this paper were performed with Autonomie, a modeling tool developed by Argonne National Laboratory. Autonomie is a plug-and-play model development environment that supports the rapid evaluation of new powertrain technologies [1]. The model and control library provided by Autonomie is forward looking and written in Matlab, Simulink, and Stateflow.

2.2 Process

For this study, due to the large number of combinations of component sizes, a large number of vehicles had to be sized and simulated — more than 200 vehicles. To run this number of simulations, a distributed computing process was implemented in Autonomie that made use of the Mathwork's Distributed Computing Toolbox. A 32 worker cluster significantly reduced the time it took to run the study; each one of the 200+ vehicles took several minutes to size and run. Figure 3 illustrates the use of distributed computing to facilitate this study.

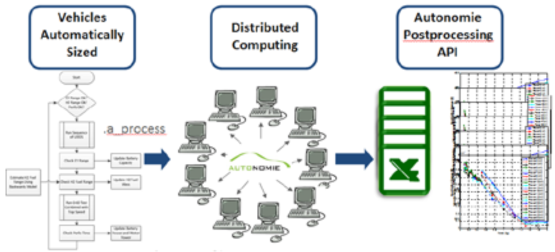

Figure 3: Autonomie Using Distributed Computing

2.3 Control

Several different control strategies were considered for managing the fuel cell APU power during a trip. Results from two strategies are discussed in this paper. The first was the maximum power strategy. It used the APU at its maximum power. The APU activated when the vehicle road load power threshold was reached. While active, the APU delivered a constant power equal to its maximum power, or rated power. The other control strategy considered was a maximum efficiency strategy. It also activated the fuel cell when the road load power threshold was reached, but it delivered the power at the peak efficiency, which was round 25% of the APU's maximum power. Figure 4 illustrates the difference in power and efficiency between these two fuel cell operating strategies. For the maximum efficiency strategy to deliver the same operating power during a drive cycle as the maximum power strategy, the fuel system had to be sized larger for the maximum efficiency strategy than for the maximum power strategy. The benefit was that the APU ran at a higher efficiency, so it consumed less fuel while delivering the same power as the maximum power strategy. Because of this, the maximum efficiency strategy could use a smaller fuel tank than the maximum power strategy. The phrase "activating the fuel cell APU" is used instead of "turning on the fuel cell APU" because the APU was idling during the entire trip. This is a standard characteristic of fuel cell systems: they require a small amount of hydrogen to be consumed to keep them alive and ready to deliver power. So, "activate," in general, refers to the net power out of the fuel cell system being greater than zero. The fuel cell is either "idling" (delivering zero net power) or "active" (delivering a nonzero net power). Thus, the power activate threshold is really a delivering power threshold.

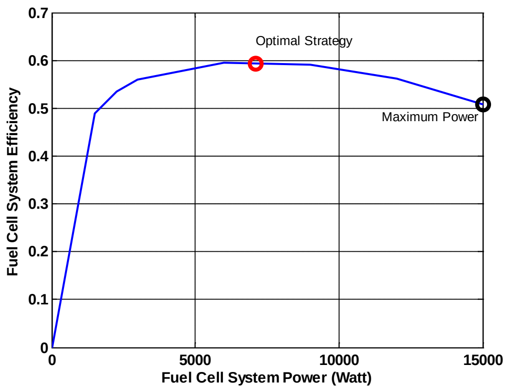

Figure 4: Fuel Cell System Efficiency Versus Power

2.4 Sizing

Since the APU power was used at its rated power, both the APU and the hydrogen mass stored on board were fixed. As a result, the main variable was the battery energy. The vehicle-level control parameter dictating when the APU provided power was part of an optimization loop that ensured that (1) all of the hydrogen was consumed at the end of the 2X trip and (2) the hydrogen was consumed throughout the cycle (i.e., not all near the beginning or all near the end). As is the case for any sizing algorithm, the process was iterative as the power and mass of each component was updated during each loop.

To begin the sizing process, a default electric vehicle was created. A simulation was then performed to determine the vehicle's all-electric range. This default vehicle was called the 1X range vehicle. The vehicle was then resized by adding enough battery power to the vehicle to double its all-electric range. This new vehicle was called the 2X range vehicle. An APU and fuel tank were added to the vehicle, and the power and fuel mass were parametrically swept. As the fuel mass increased, the battery energy was decreased to maintain the 2X range.

The flow chart in Figure 5 further illustrates the steps in the sizing process.

Step 1: Run sequence cycles. As the name implies, a sequence of a chosen drive was run. For the Class 4 P&D truck, the Class 4 HTUF cycle was used.

