Operating experiences with a molten carbonate fuel cell at Stuttgart-Möhringen wastewater treatment plant
C. Locher, C. Meyer and H. Steinmetz

ABSTRACT
Fuel cells on wastewater treatment plants are a relatively new technology to convert biogas from anaerobic digestion into thermal and electrical energy. Since the end of 2007, a type of MCFC fuel cell (>250 kWel, 180 kWth) has been installed at Stuttgart-Möhringen wastewater treatment plant. The goals of this research project are to raise the power self-sufficiency in Stuttgart-Möhringen, to further optimise high temperature fuel cells using biogas and to gain practical experience. After approximately 9,000 h of operation, a mean electrical 'gross'-efficiency of 44% was achieved. To fully exploit this high electrical efficiency, it is essential to keep the energy consumption of peripheral devices (gas pressure unit, gas cleaning unit, etc.) of the fuel cell as low as possible.

Key words | biogas, energy, fuel cell, MCFC

INTRODUCTION
Wastewater treatment plants are the biggest communal energy consumers; 0.7% of Germany’s total energy consumption is due to wastewater treatment plants. Biogas produced during anaerobic sludge stabilisation is used for power generation in many wastewater treatment plants and thus covers part of the energy demand. A survey from 2007 (Keicher & Krampe 2007) in the German federal state Baden-Württemberg showed an average power self-sufficiency rate of 25.6% (GK4: 10,000–100,000 PT) to 30.7% (GK 5: more than 100,000 PT) in wastewater treatment plants. Those values are far below the recommended levels (Haberkern et al. 2009). Molten carbonate fuel cells stand out with a high electrical efficiency which could considerably raise the power self-sufficiency in wastewater treatment plants. This research project is mainly supported by the Federal Ministry of Economics and Technology, EnBW and MTU. The remainder of the funding is provided by the city of Stuttgart. The goals of this research project are to raise the power self-sufficiency in Stuttgart-Möhringen, to further optimise this high temperature fuel cell for the use of biogas and to gain practical experience.

BASICS
In conventional combined heat and power (CHP) plants, chemical energy is used for the production of heat, which is then transformed into mechanical energy, which is used to generate electricity. Fuel cells are capable of transforming chemical energy directly into power and heat through electrochemical paths. The main principle of the fuel cell is similar to reverse electrolysis. In conventional water—oxygen-cells, fuel (hydrogen) is oxidised at the anode and oxygen is reduced at the cathode. This process induces a difference in potential and an electron flow from anode to cathode. A direct current is created, which can then be transformed into alternating current by an inverter module.

The different types of fuel cells are distinguished by the type of electrolyte used. Table 1 shows the different types of fuel cells. For use with sewage digester gas, only phosphoric acid fuel cells (PAFC) and – with an increasing share in recent years – molten carbon fuel cells (MCFC) are in use.

Sewage digester gas does not contain hydrogen, but approximately 60–65% methane. For use in fuel cells, methane has to be reformed into hydrogen; therefore, reformation reaction energy is necessary. An advantage of high temperature fuel cells such as the MCFC or the SOFC is the possibility of internal reformation of methane with water vapour into hydrogen and carbon dioxide by waste heat at the high operating temperature. Thus, high temperature fuel cells achieve a higher efficiency than low or average temperature fuel cells (Berger 2004). Additionally,
Carbon monoxide (CO) is a welcome fuel for the molten carbonate fuel cell in contradiction to other fuel cells, where it acts as a catalyst poison (Huppmann 2011).

The high operating temperatures of MCFC (approx. 650 °C) allow an electrochemical conversion without expensive noble metals (Baaske & Trogisch 2007). The anode is made of porous nickel, alloyed with chromium or aluminium, and the cathode is made of porous nickel oxide. The electrolyte of the molten carbonate fuel cell is a molten mixture of alkali metal carbonates – usually a binary mixture of lithium and potassium, or lithium and sodium carbonates, which is retained in a ceramic matrix of LiAlO2 (Larminie & Dicks 2003).

Internally generated hydrogen reacts with carbonate ions and is oxidised at the anode by separating electrons. The produced carbon dioxide is led to the cathode together with added air. At the cathode, carbonate ions are produced from carbon dioxide and oxygen by taking in electrons. Contrary to low or average temperature fuel cells, no OH− or H+ migrates through the electrolyte from cathode to anode; only CO3²⁻ ions migrate.

