COMPARISON OF THE CONVERSION EFFICIENCY
OF A DIRECT-METHANOL vs. A HYDROGEN FUEL CELL

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ABSTRACT

This paper first compares the conversion efficiency and power density of a direct-methanol fuel cell (DMFC) with the equivalent parameters of a state-of-the-art direct-hydrogen fuel cell (DHFC) – both for current DMFC data and for projected improvements in DMFC performance. The cell level comparison is then extended to the system level for potential automotive application, and limited comparisons are also made for a system based on methanol reformate fuel. It is concluded that a DMFC-powered vehicle, which apparently can meet the requirements for a general-purpose zero-emission vehicle (ZEV), can become competitive with a DHFC-powered ZEV.

INTRODUCTION

For any application of a fuel cell power system, it is important to maximize fuel utilization and energy conversion efficiency. In the specific case of an automotive fuel cell system, it is particularly critical to maximize the overall conversion efficiency (voltage efficiency \times fuel utilization) over as broad a range of cell (and system) power density as possible.

This paper compares the conversion efficiency and power density of a direct-methanol fuel cell (DMFC), which has been optimized for efficiency, with the equivalent parameters of a state-of-the-art direct-hydrogen fuel cell (DHFC). Following a brief outline of the experimental conditions used to generate data reported in this paper, a concept and technique of optimizing the conversion efficiency of a DMFC is introduced. The technique is then applied to DMFC state-of-the-art data, and to two projected data

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sets for future DMFC performance. All three of these optimized DMFC characteristics are then compared with the efficiency and power density of the DHFC state-of-the-art.

Next a "system" level comparison is introduced that captures the major differences between the DHFC and DMFC systems for automotive applications. Specifically, it highlights the impact of both the stack (efficiency and power density) and the fuel (energy storage density) on the competitiveness of automotive fuel cell power systems for general-purpose applications. This system level comparison is then used to evaluate the potential of a DMFC-powered vehicle.

Finally, the performance of methanol (and "gasoline") reformate systems is briefly analyzed and discussed. It is noted that a comparison between fuel cell vehicles (FCVs) powered by DHFC or DMFC power systems and by methanol or "gasoline" reformate fueled systems is not an "apples-to-apples" comparison since the former systems are zero-emission while the latter ones are not ZEV (zero emission vehicle) capable. However, since it is common to compare the methanol-reformate FCV with the two types of ZEVs on the limited basis of efficiency and power density, we also present that limited comparison here.

EXPERIMENTAL

DMFC performance considered in the analysis described below is based on fuel cells prepared and tested at LANL. Pretreatment of the Nafion™ 117 membrane in H⁺ form, preparation of membrane electrode assemblies (MEAs) for a DMFC using a decal technique, and the single-cell fuel cell hardware have been previously described1,2 as has the cell testing system used.3 Two unsupported Pt-Ru blacks of nominal 1:1 atomic ratio were used for DMFC anodes, both supplied by Johnson Matthey. Anode inks were made by dispersing appropriate amounts of the Pt-Ru catalyst in deionized/distilled water and adding 5% Nafion™ solution (1200 in equivalent weight, Solution Technology Inc.). The cathode inks contained unsupported Pt black (30 m² g⁻¹, Johnson-Matthey), deionized/distilled water and 5% Nafion™ solution (1100 equivalent weight, Solution Technology Inc.). In some cases, the catalyst layers involved direct application of the catalyst inks to PTFE-treated (wet-proofed) carbon cloths. The geometric active area of all the MEAs prepared was 5 cm².

Methanol solutions, between 0.25 and 2.0 M in concentration, were pumped through the DMFC anode flow field at precisely controlled rates (0.5-3.0 ml min⁻¹) using a Shimadzu LC-10AS HPLC pump. A back pressure of about 15 psig was imposed upon the anode outlet flow to ensure that the membrane would be in contact with a liquid solution of methanol at the cell operating temperature of 100 °C. The cathode gas feed...
was air 30 psig pressure and a flow rate 0.5 l/min. The air was usually pre-humidified at the same or similar temperature as the operating temperature of the cell.

