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BioZEG ï Highly Efficient Standalone Green Production of Hydrogen and Electricity

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Abstract

A prototype plant that demonstrates the ZEG-technology (Zero Emission Gas technology), that is highly efficient co-production of hydrogen and electricity with CO_2-capture has been built and installed at Hynor Lillestrøm, located at the Akershus EnergyPark, just north of Oslo in Norway. The system consists of a 30 kW_{H2} Sorption Enhanced Reforming (SER) reactor system, a 20 kW_{el} Solid Oxide Fuel Cell (SOFC) module, and a high temperature heat exchange section, for close thermal integration between the SER and SOFC.

The goal with the BioZEG-plant is to demonstrate conversion of biomethane to hydrogen and electricity at an overall system efficiency of 70%. The BioZEG-demonstration is a significant first step towards the realisation of the ZEG-technology, which aims to achieve an overall system efficiency of 80% in larger MW installations with integrated CO_2 capture.

The 20 kW_{el} SOFC-module which was custom-made for the BioZEG-plant by CMR Prototech (NO), was built using CFY-stacks delivered by a European consortium led by Plansee (AT) and Fraunhofer IKTS (DE). A dual stack configuration was chosen as the baseline for the SOFC module, which consists of 12 blocks with 2 stacks each. The concept can easily be extended for further up-scaling.

High temperature gas-to-gas heat exchangers, an integrated afterburner/pre-reformer, and other core components have also been developed within the project. The heat exchangers are essential for the close thermal integration between the SOFC module and the SER reactor system, making it possible to reach the targeted system efficiency.

The testing of the system was initiated in January 2014, and will continue throughout 2015. The purpose with this paper is to present the BioZEG-plant and the obtained initial results.

Introduction

The ZEG-technology is a hybrid technology for co-production of electric power and hydrogen from hydrocarbon fuels with integrated CO_2 capture with high total efficiency. This is facilitated by close thermal integration of Solid Oxide Fuel Cells (SOFCs) and Sorption Enhanced Reforming (SER). Surplus heat from the SOFC-module is supplied to the SER reactor system which reforms incoming hydrocarbon fuel to hydrogen. Simultaneously the SER-system yields a separate stream of CO_2. The close to pure hydrogen is fed to the SOFC where electric power is produced. The hydrogen rich SOFC exhaust is then after purification ready for a wide range of industrial applications. The ZEG-technology is able to produce energy, hydrogen and electricity, at very high efficiency; 80 % is possible, including carbon capture.

Sorption Enhanced Reforming is a novel concept for hydrogen production from natural gas with integrated CO_2-capture. In this process both the reforming and CO_2-capture is integrated within two vessels. Moreover, the water gas shift (WGS) section is eliminated. When a CO_2-sorbent (e.g. calcined dolomite; CaO-MgO) is mixed with a reforming catalyst, the CO_2 in the synthesis gas mixture is removed as it is formed, causing the reforming and water gas shift reactions to proceed simultaneously. Moreover, when CO_2 is captured *in situ*, high purity CO_2 can be obtained from regeneration of the sorbent, eliminating costly separation steps downstream. In the ZEG-technology the sorbent regeneration utilises high temperature surplus heat from a SOFC module in close thermal integration providing the high overall system efficiency.

Advantages with SER compared to conventional methane reforming is a process simplification; reforming, water gas shift and CO_2-separation occur simultaneously in the same reactor in a reaction showing larger process flexibility. In addition it is obtained an increased hydrogen yield in the single step reaction; > 95% H_2-yield in the temperature range 500 - 650ºC, reducing the needs for downstream H_2-purification and with a potential for increased efficiency, energy savings and reduced production costs.