Step 2: Check EV range and update battery capacity. Using the full history of the range attained by the vehicle from each sizing run, the desired range, and the current battery energy, a new estimate was made for the desired battery energy. The number of cells in series and parallel was held constant, so that the battery energy was changed by changing the capacity of the battery.

Step 3: Check hydrogen fuel range and update fuel cell activation threshold. The range over which the fuel cell was used during the sequence of cycles was checked. This range should equal the 2X range of the vehicle. The mass of the fuel was fixed for the vehicle based on the value chosen from the parametric sweep. However, the rate at which hydrogen was consumed was determined by the operating power of the APU and the APU activation threshold. The APU control strategy was simple. The APU remained off until the threshold was reached. Once the activation threshold was reached, the fuel cell would turn on, and it delivered a constant power until the power demand at the wheels dropped below the threshold. Hence, to control the rate at which fuel was consumed over the cycle, the "activate power" threshold had to be adjusted. A very low "activate power" threshold caused hydrogen to be used quickly, which, in turn, caused the hydrogen fuel range to fall short of the 2X target. A very high "power on" threshold caused hydrogen to be used slowly, resulting in the tank still being filled with hydrogen even after the 2X range was met. This last condition was undesirable, so the backwards estimate was set to err on the side of using the hydrogen too quickly rather than to slowly.

Step 4: Check performance run initial vehicle movement (IVM) up to 60 mph. The IVM to 60 mph is recorded for the vehicle. The definition of IVM is that the vehicle has to move 1 ft (1/3 m) before the clock starts to record the performance time. This metric provides a more consistent result and removes phenomena that are difficult to model at initial acceleration, such as tire and clutch slip, from consideration.

Step 5: Update motor power and battery power. Once the time from IVM to 60 mph had been computed from the performance simulation run, Newton's method was used to determine the motor power at which the difference between the simulated performance time and the desired performance time was 0. The sizing calculated battery power directly from this simulation run. This was done by effectively removing the battery constraint on the motor during the performance simulation run. The peak power of the battery during the simulation run was then recorded and used for the target battery power in the next iteration of the sizing loop. Thus, as the motor power converged, the battery power converged.

Once these five steps were completed, the loop began again to check that the EV range, the hydrogen fuel range, and the performance time were all within the desired tolerances.

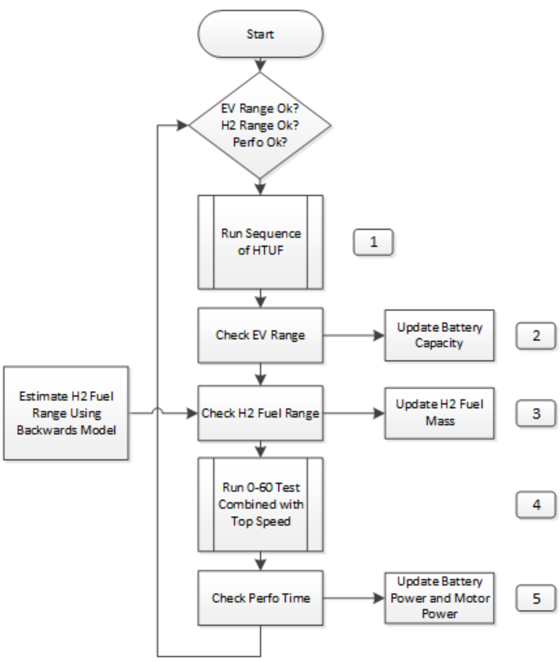

Figure 5: Sizing Algorithm

The APU activation threshold was determined by setting the desired range, choosing the battery energy, and choosing the battery power, and then assuming that the APU would deliver a constant power.

3 Vehicle Assumptions

The assumptions for the Class 4 P&D truck are shown in Table 1 [3]. The numbers represent a vehicle in 2015 (i.e., they are representative of technology assumed to be available in 2015). Recall that the fuel cell APU is assumed to idle throughout the entire trip. Thus, even when the vehicle is stopped, the fuel cell idles, consuming a small amount of hydrogen to keep the fuel cell system alive.

Table 1: Class 4 Pickup and Delivery Truck Assumptions

Assumption	Value
Vehicle test weight	3900 kg (baseline)
Transmission type	Automatic
Transmission	3.1, 1.81, 1.41, 1, 0.71
Motor type	Permanent magnet
Motor power	70 kW
Battery type	Li-ion
Battery power	345 W/cell, 83 kW/pack
Battery energy	327 Wh/cell, 80 kWh/pack
Battery capacity	84 Ah/cell
Nominal voltage	317 V
Number of cells	80 series x 3 parallel strings (240 cells/pack)
Rolling resistance	0.0075
Coefficient of drag	0.56
Frontal area	4.7500 m^2
Fuel cell APU peak eff.	60% (50% at rated power)
Fuel cell idles all the time	True
Payload	1,159 kg

Figure 6 shows the cycle used to determine the range for the Class 4 truck. The cycle is a standard medium-duty driving cycle: the HTUF pickup and delivery cycle [4].

