BioSOFC final report

3rd Generation Biomass CHP Based on Biomass Gasification Combined with SOFC

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Contents

Summary

Coupling solid oxide fuel cells (SOFC) to biomass gasification has a potential to contribute to the sustainable power generation by decentralized power plants. With both technologies having high energy efficiencies, the combination can achieve very high plant efficiencies. As an extension of preliminary tests with biomass gasification and SOFC's in other projects, this project carried out experimental research along with energy system analysis using mathematical modeling.

An experimental setup was commissioned at KT DTU, Risø campus. Extensive knowledge on installation, operation and testing of the SOFC stack has till this point resulted in tests with clean bottled cylinder gas and real Viking product gas. Further tests with direct coupling to the Viking gasifier are planned in the near future in order to further validate the longevity of the gasification-SOFC coupling. Further tests with direct coupling to the Viking gasifier are planned in the near future. The experimental results confirm that using gas resembling that of the Viking gasifier, can result in high efficiencies. Initial tests showed that the SOFC stack with a fuel utilization of 73% and an operation temperature of 700ºC can achieve an electrical efficiency of 38.8%. The experimental study also showed the high-efficient conversion in the SOFC, showing an effective efficiency of 55% at 20A. The tests with real Viking confirmed the high electric efficiencies estimated with cylinder gas and also proved that extended operation is possible. An important first step is taken in showing that gasification can be coupled to SOFC without extensive gas cleaning equipment.

Energy system analysis of the Viking-SOFC concept was carried out, using mathematical modeling. The studies investigated the Viking-SOFC and various combined cycle concepts for decentralized power generation at small-scale at ≤10 MW_e. The Viking-SOFC systems electric efficiency was found to 42% in the study, with a total efficiency (district heating included) of 82%. With traditional decentralized biomass power plants operating at 30-34% electric efficiency, the Viking-SOFC plant can be technically competitive with regards to electricity production. Various combined cycle concepts with the Viking-SOFC system were investigated, adding machinery down-stream of the SOFC. At very small-scale, a Sterling engine and organic Rankine cycle (ORC) was found to be effective, with the ORC showing high electric efficiency at 54-62%. Larger systems at 8-10MW_e using Kalina, steam and gas turbine cycles down-stream of the SOFC showed as the ORC very high efficiencies at 48-58%. These studies also revealed that the SOFC operating temperature and fuel utilization is of great importance when designed combined cycle plants. The Viking-SOFC-Sterling system proved to be cost competitive for electricity generation if used directly in e.g. building as hotels, malls, households. Producing power for the grid proved infeasible at current prices. The Viking-SOFC-STIG plant proved to be infeasible at current prices. Both studies found that the main barrier for commercialization for Viking-SOFC plants was the SOFC investment costs.

Near future tests are planned for the experimental setup, where extended operating periods are expected in order to investigate the longevity of the SOFC with the Viking gasifier. Future projects with operation of the Viking and SOFC are planned and will further investigate the gasification-SOFC platforms potential for power generation. The Viking-SOFC platform has shown able to produce power and heat at very high efficiencies. These results are demonstrated experimentally as well as theoretically in this project. The Viking-SOFC plants are technically competitive with regards to efficiency, while economic analysis shows that only some niche markets may be feasible at current prices. The main barrier for commercialization are found to be further long-time tests of SOFC's with product gas and the investment price of SOFC's.

Dansk resume

Kombinationen af fast-oxid brændselsceller (SOFC) og biomasse forgasning har et potentiale til at bidrage til den bæredygtige udvikling af decentraliserede kraftværker. Da begge teknologier har meget høje energivirkningsgrader, kan der opnås kombinationer med meget høje virkningsgrader. I forlængelse af tidligere arbejde med biomasse forgasning og SOFC, udførte dette projekt eksperimentelt arbejde og analyse af energisystemet ved brug af matematisk modellering.

Et eksperimentalt anlæg blev opstillet for KT, Risø campus og arbejdet har indtil videre indeholdt eksperimenter med SOFC-drift på flaskegas og produktgas fra Viking, og har bidraget med stor forståelse og praktisk erfaring inden installation, drift og styring af SOFC. Flere test er planlagt i nærmeste fremtid, med direkte kobling af SOFC med Viking forgasseren for at undersøge langtidsholdbarheden.
Indledende tests viser at SOFC med en fuel utilization på 73% og en driftstemperatur på 700 ºC kan opnå en elvirkningsgrad på 38.8%. The eksperimentelle arbejde viste også SOFC's evne til effektive at omdanne brændslet til el med en effektiv virkningsgrad på 55% ved 20A. Test med produktgas direkte fra Viking-forgasseren kunne eftervise den høje elektriske virkningsgrad opnået med cylindergas og samtidig vise at SOFC og forgasning kan kobles uden at skulle installere avancerede og ressourcekrævende gasrensningsenheder.

Viking-SOFC systemet blev analyseret ved brug af matematisk modellering. Flere studier har undersøgt systemet: Både som enkeltstående anlæg og i combined cycle-koncepter. Alle anlæg er projekteret som decentrale og relativt små anlæg på ≤10 MW_e. Kombinationen af Viking og SOFC blev i et studie modelleret til at have en elvirkningsgrad på 42% og en tilhørende totalvirkningsgrad (inklusive fjernvarme) på 82%. Traditionelle decentrale kraftvarmeværker har en elvirkningsgrad på 30-34% og Viking-SOFC ses derfor som teknisk konkurrencedygtigt ift. virkningsgrad. Forskellige combined cycle-koncepter blev simuleret på basis af Viking-SOFC, hvor afgasserne fra SOFC bruges til yderligere elproduktion. Ved meget små anlægskapaciteter viste Stirling- og organic Rankine cycle-koncepterne (ORC) at være effektive, hvor ORC-konceptet opnåede en elvirkningsgrad mellem 54-62%. Større systemer mellem 8-10MW_e blev udforsket for koncepter med henholdsvis Kalina-anlæg, damp- og gasturbiner tilknyttet afgassen fra Viking-SOFC-anlægget. Disse koncepter opnåede elvirkningsgrader mellem 48-58%. Modelleringsarbejdet viste også at parametre som driftstemperatur og fuel utilization er af stor betydning anlægsdesignet.
To økonomistudier på henholdsvis Stirling- og et STIG-konceptet viste at disse to koncepter ikke er økonomisk bæredygtige, sådan som priserne er på nuværende tidspunkt. Stirling-konceptet viste sig at være konkurrencedygtig for levering af el direkte til bygninger, for eksempel hoteller, indkøbscentre husstande, men ikke til elnettet. STIG-konceptet viste sig ikke at være konkurrencedygtigt til elnettet. Begge studier konkluderede at den primære barriere for kommercialisering er investeringsprisen for SOFC .