The ZEG-technology is highly flexible regarding input fuel, plant size, ratio of hydrogen to electric power production and integration into other industrial processes. A wide range of concepts and applications are developed. The BioZEG-concept provides cost-effective, distributed or standalone production of hydrogen and electric power based on locally available, cheap biomass resources; purified landfill gas, biogas or syngas from biomass gasification are all possible fuels. The hydrogen and electric power that is produced can be utilised in integrated industrial processes or for sale to the consumer directly, e.g. for transportation purposes. Distributed, local production of hydrogen from biomass feedstock will reduce the need for transportation of hydrogen to a refuelling station, in addition to reducing the CO_2-emmisions from the transport sector. Additionally, if the CO_2 that is separated in the production process is sequestered or otherwise used, the BioZEG-concept enables carbon negative energy production; i.e. a BioCCS-concept.

During 2012 and 2013 a 50 kW BioZEG-plant has been designed, engineered and constructed at the Hynor Lillestrøm hydrogen technology test facility, north of Oslo. The system consists of a 30 kW_{H2} (approximately 1 kg/h hydrogen production rate) SER-reactor system, a 20 kW_{el} SOFC-module, and a high temperature heat exchange section for close thermal integration between the SER and SOFC. During the first half of 2014 the system has undergone a thorough commissioning phase including component and system tests, and is finally put into operation. The plant will be operated throughout 2015 and will provide necessary long-term data for further development of the ZEG-technology.

System layout of the BioZEG-plant

The BioZEG-plant can be divided into four sub-systems: the SOFC-module, the SER reactor system, the thermal system including the high-temperature heat exchange section, and the overall balance-of-plant (steam supply, air blowers, cooling pumps), as schematically shown in Figure 1. In addition, there is installed a control system and DC/DC-inverter for integration with the existing local power system.

The SER reactor system is a dual bubbling fluidised bed system consisting of one reformer and one regenerator. In the SER-reformer, operated at around 600^{o}C, incoming biogas is reformed in the presence of steam and a catalyst (Ni-based; Haldor Topsøe) and CO_2 is simultaneously captured by the solid CaO-based sorbent (Arctic Dolomite; Franzefoss). In the regenerator the temperature is increased to around 850^{o}C by surplus heat from the SOFC-system causing the release of CO_2 into a separate gas stream. Thus, the SER reactor system produces close to pure hydrogen from biogas while separating the CO_2. The hydrogen production capacity is 30 kW or approximately 1 kg/h. The SER reactor system is developed, engineered and constructed by Institute for Energy Technology, Kjeller, Norway.

The biogas that is fed to the SOFC is mixed with steam before entering the pre-reformer. This unit is integrated with an afterburner and the combined pre-reformer/afterburner (Catator AB) yields the required fuel quality for the SOFC-module and boosts the temperature up to the requirement of the SER regenerator. The SOFC-module itself contains 24 SOFC-stacks each made of 30 cell plates (130 x 150 mm) with metallic CFY (chromium-iron-yttrium) interconnects. The stacks were delivered by a European consortium led by Plansee/Fraunhofer IKTS. Detailed information regarding the SOFC-stacks and their performance can be found in S. Megel et al. [1]. The SOFC-module is engineered and assembled by CMR Prototech AS, Bergen, Norway. A dual stack-configuration was chosen and the module thus consists of 12 such stack-boxes. At a nominal operating temperature of 810-840^{o}C, the SOFC-module has a rated power capacity of 20 kW_{el} running on reformed biogas.