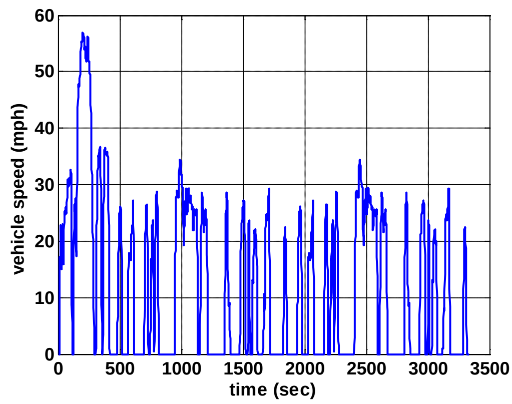

Figure 6: HTUF Pickup and Delivery

Table 2 shows the assumptions for specific power and energy for the powertrain systems. Unless otherwise noted, these are the values used.

Table 2: Specific Power and Energy Assumptions

Assumption	Value
Energy storage system (ESS) specific energy	290 Wh/kg
Battery oversizing factor	1.2
Motor specific power	1,500 W/kg
Motor control specific power	13,000 W/kg
Fuel cell specific power	617 W/kg
Fuel cell oversizing factor	1.1
Storage capacity constant	18.0 kg
Storage capacity slope	16 kg/(kg of H_2)

4 Cost Assumptions

4.1 Fuel Cell APU Cost

4.1.1 Fuel Cell APU System Base Cost

Table 3 shows the assumptions for specific cost for the APU as a function of power, assuming a production number of 10,000 units/year.

Table 3: Fuel Cell APU Specific Power Cost

Fuel Cell Rated Power (kW)	2010 $/kW at 10,000 Units/yr	Total Cost (2010 $)
15	298.33*	4,475
14	333.5	4,670
12	404.0	4,848
10	474.4	4,744
8	544.6	4,359
6	615.3	3,692
5	650.51	3,253

4.1.2 Fuel Cell APU Storage Base Cost

Table 4 shows the assumptions for the specific cost for APU storage as a function of energy stored, assuming production of 10,000 units/yr.

Table 4: Fuel Cell APU Specific Energy Cost

Fuel Cell Rated Energy (kg)	2010 $/kWh at 10,000 Units/yr	Total Cost (2010 $)
4.0	12.29	1,639
3.0	13.13	1,313
2.0	14.52	968
1.0	19.08	636
0.5	28.05	468

4.2 Battery Base Cost

Equation 1 computes cost for the battery as a function of power and energy.

$$Cost = \max\left(C_{pwr} \times P_{bol}, C_{erg} \times E_{bol}\right) \quad (1)$$

where C_{pwr} is the coefficient of power shown in Table 5, C_{erg} is the coefficient of energy shown in Table 5, P_{bol} is the beginning-of-life power of the battery, and E_{bol} is the beginning-of-life energy of the battery. These cost coefficients assume a production number of 500 000 units/year.

Table 5: Battery Cost Assumptions

Coefficient	Value (2010 $)
Power coefficient	$20/kW
Energy coefficient	$250/kWh

4.3 Levelized Cost of Driving

Unless otherwise indicated, the levelized cost of driving assumptions for the Class 4 P&D truck are given in Table 6.

Table 6: Levelized Cost of Driving Assumptions

Assumption	Value
Time frame	2015
Vehicle lifetime	5 years
Carbon cost per mile	0
Noncapital cost per mile	0
Charger efficiency	88%
Discount rate	0
Retail price equivalent	1.5
Annual miles traveled	14,529 mi
Fuel hydrogen	$3.50/gge
Electricity cost	$0.11/kWh
NPV fuel and electricity combined discount factor	1

5 Results

5.1 Fuel Cell APU Maximum Power Control Strategy

Figure 7 shows that as the amount of on-board hydrogen to consume increased, the electrical consumption decreased proportionally until the on-board 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.

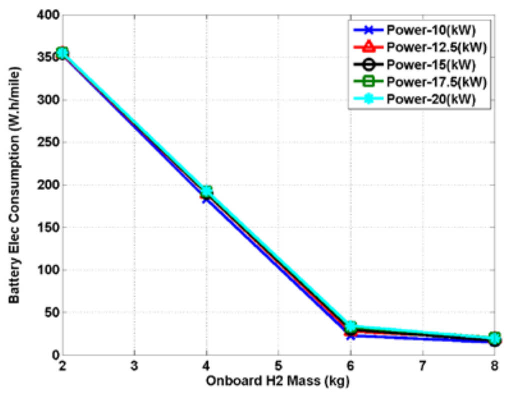

Figure 7: Battery Electrical Consumption

Figure 8 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.