Der er planlagt yderligere eksperimentelt arbejde i nærmeste fremtid på SOFC'en, hvor især langtidsdrift vil være i fokus. Projekter længere ude i fremtiden er planlagt, hvor Viking-SOFC's potentiale for elproduktion skal udforskes mere dybdegående. Viking-SOFC platformen har vist at kunne producere el med en meget høj virkningsgrad og tilhørende totalvirkningsgrad. Disse resultater er vist eksperimentelt, såvel som teoretisk i dette projekt. De modellerede Viking-SOFC-anlæg er teknisk set konkurrencedygtig ift. elvirkningsgrad, men studier viser at anlæg kun er økonomisk bæredygtige for få nichemarkeder og ikke til elnettet med nuværende priser. Den primære barriere for videre kommercialisering er lang-tids test for at udforske potentialet samt investeringsprisen på SOFC.

Introduction

This chapter includes a brief overview of the project partners, the technological background for the project and the purpose and planning of the project.

Organisation

Partners and Subcontractors

	Enterprise/Institution	Resource Persons	e-mail
Responsible Entity	DTU Chemical Engineering	Jesper Ahrenfeldt	jeah@kt.dtu.dk
Partner 1	Topsoe Fuel Cell	Jesper Noes	jesn@topsoe.dk
Partner 2	DTU Mechanical Engineering	Masoud Rokni	mr@mek.dtu.dk
Partner 3	DTU Energy Conversion	Anke Hagen	anke@dtu.dk
Subcontractor 1	Uni-tech		Uni-tech@mail.dk

Background

This section will present a brief overview of the context of the project in the current energy system and present the Viking gasifier and solid oxide fuel cell (SOFC) technologies. Both technologies are still under development and while gasifiers have been built in commercial scales, SOFC's are still approaching pilot-scale testing.

Biomass is a limited resource, it is therefore clear that this CO_2-neutral energy source must be used in a way where CO_2 emissions are minimized. This requires that biomass primarily substitutes coal, since coal is causing by far the largest CO_2 emissions per unit of energy. It is inevitable that the electricity share of the overall energy consumption will increase significantly in the future. Using biomass in CHP plants with optimal electrical efficiency, while utilizing as large a proportion of the residual heat as possible is therefore an obvious cause of action. Central heat and power plants with today's technology have the highest electrical efficiency, but utilizing all waste heat is a challenge. In this context decentralized CHP uses a much larger portion of waste heat, but here the electrical efficiency is a challenge.

It is therefore logical to carry out research and development aimed at technology that is both decentralized - i.e. can exploit virtually all waste heat while maintaining an electrical efficiency as high or even higher than the electrical efficiency at central power stations. This perspective is obtained by connecting a highly efficient biomass gasifier which can produce a clean gas, with a SOFC that can convert the gas with a high efficiency.

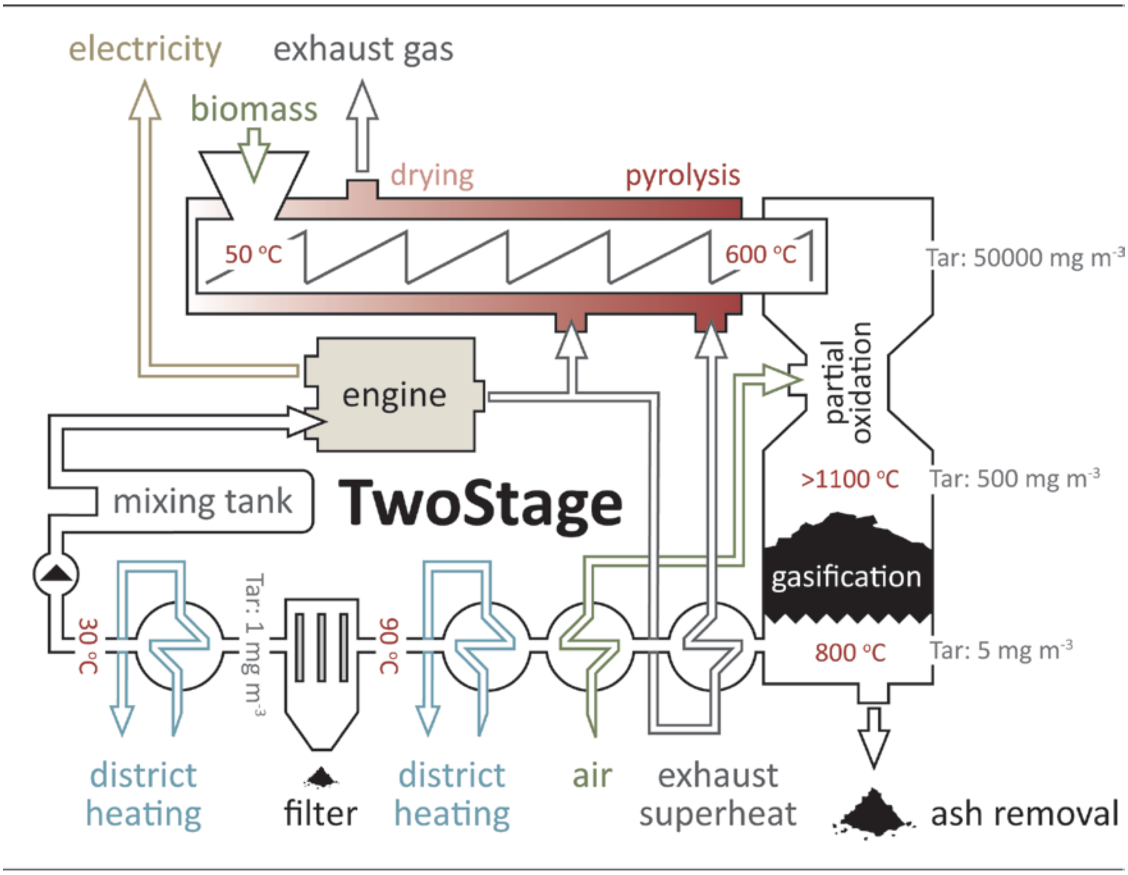
The development of 3rd generation decentralized flexible biomass based CHP will strengthen the position of Denmark as world leader in energy production from biomass and extend the utilization of biomass for CHP.

