# SOLID OXIDE FUEL CELLS FOR TRANSPORTATION

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***Abstract***

*The well-known compatibility of the SOFC with hydrocarbon fuels makes the solid oxide fuel cell a strong contender for transportation applications. Gasoline and diesel will continue to be the dominant fuels for decades to come. The 500 million automobiles, the existing fuel distribution system and the economic power of oil and automobile companies combined form a strong inertia in favour of liquid fuels and internal combustion engines. The chances are slim that hydrogen will soon appear at gasoline stations to power "PEMobiles", i.e. vehicles equipped with polymer electrolyte fuel cells.*

*Therefore, because of their compatibility with vaporised liquid hydrocarbon fuels, solid oxide fuel cells may play an important role in transportation. Basically, a typical "SOFCar" would be a hybrid fuel cell vehicle equipped with a small buffer battery and a relatively small onboard SOFC power source which is more or less continuously converting conventional gasoline or diesel fuel into DC power. The temperature of the fuel cell will be adjusted to the actual power demand.*

*The paper presents arguments for the use of light weight, compact and efficient solid oxide fuel cells in transportation. Furthermore, the SOFC is compared to the PEFC which today is highly favoured for transportation applications. Suggestions are provided for design and operation of SOFCars.*

## 1. PEFC: today's transportation favourite!

It seems to be a forgone conclusion that only the polymer electrolyte fuel cell PEFC (or PEM) has a realistic chance to replace the internal combustion engine in transportation applications. In fact, this notion is reconfirmed by convincing presentations of experimental results. Impressive investments and global business partnerships have been formed. It has certainly been established that fuel cells having solid polymer electrolytes can power vehicles. Again and again, the players in the field assure each other by reports of success. But there are still unsolved critical issues, many of which would not exist if solid oxide fuel cells were considered for transportation applications. Therefore, some of the open questions shall be recalled.

Solid polymer fuel cells need clean hydrogen. But hydrogen is expensive, not generally available and difficult to be handled safely by ordinary drivers. It must be carried along in liquid or adsorbed form at cryogenic temperatures or as compressed gas in voluminous tanks. For the onboard conversion of gas station fuels to hydrogen vehicles must carry bulky, complex and costly chemical converters. As a consequence, the driving range of hydrogen-fuelled cars, with fuel cells and internal combustion engines alike, is limited to about 200 km. Certainly, the hydrogen fuel issue is reduced for "PEMobiles" serving routine tours and returning to the same location every night. But most automobiles are operated at random, but not in well-organised fleets.

The low operating temperature of solid polymer fuel cells, often praised as key advantage, may turn out to be the Achilles heel of the technology. In hot climates the temperature of the ambient air may be too high for removing the waste heat from a stack. As a consequence, the stack temperature may rise, thus drastically increasing the need for membrane humidification. But under said conditions the required water can no longer be recovered from the exhaust air. As a result, the car must be operated at reduced power to protect the fuel cel Similarly, solid

polymer fuel cell systems need clean, demineralised water not only for membrane humidification, but also for reforming of hydrocarbon fuels. Furthermore, large quantities of reaction water accumulate in cells, manifolds and exhaust system. It needs to be resolved how to prevent system freeze-up under severe winter temperatures of down to -40°C or how a "frozen" PEFC system can be put back into operation after a cold winter night.
From a thermodynamic point of view the conversion of gas station fuels to clean hydrogen is a complex process involving many significant temperature jumps and, as a consequence, losses of exergy or energy available for conversion. Liquid fuels must be vaporised, then heated to reforming temperatures (about 250°C for Methanol and 800°C for gasoline). Steam must be added while these temperatures are maintained. Then the hydrogen-rich reformate must be cooled or heated with great accuracy to 450°C for selective oxidation of CO to $CO_2$. After that, the mixture of hydrogen and $CO_2$ is cooled down to about 70°C before it is admitted to the fuel cell. Needless to say that design and control of this process is no easy matter, but operating the process technology in road vehicles under ordinary driving conditions may be extremely difficult.

