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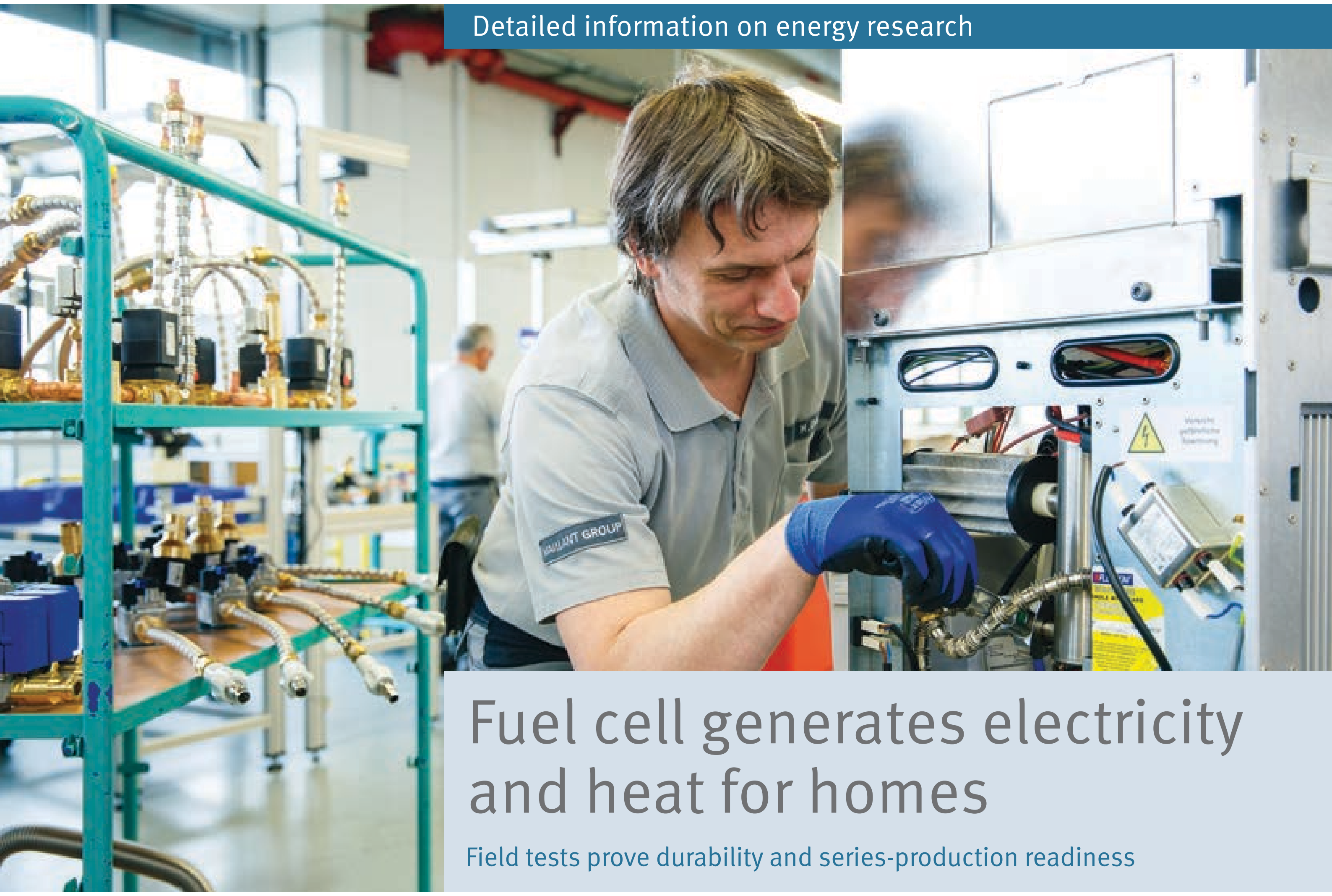
Detailed information on energy research



Fuel cell generates electricity and heat for homes

Field tests prove durability and series-production readiness

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Highly efficient, low-emission and quiet: as small-scale combined-heat-and-power stations, new fuel cell heating units produce heat energy and electrical energy with an efficiency of over 90 per cent. They have proven themselves in extensive tests in single and two-family homes, and their operation and design have been improved incrementally. The first units are now on the market. They run on natural gas, and on hydrogen and methane produced using renewable energy or biomass. Decentralised fuel cells can generate demand-oriented electricity, and they can be used in a grid-friendly or grid-independent way.