Gasification

Gasification is the thermochemical conversion of solid carbonaceous matter into gaseous fuel at high temperatures. The solid fuel is usually partially oxidized and then converted to mainly CO, H_2, CO_2, tars and N_2 (nitrogen if air injection is used) that can be further processed in e.g. combustion applications, chemical synthesis. During gasification, the fuel (usually biomass or coal) is converted in several stages at different temperatures. Initially the fuel is dried at >100ºC and releases its moisture content. Pyrolysis occurs at 200-600ºC and the organic structures of the fuel deteriorate, releasing H_2, CO, CO_2, char (carbon) and volatile organic compounds, *tars*. Tars are a troublesome and a complex group of organics that can cause rapid fouling of equipment if the necessary precautions are not taken. Tars are one of the main research subjects in gasification, as extensive gas cleaning trains are usually needed in order to utilize the product gas in down-stream applications. At >700ºC the gasification reactions initiates and convert the remaining solid char into CO, CO_2 and H_2.

The TwoStage biomass gasifier

The TwoStage gasifier concept is developed at DTU and has been built in commercial scale up to 500kW_e. The gasifier processes wood chips at temperatures up to and above 1100ºC, producing a combustible *product gas* that are utilized in an engine (in current plants). The gasifier is unique in its ability to produce gas with a very high gas quality with virtually no tars, only using a simple bag house filter. In addition, the TwoStage process operates at very high energy efficiency (biomass to product gas).



All tar concentrations measured per volume gas produced.
All gas volumes measured at Normal Temperature and Pressure i.e. 20 °C and 101325 kg m^{-1} s^{-2}

Figure 1 - Flow diagram of the Viking gasifier

A flow diagram of the TwoStage gasifier located at DTU Risø (the Viking gasifier) is shown in Figure 1. The gasifier utilizes two separate reactors for processing the fuel and is operated at atmospheric pressure levels. Wet wood chips are fed into an externally heated screw conveyor that dries and pyrolyzes the fuel up to temperatures of 600 ºC. The screw conveyor can be heated by a variety of heat sources – done by engine exhaust on Figure 1. The pyrolysis products are led to the second reactor and are exposed to partial oxidation by air injection, raising the temperature to >1100 ºC. The gas and char are then led through a hot char bed, where the char is gasified and the temperature subsequently lowered to 750 ºC at the bed outlet. The producer gas is then led through a series of heat exchangers and a simple gas cleaning unit (bag house filter) that removes a small amount of soot, tars and water.

The Viking gasifier have been moved from DTU Lyngby campus to DTU Risø and have been re-commisioned and operated several times since. The gasifier is controlled via a MS-DOS system, that was installed as the gasifier was originally commissioned. It was intended to equip the gasifier with a new data acquisition system, but this has not been completed in time for this report. Near future installment is expected.

Solid oxide fuel cell

A fuel cell is an electrochemical reactor that can convert the chemical energy captured in gaseous fuels directly into electricity. The fuel cell utilizes separate flows of fuel and oxidizer and an ion-conducting membrane to produce electricity directly and thus reduces irreversibilities associated with traditional thermal energy conversion (thermal and mechanical losses). Because of this characteristic, fuel cells can operate at very high thermodynamic efficiencies which make them an intriguing technology for future energy systems. The high efficiency of the fuel cells is the main driver compared to other power producing technologies such as engines and turbines. Even at small, decentralized scale the electric efficiency can reach up to 40-60%. The main drawback of fuel cells is currently that the gas quality requirements are very high and selected species such as sulphur, chlorine and particulates etc. have to be completely removed to sustain operation.

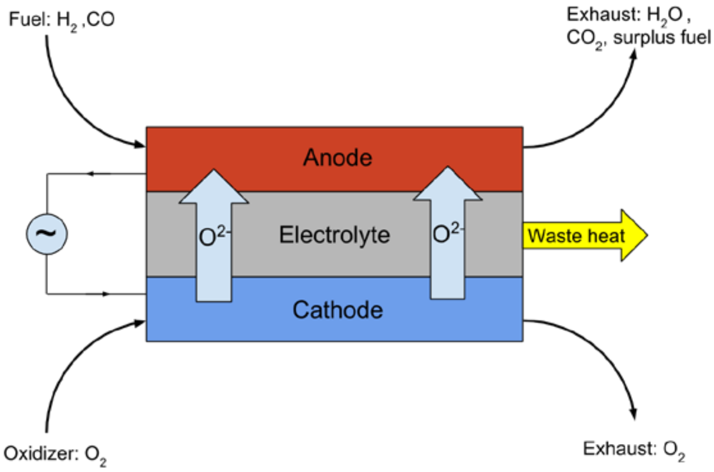


Figure 2 - Working principle of a SOFC.

Solid oxide fuel cells (SOFC) are high-temperature fuel cells (700-1000 ºC), that in opposition to many of the other fuel cells, can process CO and CH_4 along with H_2. SOFC's are constructed with three main layers: cathode, electrolyte and anode. The working principle of a SOFC is shown on Figure 2. At the cathode, oxidizer (usually air) is added and the oxygen is converted to charged oxygen-ions by electrons from an electric circuit. The oxygen-ions can as the only particles cross the electrolyte to the anode, where they react with fuel gases and release the absorbed electrons that are led through an electric circuit to the cathode. In order to avoid oxidation of the anode, fuel is added in excessive amounts to keep a reducing environment. The flow of electrons from anode to cathode creates an electric power in the circuit that can be utilized in electric applications.