## 2. SOFC - the sleeping beauty?

The dominance of the transportation sector by hydrocarbon fuels makes solid oxide fuel cells attractive for mobile applications. Partially pre-reformed ordinary liquid gas station fuels are admitted to the anode chamber of an SOFC stack. Pre-reforming is accomplished by partial oxidation or anode exhaust recycling within the hot envelope of the fuel cell stack. A wide spectrum of fuels can be converted to power. The reaction products are removed together with the hot cathode exhaust. A single counter flow heat exchanger is needed to preheat the reaction air. Waste heat is rejected through the exhaust pipe. Furthermore, no noble metal catalysts are required in the process.

SOFC automobiles or "SOFCars" are much closer to today's transportation system than "PEMobiles". The existing fuel infrastructure can be used and no new safety standards must be introduced. There are no climatic restrictions and driving range limitations. SOFCars can be introduced to existing markets.

Also, the high operating temperatures of SOFCs pose no serious problem. There is no significant difference between heating an SOFC stack or a gasoline reformer to 800°C. In both cases, no power can be generated during warm-up. The time delay must be bridged by energy from a buffer battery connected parallel to the fuel cell in a hybrid system. The gas conditioner of an SOFC is simple. It can be integrated into the hot stack envelope and works by thermo-chemical heat recovery. SOFCs can easily be kept hot for many hours (6).
Furthermore, the output of an SOFC can be varied over a decade by adjusting the operating temperature to the actual power requirements or the charge level of the buffer battery. 650°C may be sufficient to recharge the battery, 800°C may be required to provide power for city driving and 900°C may be chosen when driving on freeways or climbing hills. No other fuel cell offers similar features.

System simplicity combined with compatibility with hydrocarbon fuels make the solid oxide fuel cell a strong contender for transportation applications. Gasoline and diesel fuels will continue to be the dominant fuels for decades to come. The 500 million automobiles on the road, a world-wide operating fuel distribution system, the economic power of oil and automobile companies provide the inertia for a continued dominance of liquid fuels in the transportation sector. This should not be overlooked. The chances are slim that hydrogen for PEMobiles will soon appear at gasoline stations. Therefore, the hybrid fuel cell vehicle, i.e. an electric car with an onboard fuel cell power source operated on gasoline or diesel may have the best chance to become the car of tomorrow. While a PEFC as such is easier to operate than an SOFC, the SOFCar system offers so many advantages that it should be considered as power source for hybrid electric vehicles.

### 3. State-of-the-art SOFC

Unfortunately, the dominant SOFC developers aim at stationary applications. Such ceramic solutions are indeed heavy, sluggish, expensive and fragile and must be operated at high temperatures. But totally different SOFCs are presently developed for mobile applications. The following results, **Table 1**, have recently been presented.

*Table 1. Recent results reported by distinguished SOFC laboratories*

| Feature | Value | References |
|---|---|---|
| Power density at 800°C | 1.935 W / $cm^2$ | Berkeley Lawrence Lab. (2) |
| Stack power per volume | over 1 kW / L | Allied-Signal Aerospace (3) |
| Stack power per mass | over 1 kW / kg | Allied-Signal Aerospace (3) |
| Warm-up: to 800°C | 1 minute | Keele University (4) |
| or „to operating temperature" | 5 seconds | Keele University (5) |
| Cool-down, 1000 to 800°C | 31 hours | Univ. of California (6) |

Although these results come from different laboratories, they illustrate the potentials of advanced SOFC technology: planar, hybrid (metal-ceramic), bipolar designs with thin (5 to 10 \im) supported ceramic electrolytes and operating temperatures between 650°C and 800°C. Such light weight, compact SOFCs are under development for automotive applications. Table 2 documents what can be expected in the near future.

