International Gas Union Research Conference 2011

CERAMIC FUEL CELLS LTD RESIDENTIAL GENERATOR BLUEGEN

ULTRA-EFFICIENT DISTRIBUTED POWER GENERATION IN SMART GRID ENVIRONMENT

Main author

K. Föger

Australia

Other author
Trent Rowe

ABSTRACT

Ceramic Fuel Cells Ltd (CFCL), an Australian Company with operations in Germany and United Kingdom, was formed in 1992 to develop and commercialize Solid Oxide Fuel Cell (SOFC) technology. CFCL's headquarters, R&D and pilot production facilities are in located in Melbourne, Australia, and in 2006 the Company commenced building its first fuel cell assembly plant in Heinsberg, Germany, with the plant completed in 2009. In late 2010, CFCL also built a system assembly line in its Heinsberg facility.

The Company saw the key attraction of the technology in its potential for very high electrical efficiencies using hydrocarbon fuels and excellent part load behavior together with low emissions, noise and vibration. These characteristics qualify SOFC as "dream" technology for distributed power generation. In 2004, CFCL decided to develop micro-combined heat and power (CHP) products units for the residential power market. Since then, the company developed and field tested four generations of field test units and clocked up about 400,000 operational hours. This experience is embedded in its current product BlueGen®, a 2 kW generator with heat recovery. BlueGen holds the "world record" for conversion of Natural Gas to electricity of >60% (LHV) net AC - and also offers modulation capability from 0 to 2 kW, with electrical efficiencies between 40 and 60% available in the 25% to 100% power output range. Including heat recovery, the overall efficiency of BlueGen can be high as >85%.

The transition of the electric power grid from its traditional one way flow with controllable central base load (coal, nuclear, oil, gas) and peaking (gas) power stations, to a grid with two way flow and a significant proportion of renewable (intermittent with limited control) power sources poses significant challenges to grid stability. The installation of highly flexible generators for grid stabilization will be necessary. This is a substantial opportunity for the gas industry to position natural gas as a necessary partner for renewable power generation – primarily, using gas-to-electricity generators. Technologies will include SOFC based products (from kW scale to GW scale) and CCGT systems (>100 MWs) with electrical efficiencies >55% (LHV). A significant proportion of renewable generation (solar PV, micro-wind) is installed in the low voltage grid, leading to significant fluctuations. BlueGen is a true dispatchable generator which is controlled remotely, and not heat limited such as a traditional CHP technologies which have higher thermal outputs and low electrical efficiencies. BlueGen is therefore ideally suited to supply controllable power to the low voltage grid, and thus is an integral component of smart grid infrastructure. This further enhances smart grids into an 'integrated energy grid' where gas and electricity grids complement each other.

The paper gives a short overview of the company, introduces the unique technology approaches CFCL has chosen for meeting high electrical efficiencies, demonstrates performance parameters of BlueGen from field test data and, shows examples where BlueGen is installed in a residential smart grid environment.

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1 CERAMIC FUEL CELLS LTD.

Ceramic Fuel Cells Ltd. (CFCL) was formed in 1992 as a spin-out from the Australian government research organization CSIRO by a consortium of Australian energy companies, with the objective to develop and commercialize Solid Oxide Fuel Cell (SOFC) technology for stationary power generation (1). The company's headquarters, R&D, product development and prototyping facilities are housed in a 5000m^2 facility located in Melbourne, Australia. Assembly of the Company's Gennex® fuel cell module and BlueGen assembly is carried out in CFCL's manufacturing facility in Heinsberg, Germany. CFCL has invested over 9.5 million Euros in this manufacturing facility with a starting capacity of 10,000 stacks per year, and 1,000 BlueGen systems per year. The Gennex fuel cell module is the key component in two current product lines (2):

- A 2 kW integrated micro-CHP unit (with condensing boiler) developed together with partners (EWE & Bruns Heiztechnik in Germany, GdF-Suez & BDR Thermea in France and E.ON UK & Ideal Boilers in the UK).
- BlueGen – a 2 kW residential generator with heat recovery for sanitary hot water production. This product has been entirely developed by CFCL and is also manufactured by CFCL.