The crossover of methanol as a function of cell current density was recorded with the same cell hardware used for the corresponding cell polarization plot. The determination of crossover was based upon the amount of carbon dioxide present in the cathode exhaust, as measured using a GMM12 Carbon Dioxide IR Sensor (Vaisala Oy, Finland). The IR detector was earlier calibrated with a gaseous mixture of 4% CO₂ and 96% N₂. The CO₂ content in the cathode exhaust was then converted into the corresponding methanol flux through the membrane, expressed as current density of MeOH oxidation at the cathode.

**DMFC OPTIMIZATION**

It has been shown that it is possible to carry out an optimization of both conversion efficiency and power density for a direct-methanol fuel cell (DMFC) by varying the methanol concentration and solution feed rate at the anode. The result of such an optimization, using experimental data for a state-of-the-art DMFC cell, is shown in Figure 1 – in the form of an optimized DMFC conversion efficiency curve versus cell power density.

There would be a significant increase in DMFC performance if the crossover current were reduced and the cell voltage increased (in part as a result of a reduced impact on cathode polarization with reduced crossover current). Figure 2 illustrates the effect on the optimum efficiency curve of these two projected improvements in the characteristics of the DMFC:

(i) reduction of the DMFC methanol crossover flux by 90% (at each cell power),
(ii) combination of that 90% crossover reduction with a decrease in overall cell voltage loss by a uniform 0.1 V.

Figure 2 shows how the crossover reduction improves the conversion efficiency and shifts the peak efficiency to lower power density – with no effect on the maximum power density obtained (ca. 0.25 mW cm⁻²). In contrast, the effect of the decreased voltage loss on the projected performance of the DMFC is twofold, namely:

(i) further increase in the efficiency (especially at higher power density),
(ii) increase in the peak power density which now exceeds 0.3 W cm⁻².

As a justification for projecting these potential improvements in the DMFC performance, we note that experimental DMFC membranes have achieved significant...
crossover reduction while maintaining good protonic conductivity, and decreased DMFC cathode polarization for reduced crossover has been inferred from some experiments.5

In Figure 3, these three DMFC efficiency curves are compared to a DHFC for the same cathode air pressure and flow. With the combination of both crossover reduction by 90% and overall cell polarization reduction by 0.1 V, the maximum DMFC power density increases to roughly 55% of the direct-hydrogen cell, and the overall conversion efficiency increases to about 75% of the hydrogen cell.

Although a superficial examination of this projected performance might conclude that the DMFC is at an insurmountable disadvantage compared to the DHFC, it is necessary to critically examine the complete power systems for the DMFC and DHFC, including fuel storage, before any such conclusion is warranted.

SYSTEM COMPARISONS

The complete automotive power system includes fuel cell stack, system auxiliaries (air supply, water supply, cooling, power control), fuel supply (storage plus reformation, if necessary), and drive train (motor controller, electric motor, reduction gear). In contrast, the efficiency and power density comparisons made in the last section were only at the stack level. In this section, we will establish a basis for the required system level comparison, and extend the comparison at the system level by comparing an automotive DMFC system with a DHFC system as the benchmark.

The use of the DHFC system as a benchmark for evaluating the DMFC may seem somewhat arbitrary. However, if the DMFC is to be positioned as a Zero Emission Vehicle (ZEV) in the automotive marketplace it must compete against the DHFC system. Others have argued that the DMFC system should be compared against the reformed methanol fuel cell (RMFC) system because they both begin from the same “fuel on board”. However, we prefer the “ZEV-against-ZEV” evaluation, although it is actually a more difficult benchmark for the DMFC from the viewpoint of fuel conversion efficiency and power density.

In a later section we will discuss similar figures of merit (efficiency, power density) for the RMFC and RGFC (reformed gasoline fuel cell) systems. But, since these reformate systems are clearly not leading to ZEVs, especially in the RGFC case, the reformate-fueled systems are not legitimate “apples-to-apples” comparisons with ZEVs

* The ZEV regulations in California actually require that a ZEV have zero exhaust emissions, not zero total fuel cycle emissions but the initials remain the same in both cases – ZEV. Aside from battery powered vehicles, DMFC and DHFC are the only ZEV candidates under the current California regulations.
based on a DMFC or DHFC power system. However, reformate-fueled FCV power systems are actually easier comparisons for efficiency and power density vis-à-vis the DMFC.

