Impact of Fuel Cell System Design Used in Series Fuel Cell HEV on Net Present Value (NPV)

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Abstract – For a series fuel cell hybrid electric vehicle (FCHEV), it is critical that the degree of hybridization between the fuel cell power and battery power be determined so as to maximize the vehicle's performance variables, such as fuel efficiency and fuel savings. Because of the cost of and wide range of design choices for prototype vehicles, a development process that can quickly and systematically determine the design characteristics of hybrid systems (including battery size and vehicle-level control parameters that maximize the vehicle's net present value [NPV] during the planning stage) is needed. Argonne National Laboratory developed AUTONOMIE, a modeling and simulation framework, and, with support from MathWorks, the laboratory has integrated that software with an optimization algorithm and parallel computing tools to enable that development process. This paper presents the results of a study that used the development process, in which the NPV was the present value of all the future expenses and savings associated with a vehicle. The initial investment in the battery and the future savings that will result from reduced gasoline consumption are compared. The investment and savings results depend on the battery size and vehicle usage. For each battery size at the given fuel cell power and efficiency, the control parameters were optimized to ensure the best performance possible from using the battery design under consideration. Real-world driving patterns and survey results from the National Highway Traffic Safety Administration (NHTSA) were used to simulate the usage of vehicles over their lifetimes.

I. INTRODUCTION

A significant portion of the fuel displacement achieved by HEVs using an internal combustion engine is related to their higher system efficiency at part loads. Fuel cell systems (FCSs) have an advantage in that their efficiency does not degrade at part loads; in fact, it can be much higher. This is particularly advantageous in transportation applications, because the vehicles are mostly operated under part load conditions.

Designing advanced powertrain systems requires a detailed understanding of their interactions, including knowledge about component technologies and sizes [1]. This study evaluates the impact of the FCS's design (i.e., peak efficiency at rated power) and size (i.e., rated power) on the vehicle NPV. To provide a fair comparison between the different options, the vehicle-level control strategy parameters are optimized for each vehicle to minimize fuel consumption. AUTONOMIE [2] is used in collaboration with an optimization algorithm developed by MathWorks.

II. VEHICLE ASSUMPTIONS

The study is based on a midsized family sedan as the vehicle platform, a direct-hydrogen pressurized FCS as the energy converter, and a lithium-ion battery pack as the energy storage system. The main characteristics of the vehicles are shown in Table I.

TABLE I
MAIN VEHICLE CHARACTERISTICS

Component	Technology	Specifications
Vehicle type	Series HEV	Two-speed manual transmission
Fuel cell	Polymer electrolyte	65 to 120 kW, in 5-kW increments
		35% to 50%, in 5% increments
H_2 storage	700 bars	5.6 kg of H_2
Motor	Permanent magnet (PM) induction	120 kW of peak power
Battery	Saft, Li-ion	Optimization algorithm output
Transmission	Two-speed manual	Ratio = 1.86,1.00
Final drive	Fixed	Ratio = 4.44
DC-DC converter	Constant efficiency	Efficiency = 95%
Wheels	P195/65 R15	Radius = 0.317 m
Vehicle size	Midsize	1,720 kg excluding FC and battery weight, coefficient of drag (Cd) = 0.26, frontal area (FA) = 2.2 m^2
ICE	123 kW	

Several parameters were varied in the study:

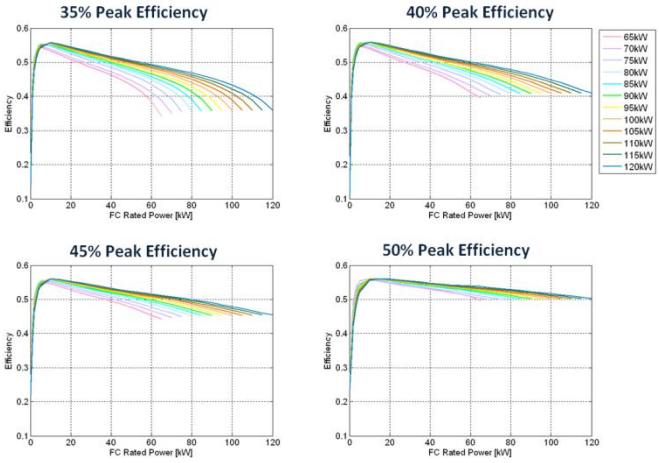
- FCS peak efficiency at rated power,
- FCS rated power, and
- Battery peak power.