*Table 2. Projected trends of development of SOFCs for transportation*

| Features | Projections |
|---|---|
| Operating temperature | (550°C) 600°C to 800°C |
| Start-up (ambient to operating temp.) | less than 2 minutes |
| Stack power per volume | 2 kW / L |
| Stack power per mass | 2 kW / kg |
| Fuel | unleaded gasoline, diesel, Methanol |
| Reforming | integrated internal and in situ |
| Cooling | air, heat rejection by exhaust |
| Duty lifetime | 5,000 hours |

### 4. Fuel cells in road vehicles

To identify the role of solid oxide fuel cells in transportation systems the function of a fuel cell in cars is analysed in general. Today's road vehicles are designed to move passengers or goods over distances of at least 500 km with energy derived from conventional commercial liquid fuels.

By definition, car engines are not replaced by fuel cells, but by electric motors, one connected to the drive shaft, or pairs of hub motors integrated into the wheels. Fuel cell vehicles will also have at least one battery to power lights and luxuries (radio, defrost etc.), to provide energy for start-ups and to maintain essential functions during emergencies. To improve fuel economy this battery must also store recuperated brake power. As a consequence, the battery is sized properly for serving as energy buffer and to provide peak power for acceleration. Batteries of advanced fuel cell vehicles will thus be bigger than batteries of conventional cars, but much smaller than batteries of all-electric vehicles, Fig. 1.

