

A Pareto Frontier Analysis of Renewable-Energy Consumption, Range, and Cost for Hydrogen Fuel Cell vs. Battery Electric Vehicles

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ABSTRACT

As automakers strategize approaches to sustainable vehicle technologies, alternative powertrains must be considered to reduce future fleet vehicle emissions and improve energy security. These alternative vehicles include different fuels and electrification. The ultimate for on-road CO₂ reductions is a zero emission vehicle, which can be achieved by either a hydrogen fuel cell or battery electric vehicle. These vehicles would also require a renewable energy source to provide their propulsion energy in order to achieve maximum sustainability for both CO₂ reduction and energy security. Renewable energy sources such as wind or solar result in heat or electricity that needs to be generated into an energy carrier such as hydrogen or stored in a battery. When examining these options based strictly on the efficiency path, previous analysis have concluded fuel cell vehicles may not be an appropriate suitability strategy in comparison to battery electric vehicles. However, the viability of an alternative vehicle requires a comprehensive assessment of the various vehicle parameters that affect the customer satisfaction. In particular, this paper examines the renewable energy consumption, range, and cost for hydrogen fuel cell and battery electric vehicles. In particular, these conflicting attributes are examined using an objective Pareto frontier analysis to evaluate the trade-offs and trends that should be considered when developing a sustainability strategy.

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INTRODUCTION

The literature contains a number of publications making the case that a hydrogen economy does not make sense because it is intrinsically less efficient than an "electron" economy. [1] The argument is basically founded on the assumption that a sustainable energy economy must eventually be based on renewable energy sources. Most of these sources produce either electricity or heat which cannot be used directly for transportation. To convert this renewable energy into transportation energy, it must be converted into a fuel, such as hydrogen, or stored in batteries. In Ulf Bossel's estimates [1], a hydrogen Fuel Cell Vehicle (FCV) would require 100kWh of renewably generated electricity to provide 23 kWh of useful energy at the wheels of the vehicle. In contrast, the same amount of renewable energy would result in 69 kWh hours of useful energy at the wheels of a Battery Electric Vehicle (BEV), as shown in [Figure 1](#). The argument then goes that, because the hydrogen pathway has only 1/3 the efficiency of the pure electric pathway, it will require 3 times as much renewable energy as the electrical pathway. In

a future constrained by limited renewable energy sources, it makes no sense to use the less efficient pathway.

This argument makes several simplifications and neglects some important considerations. First, efficiency is not the same as energy-consumption. The energy storage density of battery storage systems is much lower than that of hydrogen storage systems. Therefore, the battery storage on a BEV would be greater and consume more energy per kilometer driven than the FCV. The BEV with higher wheel energy for the same performance would counteract some of the efficiency benefit. We believe that energy-consumption is a better measure of the impact on renewable energy resources than efficiency. Second, total energy consumption is not the only measure of a sensibility renewable-energy propulsion system. There are other significant factors such as the potential range of the vehicles and the cost of the propulsion system. Third, Plug-in Electric Hybrid Vehicles (PHEVs) have the potential to capture much of the efficiency benefit of a BEV without sacrificing the range capability of conventional hybrids. It seems reasonable that, if PHEVs make sense to offset gasoline use in today's world of

constrained petroleum supply, it will also makes sense to use a PHEV propulsion architecture in a FCV to offset hydrogen use in a future with constrained renewable energy resources.

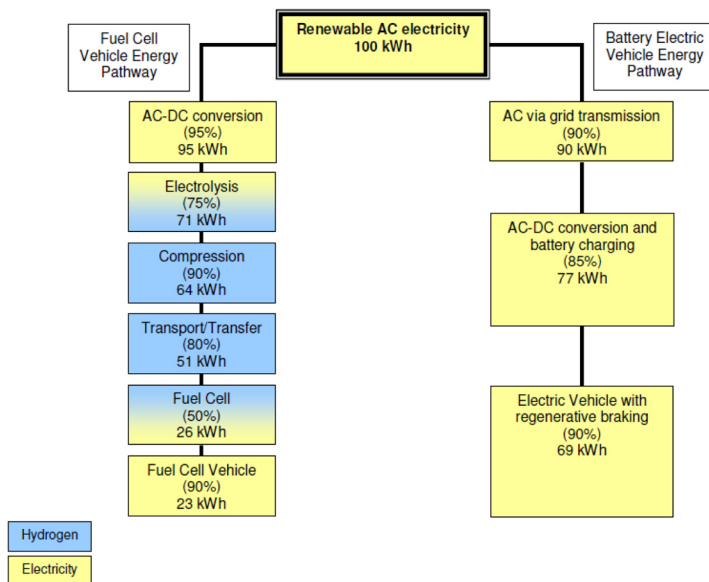


Figure 1. Energy Pathways estimated by Ulf Bossel [1]