To be able to select the most appropriate set of inputs, an NPV algorithm that takes into account both the component costs and fuel cost was used. In the NPV analysis, the cost of the fuel cell and battery were considered as investments, and

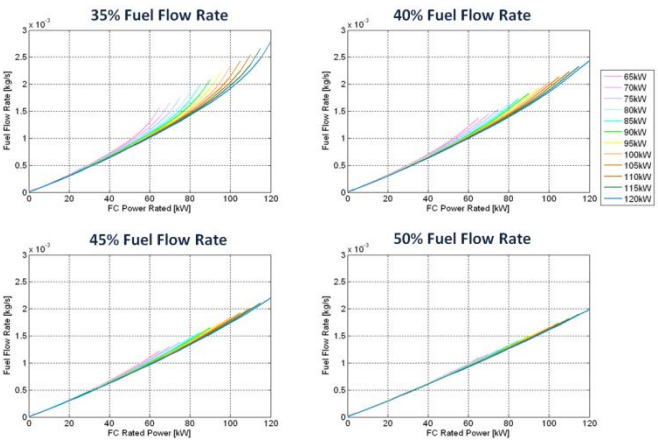
the gasoline savings (compared with cost of gas for a baseline conventional internal combustion engine vehicle [ICEV]) was considered as a cost savings. Since the investment and operating cost were specific to vehicle use during its lifetime, overall assumptions were based on the Vehicle Survivability and Travel Mileage Schedules published by the NHTSA [3].

III. Fuel Cell System Design Space

Figure 1 shows the different FCSs designed by using GCTool from the combinations of 12 different peak-rated FCS powers from 65 to 120 kWe at 5-kWe increments and 4 different peak efficiencies from 35% to 50% at 5% increments. This implies that the NPV optimization should be run for 48 different vehicles.



(a) Fuel cell rated peak power versus efficiency



(b) Fuel cell rated peak power versus fuel flow rate

Fig. 1. Characteristics of 48 combinations of FCSs

IV. Control Algorithm Assumptions

Vehicle-Level Hybrid Control Logistics: A load-following hybrid control strategy was used. In this instance, the FCS power closely follows the power required at the wheels to propel the vehicle while maintaining an acceptable battery state of charge (SOC). The FCS provides the traction power under normal driving conditions, and the energy storage system (ESS) provides boost power under transient conditions. The ESS also stores part of the energy that must otherwise be dissipated during deceleration. In addition, the following assumptions were made about the control strategy:

i. The FCS is never turned off while running on the cycle; it remains at idle (no net power) with minimum constant fuel flow.
ii. No energy is required to start the FCS.
iii. 0.8 MJ of energy is required for shut-down at the end of the trip.
iv. The FCS provides the accessory load when it is operational; the battery provides it when the FCS is idle.

The objective of the vehicle-level control strategy is to use the electrical energy captured during deceleration when the FCS efficiency is low (i.e., at very low power demands).

V. Component Cost Assumptions

Fuel Cell Systems: The costs of FCSs were estimated to range from $3,328 for an FCS of 65 kWe with 35% efficiency to $5,893 for an FCS of 120 kWe with 50% efficiency. Figure 2 shows the range of costs of FCSs used in this study. The FCS costs were defined to represent the status of the current technology based on 500,000 unit production. Figure 3 illustrates the range of FCS weights.

