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BioZEG – pilot plant demonstration of high efficiency carbon negative energy production

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Abstract

The ZEG-technology (Zero Emission Gas power) is a hybrid technology for co-production of electricity and hydrogen from hydrocarbon fuels, with integrated CO_2 capture. The technology has a potential for a very high total efficiency, more than 80% including close to 100% CO_2 capture and compression of CO_2 to 110 bar. At present the technology is being tested in a 50 kW plant based on biomethane for demonstration of 70% overall energy efficiency and the production of green hydrogen and electricity with integrated CO_2 capture. This paper present the plant and initial test results as well as the ongoing work.

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Keywords: Hydrogen; Biogas; CO_2 capture; SOFC; SER; Green energy production

1. Introduction

Future energy technology must comply with both the requirement for increased energy and cost efficiency as well as the need for significant reductions in the CO_2 emissions. According to IPCC [1] a wide range of technologies and actions are needed in order to have a likely chance to keep temperature change below 2°C by 2100, relative to pre-industrial levels. Improvement of energy efficiency, fossil energy with CO_2 capture and storage (CCS) as well as bioenergy with CCS (BECCS) are all important and needed elements.

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Fuel cells are highly efficient technology that will play an important part in the future energy system, enabling a transformation of both today's fossil fuels and the clean fuels of tomorrow into energy production. For power production stationary fuel cells, such as Solid Oxide Fuel Cells (SOFC) convert gaseous hydrocarbons into electricity and heat, achieving substantially higher efficiencies than combustion based technologies. For transportation purposes the use of fuel cell electrical or hydrogen vehicles (FCEV/FCHV) is emerging, providing efficient zero emission transportation solutions. However, in order for hydrogen to be a CO_2 free energy carrier, the production route is important. One possibility is large scale centralized hydrogen production by catalytic reforming with CCS, where hydrogen can be trucked in to refuelling stations. However, an interesting alternative is hydrogen production onsite by electrolysis with renewable energy supply or by reforming of biogas. If CO_2 captured from a bioenergy plant is sequestered or used for industrial purposes in an integrated process this could ensure a carbon negative energy production pathway.

The ZEG-technology (Zero Emission Gas power) is a hybrid technology for co-production of electricity and hydrogen from hydrocarbon fuels, with integrated CO_2 capture. The technology has a potential for a very high total efficiency, more than 80% including close to 100% CO_2 capture and compression of CO_2 to 110 bar [2]. The co-production is facilitated by using a Sorption Enhanced Reforming process (SER or SE-SMR, sorption enhanced steam methane reforming) for hydrogen production and SOFC technology for electricity production. Contrary to other known zero emission processes, the ZEG-technology does not include additional power consuming steps or additional costs for CO_2 capture. The heat produced in the SOFC is used for regenerating the CO_2 absorbent, eliminating the need for an afterburner. Excess hydrogen from this process is collected as a product. The fact that CO_2 capture is integrated without an energy penalty reduces the investment cost, reduces the fuel consumption, eliminates NO_X emission and increases the efficiency. Since the produced hydrogen is fed through the fuel cell stacks this increases the power density in the stacks, and reduces the investment cost of the fuel cell system.

In addition to high overall energy efficiency the module based ZEG-technology has a great flexibility with respect to applications and scale, from small scale distributed plants to industrial scale power plants. By using biomass resources as fuel as is being done in the BioZEG plant, the technology provide a carbon negative solution.

The main objective of the present project is to demonstrate the ZEG-technology in a 50 kW pilot plant based on local, renewable biomass, and to demonstrate a sustainable utilization of waste; cost-effective "green" production of hydrogen and electric power for transport purposes. The present paper will present the demonstration plant, initial test results as well as ongoing work.

2. The ZEG technology

The basic technologies in the ZEG-concept are electricity production by a SOFC and hydrogen production by SER. Close thermal integration of the two basic technologies is necessary in order to obtain a high total efficiency.

At an early stage of development various system integration alternatives was identified and analyzed. The system concept shown in Fig. 1 with produced hydrogen fuelling the SOFC, was identified as the most novel and efficient concept [3]. The CO_2 produced during the reforming is delivered from the plant, pure, pressurized and ready for sequestration or further industrial use.

