# Fuel cells – the future of power generation

by Erkko Fontell
Corporate Technology
Wärtsilä Corporation

**When Sir William Grove in 1839 invented the principle of the electrochemical reaction used in fuel cells, he hardly thought that his invention would still be the subject of intensive R&D work around the world in 2003. Development of fuel cell technology has continued ever since. Its first application was in the Apollo space programme where an Alkaline fuel cell was used to produce electricity and drinking water.**

The advantages of the fuel cell – they are a clean, efficient and reliable way of producing electricity – have been the driving force in the development of different fuel cell technologies for commercial applications. The working principle of the different fuel cell types is similar, but the materials, fuels, catalyst and reactions vary. Figure 1 shows the working principle of a Solid Oxide Fuel Cell (SOFC) and its primary reactions.

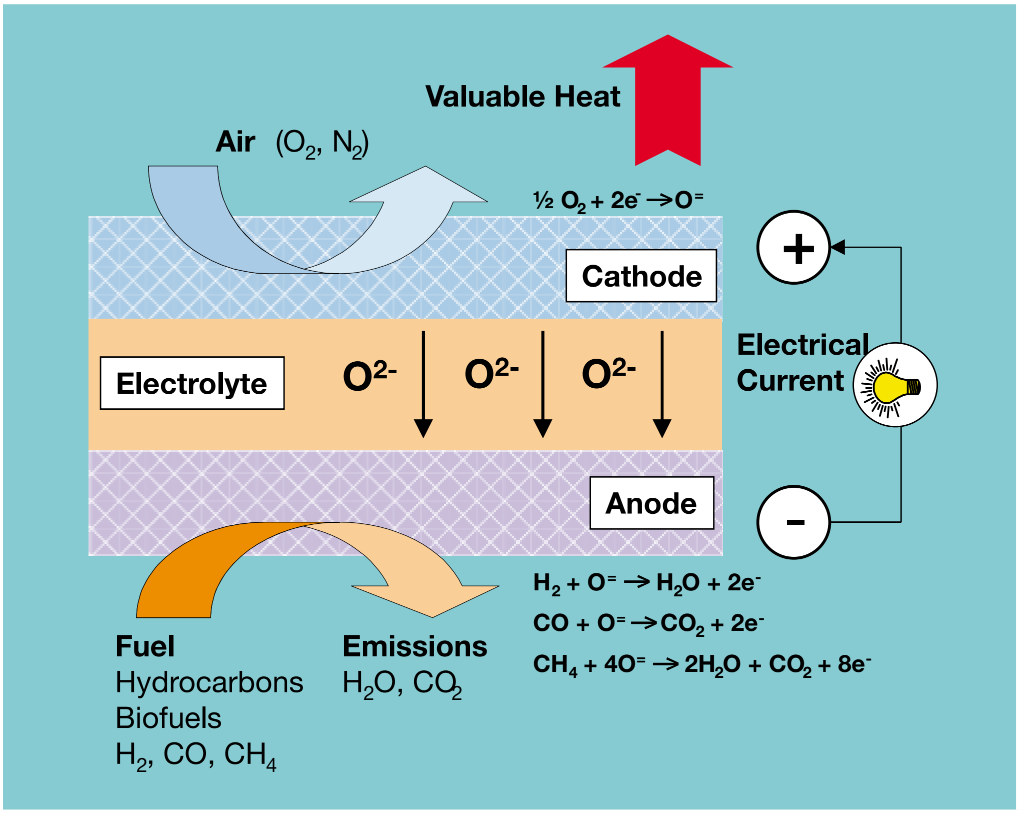


Fig. 1 Working principle of the Solid Oxide Fuel Cell (SOFC).

## Different fuel cell types and their applications

Fuel cells can be divided into three main categories: low-, intermediate- and high-temperature fuel cells. These are used for different applications owing to the differences in the operating temperature and the materials used.

Commercially the most available fuel cell technology is the Phosphoric Acid Fuel Cell (PAFC) where phosphoric acid is used as the electrolyte and platinum (Pt) as a catalyst on both the anode and cathode sides of the cell. Although PAFC technology is commercially available, it has not emerged as the long awaited breakthrough in the fuel cell market mainly due to its high production costs and fairly low efficiency.