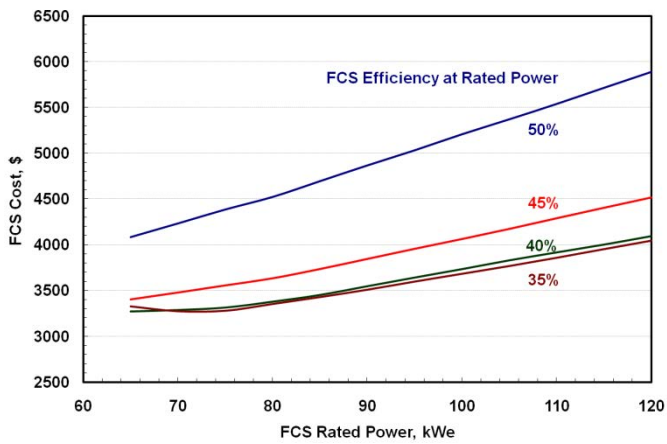


Fig. 2 Costs of FCSs

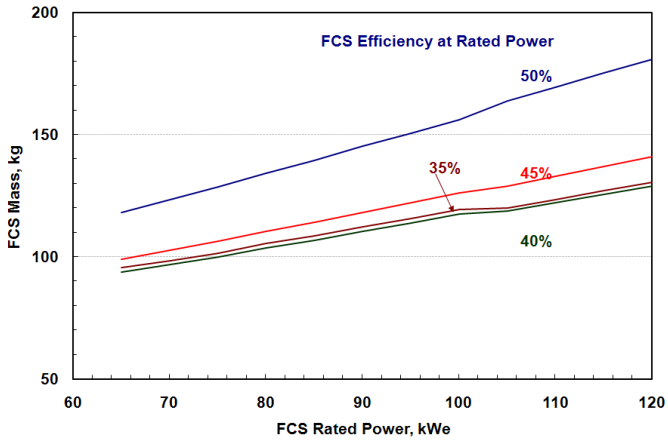


Fig. 3 Weights of FCSs

Battery: Note that Equation 1 represents the current battery cost. The optimization results obtained on the basis of this cost assumption indicate what is most beneficial under present circumstances.

Battery Cost in \$/kWh = 32 × battery power-to-energy ratio + 125 (Eq. 1)

Other Components: The characteristics of other components used in FCHEVs and baseline conventional ICEVs are shown in Table II.

TABLE II
COMPONENT COST ASSUMPTIONS

Component	Cost	Comments
Gasoline ICE	\$16/kW	
H_2 storage	\$630/H_2 kg	Based on 40-mile range
Electric motor	\$12/kW	Including electric motor and controller
Final drive	\$200	
Transmission	\$800 to \$1,300	\$800 for two-speed, \$1,300 for five-speed
Wheels	\$320	
Glider	\$9890	

The total ownership cost of FCHEVs is estimated by summing all component costs (i.e., vehicle purchase cost) and the H_2 fuel consumption cost (i.e., vehicle operating cost) with an assumed retail price equivalent (RPE) ratio of 1.5.

VI. VEHICLE USAGE ASSUMPTIONS

The series FCHEVs were compared with a midsize conventional ICEV with fuel consumption of 8.9 L/100 km (equivalent to 34 mpg). The fuel price is \$1/L (equivalent to \$3.70/gal) for gasoline and \$5/gge (i.e., gasoline gallon equivalent) for hydrogen. Fuel price variations were not considered. Studies conducted by NHTSA support the assumption that an average passenger car will travel over 240,000 km during its lifetime [2].

Figure 2 shows an assumption made about the decrease in vehicle daily distance over the life of the vehicle. The vehicle daily distance degradation was estimated on the basis of average driving distance observed in NHTSA surveys [3] and real-world driving data recorded from a group of Kansas City drivers [4]. The NHTSA survey and real-world daily distance data were based on a conventional ICEV, thus making the distance-degradation assumption in Figure 4 subject to further review as new survey and field data are obtained from vehicles with new technologies.