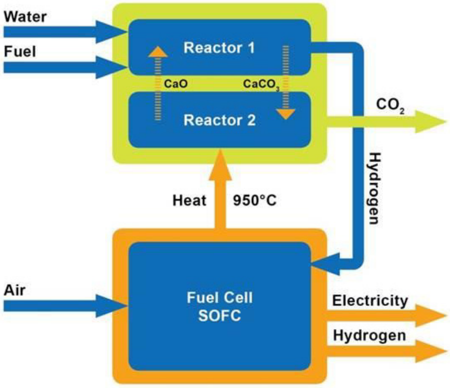

Fig. 1. ZEG Power system concept. Reforming takes place in reactor 1, and sorbent regeneration takes place in reactor 2

2.1. Hydrogen production and CO_2 capture by sorption enhanced reforming (SER)

Sorption enhanced reforming (SER) is an emerging technology for hydrogen production with integrated CO_2-capture. In this process both the reforming and CO_2 capture is integrated within two reactors, enabling hydrogen to be produced in one single step. The water gas shift (WGS) section is eliminated.

When a CO_2-sorbent (such as CaO) 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 beyond the conventional thermodynamic limits. Moreover, when CO_2 is captured in situ, high purity CO_2 is obtained by regeneration of the sorbent, eliminating costly downstream separation steps [4].

Main 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, a higher hydrogen yield is obtained in the single step reaction (95-99 mole% dry basis), reducing the needs for downstream H_2-purification and with a potential for increased efficiency, energy savings and reduced production costs.

2.2. Electricity production by solid oxide fuel cells (SOFC)

The traditional way of converting the chemical energy stored in a fuel to electricity is by combustion. The chemical energy is then converted to heat, and the mechanical energy from the heat engine is led to a generator which converts it to electricity. In a fuel cell, the chemical energy from the fuel is transformed directly into electricity and heat. This makes a fuel cell more efficient than combustion based technologies.

A general fuel cell is made up of an electrolyte placed between two electrodes. For a SOFC, air is led to the porous cathode where oxygen collects two electrons and gets absorbed into the electrolyte. The oxygen ion then travels through the electrolyte to the anode where it reacts with hydrogen to form water. In this reaction the electrons are released again. They travel through an external circuit, driving some electrical load, and back to the cathode where the whole process starts again. The basic structure and process of a fuel cell running on hydrogen and oxygen is shown in Fig. 2.

Single fuel cells can be placed together in stacks to increase the electric potential and total power output. Interconnects are then added to each electrode. The interconnects separate the anode and cathode gas streams, while at the same time collecting the current and distributing the gases uniformly. Each fuel cell stack can then be connected in series or parallel to make larger power producing units.