Researchers at the heating manufacturer Vaillant developed a heater with solid-oxide fuel cells (SOFC) that is now ready for series production. The aim was a compact device that is easy to install and operate. With an electrical output of 0.7 kW and a thermal output of 1.3 kW, it meets the basic requirements of a single and two-family home. A gas-fired condensing boiler is integrated for higher heat demands. The aim of the developers was to make the overall system cheaper and easier to manufacture, as well as to improve the quality and durability of its components.

They gradually improved the fuel cell heating appliances (FCHA) and tested them in parallel in demonstration projects such as the Callux project (see infobox). They used the data recorded from over 1 million hours of operation at the end users for further development. In the meantime, the technological maturity of the SOFC device concept has been proven for micro-CHP applications. They succeeded in halving production costs during its development. With the device generation

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Operation and performance of FCHAs

In fuel cell heating appliances, a reformer initially converts natural gas into a hydrogen-rich gas. In an electrochemical reaction that takes place in the fuel cell stack, the hydrogen-rich gas reacts with oxygen in the air. This produces steam; remaining residual gas is burned in the afterburner. FCHAs produce direct current and heat with very high level of efficiency. An inverter converts direct current into alternating current that can be used in households. Heat exchangers make waste heat produced by fuel cells and afterburners available for heating and domestic hot water heating. Compared to current condensing boiler technology, energy costs can be reduced by about 25 % and climate-harming emissions by up to 50 %. Decentralised production also relieves the distribution networks.
On average, a FCHA produces 3,500 kWh of electrical and 6,500 kWh of thermal energy per year. When the heat generated by the fuel cell is insufficient during the winter months, the auxiliary heater will guarantee a warm home. In order to ensure a long service life, FCHAs are operated as continuously as possible, without too many on-off cycles; in times of low heating demand in the summer months, they temporarily halt their operation.

Fig. 1 *Design study of the devices used in CALLUX and ene.field, with auxiliary heater, heat recovery module and buffer storage tank*

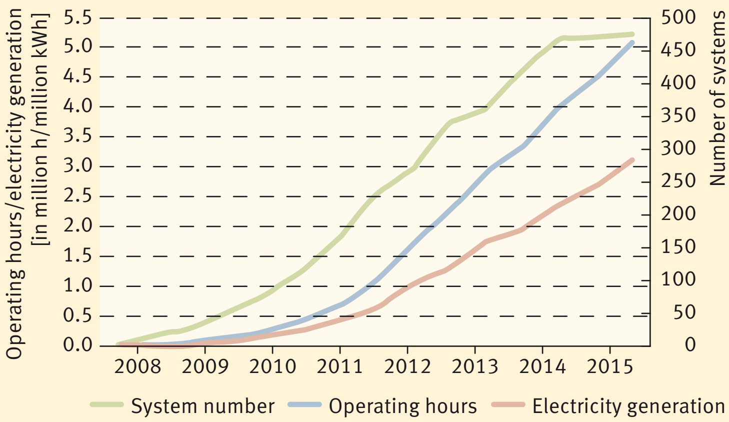

Fig. 2 *The systems reach technical maturity in the Callux field test. Almost 500 FCHAs were installed at end customers during the project.*

that is now ready for serial production, the researchers achieved an electrical FCHA efficiency of over 33 % and an overall efficiency at nominal load of more than 90 %. The higher overall efficiency versus previous models (Fig. 1) can be explained by the more compact design of the new hot box enclosing the fuel cell stack.

Development from pre-production to maturity

For a mature system, the various functions had to be housed in a single casing. When installed as complete systems, the first units had large space requirements due to the separate assembly of the components. As development progressed, the researchers employed standard parts from other devices of the company to keep development effort and costs as low as possible. In a first development step, the developers integrated the igniter and the afterburner in one component, and integrated all hot gas components including the stack module in a hot box. They combined the exhaust gas lines of the fuel cell and the auxiliary heater. Other components, such as the hot gas heat exchanger or the controller and safety board, were adapted to the specific requirements of fuel cell technology. For the heat recovery module, the developers took components from a commercial product line of the manufacturer. The integration of the entire hot gas assembly in a low-pressure housing is an important contribution to the safety of the unit. „We were able to realise a very simple and at the same time a very good safety concept in our fuel cell heating units,“ says Jochen Paulus, Head of Technology Development Fuel Cell at Vaillant. „Since all system components operate in a low-pressure environment, an exhaust fan in conjunction with a few temperature sensors will suffice, we need no further protective measures or sensors.“

Systems that operate under pressure, on the other hand, require significantly improved safeguarding against the undesired escape of gases.
The reduced system design and the use of standard components lowered material and production costs by about 60 %. Compared to the predecessor model, installation costs and the footprint of the entire system have been halved.