2 SOFC TECHNOLOGY

2.1 Technology Approaches for High Electrical Efficiency

The solid oxide fuel cell is a high temperature fuel cell, ideally suited for Natural Gas fuel, although the reactive species in the electrochemical conversion is largely hydrogen. Indeed, only a hydrocarbon fuel realizes full potential of SOFC. In the temperature range >650 °C, the heat produced in the electrochemical "combustion" reaction can be utilized to reform methane with steam to hydrogen either directly on the anode (internal reforming) or in an intimately integrated reformer reactor (2). This reforming approach is the key to high efficiency as it shifts the electricity-heat ratio ("chemical combined cycle") similar to a mechanical combined cycle (CCGT) where the heat is used to produce more electricity in a steam turbine.

Electrical Efficiency of fuel cell:

$\eta = \Delta G_T / \Delta H_T \times U_F$ – Losses (ohmic + overpotential)

$\Delta G_T / \Delta H_T \times U_F$ …….theoretical efficiency

Hydrogen conversion at 750 °C and 85 % fuel utilization:

$H_2 + O^{2-} \rightarrow H_2O$

$\Delta H_{750C} (H_2) \approx 242$ kJ/mol

$\Delta G_{750C} (H_2) \approx 195$ kJ/mol

Theoretical efficiency: 195/242x0.85 = 68 %

Methane conversion at 750 °C and 85 % fuel utilization:

$CH_4 + 2\,H_2O \rightarrow 4\,H_2 + CO_2$

$H_2 + O^{2-} \rightarrow H_2O$

$\Delta G_{750C} (CH_4) \approx 800$ kJ/mol

$\Delta G_{750C} (4H_2) \approx 781$ kJ/mol

Theoretical efficiency: 781/800x0.85 = 83 %

CFCL has applied the following key design criteria for achieving high electrical efficiency:

- Internal (on anode) steam reforming;
- Stack designs enabling high fuel utilizations (≥ 85 %);
- Operation of fuel cell at high cell voltages to minimize ohmic and overpotential losses; and
- Optimization of the system for low parasitic and thermal losses.

2.2 CFCL's Fuel Cell Technology

The key components of CFCL's fuel cell technology (4) are shown in Figure 1. The cell, a 7-layer (contact layer – substrate – anode – electrolyte – barrier layer – cathode – contact layer) ceramic laminate about 350 µm thick and 70 x 70 mm in size, is capable of achieving power densities of >600 mW/cm^2 at 0.8 V, 60 % fuel utilization in methane/steam (ratio 1:2). The interconnector with integrated gas manifolds and flow fields and the window frame are made of ferritic stainless steel. Four cells are sealed to the interconnector plate via the window frame using glass-ceramic sealing materials. The 2.3 kW DC stack (size 200 x 160 x 210 mm) is assembled from 51 of these layer sets. The stack operates in the temperature range 700-800 °C. A patented innovative staging concept allows 85 % fuel utilization over its lifetime. At typical BlueGen operating conditions the stack achieves a maximum DC electrical efficiency of >68 %. CFCL has tested this stack design in a test station for almost three years with degradation rates capable of delivering a stack lifetime of about five years.