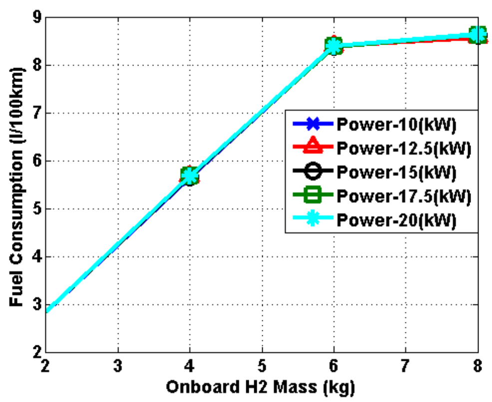

Figure 8: Fuel Cell APU Fuel Consumption

The top dashed line in Figure 9 shows the battery cost for a BEV, without the APU, using the baseline assumption 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.

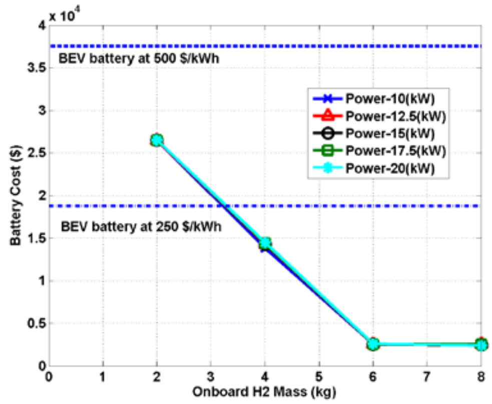

Figure 9: Battery Cost

Figure 10 shows the mass of the fuel consumed by the APU versus the mass of fuel stored on board. There should be a one-to-one relationship between these fuel amounts. Any time there is not indicates that the amount of fuel exceeded the mass of fuel that could be consumed by an APU of the given power during the duration of the trip. Any cases for which the APU power was insufficient to consume the full fuel mass over the trip was part of the inadmissible area shown in Figure 3, and consequently, it was not simulated.

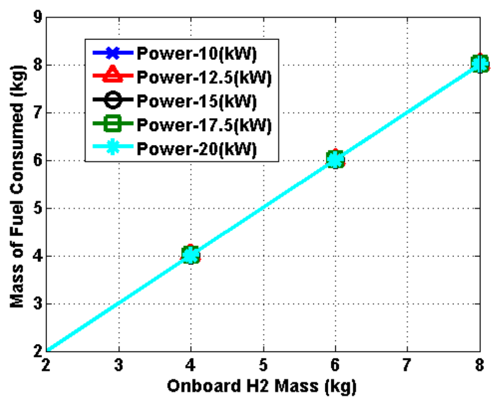

Figure 10: Fuel Cell APU Fuel Mass Consumed

The fuel cell APU cost equation had two terms: one depended on APU power, and the second depended on hydrogen storage fuel mass. The cost of APU 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 11.

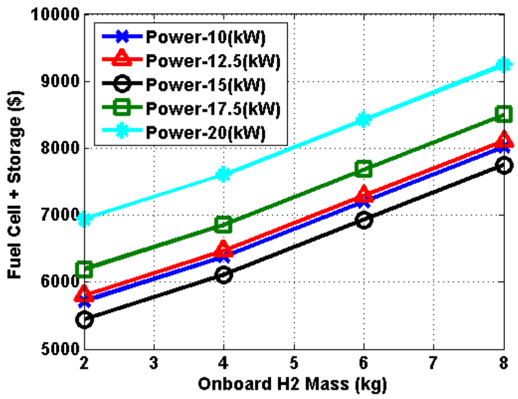

Figure 11: Fuel Cell APU and Storage Cost

These cost results indicate the 15-kW APU would be an optimal solution for this vehicle on the given trip. The 15-kW APU consumed 6 kg, the same as did the 20-kW APU, and was the cheapest option, even cheaper than the 10-kW APU. The optimal storage for this vehicle on this trip would be 6 kg of on-board hydrogen storage, since increasing the fuel mass beyond 6 kg did not significantly decrease battery cost. Figure 12 shows the relationship of APU cost and power. Between 10 and 20 kW, a local minimum can be seen at 15 kW.