Project objectives

The project aims at combining advanced biomass gasification with state-of-the-art solid oxide fuel cells (SOFC), in a highly efficient decentralized and flexible energy system for small scale combined heat and power production. The project will determine and test the optimized requirements for wood gasification when the producer gas is used for SOFC operation. Furthermore it will test and evaluate the performance of combined biomass gasification and SOFC operation. Finally it is the objective to conceptualize and optimize a gasifier-SOFC energy system with a biomass to electricity efficiency potential of +40%.
The project contains three work packages (WP), where the first (WP1) will include the design and construction of a gasifier-SOFC stack test set-up. The operation and analysis of the SOFC performance will

be addressed in WP2, and system analysis regarding the integration and optimization of the gasifier-SOFC system will be conducted in WP3.

Research activities

This section presents the research that the project has carried out. The research is split into two parts: **experimental activities** with the Viking gasifier and SOFC, and **energy system analysis research** using mathematical modeling of the TwoStage-SOFC technology platform.

Experimental activities

The experimental research to this point have included the installation, testing and operation of a solid oxide fuel cell stack (SOFC) on bottled cylinder gas resembling that of the Viking gasifier as well as gas directly from the Viking gasifier. This section will present the experimental methods, results, conclusions and future work.

Background

As both biomass gasification and SOFC technologies still are subject to extended research, only limited tests of SOFC's operated on gasification product gas have been reported in the literature. The main focuses of these studies are on the effect of various components in the fuel gas feed, e.g. tar loading, and are very empirical in nature. Most of the studies are also carried out over short operating times (<30hours), low electrical loads and on single cells and not stacks. One previous test of a SOFC single-cell with the Viking gasifier marked the longest operating time at 150 hours for such a combination at the time (2007). Therefore, extended research on the area are needed on larger SOFC systems - *SOFC stacks* - operated at high loads for a longer period of times, in order to push the technology closer to commercialization.

Figure 3 - SOFC stack used for the project

Methods

The experimental setup is centered around the SOFC stack. The stack is an anode-supported, planar 50-cell, 0.85 kW_e stack. The stack is placed in an oven to maintain high-temperatures and is operated at atmospheric levels at 700 ºC. The stack is shown in Figure 3. The SOFC is fed with gas resembling that of the Viking gasifier from gas cylinders. Two gas compositions have been tested, based on the use of either air- or oxygen-blown gasification – the used gas composition is shown in Table 1.

The SOFC have very requirements for the inlet gases, so the gases from the cylinders are led through a series of components before entering the stack. Two active carbon filters are installed prior to the gas entering the SOFC system in order to ensure removal of sulphur, chlorine, tars and other unwanted components. The carbon filters each have estimated gas residence times of 20 seconds and are operated at room temperature. Besides the carbon filters, it was originally intended to install a small local gas storage near the SOFC setup. This plan was however abandoned, as it was estimated that the gas storage installed by the Viking gasifier was sufficient to minimize fluctuations and secure a steady supply.   At the SOFC setup the fuel gases are initially fully

humidified at 60 ºC in order to avoid carbon deposits in the cell. Afterwards the gases are heated to 200ºC and led through a desulphurizer. Lastly the gases are heated to 600ºC before entering the stack. The air is also heated to 600ºC at the SOFC inlet.
The project have included installation of equipment, testing of individual components, programming of data logging, development of operating procedures and testing of the full setup.

The experimental tests have included two test with bottled gas that investigated the SOFC performance at different currents and two tests with real Viking gas that investigated SOFC performance at different currents and a 20-hour test that investigated any decline in performance.

Results

The experimental work was carried out over several days during June, July and December. A total of 31 operating hours directly on real Viking gas and 24 operating hours on cylinder gas have been carried out. The SOFC stack was tested at conditions based on Topsøe Fuel Cells operating procedures. The stack was tested at constant flow and temperature, with the electric current as a variable. By changing the current and registering the resulting voltage, the stacks power output and thermodynamic efficiency[1] can be calculated. Based on the current, the fuel consumption can be estimated with good precision and the effective efficiency of the cell can be estimated[2].

Tests with cylinder Viking-gas

The stack was tested up to 25A and 20A for the air- and oxygen-blown gas respectively, with corresponding fuel utilizations of 73% and 61%.

Gas component	Air-blown Viking gas [vol%]	Oxygen-blown Viking gas [vol%]
N_2	24.72	3.09
H_2	25.76	42.73
CO	16.74	15.68
CO_2	12.21	17.61
CH_4	1.04	1.37
H_2O	19.53	19.53

Table 1 - Gas compositions used with the SOFC. The oxygen-blown gas composition is based on theoretical calculations.

The SOFC performance was mapped during tests and correlations between voltage, current and power was obtained. The main experimental results are summarized in Table 2. The thermodynamic efficiency is seen to be very high at up to 38.8% - considering the scale of the system, that 27% of the fuel still is available in the exhaust and the high quality waste heat in the exhaust at 700ºC. The effective efficiency at 20A shows that SOFC converts the fuel at a very high efficiency, at approximately 55%. If the excess fuel could be recirculated into the SOFC, the thermodynamic efficiency would approach this very high value. A simple calculation[3] based on the thermodynamic and effective efficiency estimates an air-blown Viking-SOFC

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[1] Thermodynamic efficiency defined as power divided by inlet fuel mass flow times lower heating value $= \frac{P_{SOFC}}{(m*LH\dot{V}_{fuel})_{in}}$

[2] Effective efficiency defined as power divided by utilized fuel $= \frac{P_{SOFC}}{(m*LH\dot{V}_{fuel})_{in}-(m*LH\dot{V}_{fuel})_{out}}$

[3] Viking-SOFC system efficiency based on the SOFC and gasifier cold gas efficiency of 93% $= \eta_{SOFC} * \eta_{Viking}$

system to achieve an electric efficiency between 36% and 51%, depending on the degree of utilization of exhaust fuel in the SOFC or other down-stream applications (auxiliary consumption not taken into account).