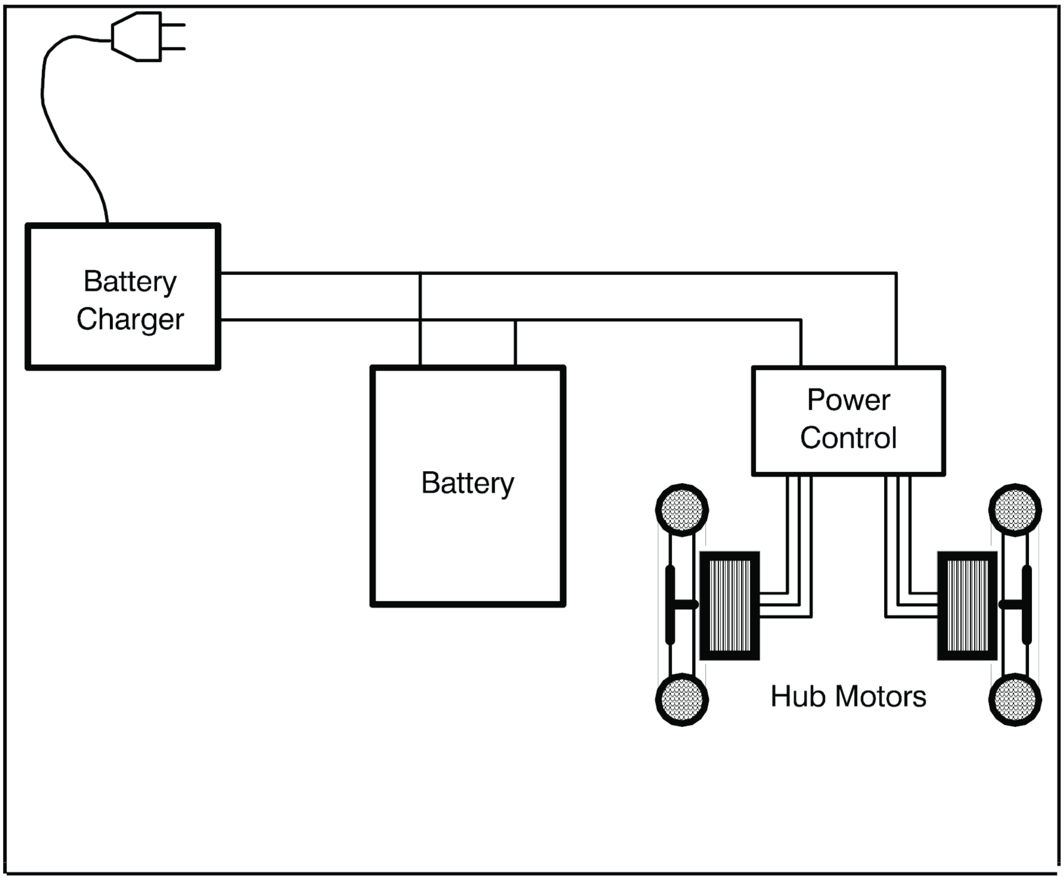


*Fig. 1. Aall-electric vehicle*

In essence, fuel cell vehicles are hybrid electric cars with an onboard power source to keep the batteries charged. Electric power is supplied to the drive motors by the cells and/or the battery. Naturally, the battery can also be charged conventionally by power from the grid. Chemical fuels are used to extend the operating range of the vehicle and to reduce its weight and overall cost. The "gas pedal" will be connected to the power control box and not to a valve in the fuel line. Also, start-up times of fuel cell power systems of a few minutes must be accepted. The choice of cell type (PEFC, SOFC, AFC etc.) becomes a matter of overall system optimisation and fuel availability.

If hydrogen is available, then the PEFC is clearly favoured, basically because the liquid electrolyte (sulfonic acid) is contained in a polymer membrane. But storing hydrogen is still a problem. H2-tanks are bulky and expensive, Fig. 2.

The situations is not changed significantly for hybrid PEMobils operated on liquid fuels. Instead of the voluminous H2-tanks heavy, voluminous and more complex fuel conditioning equipment must be fitted into the car. The range of operation is extended in exchange for useful space and weight, Fig. 3.