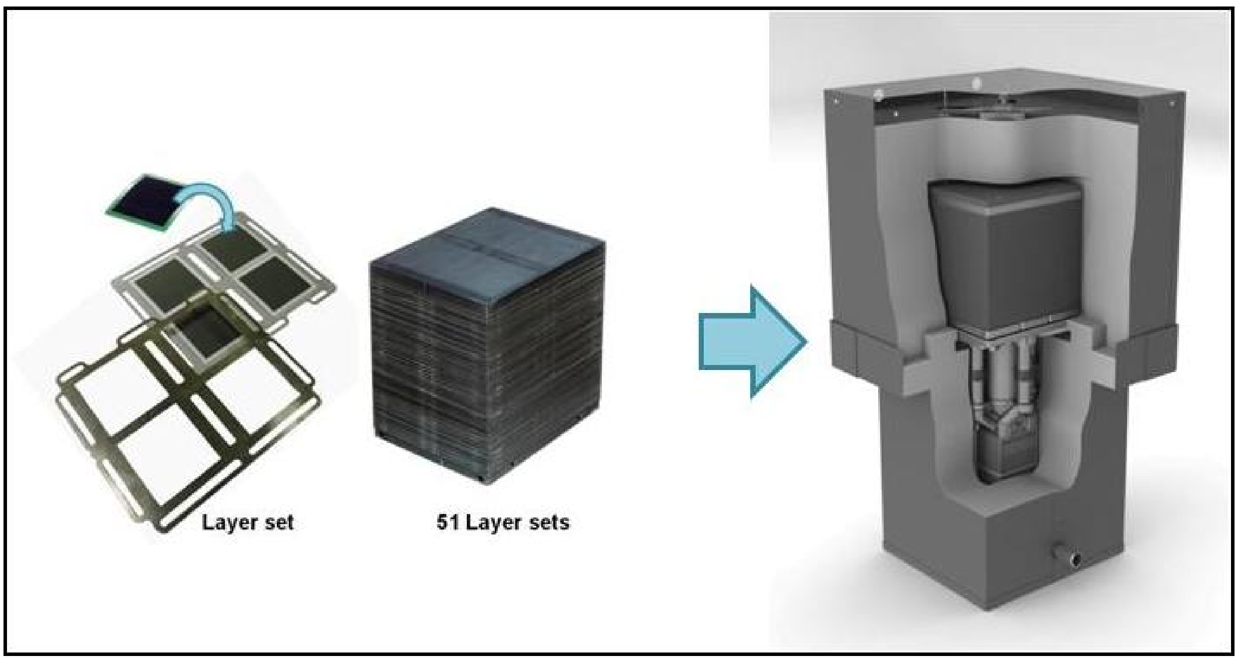

Figure 1 CFCL's stack technology and Gennex module

The stack together with its life support system – the hot balance of plant (BoP) – encased in the high temperature insulation makes up the fuel cell module Gennex (5). The hot BoP consists of the highly efficient and extremely compact 4-way heat exchanger driven by the burner off-gas with the function to preheat fuel and air and generate steam. The steam pre-reformer removes higher hydrocarbons at temperatures < 500 °C. The start-up/afterburner is a novel burner design where the flame is stable over the complete operating regime from start-up with natural gas as fuel, as well as during operation with a high CO_2 and steam diluted anode off-gas.

Compactness, manufacturability and low pressure drop were key design criteria, along with the tightly fitted micro-porous insulation and minimal feedthroughs in the hot zone ensure low heat losses – essential for maintaining high electrical efficiencies during part load operation.

3 BLUEGEN PRODUCT

3.1 BlueGen Specifications

BlueGen is a compact 2 kW_e generator with heat recovery (dimensions 660 x 600 x 1000 mm) designed for installation as a 'modular' unit within a smart home energy system or an add-on unit to existing energy installations (6). In cold climates the unit needs to be installed indoors, and in milder climates outdoor installation is possible. The built-in heat exchanger allows heat recovery as hot water and also water recycle from the exhaust gas to achieve a closed water loop. Figure 2 shows the BlueGen unit – Gennex module, water treatment, power management, air-/fuel delivery and gas safety system.

Figure 2 The BlueGen System

Fuel:	Natural Gas
Electrical Output:	2 kW AC, 230V-50 Hz (60 Hz planned for late 2011)
Heat output:	0.30-1 kW
Peak electrical efficiency:	60 % Net AC at 1.5 kW
Power Modulation:	0-2 kW (25-100% with efficiencies of 40-60 %)
Connections:	Fuel, Power, Water, Internet & Heat Recovery
Control:	Remote via internet (web-based customer interface).

BlueGen has European safety certification (the CE mark), with North American certification (CSA) planned for later in 2011. The unit has been designed for simple installation and remote diagnosis of maintenance issues. CHP and particular micro-CHP is commonly understood as a heat producing technology with electricity as by-product ("the electricity producing heating system with heat to power ratios of >3"). Micro-CHP units therefore operate in a start-stop mode and are idle during the summer months when the heat cannot be used. Low running hours affect the economic viability, and limit their use for supplying control power in a smart energy system as thermal demand and electrical demand may not occur at the same time.

In contrast, BlueGen is a highly efficient electricity generator with the option of waste heat recovery. The low amounts of high-quality thermal energy allow all year operation without excess heat limiting electricity production. Together with the ability to power modulate over the complete power range qualifies BlueGen as the ideal flexible and controllable power generation device needed in a power grid with substantial installations of intermittent renewable power sources.