Paramter	Air-blown Viking gas	Oxygen-blown Viking gas
Max current [A]	25	20
Max power [W]	873	714
Max thermodynamic efficiency[1] [%]	38.8	33.8
Max fuel utilization [%]	72.8	60.8
Effective efficiency[2] at 20 A [%]	55.6	54.8

Table 2 - Main experimental results with cylinder gas.

Tests with real Viking gas

Two tests was carried out with direct coupling of the SOFC setup to the Viking gasifier. The main objective of these tests was to validate the previous obtained data from cylinder gas and to test if the SOFC could maintain a high performance despite fluctuations in gas composition and the addition of inorganic and organic in the gas. These tests are performed at 700C with gas flows equal to those with cylinder gas. The connection between the two setup was, as described, associated with the installation of two active carbon filters and a small gas pump – in order to clean the product gas to an estimated sufficient level.

The gas composition during the tests is shown as an average in table Table 3. The gas composition is seen to differ from the utilized composition with cylinder gas, which is due to differences in operating procedures for the Viking gasifier (the cylinder gas test is based on previous tests with the gasifier). The real Viking gas has therefore a lower heating value with significantly more N_2 and lower amounts of H_2 and CO.

It should be noted that these test are dictated primarily by standard operating procedures from Topsøe Fuel Cells. Therefore higher electric efficiencies should be expected when SOFC operation is optimized to a given system (e.g. gas composition) and criteria.

Gas component	Average real Viking gas [vol%]
N_2	34.74
H_2	21.26
CO	12.34
CO_2	11.55
CH_4	0.57
H_2O	19.53

Table 3 - Average gas compostiion af real Viking gas.

The real gas was tested in steps up to 24.1 A. The main results are shown in Table 4. While there is a significant difference in gas composition, the thermodynamic efficiency is seen to be similar to the one obtained with cylinder gas. The power output and effective efficiency is however lower, which is namely due to the lower quality of gas.

Paramter	Real Viking gas
Max current [A]	24.1
Max power [W]	771
Max thermodynamic efficiency[1] [%]	38.2
Max fuel utilization [%]	83.8
Effective efficiency[2] at 24.1 A [%]	44.9*

Table 4 - Main experimental results with real gas. *Corresponding value for cylinder gas is 53%.

The long-term test was carried out over 20 hours of operation at a current of 20 A. The first 16 hours of operation are shown on Figure 4 – the remaining 4 hours are not shown due to large fluctuations in gas composition and pressure (for which the reasons are currently unknown). During the 16 hours of testing, the voltage only fluctuated within 1.3 V and the power within 25 W. The small fluctuations are expected to be mainly because of small fluctuations in gas composition. The SOFC displays good stability during operation on a live gas composition. No decline can be verified at the moment and further testing is needed for further validation. Further tests are planned in January 2015.

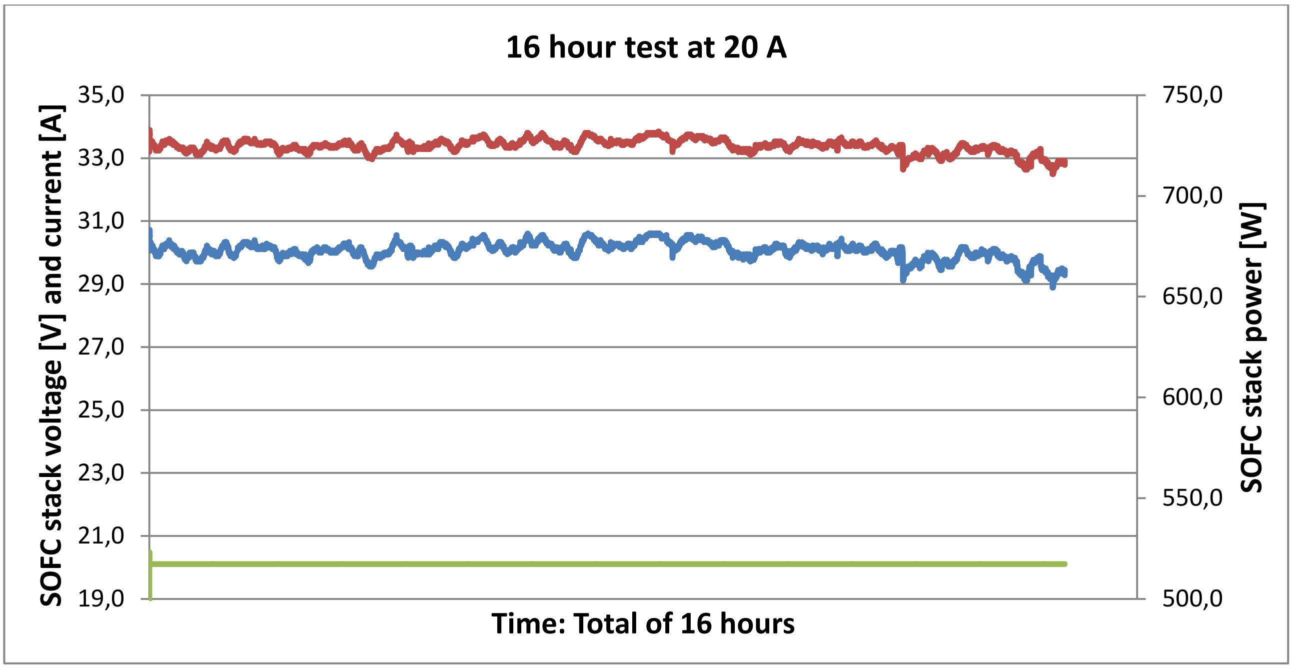

Figure 4 - Long-term test on real Viking gas: 16 hours at 20 A. The green curve is current [A], the red curve is voltage [V] and the blue curve is power [W] of the stack.