Cheaper and more efficient fuel cell technologies, such as the Solid Oxide Fuel Cell (SOFC) and Molten Carbonate Fuel Cell (MCFC), have been developed for industrial energy production. These technologies are expected to become more competitive than PAFC within a few years.

The low-temperature fuel cells, especially PEM, have been developed for transportation and portable applications where fast start-up, compactness and a low temperature level is needed. In these applications the waste heat is not usually utilized. The main disadvantage of these technologies is the high purity requirement for hydrogen and the need for noble metals (Pt) as the catalyst.

The high-temperature fuel cells (SOFC and MCFC) are more suitable for industrial applications where their high efficiency and waste heat can be fully utilized. In continuous operation the long start-up time of the units is not a problem. SOFC technology is currently being developed intensively for APU (auxiliary power unit) applications to power the increasing demand for electricity in cars and trucks.

## Wärtsilä's role in fuel cell technology

Wärtsilä's interest in fuel cell development is clearly focused on development of a highly efficient fuel cell system for power generation in stationary power plants and marine applications. The most potential technology for these applications is the SOFC due to its high efficiency and suitability for CHP.

Wärtsilä intends to develop complete power units based on the most advanced SOFC technology, benefiting in this work from its existing system and application know-how and the global Wärtsilä sales and service network. In August 2002 Wärtsilä began co-operation with the Danish technology company Haldor Topsøe A/S, an acknowledged developer of SOFC technology, in order to ensure optimal system integration. Wärtsilä will develop highly efficient and cost-competitive fuel cell products based on the SOFC technology.

## Planar SOFC technology

SOFC technology is divided into 'tubular' and 'planar' technologies. Westinghouse started development of tubular SOFCs in the late 1950s and this development today is continued by Siemens-Westinghouse.

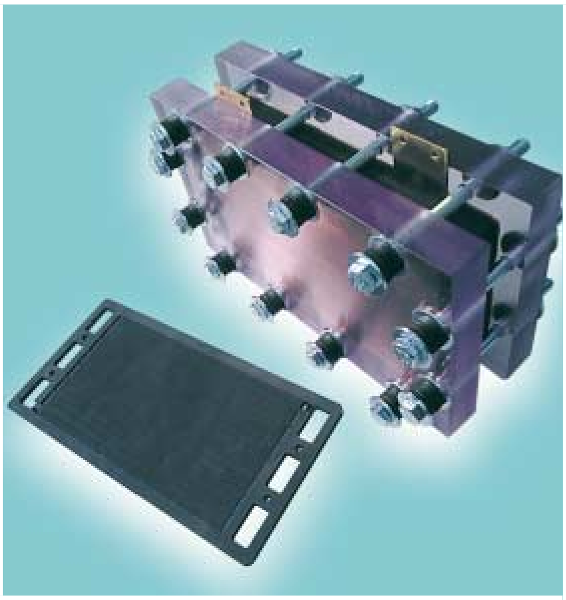

Fig. 2 PEM fuel cell stack.

Fig. 3 Typical planar solid oxide fuel cells.

| FC Type | Anode flow | Cathode flow | Operating temperature (°C) | Efficiency (LHV) | Application |
|---|---|---|---|---|---|
| **Low-temperature** | | | | | |
| PEM Proton Exchange Membrane | $H_2$ | Air | 60 - 80 | 30 - 40 | Portable Residential Transportation |
| AFC Alkaline | $H_2$ | $O_2$ | 65 - 220 | 30 - 40 | Portable Residential Transportation |
| **Intermediate-temperature** | | | | | |
| PAFC Phosphoric Acid | $H_2$ | Air | 150 - 200 | 35 - 45<br>50 - 70* | Industrial Commercial |
| **High-temperature** | | | | | |
| MCFC Molten Carbonate | $H_2$ ,CO, $CH_4$, $NH_3$ | Air + $CO_2$ | 600 - 700 | 45 - 55<br>80 - 90* | Industrial CHP** Commercial Marine |
| SOFC Solid Oxide | $H_2$, CO, $CH_4$, $NH_3$ | Air | 650 - 1000 | 45 - 55<br>80 - 90* | Industrial CHP Commercial Marine |

* In co-generation
** CHP (Combined Heat and Power)

Table 1. Different fuel cell types and their properties.

Planar technology is currently being developed by a number of companies and research institutes around the world.