In this paper, we do not attempt to question or modify any of the efficiency assumptions made in Bossel's original projections [1]. Instead, we use these assumptions to calculate the logical evaluation of the energy-consumption for BEVs and Plug-in FCVs. The analysis equates the vehicle tractive energy requirements scaled with the mass of the vehicle in conjunction with the off-board energy conversion efficiency for a complete assessment of energy-consumption. This allows us to investigate various vehicle configurations in respect to sizing of the on-board energy storage system and the resulting vehicle range. We also evaluate the cost implications of these on-board energy systems using a multi-variable optimization modeling to identify the Pareto frontier for the vehicle configuration with the minimized energy-consumption and maximized driving range for the least vehicle cost.

ENERGY-CONSUMPTION AND RANGE MODEL ASSUMPTIONS

ENERGY-CONSUMPTION MODEL

The analysis of alternative transportation fuel strategies requires a comprehensive evaluation of the entire well-to-wheels energy pathway. The isolation of a certain segment in the energy pathway could result in an inaccurate conclusion. For example, the current battery electric vehicles emit zero emissions but in combination with the current US electric grid (primarily generated from coal) the well-to-wheels emissions are almost equivalent (slightly under) to the emissions of a gasoline HEV. The comprehensive well-to-

wheels energy pathway is shown in figure 2 and is considered in the energy-consumption model within this paper.

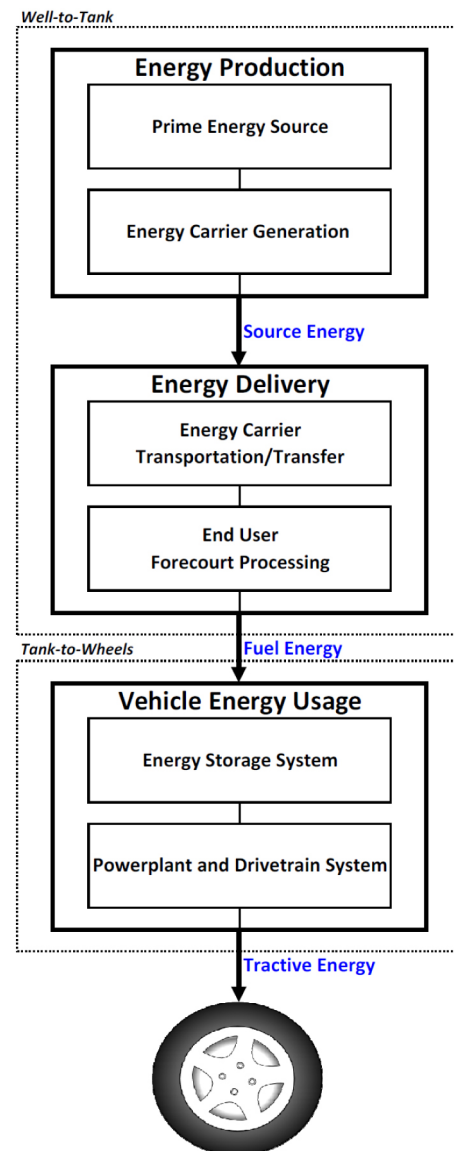


Figure 2. Well-to-Wheels Energy-Consumption Pathway

The energy-consumption model depends on the tractive energy of the vehicle, the efficiency of the propulsion system, the losses associated with the energy delivery, and the initial energy required for production. The foundation of the energy-consumption model is the equation for vehicle tractive energy required at the wheels. The tractive force for propelling a vehicle is a function of the vehicle inertia, aerodynamic drag, rolling resistance, and grade resistance. For a level grade, the tractive force can be expressed as the following equation [2]:

$$F_{TR} = r_0 M g + C_D A \frac{V^2}{2} \rho + \left(M + 4 \left[\frac{I_w}{r_w^2} \right] \right) \left(\frac{dV}{dt} \right) \quad (\text{Eq. 1})$$