Future work

Tests with the Viking and SOFC for an extended period of time (>100 hours) is planned in January 2015. These tests will namely investigate the effect of long-term operation.

The Viking gasifier is planned to operate with oxygen-steam injection (instead of air) in a future project. The SOFC stack will in that project be tested on the resulting product gas – which should also acts as a validation of the oxygen-blown Viking gas results in Table 2.

Milestones and status

Table 5 presents the specific milestones of the experimental research and the status of these. Milestone M1.2 has been carried out for the SOFC system, but the Viking gasifier has not been equipped with a new data system. A new system is expected in January 2015. Further tests within Milestone M1.3 is planned – especially further long-term testing on real Viking-gas. Milestone M1.4 has been aborted due to the department closure of project partner Topsøe Fuel Cell – therefore 2.5 G SOFC's are not discussed further here.

WP1	**Milestone**	**Status**
M1.1	Design and construction of SOFC stack set-up	OK
M1.2	Installation and programming of data acquisition system for gasifier and SOFC stack set-up	Partially
WP2	**Milestone**	**Status**
M1.1	Commissioning of the SOFC stack set-up	OK
M1.2	Initial tests with the SOFC stack	Ok
M1.3	Extended test with SOFC stack operation on biomass product gas	Ok
M1.4	Tests of 2.5 G single cell operation on synthetic product gas	Aborted

Table 5 - List of project milestones and status.

Energy system analysis research

This section presents the research that has been carried out regarding modeling, optimization and analysis of energy systems with the Viking gasifier and SOFC.

Background

Studies have shown that the integration of biomass gasification and SOFC has a great potential for being a technology that may supply electricity and heat at high efficiency from renewable energy sources. In this part of the project, further investigations will be carried out with focus on detailed understanding of the operation of the system in a real application. Significant research has been done on development of simulation software and models of components present in systems involving biomass gasification and SOFC's. These component models will be applied in the development of the system models to be studied.

Methods

The modeling work was carried out in the programming tool Dynamic Network Analysis (DNA), which is a zero-dimensional modeling tool, well equipped for advanced thermodynamic energy system analysis. The modeling and analysis have been carried out in different stages over the course of the project. Initially, identification and development of individual modeling components and system setups was done. Next, optimization of design and operation was carried out, followed by investigation of alternative plants designs.

The investigated plants have all included the Viking gasifier coupled with a SOFC stack, with off-gases from the SOFC being utilized in various subsystems. The subsystems include Stirling engines, organic Rankine cycles (ORC), Kalina cycles, steam cycles and gas turbine cycle designs. The focus of the work has been on plant electric and total efficiency, and technical-economic analysis. All of the studies have been on small-scale systems at ≤10 MW_e. Exergetic analysis are only applied for stand-alone components in the studies and are thus not carried out in detail in this project. All of the plants are investigated in steady state operation and thus not in part-load operation.

The gasifier model

Here follows a very brief description of the modeling of the gasifier. For further description please see the published articles under Dissemination.

The gasifier is modeled by implementing a simple Gibbs reactor; thus, when chemical equilibrium is reached, the Gibbs free energy will be at a minimum. This characteristic is used to calculate the gas composition at a specific temperature and pressure without taking the reaction paths into account and will be briefly explained below. The Gibbs free energy of a gas (assuming a mixture of *k* perfect gases) is:

$$\dot{G} = \sum_{i=1}^{k} \dot{n}_i \, [g_i^0 + RTln(n_{ip}) \,]$$

where g^0, R and T are the specific Gibbs free energy, universal gas constant and gas temperature, respectively. Furthermore, each atomic element in the inlet gas is in balance with the outlet gas composition, which shows that the flow of each atom must be conserved. The model calculates the product gas composition and produced ashes based on the inlet media compositions (dry wood, steam and air) and the operating conditions. The ashes originate from a defined content in the inlet biomass. An option to adjust the CH4 content in the equilibrium product gas composition is included in order to reach realistic product gas compositions.

The SOFC model

Here follows a very brief description of the modeling of the SOFC. For further description please see the published articles under Dissemination.

The SOFC component model determines the electric power production depending on the fuel input and the SOFC efficiency. The SOFC efficiency is defined as:

$$\eta_{SOFC} = \eta_{rev} \, \eta_V \, U_f$$

The fuel utilization factor U_f is estimated, while the reversible efficiency η_{rev} is the maximum possible efficiency defined as the relationship between the maximum available electrical energy (change in Gibbs free energy) and the change in enthalpy of formation, both of which are associated with full oxidation of the fuel. This relationship is shown in the following equation:

$$\eta_{rev} = \frac{\Delta \bar{g}_{f,FO}}{\Delta \bar{h}_{f,FO}}$$

The voltage efficiency η_V is a measure of the electrochemical performance of the SOFC and it is defined as:

$$\eta_V = \frac{V_{cell}}{E}, \qquad V_{cell} = E - V_{act} - V_{ohm} - V_{conc}$$

An electrochemical model, depending on operating conditions such as temperature, pressure, average species concentrations and current density, predicts the Nernst potential and overpotentials. The average species concentrations are based on an arithmetic mean of the inlet and outlet concentrations, both of which are assumed to be at chemical equilibrium (equilibrium concentrations are found by using the Gibbs free energy minimization method at anode inlet and outlet). The Nernst potential is defined below. Though in this model, only H_2 is electrochemically converted (and not CO and CH_4), but because the fuel reaches chemical equilibrium at the anode inlet in this model, H_2 will be produced from CO and CH_4 through steam reforming and water gas-shift reactions. Any remaining CO and CH_4 after reaching chemical equilibrium at the anode inlet are considered inert gases regarding the electrochemical conversion in the SOFC. The temperature used in the electrochemical model should represent the temperature of the solid structure of the SOFC and it is assumed to be equal to the operating temperature of the SOFC T_{SOFC}.

$$E = \frac{\overline{-\Delta g^0}_f}{2F} + \frac{RT_{SOFC}}{2F} \ln\left(\frac{\bar{p}_{H2}\sqrt{\bar{p}_{O2}}}{\bar{p}_{H2O}}\right)$$

Further descriptions on the gasifier, SOFC, other component models and assumptions can be found in the appendices which contain the dissemination articles and projects related to this project.