Wärtsilä is mainly interested in planar SOFC technology due to its suitability for cost-effective mass production and its potential for high power densities. Planar SOFC technology can operate in the temperature range of 650 - 800 °C, which allows the use of conventional materials in the balance of plant components. This will further improve the competitiveness of the planar SOFC technology.

## Fuels

In an SOFC the primary reaction that produces electricity and heat occurs when hydrogen ($H_2$) or carbon monoxide (CO) atoms react with oxygen ions ($O^{=}$). Regardless of which fuel is used, the fuel must be prepared in different ways and phases to provide these reactants for the cell reaction.

Hydrogen is the most suitable fuel for solid oxide fuel cells because it does not require pre-reforming. However, since pure hydrogen is costly and available in only limited quantities a number of other fuels have been used with SOFCs such as methanol ($CH_3OH$), natural gas, gasoline and even diesel oil and ethanol ($CH_3CH_2OH$).

After removing particles from the fuel by filtering, the sulphur (S) compounds must be reduced to a level suitable for the fuel reformer and fuel cell. It is normally necessary to reduce sulphur compounds to below 1 ppm (parts per million), which requires efficient cleaning devices.

The fuel can be reformed in different ways depending on the fuel used and type of fuel cell. Steam reforming and Auto Thermal Reforming (ATR) of natural gas is often used for larger unit sizes. For smaller units Partial Oxidation (POX) is a more compact reforming method.

### Natural gas

As Wärtsilä is interested in SOFC applications larger than 200 kW for marine and stationary power production, the most potential fuels are natural gas and low-sulphur diesel. In stationary applications natural gas is widely used and reforming of natural gas is conventional technology. For SOFCs the higher hydrocarbons in natural gas are converted to methane ($CH_4$), hydrogen ($H_2$) and carbon monoxide (CO). Part of the methane can be internally reformed to CO and $H_2$ in the SOFC stack.

### Diesel oil

For marine applications the use of diesel oil would be most suitable. Diesel fuel can also be reformed after the sulphur content of the fuel is reduced prior to the reformer. In the future the removal of sulphur will most likely be done at the refineries to a level of 5 - 10 ppm, which would allow commercially sustainable fuel cleaning in a marine vessel.

### LNG

LNG is also an option for fuel cell ship applications operating in coastal areas. However, it is not likely that LNG will be used for auxiliary power only if the main engines use diesel oil. Even a small gaseous fuel installation will complicate the entire machinery installation. On the other hand, it is easier to reform LNG than diesel oil.

### Hydrogen

The use of hydrogen has been the subject of considerable interest in several development projects. The storage of the hydrogen is one of the main problem areas. For example a high-pressure storage, metal hydride and hydrogen rich chemical compounds, such as sodium borohydride ($NaBH_4$) have been studied. After the storage issues have been solved and if a cost efficient hydrogen production can be established, hydrogen may become a future fuel both for fuel cells and for conventional combustion engines.

## Emissions

The other major benefit of fuel cell technology besides high electrical efficiency is low emission levels. Generally fuel cells have no sulphur emissions since the sulphur is removed from the fuel before use. $NO_X$ emissions are also minimal because nitrogen ($N_2$) is not a reactant in the fuel cell process. $NO_X$ emissions from SOFC systems are below 0.5 ppm and are mainly formed in an afterburner where residual gases from the fuel cell are burned. Table 2 describes the primary fuel cell reactions for different fuel cell types.

As the table shows, when hydrocarbons are used as fuel the emissions from the reactions are water and carbon dioxide ($CO_2$). The table also describes how methane can be used directly in the SOFC.

### SOFC system

The main components in the SOFC system are presented in Figure 4.

The fuel stream is filtered, pressure controlled and preheated prior to the sulphur removal unit. The sulphur can be removed either at a low or a high temperature. After sulphur removal the fuel is led to the fuel reformer. Prior to the reformer, part of the residual gases from the anode are re-circulated and mixed with the incoming fuel. This recirculation increases the system's efficiency and provides the necessary steam for the steam reformer. After the reformer the reformat is preheated prior to the SOFC stack. After the stack the remaining gases are burnt in a post-combustion unit.

The air side is simpler than the fuel side. In addition to being an oxygen carrier the supplied air acts as a cooling media in the stack. For this reason the volume of air flow varies by containing 2 - 5 times more oxygen than is needed in the reactions.