In this equation, r_0 is the coefficient of rolling resistance, M is the mass of the vehicle, g is the gravitational acceleration, C_D is the aerodynamic drag coefficient, A is the vehicle frontal area, V is the velocity, ρ is the air density, I_w is the polar moment of inertia of a wheel, and r_w is the effective wheel rolling radius. The instantaneous vehicle tractive force to achieve a velocity for a given time, t , defines the energy required at the wheels. The integral over a drive event will provide the total vehicle tractive energy, E_{veh} , for propulsion during a drive cycle.

$$E_{veh} = \int F_{TR} V(t) dt \quad (\text{Eq. 2})$$

Ultimately, the drive cycle for evaluating fuel economy performance is prescribed by the EPA. The historical drive cycles in the US are identified as the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Driving Schedule (HWFET). Based on the previous equations, Sovran et al. [2] developed a linear expression for tractive energy with coefficients defined based on a given drive cycle.

$$\frac{E_{veh}}{MS} = \alpha r_0 + \beta \left(\frac{C_D A}{M} \right) + \gamma \left(1 + \frac{4I_w}{M r_w^2} \right) \quad (\text{Eq. 3})$$

or tractive energy per distance traveled (kJ/km)

$$\varepsilon_{veh} = \frac{E_{veh}}{S} = \alpha r_0 M + \beta C_D A + \gamma \left(M + \frac{4I_w}{r_w^2} \right) \quad (\text{Eq. 4})$$

In this expression, α , β , and γ are the drive cycle constants and S is defined as the total distance traveled in the drive cycle. Through closed form averages, the coefficients were determined for the historical EPA drive cycles based on the total energy required, shown in Table 1. The remaining parameters represent the mass of the vehicle (M) and other vehicle attributes, which are further developed in section 2.3.

Table 1. Drive Cycle Coefficients for Tractive Energy Equation

Coefficient	UDDS	HWFET	5U/3H
α [m/s ²]	7.344	8.986	8.087
β [kg/ms ²]	108.0	291.0	190.8
γ [m/s ²]	0.1551	.0425	0.1041
S [km]	11.99	16.51	-

The next portion of the energy-consumption model is to calculate the fuel energy utilization to meet the required tractive energy. For the BEV, the fraction of source energy utilization is clearly 100% electrical energy to the electric motor. If the FCV has plug-in capability, the fraction of fuel energy utilization met by electrical energy will range 0% for FCVs without plug-in capability up to some nearly 100% for FCVs with very large plug-in capacity. The remaining fuel energy will be supplied by hydrogen to the fuel cell stack. The fraction of fuel energy that can be offset by plug-in electrical energy depends upon the distribution of trip length, the plug-in battery capacity, and the depletion strategy. The electrical energy consumed during depletion phase of battery and the fuel energy consumed during sustain phase is given by:

$$\varepsilon_{el}^D = \frac{\varepsilon_{veh}}{\eta_{el}} p(x) \quad \varepsilon_F^S = \frac{\varepsilon_{veh}}{\eta_F} [1 - p(x)] \quad (\text{eq. 5})$$

The $p(x)$ is the probability function that the distance between charging will be a certain length. Efficiency η_F and η_{el} are the efficiencies of the vehicle fuel cell and battery propulsion systems respectively. In this paper, we assume that $\eta_F=0.45$ and $\eta_{el}=0.9$ in order to maintain the assumptions from Ulf Bossel's analysis [1]. For a BEV, the energy consumption is simplified by only depletion consumption, ε_{el}^D , and the probability expression equal to 100%. For a plug-in FCV, the probability function needs to be determined for an appropriate representation of the energy utilization on the vehicle. In the reference paper [3], a wide-range of miles driven distribution was shown to fit well with a 3-parameter Dagum distribution. The Dagum distribution has a cumulative probability distribution of the following form:

$$F(x; a, b, \mu) = \left[1 + \left(\frac{x}{\mu} \right)^{-a} \right]^{-b} \quad (\text{eq. 6})$$

Using this distribution, the amount of plug-in electrical energy and the amount of hydrogen fuel energy can be calculated in closed form in terms of an incomplete beta function. These functions have particularly simple form for $a=2$ and $b=0.5$. Based on fits presented in [3], these values are very reasonable. In this approximation, the amount of hydrogen fuel energy used is

$$\varepsilon_F^D = \frac{\varepsilon_{veh}}{\eta_F} \left\{ \sqrt{1 + \left(\frac{R_{el}}{\mu} \right)^2} - \frac{R_{el}}{\mu} \right\} \quad (\text{eq. 7})$$

and electrical energy used

$$\mathcal{E}_{el}^S = \frac{\mathcal{E}_{veh}}{\eta_{el}} \left\{ 1 + \frac{R_{el}}{\mu} - \sqrt{1 + \left(\frac{R_{el}}{\mu} \right)^2} \right\} \quad (eq. 8)$$