Results

The coupling of the Viking gasifier and the SOFC technologies have proven to be a high-efficient system for biomass fueled combined heat and power generation. The main modeling results are summarized in Table 6. At small scale, 1.4MW$_e$, the Viking-SOFC system can achieve electric efficiencies up to 44.9%, which is significantly higher than the efficiency of traditional decentralized biomass power plants, which typically are 30-34% (at 5-25 MW$_e$). A study calculated the total efficiency (district heating included) of a Viking-SOFC system to 82%.

The Viking-SOFC coupling has been studied extensively with other power generating units downstream of the SOFC in combined cycle concepts. The waste heat and fuel in the exhaust of the SOFC is of very high quality and are projected to be used with various machinery.

At very-small scale, Viking-SOFC systems have coupled to a Stirling engine and an organic Rankine cycle (ORC). The Stirling system is mainly projected for direct use in buildings, e.g. hotels, malls and households. Using a Stirling engine could increase the total system electric efficiency as much as 29% to a total of 42%. The total system efficiency (district heating included) was found to 89%. The usage of an ORC with the Viking-SOFC proved to achieve very high electric efficiencies between 54-62%. The ORC application is especially useful at lower dimensions (<500kW$_e$), where waste heat can be utilized to a higher degree than with steam cycles due to downscaling-issues of steam turbines.

Larger systems between 8-10 MW$_e$ effect was modeled with Kalina, steam and steam injected gas turbine (STIG) cycles. All of these systems achieved very high electric efficiencies between 48-58%. These efficiencies are significantly higher than the traditional decentralized biomass power plants at 30-34%.

The energy system analysis studies have also included analysis of operating parameters. Based on several of the studies, some general conclusions can be drawn. The SOFC operating temperature is of high importance when coupling the Viking-SOFC system with downstream machinery. The general trend is that lowering the SOFC temperature (which is wanted due to increased longevity), reduces the net power output and hence efficiency – economic analysis will have to clarify the best suitable temperature levels. The fuel utilization (amount of fuel used in SOFC relative to SOFC fuel input) is also of significant importance and usually has a set max limit from the producers. While a feasible lower limit of 65% was found in one study, this parameter has to be carefully optimized to achieve the maximum in a combined cycle concept. The cold gas efficiency (product gas energy relative to biomass input energy) of the gasifier is of high importance, when coupled to a SOFC. Efforts to increase this efficiency and gasify at relative low temperatures should be pursued to increase efficiency of the gasifier-SOFC concept.

In order to estimate the cost of a Viking-SOFC system, thermo-economic analysis has been applied in two of the studies: coupling of the Stirling engine and the STIG. The Sterling engine concept proved to be competitive for in-house use, such as for hotels, malls and household. The study showed that especially the SOFC technology needs to enter the commercialization phase (and hence reduce costs) before the system would become competitive for distribution to the grid.
Thermo-economic analysis of the Viking-SOFC with STIG concept showed that the usage of a STIG cycle was infeasible for the given scale of 10MW$_e$. The study also included a model of a Viking-SOFC with gas turbine concept that proved equally infeasible. The main barrier towards reducing costs was found to be SOFC investment, similar to the study with the Sterling concept.

Scenario	**Scale** [MW$_e$]	**Electric efficiency** [%]	**Total efficiency** [%]	**Economic analysis comment**
Viking-SOFC	1.40	44	82	-
Viking-SOFC Stirling engine	0.12	42	89	Cost effective for direct use in buildings, not grid
Viking-SOFC ORC	0.10	54-62	-	-
Viking-SOFC Kalina cycle	8	49-58	-	-
Viking-SOFC steam cycle	10	48-56	-	-
Viking-SOFC STIG-cycle	10	48-50	-	Not feasible at <10MW$_e$

Table 6- Main modeling results

Milestones and status

Table 7 presents the specific milestones of the energy system analysis research and the status of these. Two parts if the Milestone M4.5 have not been reached: studies of alternative configurations with regards to scenarios including gasification with enriched air and increasing the methane content in the product gas. While there have not been modelled scenarios with enriched air, test with cylinder gas resembling oxygen-blown gasification is carried out.

WP4	Milestone	Status
M4.1	Assessment required development of component models	OK
M4.2	Component models development (reformer, gasifier, fuel cell)	OK
M4.3	Definition of system configuration; simulations and optimization of design	OK
M4.4	Simulation of system operation in annual operation; optimization of operation	OK
M4.5	Studies of alternative configurations *- gasification with enriched air scenarios* *- increasing the methane content in product gas*	OK *Not done* *Not done*
M4.6	Utilization of off gases	OK
M4.7	Cooling system optimization	OK
M4.8	Report	OK

Table 7 - List of project milestones and status.

Utilization of project results

The research carried out in this project clearly shows that the coupling of the Viking and SOFC technologies has a high potential for providing CO_2-neutral combined heat and power generation in the future. Very high efficiencies are expected. The experimental data for the SOFC is in agreement with the theoretical models. Extended experimental tests of the Viking-SOFC are however still needed to verify the longevity of the coupling of the two technologies. An important first step is however taken – showing the possibility for coupling of a biomass gasifier and a SOFC without extensive gas cleaning. The main barrier towards commercialization is identified in the modelling studies to be namely the investment cost associated with SOFC's. Further research should aim at solving these challenges.

Further research within the field of Viking-SOFC has begun as a part of the ForskVE project no. 12205. The main results from the present project will be utilized to design and operate a Viking-SOFC system, that is flexible and can either produce power (when demand is high) or biofuels (using power when demand is low). The project will be an extension of this project and will involve some of the same partners.

Dissemination

The project have resulted in several publications, conference presentations etc. The research has been presented on the following occasions:

- Rokni, M. and Pierobon, L., 2011, "Integrated Gasification SOFC Plant with a Steam Plant", Risø International Energy Conference 2011, pp. 288 – 297, ISBN: Risø-R-1776(EN), 10–12 May 2011, at

Risø National Laboratory for Sustainable Energy, Roskilde, Denmark.