All of the system comparisons in the present study are for “load-following” power systems, i.e., the system is not “hybridized” with other energy or power sources. Whenever no realistic or reliable information is available, we will, for the sake of providing a comparison, make several approximations and assumptions. The approximations and assumptions, including their consequences, are:

(i) The DMFC and DHFC fuel cell vehicles will be of the same design and approximately the same weight. (This approximation means that the same total system power is required to provide equivalent acceleration performance for the two FCVs, and the total power systems must fit into the same space, i.e., must have the same overall system power density.)

(ii) Since the same total system power is needed, the drive train components (motor controller, electric motor, and gear train) can be ignored in the comparison, as can the power controller and system controller for the fuel cell power system. (This means that the comparison is reduced to only the stack, auxiliaries, air supply and fuel supply.)

(iii) In the absence of any actual detailed information, we assume that the air supply sub-system for each type of fuel cell system will be roughly equivalent in size and power losses for both types of systems. (One can actually argue in both directions on this point, but, as an assumption, this removes the air supply system from the comparison, leaving only the stack, other auxiliaries, and fuel supply.)

(iv) We assume, again in the absence of any actual detailed information, that the demands, size, and power drain of all of the other auxiliary sub-systems (water, cooling, etc.) will be roughly equivalent for both types of systems. This seems over-generous for the DMFC, the RMFC, and especially the RGFC – since there is more rejected heat in the stack for all of these systems. However, some credit should be taken in the case of the DMFC for cooling by liquid feed to the anode.

This finally brings us to the benchmark being a DHFC “system” that consists of the DHFC stack and fuel supply, only.

The chain of reasoning above leads to a fairly simple comparison basis for the DMFC versus the DHFC “system”. However, in spite of its relative simplicity, this basis exposes the major differences between the DHFC and DMFC systems, and, in fact, among all of the alternative fuel cell systems for automotive applications. Specifically, it captures...
the significant impacts of both the stack (efficiency and power density) and the fuel (energy storage density) on the competitiveness of FCVs using alternative fuels.

One final basis of comparison is needed—a criterion related to fuel characteristics. The most obvious choice would simply be fuel efficiency itself. However, the experience in the marketplace with battery electric vehicles (BEVs which are the “other ZEVs”) has taught us that it is not that simple. Although the BEV has exemplary fuel efficiency (defined with respect to the electricity stored on-board), its characteristic lack of driving range has effectively relegated it to niche applications.

From this real-life experience we suggest that the range of a future general-purpose passenger FCV must be roughly the same as that of current general-purpose passenger vehicles (ca. 300-400 miles). This criterion is related to fuel conversion efficiency, but, by using a range requirement, it also establishes the practical need to carry a minimum amount of the “fuel” on-board for a realistic general-purpose FCV.

In turn, this range requirement effectively defines the volume required for fuel storage—through the intermediary of the stack fuel utilization. Finally, this fuel volume is a major determinant of the “system” power density, for the DHFC benchmark, defined here for comparison purposes. This will become clearer for the example that we consider next—the DHFC “system”.

**DHFC AND DMFC “SYSTEM” COMPARISONS**

Based on the foregoing discussion, the DHFC benchmark “system” to be used for our exercise consists of the direct-hydrogen stack plus compressed hydrogen fuel stored in high-pressure tanks. This will be the basis of comparison for the equivalent DMFC “system” which consists of the DMFC stack and the methanol fuel storage tank. The comparison criteria we will use here are the overall “system” power density and, as explained above, an FCV driving range of nominally 350 miles.

**Direct-hydrogen fuel cell “system”**

We apply these criteria to the DHFC “system” as follows. First we assume that a lightweight FCV design, such as the proposed Ford “P-2000” FCV, is implemented and achieves current PNGV vehicle design goals for vehicle energy efficiency. The combination of a 60 kW peak power DHFC stack (power density of 1 kW L⁻¹ per Ballard Power specifications), and a 5000 psi compressed hydrogen supply for this FCV (with a
roughly 350 mile range), would require about 240 liters of volume (60 l for the stack and 180 l for the hydrogen at 5000 psig).

Direct-methanol fuel cell “system”

For an equivalent DMFC “system”, we would require the same “range” (with our actual calculation being fuel cell stack conversion efficiency times fuel energy on-board). This yields a volume of fuel (to achieve the required range) corresponding to each value of DMFC “system” conversion efficiency used for calculation. Subtracting this fuel volume from the available volume for the DHFC “system” in the FCV (240 l) leaves us with the volume available for the 60 kW DMFC stack – and hence determines the required DMFC stack power density. The final step is then to translate this stack power density into an equivalent cell power density (as shown in Figures 2 and 3).