Donations of electrons at the anode and reception of electrons at the cathode induce the current flow. Figure 1 shows the reactions of a MCFC.

Compared to conventional CHP plants, there are several advantages of high temperature fuel cells used on wastewater treatment plants:

- High electric efficiency
- Good partial load performance
- Negligible pollutant emissions
- Low noise and vibration operation.

According to our knowledge, there are only 15 MCFCs in use for digester gas worldwide. The majority of these plants are located in the USA and Japan. In Germany, there are three MCFCs in use at wastewater treatment plants. They are located in Ahlen, Moosburg and Stuttgart-Möhringen.

**INSTALLATION OF THE FUEL CELL AT STUTTGART-MÖHRINGEN WASTEWATER TREATMENT PLANT**

Stuttgart-Möhringen wastewater treatment plant

Stuttgart-Möhringen wastewater treatment plant is an activated sludge plant with upstream denitrification, simultaneous precipitation and anaerobic sludge stabilisation. At present, 57,000 PT are connected to the plant. On average, 6,400 kg TS/d of raw sludge (consisting of primary sludge and excess sludge) are produced. A high gas production of up to 1,900 m³ a day can be achieved by in-plant measures and by adding defrosting water loads from Stuttgart airport directly into the digester. This process is equivalent to a digester gas production of about 32 L/(PT* d). Thus, the specific digester gas production is higher than the 30 L/(PT* d) recommended in Haberkern et al. (2006). Besides the fuel cell, there are three CHP units, each with a power output of 117 kWel and 180 kWth, and two boilers, each with 600 kWth power output, installed and in operation.

**Integration of the fuel cell**

For the use of the high temperature fuel cells, it is necessary to treat the biogas from the digester, because the fuel cell needs definite pressure and gas quality. Thus, the pressure of the digester gas (gas storage, approx. 1,500 m³) is raised.
from 34 to 800 mbar (Steinmetz & Klein 2008). Then the digester gas is purified according to the requirements of the fuel cell. The gas preparation is done in two steps. In a gas drying unit, water vapour is separated, and other harmful associated materials are partially separated. After reheating the gas, the harmful substances (siloxane, hydrogen sulfide, halogenic compounds) are eliminated through adsorption with two activated carbon filters placed in series. Purified digester gas is then fed to the high temperature fuel cell.

The high temperature fuel cell, type HM 310 from MTU, is comprised of three components:

At the **media supply unit**, deionised water is added to the digester gas in the Humihex and is preheated by waste heat from the fuel cell.

The **HotModule** consists of two fuel cell stacks with 422 single units. Here, at the anode and cathode, the actual electrochemical reactions that generate the DC voltage take place. The HotModule also contains a catalytic burner and a mixing chamber for fresh air, gas from the anode and air from the cathode.

The **Control Unit** contains the control for the plant, the DC/AC-inverter and a transformer.

Energy generated by the fuel cell is supplied to the net virtually and refunded due to the Renewable Energy Sources Act. Waste heat exhausts at 400 °C are used via heat exchangers for heating the plant buildings and the digester sludge.

The performance data of the fuel cell are presented in Table 2.

Additionally, numerous power and heat meters have been installed to capture the produced and used energy of the fuel cells and the energy of the whole wastewater treatment plant separately.

### RESULTS AND DISCUSSION

After the official start-up of the fuel cell in November 2007, continuous operation began on 17 January 2008. Due to very high temperatures in the stack, the fuel cell has been out of operation since 3 March 2009. The reasons for the rise in temperature are not yet clear but are currently in investigation. The operation results from 17 January 2008 until 3 March 2009, are presented here. Figure 2 shows the chronological sequence of generated electrical power. Between April 2008 and June 2008, the fuel cell was not operated due to an observed rise in temperature. During this time, the fuel cell was inspected endoscopically by the manufacturer. There were also some other short time standstills of the fuel cell, which were mainly due to safety issues. Even with small disturbances, the fuel cell was shut down for precautionary fault diagnostics. During those standstills, the digester gas was supplied to the CHP units.