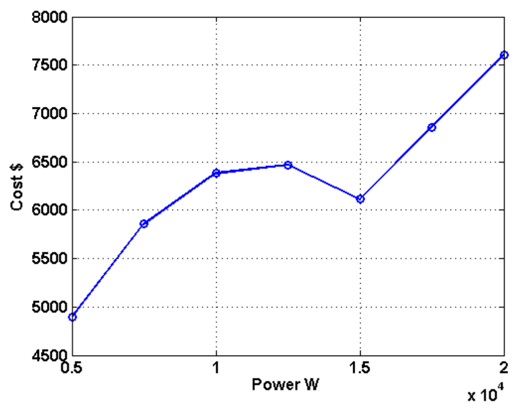

Figure 12: Relationship between Cost and Power for the Fuel Cell APU

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 on-board storage. Figure 13 shows this result. Four other interesting vehicle cost cases are also shown in Figure 13 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 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 [2]. 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 on-board storage. However, if the production number were to increase significantly by a factor of 50, the fuel cell HEV would become the most cost effective option.

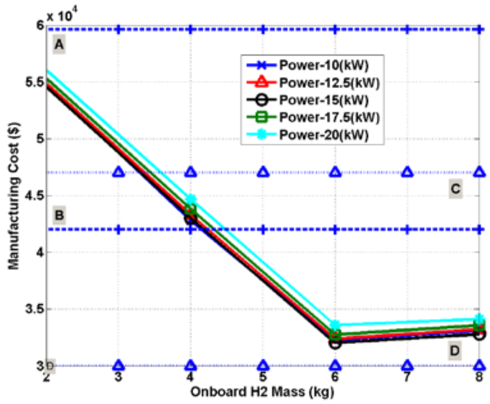

Figure 13: Manufacturing Cost for APU Vehicle

The LCOD is shown in Figure 14; it decreased by 38% compared to that of a 2X BEV (Case A in Figure 13), when using 6 kg of hydrogen. This figure uses the assumptions from Table 5, including a 5-year vehicle 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.

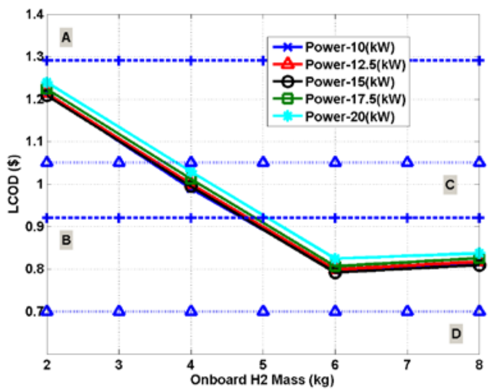

Figure 14: LCOD for APU Vehicle

Figure 15 shows the LCOD using the base assumptions but assuming that the vehicle life is doubled to 10 years. Doubling the vehicle lifetime decreases the benefit seen in the LCOD because of the higher fuel cost. The benefit decreases from 38% to 31%. Line A shows the 2X BEV LCOD. Line B shows the fuel cell HEV LCOD at 10,000 production units/year.

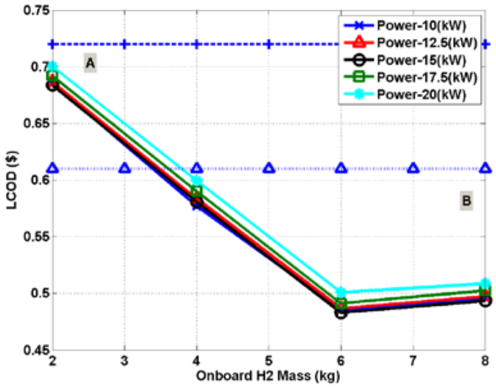

Figure 15: LCOD for 10-Year Vehicle Lifetime

Figure 16 shows the effect of doubling the annual driving distance on the LCOD. The LCOD for the APU vehicle drops to \$0.45/mile, while the 2X BEV drops to \$0.66/mile (Line A). Doubling the annual distance has an effect similar to that of doubling the lifetime, since the benefit of the BEV with APU over the 2X BEV decreased from 38% to 30%, which was the same result when the lifetime was doubled. Generally, as lifetime and range go up, fuel consumption costs cut into the initial benefit of the cheaper APU. Line B shows the FC HEV LCOD for the increased lifetime.

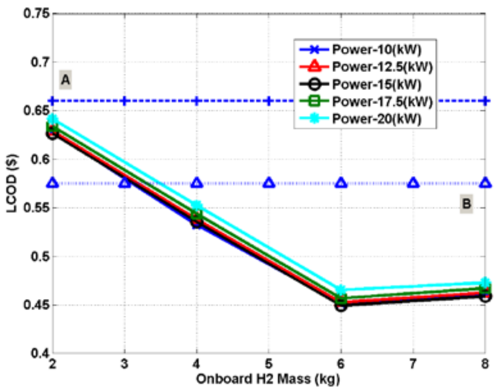

Figure 16: LCOD for Driving 30,000 Miles/Year

It is worth noting that combining the 10-year vehicle lifetime with a driving distance of 30,000 miles/year dropped the LCOD to \$0.36/mile, as shown in Figure 17. Keeping the vehicle longer and driving it farther lowers the LCOD, since the initial upfront cost of the vehicle is averaged over more lifetime miles and that results in the lower LCOD.