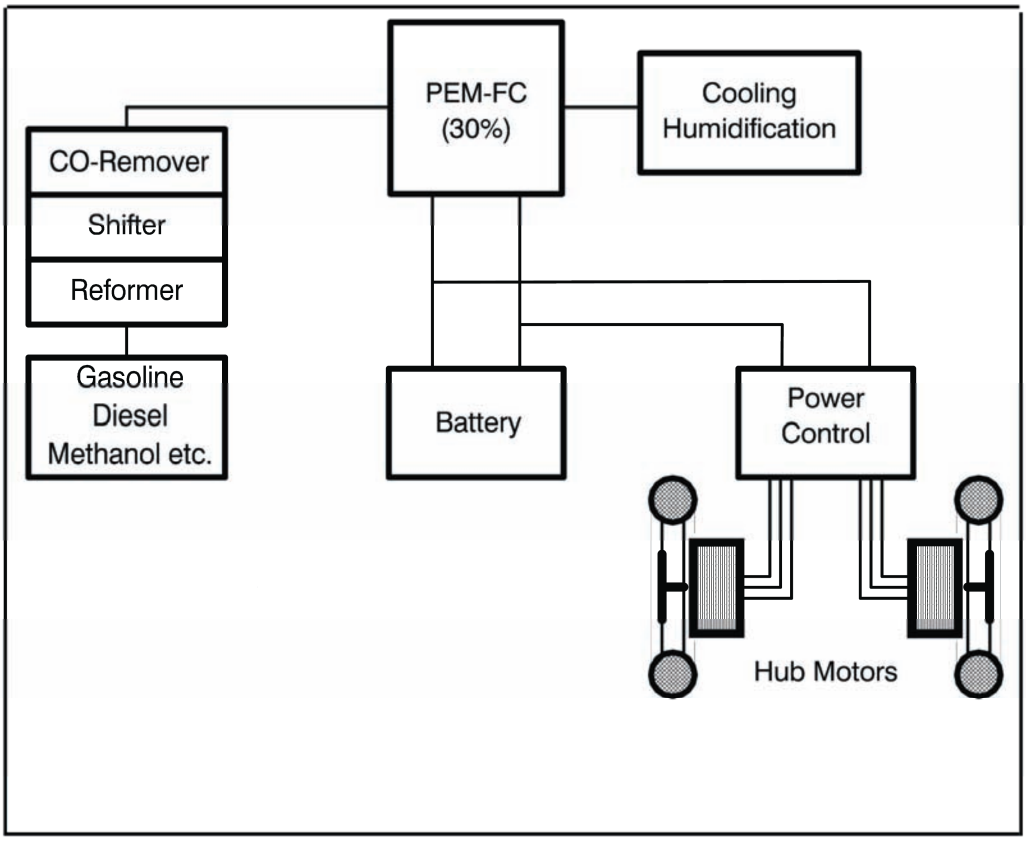


*Fig. 2. PEMobil: hydrogen & PEFC*

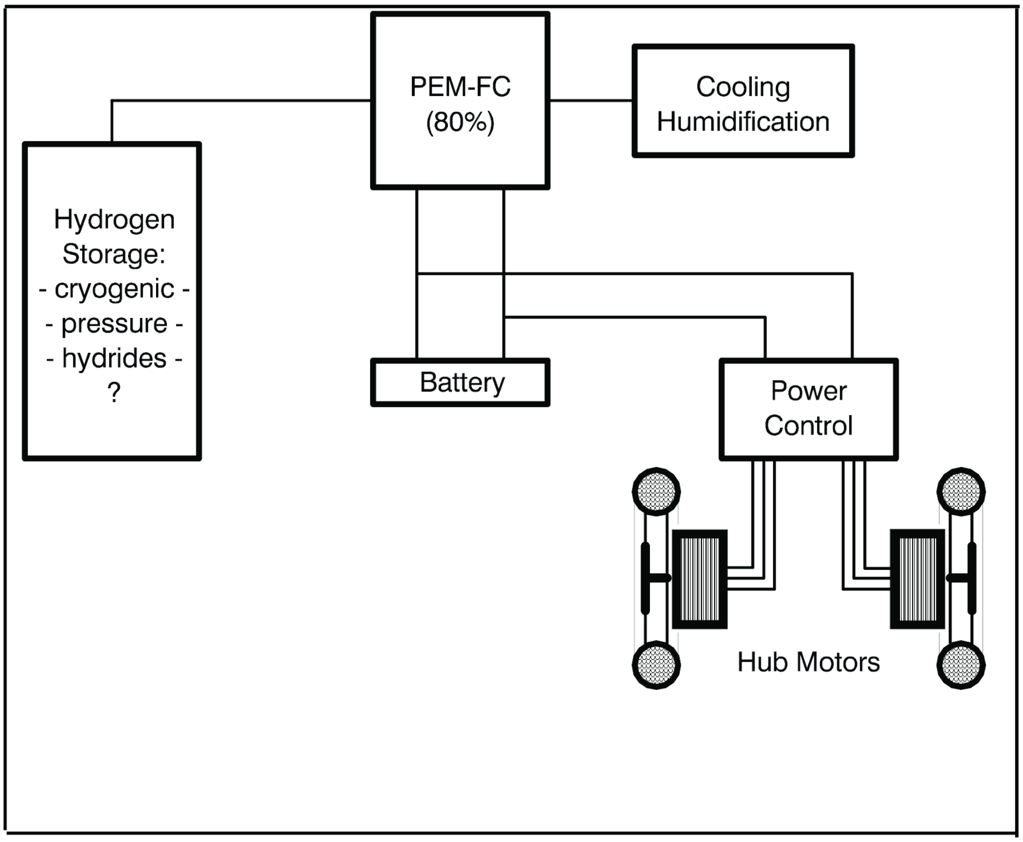


*Fig. 3. PEMobil: gasoline & PEFC*

But the SOFCar has the potentials to replace the conventional drive train by a fuel cell system without significant changes of comfort. There are interesting options for the optimisation of weight, volume, initial cost and operating expenses of such low emission vehicles. SOFCars will certainly surpass all-electric cars with respect to overall energy efficiency, driving range, maximum speed and environmental friendliness Fig. 4. Operation with hydrocarbon fuels, in particular with unleaded gasoline or diesel, will extend the driving range of SOFCars to 800, perhaps 1,000 miles between tank refills.