Proven and new technology wrapped up in one tight package

As a floor standing compact unit (Fig. 4), the new model combines all technical components in a single housing. It houses the actual fuel cell module alongside a condensing unit and the hydraulic module. Only the buffer storage tank has to be added. As a starting point, the company used a series gas heating system. What remains unchanged is the top module with a gas-fired condensing boiler. The fuel cell and the associated components replace the storage system in the lower part.
Other employed components include series components from condensing boilers such as exhaust gas heat exchangers, gas and air valves for power control and hydraulic components (pumps, valves). Since the previously used exhaust gas heat exchanger did not work to their full satisfaction, it was replaced by a series aluminium heat exchanger for condensing boilers up to 20 kW_{th}. The developers replaced the external heat recovery module with an integrated pulse width modulated pump. Sensors and actuators were simplified, and a new function and cost-optimised inverter was developed.

Electrical output	*0.7 kW*
Thermal output	*1.3 kW*
Electrical efficiency	*33 %*
Overall efficiency	*93 %*
Fuel	*Natural gas*
Dimensions	*1,640 × 599 × 693 mm*
Weight	*150 kg*

Fig. 3 *Specifications of XellPower FCHA from Vaillant*

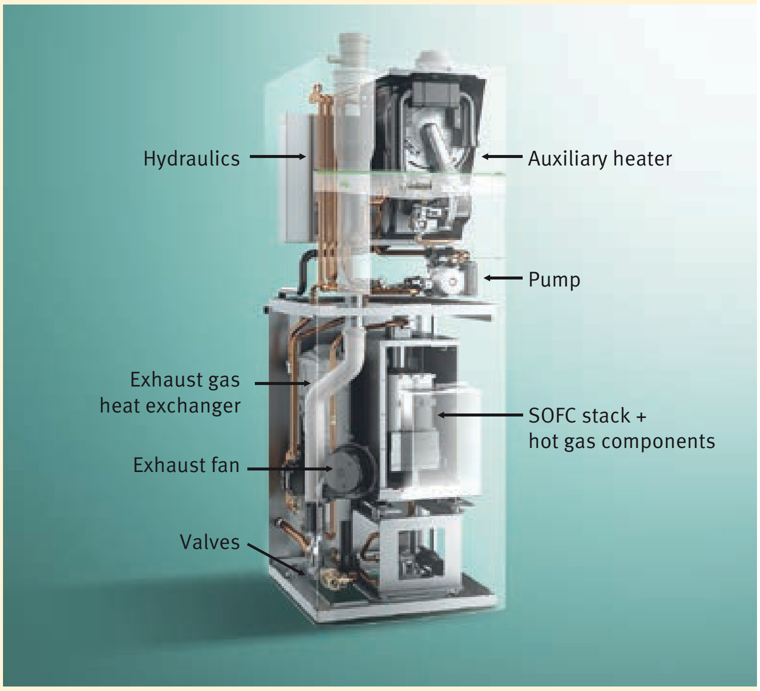

Fig. 4 *Structure of the current XellPower FC heating appliance: the fuel cell system with the auxiliary units is below, the auxiliary condensing gas boiler heater is above.*

Improvement and development of system components

On the way towards series production, the researchers had to improve and develop a number of components. For the stack, they focused on the solid-oxide fuel cell (SOFC) with a ceramic solid electrolyte. During the trial, they examined fuel cell stacks from Sunfire made of ferritic steel plates, and stacks developed by the Fraunhofer Institute for Ceramic Technologies and Systems IKTS based on powder-metallurgically produced bipolar plates from the Austrian supplier Plansee SE. The studies on durability and robustness yielded good results for both stacks. The developers are relying on stacks from Sunfire for the upcoming series production. To further optimise them, they modified the control algorithms of the SOFC module, amongst other things, based on field test experience in order to ensure a more gentle operation.

The fuel cell heating appliance requires a smaller start burner to heat up the system for cold and warm starts, and in combination with a downsized hot gas heat exchanger and simplified insulation, this resulted in a more compact design. This allowed for a significant reduction of construction volume, weight and cost compared to the previous model.

Desulphurisation prevents sulphur compounds in natural gas from damaging the reformers or stacks, which can cause a significant performance drop. For this purpose, the company uses a desulphurisation cartridge with a packed bed consisting of several different adsorbents. At 20–70 °C, this adsorption cartridge fully removes all natural sulphur compounds from the gas, along with those added for odorising purposes.