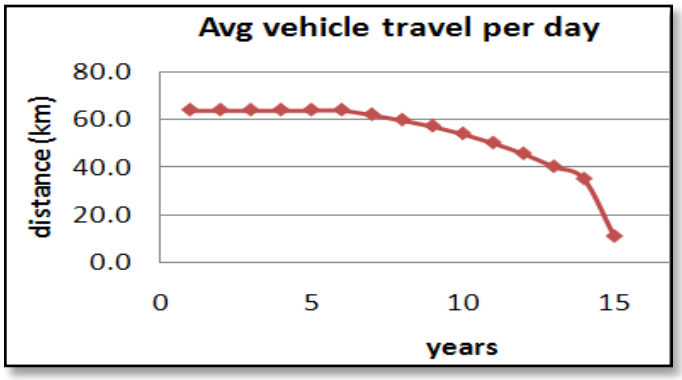


Fig. 4 Vehicle daily distance

The fuel consumption of any vehicle depends on how it is driven. The studies conducted in Kansas City [3] gave an accurate picture of real-world driving characteristics in a North American city. A representative sample from the real-world drives was used in this study to estimate the fuel consumption values for the series HEVs with varying fuel cell and battery sizes. The main characteristics of Kansas City real-world drive cycles are shown in Table III. Many simulation runs over these cycles were necessary to optimize the battery size.

TABLE III
CHARACTERISTICS OF KANSAS CITY REAL-WORLD DRIVE CYCLES

Parameter	Value
Average daily driving distance	58 km
Average vehicle speed	52 km/h
Average energy consumption	286 Wh/mi

VII. NET PRESENT VALUE CALCULATION

The NPV calculation used in this study has been used previously [5]. It is illustrated in Figure 5.

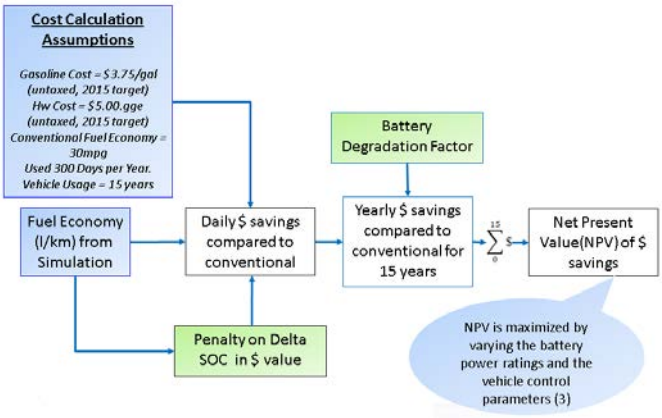


Fig. 5 NPV calculation for equivalent gasoline savings over vehicle life

The amounts of fuel consumed by HEVs over the real-world drive cycles were obtained from the simulation. The HEV H_2 savings in terms of equivalent gasoline savings, in comparison with the cost of gas for a conventional ICEV, were calculated for each battery peak power and energy management strategy over a fixed set of real-world drive cycles. This led to an optimal battery peak power and energy management strategy that considered the amount of gasoline saved per day over the vehicle's life.

The additional cost of the FCS and battery were spread evenly over the entire life of the vehicle. Therefore, the yearly savings obtained from the vehicle factored in the savings from H_2 displacement and the fraction of the battery cost. The yearly savings were repeated for the 15 years of vehicle life, which resulted in a series of numbers that represented the yearly expenses/savings from owning and using an HEV. The NPV for each set of expenses/savings provided a dollar amount for the present worth of those expenses/savings.

The Direct Search numerical optimizer, available in MATLAB®, was used to read the output of the NPV calculations and to apply its optimization algorithm to command new battery size parameters and vehicle control parameters so as to maximize the NPV. The optimization problem statement is shown in Figure 6.

The left side of Figure 6 shows four independent optimization variables related to the vehicle control and battery design variables manipulated by the numerical optimizer to maximize the NPV calculation over a set of 30 real-world drive cycles. Simultaneous optimization of the vehicle control and battery design parameters was necessary to achieve a realistic result, since the influential interactions between the control and hardware design parameters have reached an equal level of importance and design sensitivity in modern vehicles.