The other main areas in a SOFC system are system control and power electronics, which converts the low-level DC voltage to a suitable AC current for connection to an external grid.

### SOFC development today

Development of fuel cell power generation applications was started in the late 1970s by United Technologies Corp. (UTC) (PAFC) and Siemens (SOFC). The first commercial unit, launched in 1991, was a 200 kW PAFC system by ONSI (a subsidiary of UTC).

Other fuel cell technologies developed for power generation are the Alkaline Fuel Cell (AFC), the Proton Exchange Membrane Fuel Cell (PEMFC), the Molten Carbonate Fuel Cell (MCFC), and the Direct Methanol Fuel Cell (DMFC).

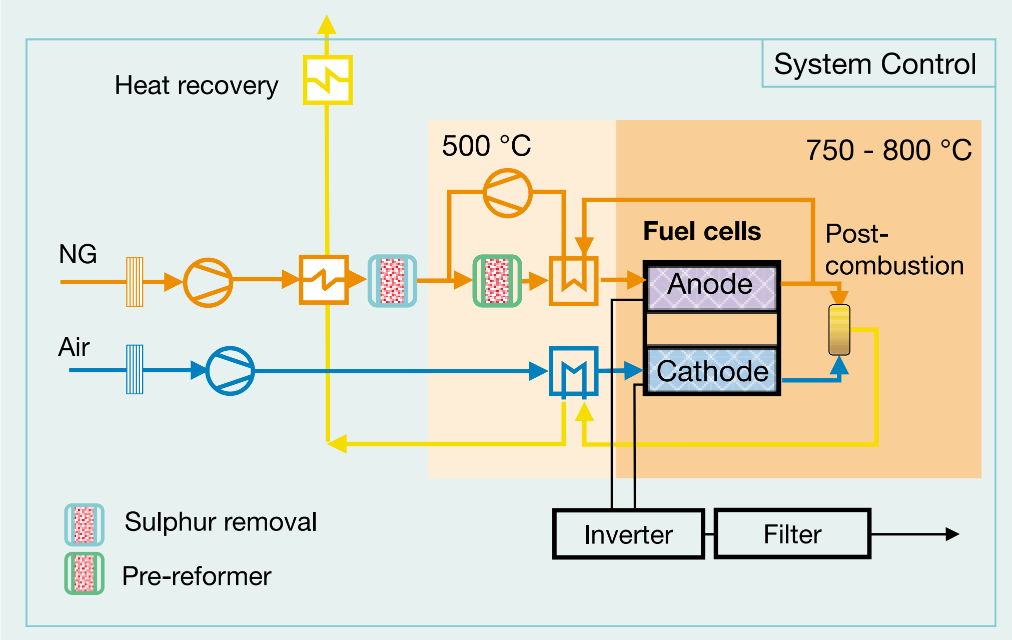


Fig. 4 Schematic of a SOFC system.

| Fuel cell | Anode reaction | Cathode reaction |
|---|---|---|
| PEM and PAFC | $H_2 \rightarrow 2H^+ + 2e^-$ | $1/2\ O_2 + 2H + 2e^- \rightarrow H_2O$ |
| Alkaline | $H_2 + 2(OH)^- \rightarrow 2H_2O + 2e^-$ | $1/2\ O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$ |
| Molten Carbonate | $H_2 + CO_3^= \rightarrow H_2O + CO_2 + 2e^-$<br>$CO + CO_3^= \rightarrow 2CO_2 + 2e^-$ | $1/2\ O_2 + CO_2 + 2e^- \rightarrow CO_3^=$ |
| Solid Oxide | $H_2 + O^= \rightarrow H_2O + 2e^-$<br>$CO + O^= \rightarrow CO_2 + 2e^-$<br>$CH_4 + 4O^= \rightarrow 2H_2O + CO_2 + 8e^-$ | $1/2\ O_2 + 2e^- \rightarrow O^=$ |

Table 2. Electrochemical reactions in fuel cells.

Of the technologies under development, only PAFCs, SOFCs and MCFCs are considered to have commercial potential in stationary power production plants of 0.2 - 5.0 MW size.