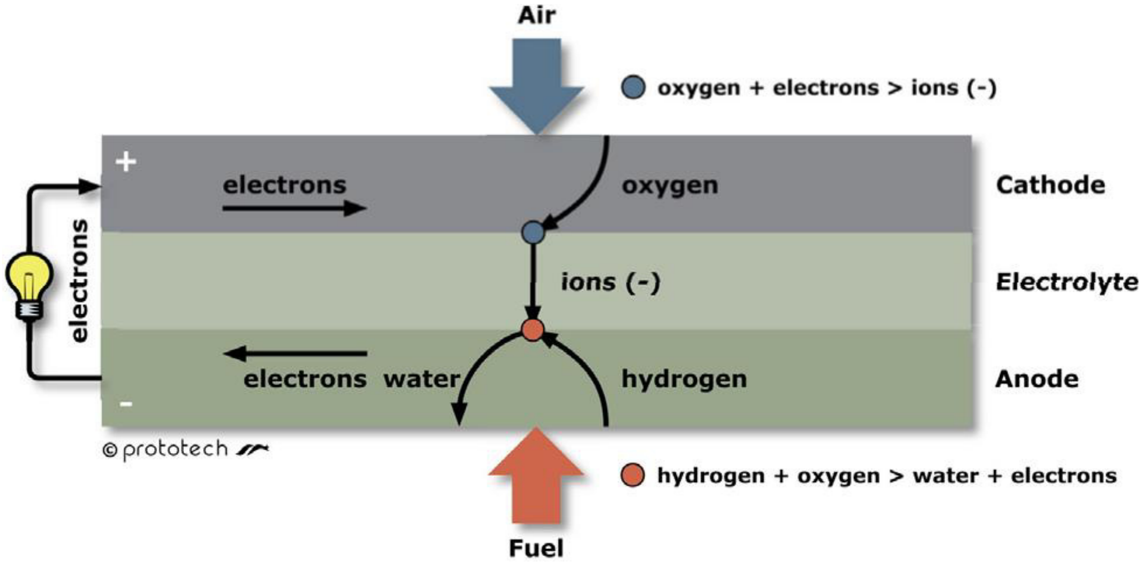

Fig. 2. Schematic drawing of a single fuel cell running on oxygen and hydrogen [5]

SOFCs have been developed for different applications and emerging energy markets, ranging from micro-scale portable systems (< 1 kW) to larger scale integrated power plants (> 200 kW). A 200 kW unit is enough to meet the base load needs of 160 average homes or an office building [6].

Most systems and concepts today are based on a large number of smaller units. Further up-scaling of a module from 200 kW to 1 MW will enable SOFC systems for full scale (400 MW) power plants.

3. The BioZEG plant

The BioZEG-plant is a 50 kW prototype plant that has been built and installed at Hynor Lillestrøm, a renewable hydrogen station and technology test center in the city of Lillestrøm, 13 miles northeast of Oslo, Norway [7]. The main objective of the test center is to design, build and operate a hydrogen station based on local renewable energy sources, and to demonstrate new and innovative hydrogen technology.

Hynor Lillestrøm is equipped with a pipeline from a municipal waste landfill site and an upgrading gas system providing a biomethane output purity of 85-90%. In addition it is possible with trucked in biomethane from the biogas plant handling wet organic waste from the city of Oslo [8].

The BioZEG-plant consists of a 30 kW_{H2} 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. The main technology challenge addressed in the plant is to demonstrate 70% overall efficiency for co-production of hydrogen and electricity with integrated CO_2-capture.

The plant is in addition constructed such that both basic technologies, SER and SOFC can be tested and optimized separately for stand-alone production of hydrogen and electrical power.

3.1. System layout of the BioZEG plant

The BioZEG-plant can be divided into four sub-systems: a SER reactor system, a SOFC-module, thermal system integration of the two basic technologies as well as balance-of-plant. The overall system is schematically shown in Fig. 3.

The SER reactor system is a dual bubbling fluidized bed reactor system (DBFB) consisting of one reformer and one regenerator. The SER-reformer has a hydrogen production capacity of about 10 Nm^3/hour (1 kg/hour). The reformer is operated at around 600°C and biomethane is reformed in the presence of steam and a Ni-based catalyst.

CO_2 is simultaneously captured by a solid CaO-based sorbent, arctic dolomite. When the SER reactor system is run as a part of the BioZEG-plant the temperature in the regenerator is increased to around 850°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 biomethane while separating the CO_2. The SER reactor system and obtained test results are described in detail by Meyer et al. [4].

In an optimal ZEG-system high temperature SOFC (1000°C) with ceramic interconnects is preferred due to the high temperature needed for regeneration of the solid sorbent. However in the present plant a medium temperature SOFC (850°C) with metallic interconnects has been chosen in order to reduce overall project risk and complexity. Compared to an efficiency optimized configuration of a ZEG plant, three adjustments are made; the SOFC operating temperature is reduced, SOFC fuel recycling is excluded, and an afterburner is added in order to boost the temperature.