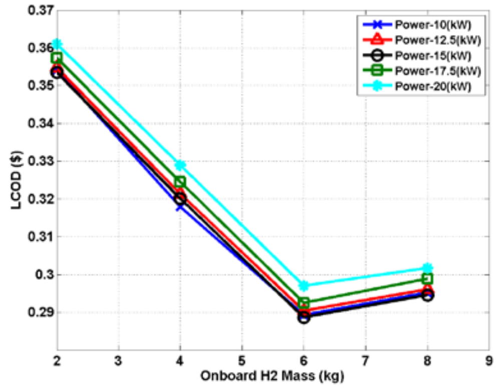

Figure 17: LCOD for 10-Year Vehicle Lifetime and Driving 30,000 Miles/Year

5.2 Fuel Cell Maximum Efficiency Control Strategy Result

The main advantage of using the maximum efficiency control strategy over the maximum power strategy is that because the hydrogen is consumed more efficiently, additional electrical energy will be displaced for every kilogram of hydrogen (i.e., less on-board hydrogen will be needed to double the range of the vehicle). However, this benefit comes at the cost of having a higher maximum power for the fuel cell APU, which comes at a higher initial cost. The main question is whether the additional fuel savings will compensate for the higher initial cost of using a larger fuel cell. Remember the APU operating power has to be high enough to allow the full amount of on-board hydrogen to be consumed.

Figure 18 shows the electrical consumption as a function of APU power. Note the much larger maximum power values for these APUs when compared with the APUs used with the maximum power strategy. The APU still needs to operate at around 10 to 20 kW to consume 6 kg of fuel, and since the maximum efficiency point is around 30% of rated power, the APU maximum power has to be around 30 kW, at a minimum, to achieve 10 kW of continuous power operation. Figure 18 demonstrates that at around 6 kg of fuel mass, the electrical consumption crosses over from net charge-depleting to net charge-sustaining behavior. The transition from net charge-depleting to net charge-sustaining behaviour occurs earlier for the maximum efficiency strategy than it does for the maximum power strategy because for every kilogram of hydrogen the vehicle is forced to use, the amount of energy displaced from the battery is greater due to the higher operating efficiency of the APU. The deviation from 6 kg to 8 kg is due partly to variation in the range constraint. The amount of hydrogen added is enough that the range optimization has a harder time converging due to the excess energy.

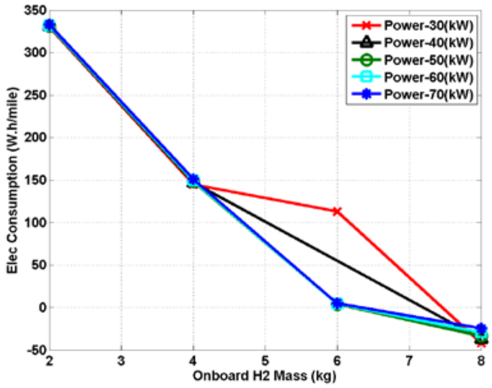

Figure 18: Maximum Efficiency Strategy Electrical Consumption

Figure 19 shows a fuel consumption trend similar to that seen in the previous result under the maximum power strategy. Fuel consumption increases as fuel mass is added until 6 kg is reached, at which point, the vehicle begins to operate in a net charge-sustaining mode due to the excess energy from the APU. As before, this is expected since the fuel tank must be empty at the end of the trip and as the fuel mass increased, the range was held fixed.

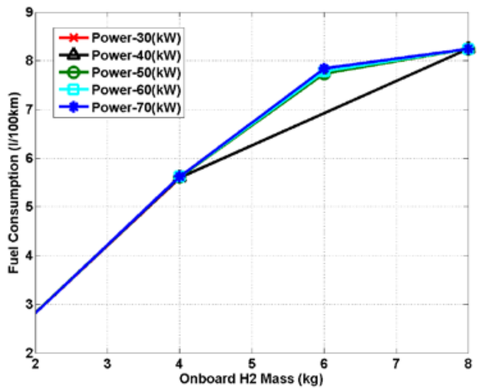

Figure 19: Maximum Efficiency Strategy Fuel Consumption

Figure 20 shows that the battery energy decreases substantially, to the point where it becomes charge sustaining. At 6 kg of fuel mass, the maximum efficiency strategy's use of the APU essentially overwhelms the powertrain with excess energy beyond what the vehicle needs to complete the trip. Battery energy creeps back up from zero because range slips beyond the 160-mile sizing constraint, although it stays within a 20% tolerance.