Currently close to 350 PAFC units have been sold, out of which around 200 units are in commercial operation. Siemens-Westinghouse Power Generation have collected the widest experience of SOFC technology with their tubular SOFC products. In the current demonstration programmes 100 kW, NG-fuelled SOFC units have been operated for over 20,000 h with 46% electrical efficiency. These programmes have fulfilled the promise of fuel cells as an efficient, emissions-free and reliable power source. However, the challenge still remains to make fuel cells commercially competitive.

In addition to the cost, a major development target of planar SOFC technology is the lifetime and durability of the planar SOFC stack. Current development programmes aim to achieve a 40,000 h stack lifetime with a system cost target of 400 - 800 €/kW. Long-term tests (up to 15,000-20,000 hours) on planar SOFCs have been carried out for 1 kWe stack units, and tests of 5-10 kWe stacks have been started. Once the durability and cost targets are achieved, the SOFC will provide a very competitive alternative for CHP use both in marine and stationary applications.

Several ongoing projects plan to demonstrate 25 - 50 kW SOFC products in the next three years. Units of 250 - 500 kWe size could enter the market by 2010, and plant sizes could be increased to several MW before 2020. Wärtsilä is among the world's front-line pioneers of this technology and plans demonstration programmes on the way to developing over 200 kW products based on planar SOFC technology.

### Fuel cells in ships

The marine industry is coming under ever increasing pressure to reduce emissions and to become more environmentally friendly in other respects as well. Certain segments, such as cruise vessels and coastal ferries, have been a particular focus of attention and this has created a need for more environmentally friendly machinery


Fig. 5 One of the potential marine fuel cell applications.

solutions for ships. The low emission levels offered by fuel cells make them an interesting option as a future ship power source.

In addition to increased efficiency and environmental benefits, fuel cell technologies also offer a silent and vibration-free method of generating electricity. Since a fuel cell system has very few moving parts their service need will probably be considerably lower and system reliability higher when compared to conventional technologies.

However, there are a few drawbacks and uncertainties which need to be overcome before fuel cells can be introduced on the marine market on a large scale. The largest obstacles are the high investment cost, high fuel quality requirements and the relatively immature state of fuel cell technology today.

#### First marine applications

Owing to the small size and high investment cost of FC modules envisaged today the use of fuel cells will initially be limited to low-power installations and auxiliary applications. The first civil marine applications are estimated to be private yachts where silent and emission-free power generation is needed during slow manoeuvres and in harbour operation. This niche market is also capable of bearing the higher investment cost.

A more commercial application is expected to be found in small passenger and cargo vessels that operate in coastal areas where a low emission level is important and where the availability of a high-quality fuel can be assured.

Fuel cells will also be used as auxiliary power units to supply power for cruise vessels especially during harbour operation. The use of fuel cells would be motivated both by low emissions and by the owner's improved public image through environmental friendly power generation.

In Iceland where the government is committed to increasing the use of hydrogen instead of fossil fuels, fuel cells are considered to be an alternative for power generation in the Icelandic fishing fleet.

These niche markets are estimated to be the first commercial marine applications. It will take several decades of development before fuel cells are widely used as main propulsion units for larger commercial vessels where power demand is tens of megawatts.

#### Future outlook

The potential market for different fuel cell technologies is enormous given their outstanding potential advantages of clean and highly efficient power production. The applicability of fuel cell technology and the flexibility to size the units for different purposes will extend the potential market from small portable power units up to industrial applications of intermediate size.

The ongoing research and product development activities around the world are making every effort to turn this potential into reality. As noted, the major challenges in the development of the commercial fuel cell are current cost levels and the lifetime of the fuel cell stacks. Therefore the first commercial applications will be seen in portable devices, in small residential applications and in Uninterrupted Power Source (UPS) solutions where their increased reliability and flexibility will justify the higher investment cost per kW.

In large commercial and industrial power generation it is expected that MCFC and SOFC products will replace PAFC technology. Planar SOFC products have the potential to reach a competitive cost level in mass production. If, and when, low-cost manufacturing of SOFC products is achieved it will change our way of producing electricity and consuming energy in the power range below 2 MW. In power ranges above 5 MW the current combustion technologies will still dominate for several decades to come.

Wärtsilä is committed to providing sustainable power solutions to its customers and it is therefore vital that we are involved in the development of the power generation technologies of the future – such as fuel cells. ■

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