The chemical energy density of methanol (kWh l⁻¹) is approximately five times larger than the energy density of hydrogen compressed at 5000 psi. Thus, if the DMFC stack had the same conversion efficiency vs. methanol as the DHFC stack has vs. hydrogen, then – for the same FCV range – the methanol fuel required would be 20% of the volume of the hydrogen. Or, at the other extreme, if the DMFC stack has only 50% of the DHFC stack efficiency, the volume of methanol fuel need on-board is 40% of the hydrogen volume.

Using the lower value of 50% of the DHFC stack efficiency as a working assumption (this appears to be attainable based on Figure 3), the methanol fuel volume is 72 l (40% of the 180 l needed for hydrogen), and the allowable DMFC stack volume is approximately 170 l (240 l minus 72 l). For a peak stack power of 60 kW, this leads to a required DMFC stack power density of 0.35 kW l⁻¹ (35% of the demonstrated 1 kW l⁻¹ power density for a DHFC stack).

Cell vs. stack power density

The final link in our comparison is to relate the cell power densities for the DMFC and DHFC technologies (see Figures 2 and 3) to the respective stack power densities (computed above in our comparison). As a first approximation, the stack geometry (volume for the cell MEA, electrodes, backing layers, bipolar plates, reactant gases or liquids, cooling channels and plates, humidification cells, etc.) would be expected to be roughly the same for both DHFC and DMFC. At this time there is no clearly compelling argument that the cell power density and the stack power density should not be in roughly the same ratio for both types of stack when they reach a similar commercialization stage.
In other words, the relative power density performance at the cell level would carry through to the stack—roughly unchanged.

For the calculation above, which assumes a DMFC conversion efficiency of only 50% of the DHFC value, the DMFC power density at the cell level should be at 35% or greater of the DHFC cell power density. This combination of relative values for cell conversion efficiency and power density is roughly met by the state-of-the-art data for the DMFC in Figure 3, and is clearly exceeded by the projected performance levels for reduced crossover and increased cell voltage (the same figure).*

Summary: DMFC versus DHFC “systems”

Overall, the summary of the above calculations is that a DMFC powered FCV could meet the requirements for a general-purpose ZEV and be an effective competitor to a DHFC-based FCV. It would have an equivalent range of 350 miles, and provide the same class of performance (acceleration) as a hydrogen-fueled FCV, if:

(i) the cell/stack power density were at 0.35 kW l\(^{-1}\),
(ii) the stack conversion efficiency over the required drive cycle were at 50% of the equivalent DHFC stack efficiency.

These criteria are marginally met for the current state-of-the-art DMFC cell (see Figure 3). If the reductions in methanol crossover and cell polarization assumed in Figures 2 and 3 are achieved, a DMFC power system would exceed these criteria very comfortably. Another factor that could facilitate DMFC stack competitive position is effective cell packaging, a quite likely achievement according to some initial results.

REFORMATE FUEL CELL POWER” SYSTEMS”

As noted earlier, comparisons between FCVs powered by DHFC or DMFC power systems and FCVs fueled by methanol (or “gasoline”) reformate is not a valid “apples-to-apples” comparison, because of the non-zero emissions expected from reformate systems. However, the performance of these reformate systems is worth briefly analyzing from the point of view of fuel efficiency and power system density, using the same DHFC benchmark criteria.

* A recently LANL-demonstrated short DMFC stack reached packing density of 5 cells per cm, but is still to be tested to confirm repetition of single cell DMFCs at at 100°C, the temperature used in this analysis.
Fuel efficiency of the RMFC “system”

There are several conversion-efficiency and fuel-utilization losses in the methanol reformate “system”. These are:

(i) Because of the dilution effects for reformate fuel (about 70% mole fraction hydrogen for methanol steam reformate, and as low as 20% mole fraction for partial oxidation methanol reformate), there is some drop in conversion efficiency in the reformate stack at given power, particularly so at higher dilution and higher power levels. The primary losses are due to increased anode polarization from mass transport limitations in the anode backing and catalyst layer. A loss in maximum power density (relative to a direct-hydrogen fuel cell stack) has been estimated theoretically (and also measured) in the range of 10 to 25% for fuel cell stacks using methanol reformate rather than neat hydrogen.