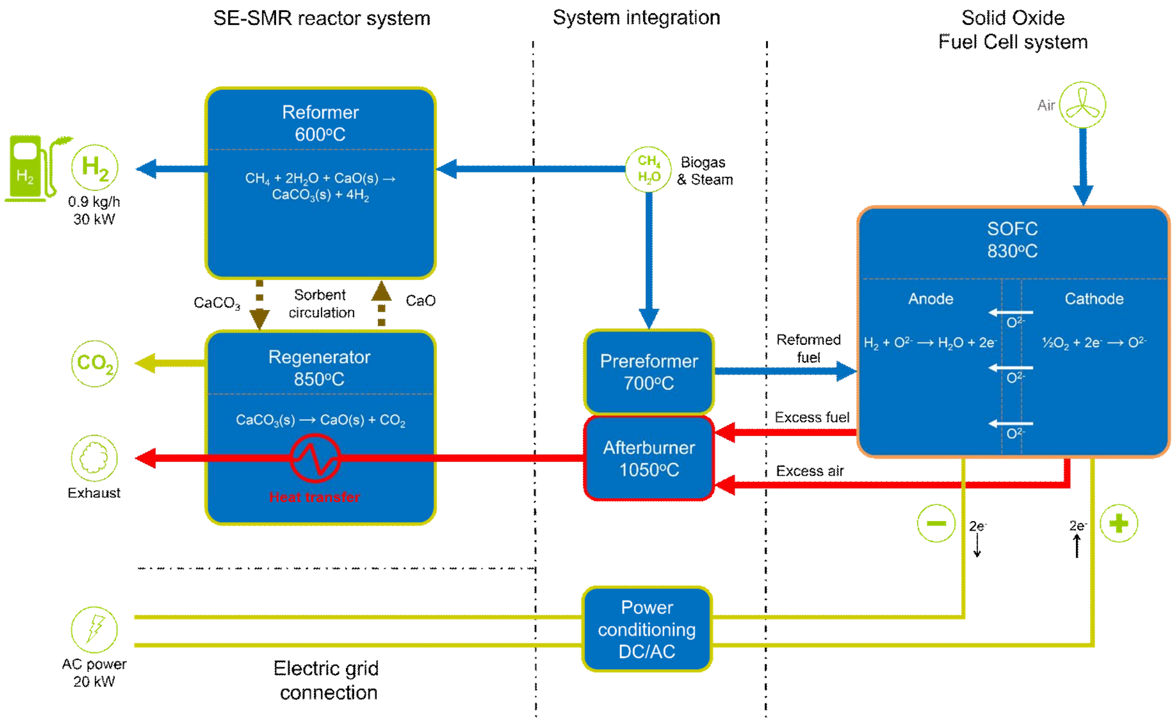

Figure 1. Schematic BioZEG-plant system layout.

In an efficiency-optimised ZEG-system the SOFC-module uses the hydrogen produced by the SER reformer as fuel. However, due to the need to reduce project risk and cost, the current BioZEG-plant is configured with separate fuel lines to the SER reactor system and the SOFC-module. This also enables separate stand-alone operation of the two systems. The chosen SOFC stack-technology and thus the maximum operating temperature of the SOFC-module additionally require the afterburner to increase the temperature up to the level needed for the SER regenerator. Even with these two design choices, which reduce the efficiency, system efficiency (hydrogen and electric power) is as high as 70% including CO_2-capture.

Preliminary results

The 20 kW_{el} SOFC-module is currently undergoing an extensive verification and test period. This work will continue throughout 2015. The SOFC-stacks and the dual stack-box design were tested prior to the module test campaign. Each individual stack was leak and performance tested by Plansee/Fraunhofer IKTS. At CMR Prototech a small testing facility was established in order to test and verify the baseline performance of a single dual stack-box. Thus, the most crucial part of the module design has been well tested prior to the commissioning and operation of the 20 kW_{el} SOFC module.

The dual stack-box has been operated both at fixed load conditions and at highly varying load levels for more than 500 hours. The test period also included eight thermal cycles. The dual stack performance during the last thermal cycle is shown in Figure 2. The anode side fuel feed was a mixture of $H_2/N_2/H_2O$ at ratios 55/32/13 (%-vol), respectively and at a rate of 23 Nl/min. The air flow rate to the cathode side was 200 Nl/min. At 20 A this corresponds to a fuel utilisation of 66% at which the power production was around 1 kW_{el}.