Nevertheless, chemical fuel processing must be considered for all types of fuel cells. Fortunately, the SOFC can operate on partially pre-reformed hydrocarbons (unspecified mixture of H2, CO and CmHn) as the reforming process is continued in the cell itself and carbon poisoning is not an issue. The endothermic process can be integrated into the gas manifolds or the stack itself to provide cooling and to recover waste heat for the chemical conversion. As a consequence, SOFCs with integrated reformer can reach overall conversion efficiencies of over 60%.

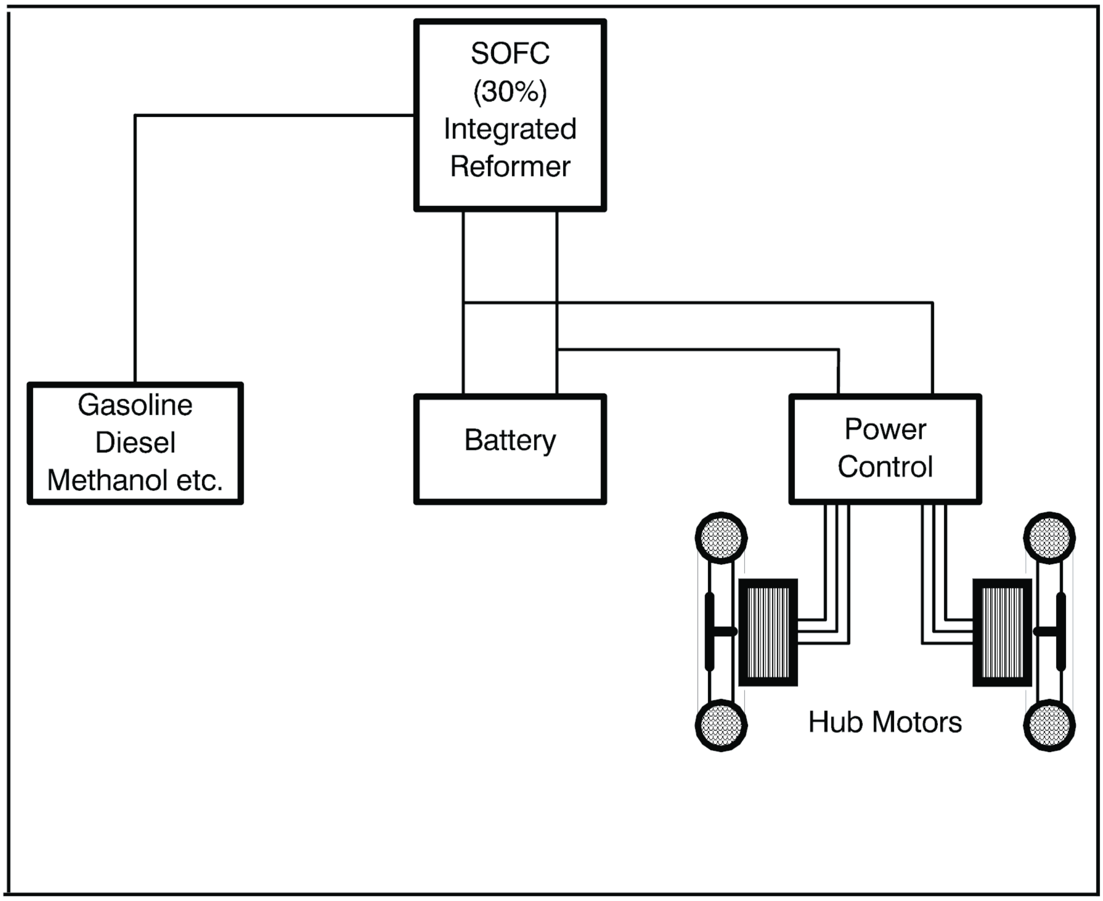


*Fig. 4. SOFCar: gasoline SOFC*

**5. PEMobil versus SOFCar**

It is difficult to compare two conceptual designs of systems which are still on the drawing board. The comparison is attempted for out-of-town (500 km range) hybrid fuel cell vehicles operated on conventional hydrocarbon fuels. Also, no quantified evaluation can be presented at this time. The arguments collected in Table 3 may thus include personal views and experience. Still, some points are worth noticing.

## 6. Conclusions

PEFC fuel cells have gained wide acceptance for use in hydrogen-powered busses and cars. There is no question that this cell is better suited for hydrogen than any other type of fuel cell. The impressive success of Ballard and associated car manufacturers is convincing by itself and will promote diverse applications of fuel cells in transportation for traction and onboard power.

But the limited range of operation of hydrogen powered vehicles, whether equipped with fuel cells or internal combustion engines cannot be neglected. The economic storage of hydrogen or other gaseous fuels at cryogenic temperatures in the liquid or adsorbed state, or at ambient temperatures but high pressures is a still unsolved problem. Also, refilling hydrogen storage tanks at gas stations requires not only new technologies and safety legislation, but also more time than ordinary drivers are willing to accept.

Consequently, PEMobiles may conquer the attractive and substantial market of structured mobility (city busses, postal services, taxis, city cars etc.) where hydrogen can be supplied to the vehicles from central tanks at scheduled intervals. But they may not succeed in the much broader market sector of random mobility (private cars, trucks, tour busses, military vehicles etc.).