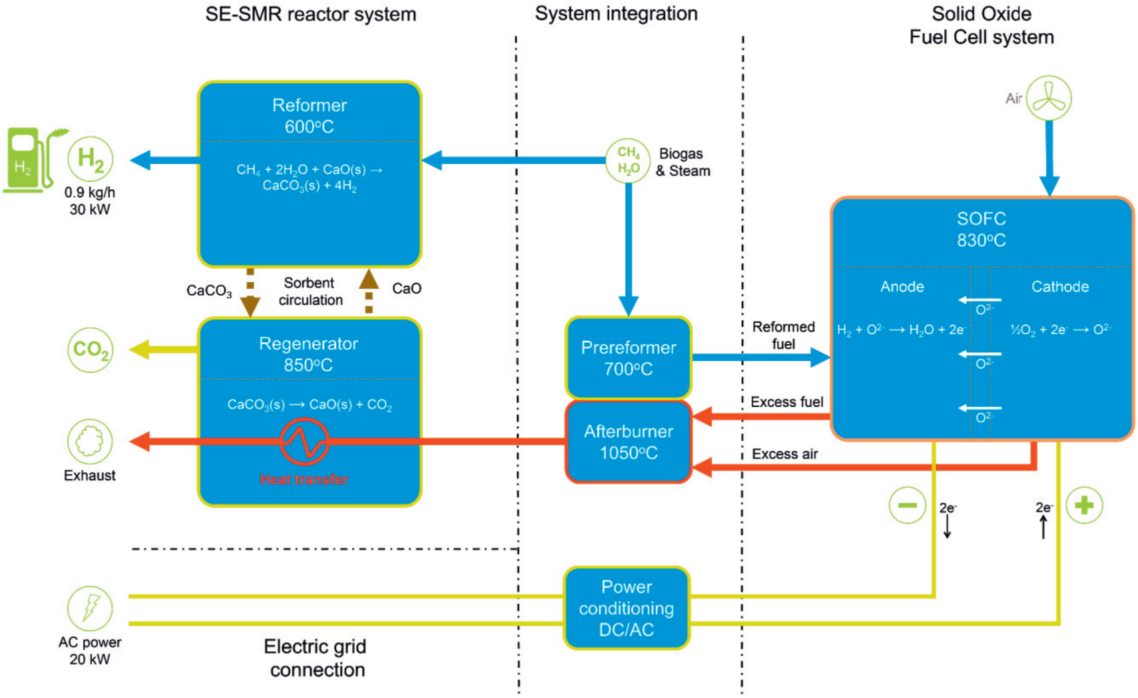

Fig. 3. Schematic BioZEG-plant system layout [9]

The SOFC module is custom made for the BioZEG-plant and is engineered and assembled by CMR Prototech [5]. 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 are delivered by a European consortium led by Plansee [10] and Fraunhofer IKTS [11]. The SOFC-stacks and their performance are described in detail by Megel et al. [12].

For the SOFC-module a dual stack-configuration is chosen and the module consists of 12 hot boxes with two stacks in each box. At a nominal operating temperature of 810-840 °C, the SOFC-module has a rated power capacity of 20 kWel running on reformed biomethane. The chosen concept can easily be extended for further up-scaling. A SOFC DC/DC converter is designed and engineered by Hot Platinum [13], allowing produced power to be delivered to the grid.

The biogas that is fed to the SOFC is mixed with steam before entering a pre-reformer. This unit is integrated with an afterburner and the combined pre-reformer/afterburner unit yields the required fuel quality for the SOFC-module and boosts the temperature up to the requirement of the SER regenerator.

High temperature gas-to-gas heat exchangers and other core components are also 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 of 70%.

4. Initial test results

Long term operational stability and low degradation rates of the SOFC module are important for industrial ZEG-technology applications, and the most crucial part of the module design has been thoroughly tested prior to the commissioning and operation of the 20 kW SOFC module.

Each individual stack is leak and performance tested before delivering, and in addition the baseline performance of a single dual stack-box is tested and verified. The dual stack-box has been operated both at fixed load conditions and at highly varying load levels for more than 1000 hours. The test period also included several thermal cycles. Figure 4 shows the dual stack performance during the eight thermal cycle. The anode side fuel feed was a mixture of hydrogen, nitrogen and steam at ratios (volume %) 55/32/13, 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 utilization of 66% at which the power production was around 1 kW [9].