3.2 BlueGen Performance Data

The specifications have been demonstrated in over 50 installations in different customer environments from test laboratories to real end-user installations. Figure 3 shows electrical (◊), thermal (☐ - heat recovery at 30 ^{o}C return temperature) and total efficiency (Δ) data measured to 1.5 kW_e output by Gas- und Umwelttechnik GmbH (DBI), a test laboratory of the German Gas Association (DVGW). At 500 W (25%) electrical output, the electrical efficiency is >40 % net AC, with the peak electrical efficiency of 61 % and a total efficiency of about 85 % achieved at 1.5 kW_e (LHV). Recoverable heat at 30 °C return temperature is about 300 W_{th} at 0 W_e export, 340 W_{th} at 500 W_e export, 400 W_{th} at 1 kW_e export, 540 W_{th} at 1.5 kW_{th} and 825 W_{th} at 2 kW_e export.

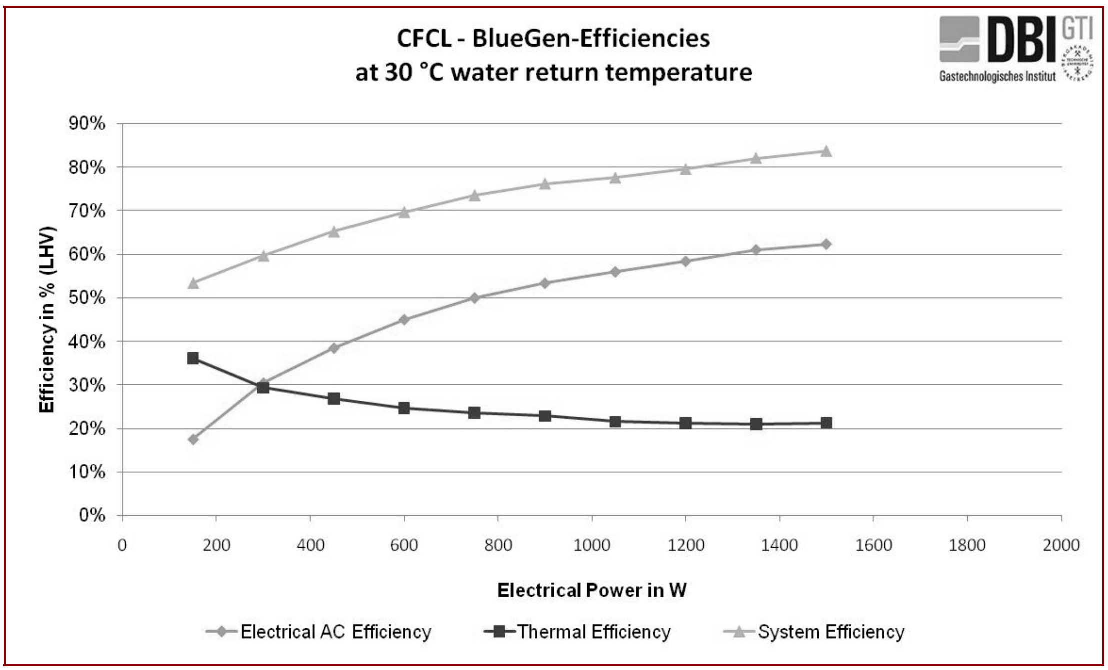

Figure 3 Efficiencies of BlueGen as function of power output

Figure 4 shows the initial electrical efficiencies of over 70 installed systems. Deviations are relatively small and lower for the production systems compared to the early development systems, and the average value is 60.8 % net AC (LHV).