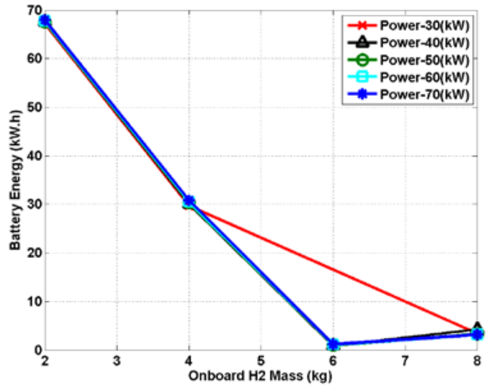

Figure 20: Maximum Efficiency Strategy Battery Energy

Figure 21 shows the battery cost as on-board fuel mass is added to the APU vehicle using the maximum efficiency control strategy. The battery cost decreases by about 90% since the vehicle's average power requirement is supplied by the APU and power transients are supplied by the battery.

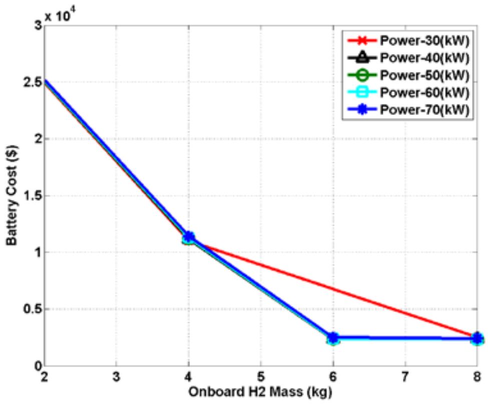

Figure 21: Maximum Efficiency Strategy Battery Cost

Figure 22 demonstrates that all of the fuel is consumed over the cycle.

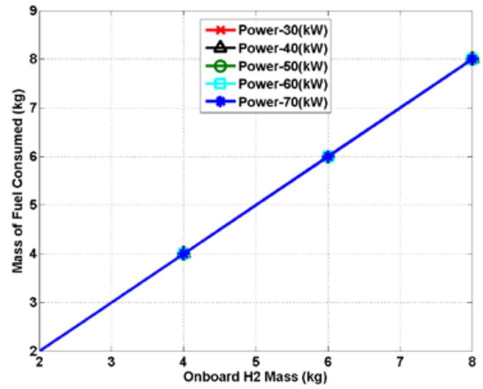

Figure 22: Maximum Efficiency Strategy Mass of Fuel Consumed

Figure 23 shows the cost relationship for the APU. The APU cost is dominated by power and increases slowly, with the amount of hydrogen stored going from 2 to 8 kg, adding about $2,000 to the vehicle cost. Doubling the power of the APU just about doubles the cost. Quadrupling the amount of stored hydrogen increases the cost by about $2,000.

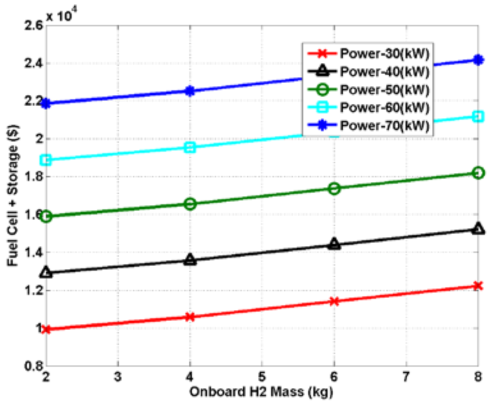

Figure 23: Maximum Efficiency Strategy Fuel Cell and Storage Cost

Due to the sharp drop in battery energy and subsequently in the battery cost, the manufacturing cost of the vehicle drops by $20,000 as the hydrogen storage is increased, supplanting electrical energy storage. Line A in Figure 24 represents the cost of an APU vehicle. Most APU vehicle cases fall below this line, except those that have 2 kg of on-board storage and fuel cell power between 40 and 60 kW.