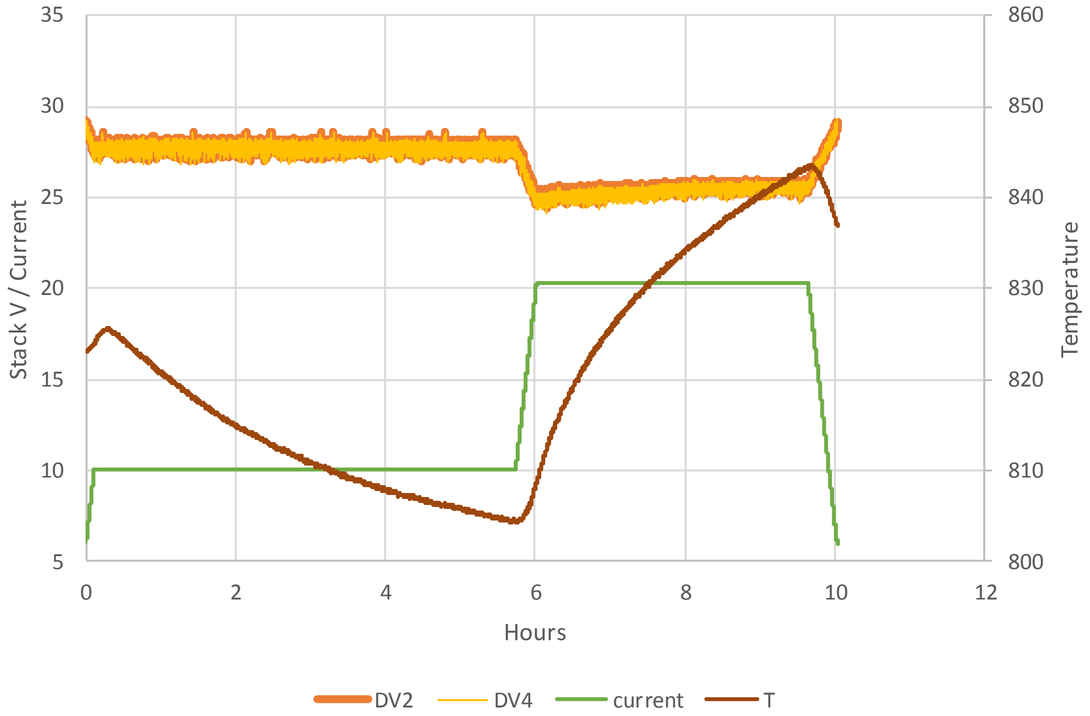

Fig. 4. Dual stack-box performance during one thermal cycle.
DV2: Voltage over stack no 1; DV4: Voltage over stack no 2; T: temperature (C) [9].

The initial tests showed that the stack design is very robust, and the electrolyte supported cells can tolerate several redox cycles without significant degradation. High heat conductivity and high thermal mass of the interconnects means that even a momentary current cut-off does not produce too high thermal stresses in the system. The thermal expansion of the materials is well matched and the stack can be cooled and heated without observable loss in performance. High thermal mass means that significant heat is required for start-up, still start-up can be performed in less than 6 hours.

The initial results shows that the chosen SOFC stacks and dual stack-box design seem to meet the ZEG-technology's requirements regarding the tolerance towards thermal cycles, level of power production and load variation possibilities.

5. Ongoing work

The 20 kW SOFC-module is currently undergoing an extensive verification and test program that will continue throughout 2015. The primary objective is to establish operational knowledge of the SOFC module performance, durability and thermal integration as a basis for optimization of integrated BioZEG-plants and operation modes.

The robustness and the durability of the SOFC stacks have not been previously studied in a multi-stack module configuration. New process parameters will come into play such as fuel and air distribution amongst the 12 stack-boxes (dual-stack assemblies), stack-to-stack interactions within stack-boxes and within the module and distribution of electricity production between the stacks. The module performance will be studied both through long-term steady-state operation and through industrially relevant load following transients. Long-term SOFC operation will give highly relevant data to assess operating costs and the lifetime of different system components. This will provide new knowledge on multi-stack module operation which is a highly important issue to be able to upscale and optimise the SOFC modules.

The main challenge of the integrated operation of the ZEG-technology is the heat transfer from the SOFC module to the SER regenerator. The thermal integration is crucial in order to achieve the high system efficiency potential. The challenge to be addressed in this work package is to verify the feasibility of the designed solution for thermal integration and to optimize the operating parameters of the heat exchangers. Depending on the application of the ZEG-technology, the system will be configured for different operating conditions and variations thereof. The basic technologies must handle different conditions for load variations, load following rates, idling and peak load demands in different configurations. Furthermore, the fuel composition will vary, especially when using biomass based feedstocks such as biogas. Different steady-states will be tested in order to determine peak load limits. The transients and load programs will be based on system demands in different industrially integrated processes.

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