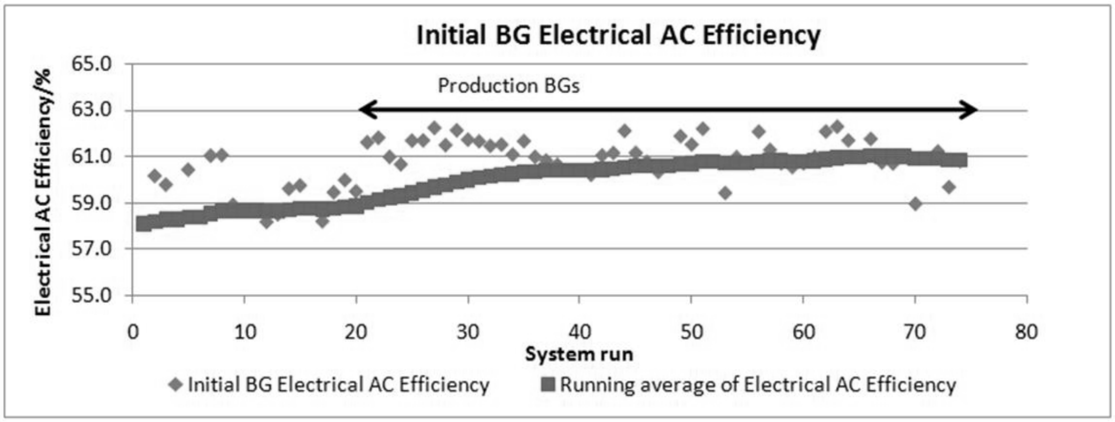

Figure 4 Initial AC Efficiencies of installed BlueGen systems

BlueGen can be power modulated over the complete range 0–2 kW within a 15 minute time period. The relatively fast response time enables the system to follow home demand curves, and supply both secondary control power and minute reserve power – for grid stabilization. BlueGen can be classified as a true controllable distributed mini power station in the home, and the remote control capability will allow aggregating a large number of units to a highly efficient virtual power station to supply both base power, peak power and control power in a smart energy system, where both the electrical and gas grids will become interlinked for secure energy delivery to end customers.

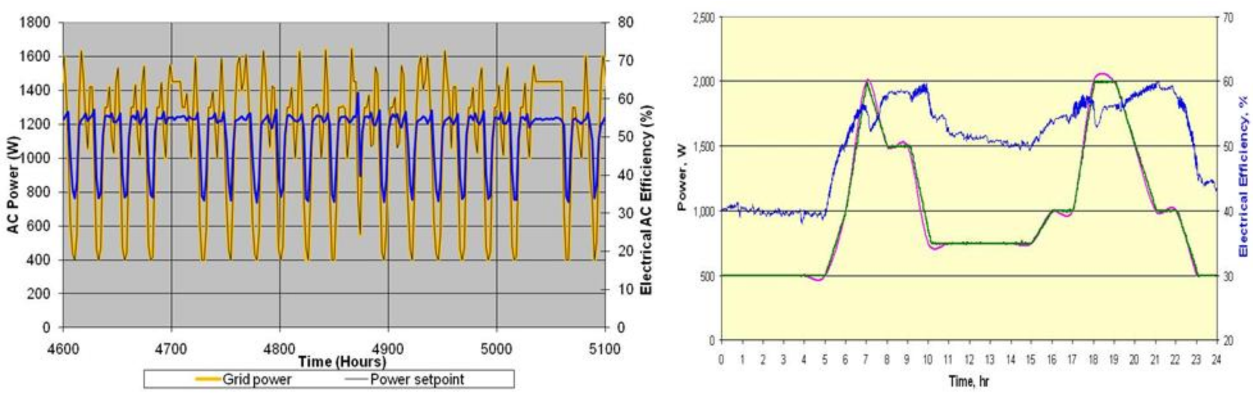

Figure 5 Power modulation with BlueGen

Costs and life are commonly quoted as the ‘Achilles heel’ of fuel cell systems. Since CFCL started field testing of residential power systems in 2006, the company’s systems have clocked up over 400,000 operating hours and BlueGen over 200,000. A stack test of similar configuration as in BlueGen was operated for 23,000 hours and showed a degradation profile of initially faster degradation decreasing with operating hours (no accelerated degradation). Such behavior has also been observed in systems although the longest BlueGen systems have been operating is just over a year. Degradation is commonly expressed as voltage loss with time (at constant current operation), but as CFCL’s systems are operated at constant power (current is increased as voltage decreases) and therefore a more meaningful parameter is decrease in efficiency.

Mathematical functions fitted to BlueGen electrical efficiencies as function of operating time are shown in Figure 6. Extrapolating the data to 40,000 operating hours still delivers efficiencies over 50 % net AC power export (LHV). CFCL has improvements in the development pipeline lowering degradation even further.