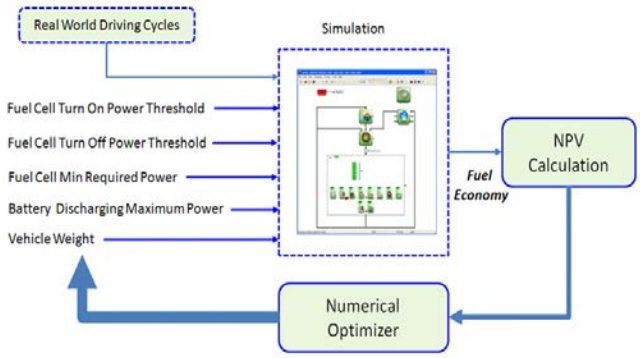


Fig. 6 Optimization problem statement: Maximize the NPV by changing battery and control parameters

VIII. Optimization Approach

Figure 7 shows the top-level optimization process used to optimize the battery and control design parameters across a set of 30 real-world drive cycles. Starting with a nominal set of four control and battery design parameters, a Direct Search optimization algorithm was used to generate an initial set of eight normalized variation coordinates in the four dimensions being searched. The initial eight-point grid was scaled to cover the entire range of the four design parameters so that local minima could be avoided. At each of the eight initial points, 30 real-world drive cycles were simulated in parallel computing rapid-accelerator operating mode to determine the NPV for each point.

The four-dimensional coordinate with the highest NPV was then chosen as the new center point of the optimization, and the span of subsequent variations was reduced until a 1% normalized parameter variation tolerance was met. The optimization approach shown in Figure 7 was chosen to avoid the problem of local minima, which is often encountered in systems that have discrete state changes due to variations in control and hardware parameters, and to provide a simple, robust approach to finding the global maximum NPV value.

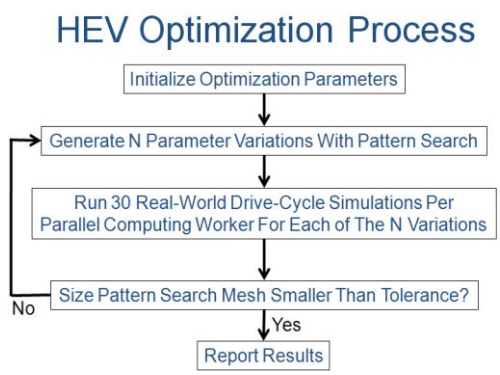


Fig. 7 Direct search optimization approach

For the AUTONOMIE HEV model involved in this study, a typical four-variable battery and control parameter optimization that used 30 real-world drive cycles per simulation required a total of about 1,000 simulations to be executed. The process required about 4 hours of run time on a single quad-core PC.

As shown in Figure 8, three vehicle-level control parameters were selected for the optimization: FCS activation threshold, FCS deactivation threshold, and minimum FCS power limit. These parameters were selected because they have the highest impact on fuel consumption. The minimum power limit forces FCS to operate at minimum power to avoid operating in the inefficient operating region.

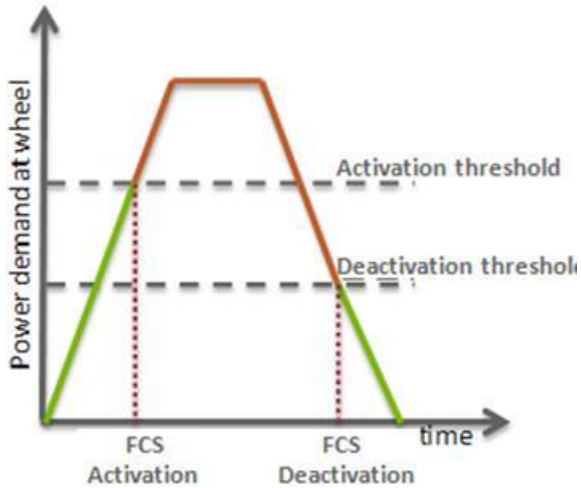


Fig. 8: Control parameters:
FCS activation/deactivation thresholds

IX. Optimization Results

The operating costs of FCHEVs and conventional ICEVs can be compared in terms of equivalent gasoline consumption. For any specific component size, we can compute the optimum gasoline consumption for the vehicle as part of the control optimization. A conventional ICEV consumed about $18,000 worth of gasoline over its 240,000-km lifetime.