Results of the field tests

As part of the Callux field test from 2008 to 2015, nearly 500 fuel cell heating appliances had been installed and tested in single and two-family homes. The project was backed by partners from the energy and heating appliances industries, and was supported by the German federal government. In total, the tested FCHAs produced over three million kWh of electrical energy in five million hours of operation (Fig. 2). The manufacturers achieved the following milestones during the project:

- Dimensions and weight halved
- Connection to building services equipment significantly simplified
- Maintenance requirements lowered
- Increased annual operating hours by demand-oriented modulation
- Stack life spans of approx. 10,000 h proven
- Stack degradation rates below 0.2 % per 1,000 h.

In 12 EU countries, 26 partners, 9 of which appliance manufacturers, are participating in the European field test ene.field. They are installing and testing some 1,000 micro-CHP systems in residential buildings. As part of the Callux field test, Vaillant had installed 124 systems from different generations, for ene.field over 140 so far. To date, the more than 250 pre-production systems accumulated 2.9 million total operating hours. About 50 units have already reached operating hours in the range of 15,000–24,000 h.

To convert natural gas into hydrogen-rich fuel gas, the manufacturer uses a so-called CPOx fuel reformer. CPOx stands for catalytic partial oxidation, which is promoted by the reformer. It does not require water management, and therefore has a simpler design than the steam reformers used by the competition to process the gas. As a result of this improved integration, the service life of the reformer increases from a verified 20,000 hours to an expected 40,000 hours.

Available systems and need for further development

At the Hanover Fair 2016, Initiative Brennstoffzelle presented FCHAs from the manufacturers Buderus, Elcore, Hexis, Senertec, Solidpower, Vaillant and Viessmann. The presented systems are either heat or power-controlled, depending on the energy requirements of being full or auxiliary heating systems. In Japan, more than 150,000 FCHAs are already in operation following a market launch programme.

German manufacturers see a key challenge in lowering manufacturing costs at the start of series production. The goal is to improve the service life of the fuel cells beyond 20,000 hours towards 60,000 hours of operation. Fuel cell heating units currently cost approximately 20,000 euros.

Mobile with hydrogen and fuel cells

Fuel cells are not only suitable for the boiler room: the first series-produced fuel cells vehicles are now on the road. Fuel cell-based power supply systems for on-board systems in camping vehicles or boats have been available for a longer time. Fuel cell-powered public-transit buses have proven themselves in operation tests. While they can get by with one central hydrogen fuelling station, the infrastructure is not yet sufficiently developed for conventional long-distance driving. As long as hydrogen supply is not guaranteed, most systems continue to rely on propane, natural gas, methanol and diesel as fuels. Renewable energy is to replace the currently used fossil fuels in the mobility sector as well. Hydrogen, produced with solar and wind power through electrolysis, allows for almost emission-free mobility.

Fuel cells are efficient when it comes to driving vehicles: they reach a system efficiency of up to 65 %, this is about twice as high as that of an internal combustion engine. Initially used as auxiliary power supply units for on-board systems, fuel cells are becoming increasingly attractive as electric engines at land, sea and air. In various research projects, scientists are developing and optimising fuel cell systems and components that are suitable for mobile applications. They have to be durable and powerful while being lightweight, compact, robust and vibration-tolerant—and inexpensive on top of that.

In aircrafts, fuel cell systems are to replace the entire auxiliary power unit. While the main engines are resting, they can supply power to the electrical systems, the air pressure systems and the air conditioning on board. A fuel cell-driven nose wheel has also been successfully tested; with it, aircrafts were able to taxi quietly and without any emissions.

On and under water: fuel cells propel submarines and are suitable for use as power supply units for on-board systems and as energy sources for propulsion. Diesel, natural gas, methanol, or hydrogen can be used as fuels.

As part of the National Innovation Programme NIP, the German Federal Government is promoting the widespread adoption of this technology with demonstration projects: the Clean Energy Partnership aims to demonstrate the road capability of hydrogen as a fuel, E4Ships are researching fuel cells for ships and ferries, and the Bodensee project is examining its application for camping and recreational vehicles.

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- **Stack development:** Fraunhofer Institute for Ceramic Technologies and Systems, Dresden, www.ikts.fraunhofer.de
- **Inter-connectors for stacks:** Plansee SE, A-Reutte, www.plansee.com
- **Inverter development and production:** LTI Motion GmbH, Lahnau, www.drives.lt-i.com

Links and literature

- Initiative Brennstoffzelle, www.ibz-info.de
- Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie (NOW), www.now-gmbh.de
- Wasserstoff- und Brennstoffzellenprojekt Callux, www.callux.net

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