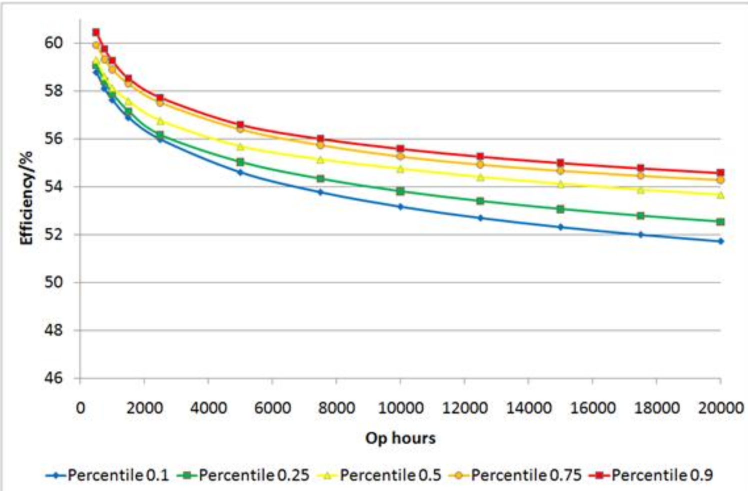

Figure 6 Efficiency degradation vs operating hours

3.3 Remote control & monitoring (BlueGen-net)

BlueGen systems installed at customer sites are supported with full remote monitoring & control capability via the BlueGen-*net* software package developed by CFCL, a suite of monitoring and reporting tools covering 3 access levels – tier 1 (CFCL, utility or aggregator), tier 2 (maintenance contractor) and tier 3 (end customer). The end-user reporting tool located at www.bluegen.net offers visibility on the unit's performance (see Figure 7) capable of access anywhere, anytime – either as snapshot view or through interactive tables. BlueGen-*net* also allows users to produce graphs on BlueGen performance (CO_2 savings, efficiencies, generated power as function of runtime). For the maintenance contractor BlueGen-*net* allows timely responses to maintenance warnings and alarms, the utility (aggregator) can use it for control of the BlueGen park as virtual power station, and for CFCL it provides invaluable data for further improvements of the product. The tool will be developed further leading to additional functionality and mobility in the future.

Figure 7 Customer portal of BlueGen-net

4 SMART GRID - SMART GENERATION

Future electricity grids will be organized more like IT networks with two way flow, and each level – high voltage transmission, medium voltage distribution and low voltage grid – viewed as individual but interlinked control node. However, the conversion of the electric power grid from its traditional one way flow with controllable central base load (coal, nuclear, oil, gas) and peaking (gas) power stations, to a grid with two way flow and a significant proportion of renewable (intermittent with limited control) power sources poses significant challenges to grid stability, and requires a level of flexibility not delivered by the traditional base load power stations. This offers a unique opportunity to the gas industry to position Natural Gas as an ideal partner for renewable power generation as primarily gas generators provide this function and link the power grid and gas grid to form a smart energy infrastructure. Hydrogen or synthetic natural gas make from excess renewable power and stored in the gas grid is another key element of this synergy (7). SOFC based products (over the full capacity range kWs to GWs) and CCGT systems (>100 MWs) are flexible, fast response generators that also convert NG with electrical efficiencies >55 % (LHV).

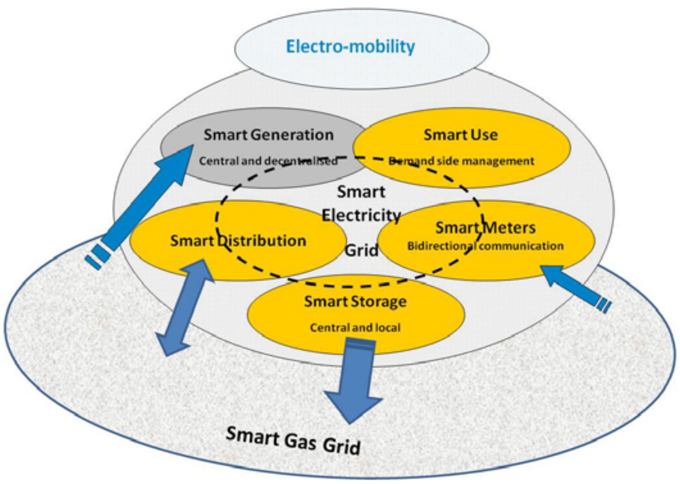

Figure 8 Smart Energy Grid merges gas and electric grids

A significant proportion of renewable generation (solar PV, micro-wind) is installed in the low voltage distribution grid, leading to significant fluctuations. Micro-CHP has been proposed as supplier of secondary and tertiary control power, but most of the systems are heat producers with electricity as by-product, and can only be operated when heat is required. In contrast, BlueGen is a truly controllable (remote control) electricity generator capable of operating all year round and therefore ideally suited to complement renewable in the low voltage grid as an integral component of a smart grid structure.