As shown in Figure 9, the optimization algorithm found that using 95 kWe of FCS with 40% peak efficiency combined with a 25.7-kW battery results in the most cost savings with reasonable fuel consumption when compared with the cost of using a baseline conventional ICEV in 30 different real-world driving patterns.

Observe that the maximum NPV was found with 95 kWe of FCS at any given efficiency. This result occurred because the purchase cost of any FCS larger than 95 kWe surpasses the cost saving in fuel consumption realized by increasing the size of FCS. Also, notice that FCSs with 50% rated efficiency have a lower NPV because of their higher purchase cost.

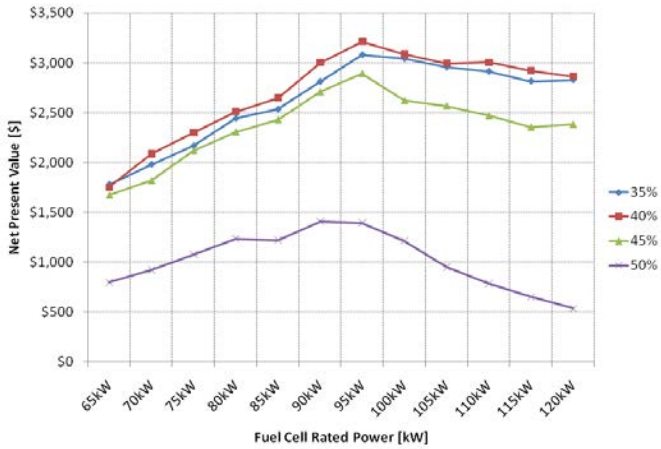


Fig. 9 Variations in operational cost savings associated with battery size

As shown in Figure 10, FCHEVs achieve fuel economy that is 1.7 to 2.2 times higher than that of their conventional counterpart. The fuel economy increases with FCS size and efficiency. The percentage decrease in fuel consumption as FCS power goes from 65 to 120 kWe is proportional to the percentage increase in the efficiency at the given rated power of two systems.

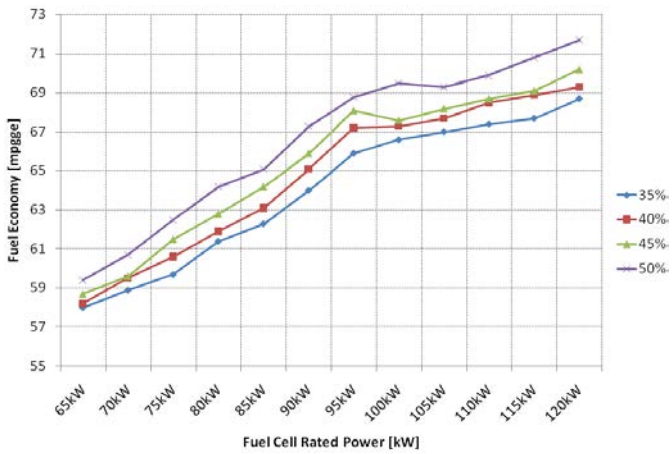


Fig. 10 Fuel economy variation

Figure 11 shows the relationship between fuel economy and the NPV of FCHEVs. An FCS of 95 kWe combined with a 27.4-kW battery is the best choice for achieving both cost savings and fuel economy objectives.