(ii) There is also an energy loss in the fuel reformer itself, variously estimated at 20-30% for steam and partial oxidation reformers.

(iii) Finally, there is a need to circulate more than the stoichiometric equivalent of hydrogen through the anode of a reformate cell. The dilution of hydrogen in the reformate means that excess hydrogen is needed to provide adequate hydrogen concentration at the anode catalyst layer and reduce anode polarization losses. Since it is not possible to recirculate a reformate fuel – as can be done for pure hydrogen or methanol – this represents a direct loss of fuel for the reformer-based system. For a dynamic automotive system application, this excess hydrogen will be difficult to completely use in the overall system, particularly for a partial oxidation reformer, so it should be counted, at least for the moment, as a loss at the system level. Losses from this effect have been estimated at 15-30% of the reformate hydrogen (depending on the hydrogen mole fraction in the reformate).

The most favorable estimate for a methanol reformer-based system can be calculated from the highest values of the ranges listed above. Using the upper values of 90% relative voltage efficiency (direct hydrogen dilution loss in the stack), 80% reformer efficiency, and 85% fuel utilization (excess fuel stoichiometry) yields a relative efficiency of about 60% for a steam methanol reformate stack vis-à-vis fuel conversion efficiency of a DHFC stack.

Following the process used above for the DMFC “system”, this RMFC “system” efficiency estimate can be used to calculate a volume requirement for the methanol storage in the steam reformer RMFC “system”. The result is that the RMFC “system” needs about 1/3 of the volume of the hydrogen for the DHFC “system”, or 601. Subtracting this from the total “system” volume available (240 l for the DHFC “system”) leaves 180 l for the remainder of the RMFC “system”. However, for the RMFC “system” this added
volume must also include the fuel reformer sub-system. The impact of this additional sub-system on the required RMFC stack power density is evaluated next.

**Power density of the RMFC “system”**

The primary impact on the peak power density of the methanol and “gasoline” reformate fueled stack is the effect of the diluted hydrogen on anode polarization. For the range of dilution expected, i.e., 70% to 20% hydrogen mole fraction, the stack power density would be reduced to the range of 90% to 80% of the DHFC stack, respectively. For steam reformed methanol, the 90% level of power density – compared to the DHFC – is chosen here for comparison.

In addition, for reformate fuel cell systems there is a further loss of power density at the “system” level due to the volume required for the fuel reformer sub-system, e.g., fuel pre-heater, air compressor, main reactor, CO cleanup, expansion and cooling. As with most of the components in reformate systems, there is no accurate information, or common agreement, on the probable volume and weight of such a reformer. For the present discussion, we will – simply as an example for the purposes of providing an estimate – analyze the effect of fuel reformer power density in the range of 0.5 to 1 kW l⁻¹. The latter figure is a commonly stated goal for the complete fuel reformer sub-system, but 0.5 kW l⁻¹ is possibly a more realistic expectation.

Using the 1 kW l⁻¹ figure to compute the required stack power density for a methanol steam reformate “system”, we see that the reformer sub-system requires an additional 60 l from the overall volume available for the RMFC “system”. This, plus the 60 l computed for methanol storage (see above), leaves 120 l for the RMFC stack. So, for the required 60 kW “system” power, the required RMFC stack power density is 0.5 kW l⁻¹ (if the reformer power density is indeed 1 kW l⁻¹).

If we use the lower value of 0.5 kW l⁻¹ for the fuel reformer power density, we find that the reformer sub-system requires an additional 120 l. This, plus the 60 l computed for methanol storage, leaves only 60 l for the RMFC stack. So, at the required 60 kW “system” power, the required RMFC stack power density must be 1 kW l⁻¹, or exactly the same as the DHFC stack (for a reformer power density of 0.5 kW l⁻¹).