In both of these expressions, R_{el} is the effective all electric range of the vehicle. The remaining step in the energy consumption model is to include the energy delivery and production losses. The Ulf Bossel assumption was that the hydrogen production from electrolysis including AC-DC conversion is 0.71 efficient and the hydrogen delivery including compression is 0.72 efficient resulting in an overall wells to tank efficiency, $\eta_{H_2 WTT} = 0.51$. The assumption for electrical energy delivery and production losses were limited to the grid transmission, AC-DC conversion, and battery charging which results in $\eta_{el grid} = 0.77$. The resulting total energy consumption model can be expressed as the following:

$$\gamma_{Total} = \frac{\mathcal{E}_{el}^D}{\eta_{grid}} + \frac{\mathcal{E}_F^S}{\eta_{H_2 WTT}} \quad (eq. 9)$$

DRIVING RANGE MODEL

The vehicle driving range for traditional powertrains is a product of the rated usable capacity of the fuel system and the fuel economy of the vehicle. The effective all electric range of the vehicle can be expressed at the following with E_{batt} equal to the energy stored in the battery:

$$R_{el} = \frac{E_{batt} \eta_{el}}{\mathcal{E}_{veh}} \quad (eq. 10)$$

For the plug-in FCV range assumption, we assume that all of the battery capacity and the full energy capacity of the hydrogen storage tank are depleted. This approach of independently utilizing the entire capacity of battery and full system is consistent with the EPA expression for range on Monroney sticker for plug-in vehicles. Under this assumption, the unadjusted range of the FCV vehicle with E_{HS} equal to the energy stored in the hydrogen storage system is:

$$R_F = \frac{E_{batt} \eta_{el} + E_{HS} \eta_F}{\mathcal{E}_{veh}} \quad (eq. 11)$$

Based the post-2008 EPA fuel economy rating, a 5-cycle adjusted fuel economy value can be calculated based from prior regression correlation [4] and combined to an expected fuel economy rating. The following expressions were used in

eq. 10 and 11 to determine the EPA advertised range of the vehicle:

$$\mathcal{E}_{veh-adj UDDS} = 0.003259 + 1.1805 \mathcal{E}_{veh UDDS}$$

$$\mathcal{E}_{veh-adj HWFET} = 0.001376 + 1.3466 \mathcal{E}_{veh HWFET}$$

$$\mathcal{E}_{veh-adj} = .55 \mathcal{E}_{veh-adj UDDS} + .45 \mathcal{E}_{veh-adj HWFET} \quad (eq. 12)$$

VEHICLE PARAMETERS

By choosing a vehicle class, we can set reasonable values in eq. 4 for the coefficient of rolling resistance (r_0), drag coefficients (C_D), frontal area (A), wheel inertia (I_w), and wheel radius (r_w). For the vehicle mass, we assume a vehicle glider mass with a cargo mass and then add the mass of the battery, fuel cell system and hydrogen storage system depending on the propulsion system. The analysis will include two levels of vehicle classes for a sensitivity evaluation. Based on our experience with our Fuel Cell Focus and Fuel Cell Explorer along with other references, the vehicle parameters are defined in the following table:

Table 2. Vehicle Class Parameters

Attribute	C-class Vehicle	J-Class Vehicle
Vehicle Glider Mass (without powertrain systems)	1350 kg	2100 kg
Frontal Area	2.2 m ²	2.8 m ²
Drag Coefficient	0.32	0.41
Rolling Resistance	0.009	0.015
Wheel Inertia	.86 kg m ²	1.32 kg m ²
Wheel Radius	.30 m	.36 m

MASS AND COST MODEL ASSUMPTIONS

MASS PARAMETERS

The vehicle glider mass as described with vehicle parameters is the complete vehicle with a test cargo mass excluding the mass of the high voltage battery, hydrogen storage system and fuel cell system. These systems are excluded to facilitate our multi-objective analysis. The resulting total vehicle mass model can be expressed as the following:

$$M_{veh} = M_{Glider} + ED_{Batt} E_{Batt} + ED_{HS} E_{HS} + PD_{FCS} P_{FCS} \quad (eq. 13)$$

In this equation, ED refers to the gravimetric energy density of the battery or hydrogen storage system, PD_{FCS} is the power density of the fuel cell system, and P_{FCS} is the fuel