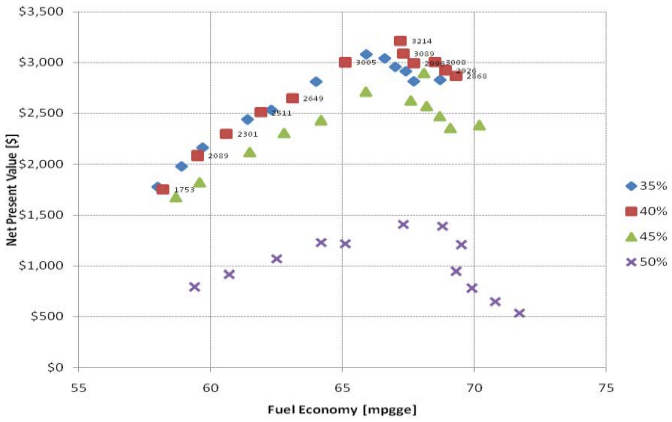


Fig. 11 Fuel economy versus net present value

Figure 12 shows the ownership cost of FCHEVs used in this study. As described, the ownership cost included the cost of glider, powertrain, fuel storage, fuel, and operations and maintenance (O&M) ($0.043/gge). The total ownership cost of a conventional ICEV is about $44,884. The cost of FCHEVs ranges from $41,657 to $44,333 over the life of vehicle (15 years or 15,000 miles). As shown in the figure, the cost of the FCS and the cost savings in fuel consumption are the factors that have the most impact on ownership cost.

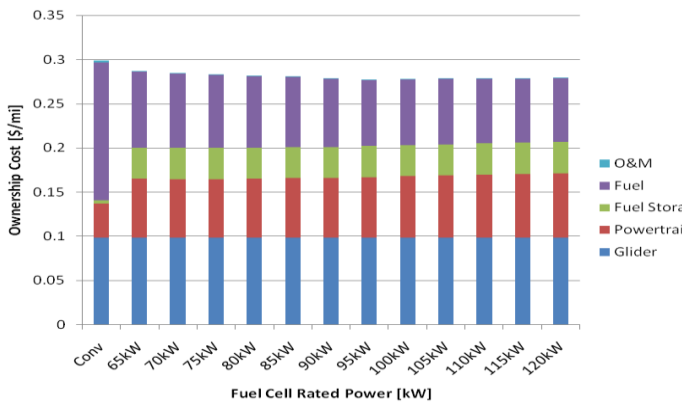
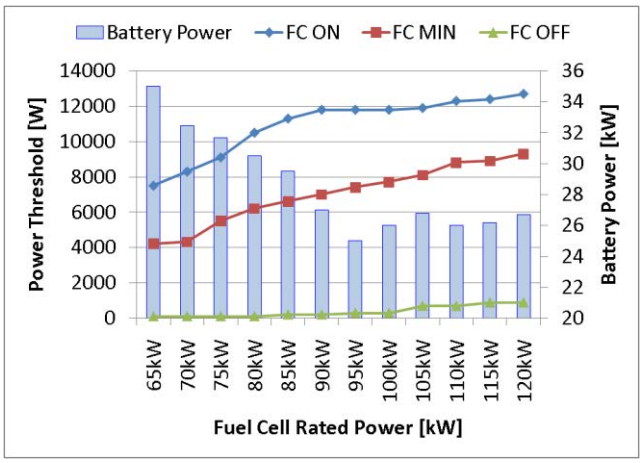


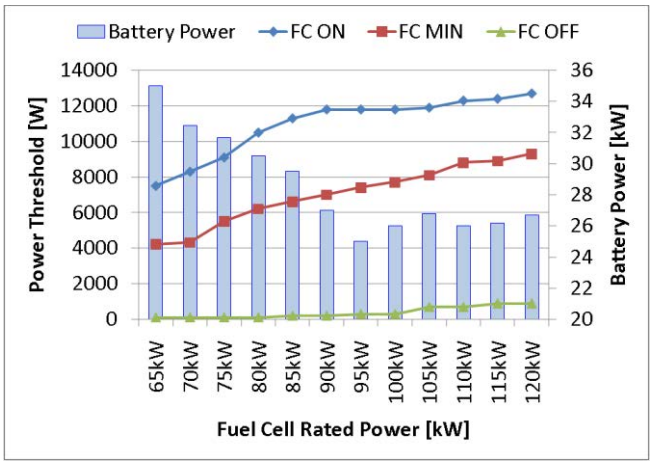
Fig. 12 Vehicle ownership cost

Figure 13 shows that the battery power must exceed 25 kW to capture the vast majority of the regenerative power from the wheels. As the power of the FCS goes below 90 kW, where the FCS is no longer able to operate in its optimum region, the power of battery increases to allow the FCS to operate in the optimum region as long as possible.