The black line is the power output produced by the fuel cell. On average, 146 kW could be supplied to the net virtually. The maximum supplied power was over 250 kW, which lasted for a short period of time. On average, per every m³ of digester gas, 2.62 kWh have been produced.

In order to operate the fuel cell, electric energy is necessary, i.e. energy of the fuel cells themselves (fans, pumps, control unit, electric devices), for aeration and for conditioning of gas. In the following text, this energy will be referred as the ‘internal energy demand’. In Stuttgart-Möhringen, this ‘internal energy demand’ has been recorded since 9 April 2008. From this day on, a gained ‘net’ power output can be calculated. The lower, light-grey line in Figure 2 shows the measured ‘internal energy demand’, while the higher, dark-grey line shows the ‘net’ power which is the power virtually supplied into the net minus the ‘internal energy demand’. The average net power (starting from 9 April) was 123 kW. For ‘internal energy demand’, an average of 23 kW was necessary. The proportion of the ‘internal energy demand’ on the total generated power was on average 17%. The use of the fuel cell itself had the largest share of the ‘internal energy demand’ with on average 57%; gas conditioning had an average of 34% and the ventilation another 9%. Especially with the gas conditioning and ventilation, the use of electrical energy was almost independent of the power generated by the fuel cell. Therefore, with increasing power supplied to the net, the proportional value of the ‘internal energy demand’ on the fuel cell itself decreased.

Figure 3 shows both the gross and net electrical power and electrical efficiency depending on the added gas input. Electrical gross efficiency of the fuel cell is mainly between 38 and 47%.

The average efficiency over the whole operation period was 44% and the average net efficiency was 36%. The comparably low net value was mainly caused by the partial load operation over a long period of time, which caused

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**Table 2 | Performance data of the fuel cell**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric net power</td>
<td>≥250 kW</td>
</tr>
<tr>
<td>Thermal power</td>
<td>180 kW</td>
</tr>
<tr>
<td>Number of cells</td>
<td>422</td>
</tr>
<tr>
<td>Temperature</td>
<td>ca. 650 °C</td>
</tr>
<tr>
<td>Waste air temperature</td>
<td>400 °C</td>
</tr>
</tbody>
</table>
a higher share of ‘internal energy demand’. The accumulation of points results from adjusted current densities between 20 and 100 mA/cm². The current density is the ratio between the produced electric current and the active area.

Apart from the two month standstill in the summer of 2008, the fuel cell was out of order in 5.9% of the operation period due to smaller disturbances like too high pressures or condenser water in the gas preparation.

With the use of fuel cells, the generated electrical energy amount could be increased considerably compared to that of standard CHP-plants. Analysis of the operation data of the gas motor block heat power plant from 2005 to 2007 showed an average electrical efficiency of
CONCLUSION AND OUTLOOK

The type MCFC fuel cell in Stuttgart-Möhringen is the first of its type in Europe which is supplied directly and exclusively with digester gas. Through the analysis of the results, conclusions can be made about the use of fuel cells on wastewater treatment plants.

From 17 January 2008 until 3 March 2009, the fuel cell produced 1,173 MWh of electrical energy and a projected 718 MWh of thermal energy. Electric power of over 250 kW could be obtained with an electric efficiency of >47%. On average, the electric efficiency was 44%, which is considerably higher than conventional CHP-plants. It has to be kept in mind, that the ‘internal energy demand’ of the fuel cell, including gas conditioning and ventilation, have not been considered. The mean ‘net’ efficiency from 9 April 2008 until March 3, 2009 was 36%. Since 3 March 2009, the fuel cell was out of operation because of too high temperatures in the Hotmodule.

Through operation of a type of MCFC fuel cell, a significantly higher amount of power can be produced than with conventional CHP-plants. The percentile share of generated electrical energy for ‘internal energy demand’ of 17% is comparably high, though. Further investigations should be made to reduce this share.

By the use of a type MCFC fuel cell, the power self-sufficiency on wastewater treatment plants can be raised considerably and thus CO₂ emissions can be reduced. A prerequisite for an economical use of this energy transformation system in wastewater treatment plants is a drop in investment costs, which are still at about 4,500 €/kW (Cigalotti et al. 2008), and far above those of a conventional CHP plant.

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