*Table 3. Comparison of the PEMobil and the SOF Car*

| Features | PEMobil | SOFCar | Remarks |
|---|---|---|---|
| Availability of fuel cell | yes | not yet | SOFC about 5 years behind |
| Operating temperature | 80°C | 750°C | SOFC perhaps 600°C |
| Cost of fuel cell | ? | ? | similar |
| Stack power / weight | ≈ 1 kW / kg | ≈ 1 kW / kg | similar |
| Stack power / volume | ≈ 1 kW / L | ≈ 1 kW / L | similar |
| Start-up time of stack | seconds | minutes | |
| Stack duty life time | 5,000 hours | 5,000 hours | matter of design |
| Electrolyte maintenance | yes | no | PEM: humidification |
| Start-up time of system (stack and reformer) | minutes | minutes | similar |
| System response time | seconds | seconds | similar |
| Electrical system | more complex | simpler | PEMobile: add fuel conditioning, cooling |
| Buffer battery capacity | ? | ? | similar |
| Fuel tank capacity (gasoline, diesel) | 50 L | 50 L | similar |
| Fuel conditioning hardware | reformer, shifter & CO-remover | almost none | SOFCar with integrated reforming |
| Overall efficiency | ≈ 40 % | ≈ 50% | |
| Operating range | ≈ 800 km | ≈ 1,000 km | |
| Cooling system | needed (water) | not required | |
| Antifreeze protection | needed | none | |
| Defrost and heating | waste heat | waste heat | easier for SOFCar |
| Occupied volume | larger | smaller | |
| System weight | heavier | lighter | |
| System complexity | high | low | |
| Useful weight & volume | less | more | |

For this established market the SOFCar may establish itself as the ultimate winner. Recent developments suggests that SOFCs could play an important role in transportation. This should be explored by initiating particular research efforts and by building a SOFCar as envisioned in this paper.

Nevertheless, overall system optimisation and economics will determine the role of fuel cells in transportation and which type of cell will ultimately appear in cars. PEMobiles operated on stored hydrogen are only forerunners of fuel cell cars which, ideally, share fuels with internal combustion engines while providing the same comfort as ordinary cars. SOFCars appear to be able to satisfy these goals.

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