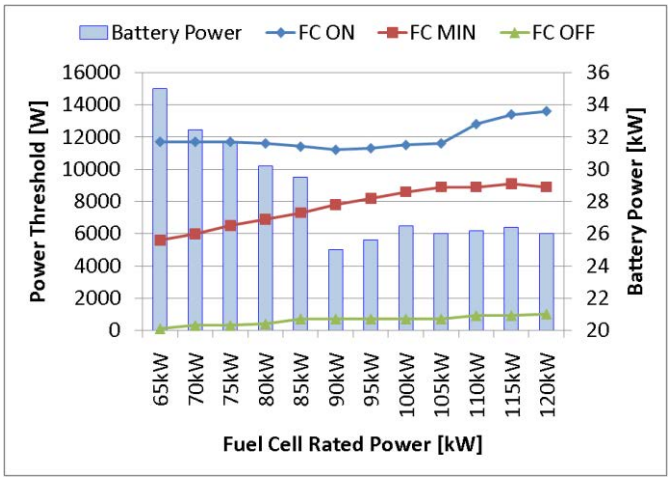
Similarly, the FCS activation (ON) thresholds are chosen as to be active near the peak efficient region, and the FC deactivation (OFF) thresholds are defined to avoid the inefficient region, where the power is less than 9 kWe. Note that the minimum power thresholds of FCSs are close to zero, because then FCSs can operate over their entire power range rather than being limited in their operation to a specific point.



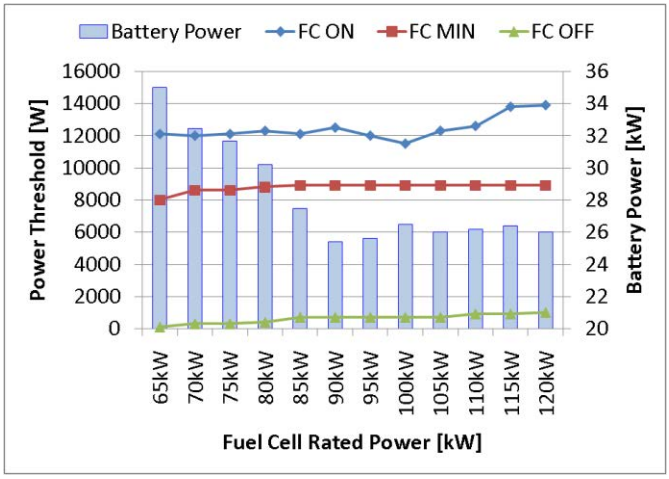
(a) 35% efficiency at rated power



(b) 40% efficiency at rated power



(c) 40% efficiency at rated power



(d) 50% Efficiency at rated power

Fig. 13 Output of optimization:
FCS activation threshold, FCS deactivation threshold,
FCS minimum operating power, and battery peak power

X. Conclusions

This paper compares the NPVs and fuel consumption for 48 different designs of midsize series FCHEVs with a baseline conventional vehicle. For the vehicle class and component assumptions considered, a 95-kWe FCS with a peak efficiency of 40% at rated power combined with a 25.7-kW battery provides the greatest cost savings over the vehicle's life. FCS efficiency has less impact on the NPV than the rated power. The NPV is optimized when the battery power is designed to absorb the maximum regenerative power from the wheels. From a control point of view, the optimum NPV can be obtained when the FCS is activated around the system's peak-efficiency region and is maintained to operate near the optimum region.

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