A first case study of BlueGen in a smart home environment is being carried out by Ausgrid, an integrated electricity and gas utility New South Wales. Ausgrid built in 2010 a SmartHome in Sydney, incorporating solar panels, energy efficient appliances, an electric vehicle and a BlueGen unit. A family of three moved into the house and blogged about their experiences. The unit has been operating either at a constant power output of 1.5 kW, or in dispatch mode – where the power output is modulated to a predefined daily profile. The unit has now been operating for over 7,500 hrs, and produced about 9.9 MWhr of electricity and saved over 7 tonnes of CO_2. During peak times, the cost of electricity produced from BlueGen was approximately half the retail cost.

Ausgrid has ordered a further 25 BlueGen units for the '*Smart Grid, Smart City*' initiative. This initiative is Australia's first commercial-scale smart grid project, and will be based in Newcastle, New South Wales, with the objective to lead to Australia-wide advances in energy management.

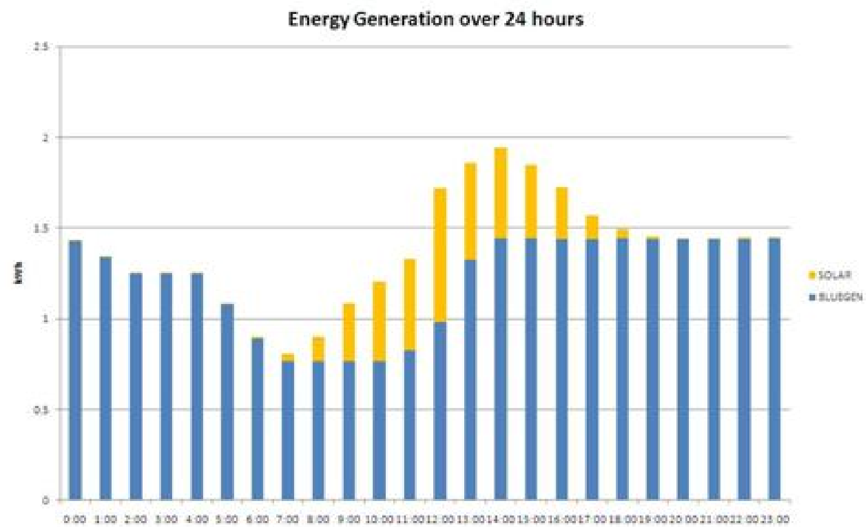

Figure 9 BlueGen and solar PV output in Smart Home over a 24 hour period

5 SUMMARY

Ceramic Fuel Cells has demonstrated with its BlueGen product the full potential of solid oxide fuel cell technology for distributed power generation. The 2 kW_e residential power generator electrochemically converts natural gas to electricity with up to 60 % electrical efficiency (net AC LHV) and low thermal outputs, therefore allowing year-round operation. This high efficiency together with power modulation capability over the complete range and with electrical efficiencies between 40 and 60 % in the 25-100 % power range qualifies BlueGen as an ideal complementary technology in an increasingly renewable energy scene. The large scale deployment of the product provides significant benefits to gas utilities, including predictable base consumption of gas across the distribution network over the year, increased gas sales of two or three times to residential customers *with lower carbon emissions compared traditional energy supply (in times when heating demand is decreasing due to improved building efficiencies) and a*llows stronger and longer-term consumer relationships.

It is recognized that large scale deployment of intermittent (largely un-controllable) renewable power sources leads to grid stability issues, requiring very flexible controllable “power stations” to supply balancing and control power. Only gas fuelled generators provide this flexibility. SOFC (over complete power range) and CCGT (>400 MW) with electric conversion efficiencies of up to 60 % - and BlueGen complements rooftop solar PV in the low voltage grid. This is a unique opportunity to establish natural gas as an essential complimentary energy source to renewable power generation. The proposals to use the gas grid as storage medium for hydrogen or synthetic methane from excess e.g. wind power by electrolysis further interlinks gas and electricity grids to form the smart energy grid of the future – a significant advantage for gas utilities compared to the possibility that it is no longer economical viable to install gas networks in new estates due to low gas sales.

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