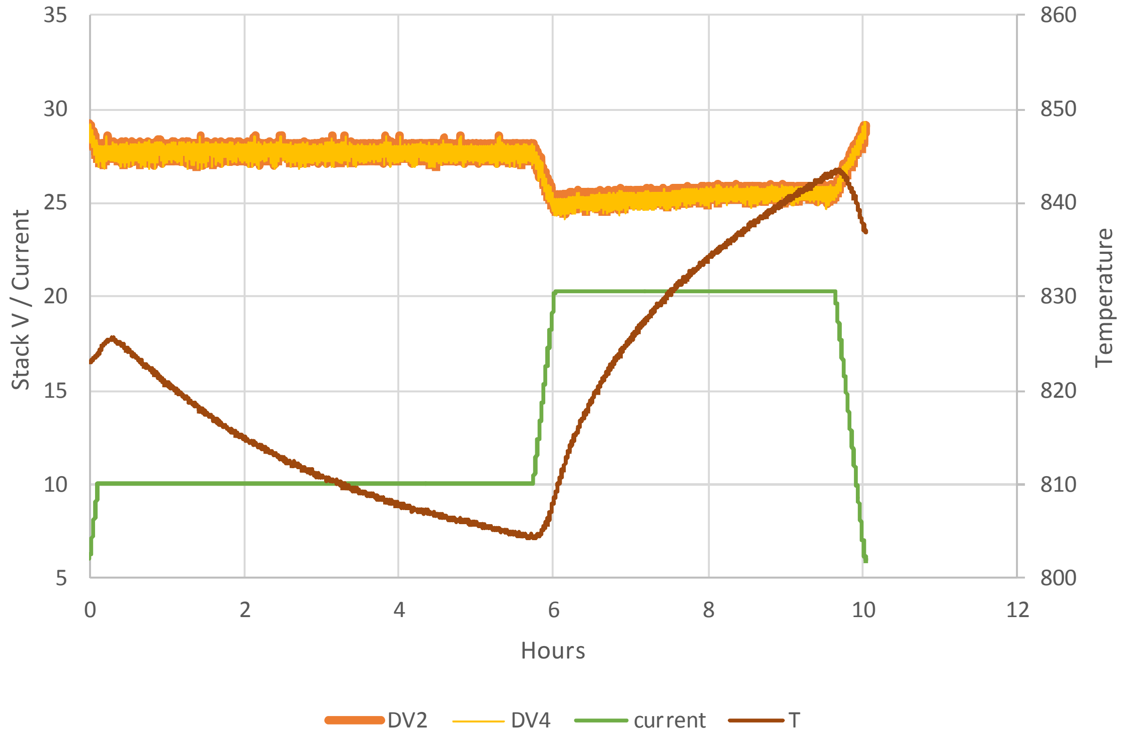

Figure 2. Dual stack-box performance during one thermal cycle. Fuel: 23 Nl/min $H_2/N_2/H_2O$ (55/32/13 %-vol); Air: 200 Nl/min. DV2: Voltage over stack no 1; DV4: Voltage over stack no 2; T: temperature (C).

These data show that the SOFC stacks from Plansee/Fraunhofer IKTS and CMR Prototech's dual stack-box design seem to meet ZEG Power's requirements regarding the tolerance towards thermal cycles, level of power production and load variation possibilities. The BioZEG-module will run on reformed methane as fuel and at an optimised fuel utilisation. It is therefore expected that the power production and overall system efficiency targets will be met.

Further work

The ongoing test campaign for the BioZEG-plant is aimed at establishing operational knowledge of SOFC-module performance, durability and thermal integration as a basis for optimisation of the BioZEG-concept. The tests will also provide data for further improvement of system efficiency by optimised thermal integration between the SER-reactor system and the SOFC-module. Additionally, operational flexibility of the SOFC-module will be addressed along with its long-term performance stability.

Acknowledgements

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References

[1] S. Megel et al., CFY-Stack: from electrolyte supported cells to high efficiency SOFC stacks. Proceedings of the 10th European SOFC Forum 2012, Lucerne, Switzerland, June 2012. Paper A1203.