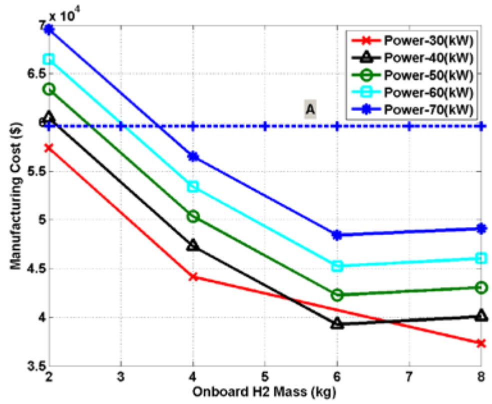

Figure 24: Maximum Efficiency Strategy Vehicle Manufacturing Cost

One might ask, "Does the maximum efficiency strategy actually lower the LCOD cost through fuel savings?" Figure 25 attempts to answer this question. It shows the LCOD for the maximum efficiency strategy along with the most expensive maximum power strategy — the 20-kW case. For a fuel price of $3.50/gasoline gallon equivalent (gge), a vehicle lifetime of 5 years, and a distance traveled of 15,000 mi/yr, the maximum efficiency strategy does not beat the maximum power strategy. The maximum power strategy has a lower LCOD of about $0.20/mi. Basically, the more expensive upfront cost of the larger fuel cell is not recovered through fuel savings from operating the fuel cell more efficiently. A higher fuel price could change this relationship. One can see that the maximum power strategy consistently outperforms the maximum efficiency strategy for almost all amounts of fuel cell maximum power and on-board fuel mass. Line A in Figure 25 shows the 2X BEV cost as a reference.

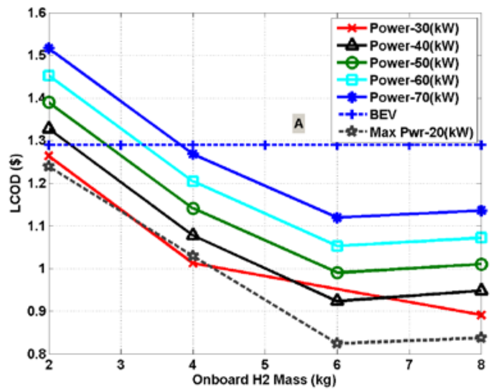

Figure 25: Maximum Efficiency Strategy LCOD with 20-kW Maximum Power Strategy Case LCOD

If the fuel cost is more than doubled to $8/gge, the LCOD actually trends upward when on-board storage goes from 2 to 8 kg. The lowest power APU (30 kW) begins to have a lower LCOD for the maximum efficiency strategy than for the maximum power strategy, but it is lower, at most, by a cent per mile. Even at $8/gge, a 10-year lifetime, and a distance traveled of 30,000 mi/yr, the maximum power strategy is still cheaper than the maximum efficiency strategy by about a cent per mile at 2 kg of on-board storage.

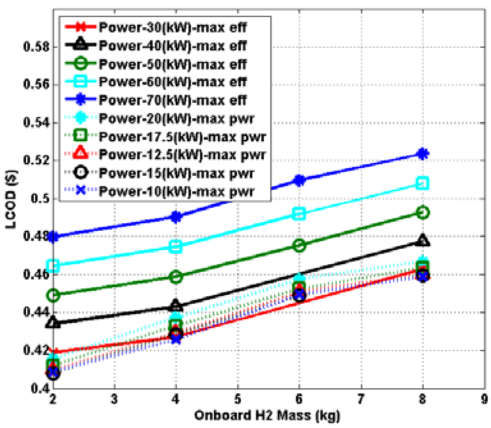

Figure 26: Maximum Power Strategy Compared to Maximum Efficiency Strategy at $8/gge, 10-year lifetime, 30,000 mi/yr Traveled, $500/kWh

6 Conclusions

On the basis of the cost assumptions and drive cycles considered in this paper, 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, an 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 HTUF drive cycle considered and when the default LCOD assumptions in this paper are used, a 10-kW fuel cell system with 6 kg of on-board 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 on-board mass dropped to 2 kg for both the maximum power strategy and the maximum efficiency strategy when the fuel cost was $8/gge (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.

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Authors

Phillip Sharer is senior developer of the Autonomie process architecture. He has been a research engineer at Argonne National Laboratory for 14 years. During this time, he has authored or co-authored numerous papers in the area of advanced vehicle technology. He also co-developed the Powertrain Systems Analysis Toolkit (PSAT). He received a Master of Science in Engineering from Purdue University, Calumet.

Aymeric Rousseau is Manager of the Vehicle Modeling and Simulation Section at Argonne National Laboratory. He received his engineering diploma from the Industrial System Engineering School in La Rochelle, France, in 1997. After working for PSA Peugeot Citroen in the hybrid electric vehicle research department, he joined Argonne in 1999. He is now responsible for the development of Autonomie. He received an R&D 100 Award in 2004 and a Vehicle Technologies Program R&D Award in 2010. He has authored more than 40 technical papers in the area of advanced vehicle technologies.