For the assumed range of reformer power density – 1.0 to 0.5 kW l⁻¹ – the RMFC stack power density must be in the range of 1.0 to 0.5 kW l⁻¹, in inverse relationship. Since we expect the RMFC cell power density to be about 80-90% of the DHFC cell power, this range of 50-100% of the DHFC power density seems reasonable. If the RMFC stack is at 90% of the DHFC stack power density, then the reformer must achieve 0.55 kW l⁻¹ for parity.
Summary: RMFC steam reformer “system”

Our conclusion is that it will be possible for the RMFC “system” to achieve the required range and power needed to provide a general purpose FCV with comparable range and performance to that of a DHFC vehicle (based on the PNGV vehicle efficiency goals). This is the result even if the reformer sub-system power density falls to roughly 55% of the goal of 1 kW l⁻¹ power density. However, if the steam reformer power density falls below 0.55 kW l⁻¹, the steam reformer RMFC “system” power density will fall commensurately short of the required performance for a general purpose FCV.

In summary, a fuel cell power system based on a methanol steam reformer can be expected to be roughly competitive with a DHFC power system for a general purpose vehicle – but without the “redeeming virtue” of ZEV emissions. The cell power density and power system conversion efficiency will be intermediate between the DHFC and DMFC values, and, without ZEV status, the RMFC powered FCV will not be fully competitive to the DHFC (or DMFC) vehicles.

Comments on partial oxidation reformer “systems”

Although we will not consider the cases of partial oxidation reformer “systems” here in any detail, there are several factors that should be noted. Namely:

(i) The relative efficiency of a partial-oxidation “gasoline” reformer system is lower than that computed above for the methanol steam reformer case. A rough figure for the “gasoline” case can be calculated from the following figures – 80% efficiency due to the dilution loss, 70% reformer efficiency; and 75% fuel utilization of neat oxygen in the stack. The overall efficiency is therefore calculated to be about 40% of that of the DHFC system – i.e.; roughly equivalent to the DMFC state-of-the-art.

(ii) Since the partial oxidation reformation process for both “gasoline” and methanol is exothermic, there is limited opportunity to recover the excess (fuel cell exhaust) hydrogen energy within the overall partial oxidation fuel cell system.

(iii) A partial-oxidation methanol system would have fuel conversion efficiency somewhat higher than the “gasoline” example calculated above (40% of the DHFC benchmark) but lower than the steam reformed methanol case. A figure of about 50% seems reasonable in comparison to the DHFC “system”. This is within the range of current to projected DMFC values.
These factors suggest that the partial oxidation systems, particularly for the "gasoline" case, will require reformer power densities closer to the 1.0 kW l⁻¹ level than in the methanol steam reformer case.

CONCLUSIONS

A direct-methanol fuel cell powered FCV could meet the requirements for a general-purpose ZEV, and therefore could be an effective competitor to a direct-hydrogen fuel cell powered FCV. In addition to its ZEV status, it could reach an equivalent range of 350 miles, and provide the same class of performance (acceleration) as a hydrogen-fueled FCV, if

- cell/stack power density is at 0.35 kW l⁻¹ (35% of the direct-hydrogen value),
- stack conversion efficiency (over the required drive cycle) is at 50% of the DHFC drive cycle stack efficiency.

These criteria are marginally met for the current state-of-the-art DMFC cell (see Figure 3). If the reductions in methanol crossover and cell polarization that are assumed in Figures 2 and 3 are achieved, a DMFC power system would exceed these criteria very comfortably. Another element of DMFC technology that would assist in enhancing power density is high cell packing density in the stack. In addition, the direct-methanol powered vehicle is a ZEV, and can therefore compete with the DHFC on an equal footing in all markets.

Based on a similar comparison, the methanol (steam) reformer fuel cell system can be expected to provide an FCV power system that is also competitive with a DHFC powered general purpose vehicle, in terms of range and performance. However, the reformed-methanol fuel cell system cannot meet the ZEV emissions required for direct competition with the direct-hydrogen (or direct-methanol) systems in every market. Even so, it is frequently compared with the direct-methanol power system, simply because it uses the same fuel.

Finally, the requirements on the reformer power density for a partial oxidation FCV power system (especially the "gasoline" case) are more demanding than those for the reformer in a methanol steam-reformer power system.
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FIGURES

![Figure 1](image)

**Figure 1.** Optimum overall conversion efficiency vs. cell power density (voltage efficiency \(\times\) fuel utilization) for a DMFC, based on experimental data and varying feed conditions with cell power.

![Figure 2](image)

**Figure 2.** Conversion efficiency of a DMFC with (i) reduced methanol crossover, and (ii) reduced crossover plus decreased voltage loss.
Figure 3. Comparison of overall conversion efficiency of a direct-methanol vs. hydrogen fuel cell.