- Rokni, M. and Pierobon, L., 2011, “Integrated Gasification SOFC Plant with a Steam Plant”, Risø International Energy Conference 2011, pp. 288 – 297, ISBN: Risø-R-1776(EN), 10–12 May 2011, at Risø National Laboratory for Sustainable Energy, Roskilde, Denmark.

- Rokni, M.., 2013, “Thermodynamic Analysis of a Woodchips Gasification Integrated with Solid Oxide Fuel Cell and Stirling Engine”, 6th International Conference on Sustainable Energy and Environmental Protection – SEEP2013, 20 – 23 August, Maribor University, Maribor, Slovenia, ISBN 978-961-248-379-1, pp 432-438.

- Mazzucco A. and Rokni M., 2013, “Thermoeconomic Analysis of a Gasification Plant Fed by Woodchips and Integrated with SOFC and STIG Cycles”, SDEWES2013 Conference, Dubrovnik, Croatia, pp:0210-1 to 0210-21.

- Rokni M., 2013, “Thermodynamic and Thermoeconomic Investigation of an Integrated Gasification SOFC and Striling Engine”, SDEWES2013 Conference, Dubrovnik, Croatia, pp:0166-1 to 0166-23.

The following articles related to the project have been published in international journals:

- Rokni, M., 2012, “Thermodynamic investigation of an Integrated Gasification Plant with Solid Oxide Fuel Cell and Steam Cycle”, *J. GREEN*, Vol. 2, issue 2-3, pp. 71-86.

- Pierobon, L., Rokni, M., Larsen, U. and Haglind F., 2013, “Thermodynamic analysis of an integrated gasification solid oxide fuel cell plant combined with an organic Rankine cycle”, *Renewable Energy*, Vol. 38, pp. 226–234.

- Bang-Møller, C., Rokni, M., Elmegaard B., Ahrenfeldt J. and Henriksen U.B., 2013, “Decentralized Combined Heat and Power Production by Two-Stage Biomass Gasification and Solid Oxide Fuel Cells”, *Energy*, Vol. 58, pp. 527–537.

- Pierobon, L. and Rokni, M., 2013, “Thermodynamic Analysis of an Integrated Gasification Solid Oxide Fuel Cell Plant with a Kalina Cycle”, *Int. J. Green Energy*, DOI: 10.1080/15435075.2013.867267.

- Rokni, M., 2014, “Biomass Gasification Integrated with a Solid Oxide Fuel Cell and Stirling Engine”, *J Energy*

- Rokni, M., 2014, “Thermodynamic and Thermoeconomic Analysis of a system with Biomass Gasification, solid oxide fuel cell (SOFC) and Stirling Engine”, *J Energy*

- Mazzucco A, Rokni M., 2014, “Thermoeconomic Analysis of a SOFC and STIG Plant Integrated with Woodchips Gasification, *Energy*

Other publications that are connected to the project in different capacities:

- Bellomare F., and Rokni M., 2013,”Integration of a Municipal Solid Waste Gasification with Solid Oxide Fuel Cell and Gas Turbine”, *Renewable Energy*, Vol. 55, pp. 490-500.
- Rokni, M., 2013, “Thermodynamic Analysis of SOFC-Stirling Hybrid Plants using Alternative Fuels”, *Energy*, Vol. 61, pp. 87–97.
- Rabbani, A. and Rokni, M., 2014, “Modeling and Analysis of Transport Processes and Efficiency of Combined SOFC and PEMFC Systems”, *Energies*, Vol. 7, pp. 5502–5522.
- Gadsbøll, R., Thomsen, T., 2014, “Experimental analysis of solid oxide fuel cell coupled to biomass gasification”, master project, DTU CHEC.

Planned presentations and articles:

- Gadsbøll, R., 2015, “Experimental analysis of a solid oxide fuel cell coupled with biomass gasification”, European Biomass Conference and Exhibition 2015 Vienna, Planned presentation and article of experimental results with the Viking gasifier and SOFC.

Summary and perspective

Coupling solid oxide fuel cells (SOFC) to biomass gasification has a potential to contribute to the sustainable power generation by decentralized power plants. With both technologies having high energy efficiencies, the combination can achieve very high plant efficiencies. Only limited research has been done on the subject and further research on the subject are needed to evaluate the combined technology platform. As an extension of preliminary tests with biomass gasification and SOFC’s in other projects, this project carried out experimental research along with energy system analysis using mathematical modeling.

An experimental setup with a Topsøe Fuel Cell, 0.85 kW$_e$ SOFC stack with auxiliaries was commissioned at KT DTU, Risø campus. Extensive knowledge on installation, operation and testing of the SOFC stack has till this point resulted in tests with clean bottled cylinder gas and real Viking product gas. Further tests with direct coupling to the Viking gasifier are planned in the near future in order to further validate the longevity of the gasification-SOFC coupling.
The experimental results confirm that using gas resembling that of the Viking gasifier, can result in high efficiencies. Initial tests showed that the SOFC stack with a fuel utilization of 73% and an operation temperature of 700ºC can achieve an electrical efficiency of 38.8%. The experimental study also showed the high-efficient conversion in the SOFC, showing an effective efficiency of 55% at 20A. The tests with real Viking confirmed the high electric efficiencies estimated with cylinder gas and also proved that extended operation is possible. An important first step is taken in showing that gasification can be coupled to SOFC without extensive gas cleaning equipment.

Energy system analysis of the Viking-SOFC concept was carried out, using mathematical modeling. The studies investigated the Viking-SOFC and various combined cycle concepts for decentralized power generation at small-scale at ≤10 MW_e. Thermo-economic analysis was applied for some of the studies. The mathematical modeling of the gasifier and SOFC was presented briefly.
The Viking-SOFC system was analyzed and showed high efficiencies. The electric efficiency was found to 42% in the study, with a total efficiency (district heating included) of 82%. With traditional decentralized biomass power plants operating at 30-34% electric efficiency, the Viking-SOFC plant can be technically competitive with regards to electricity production.
Various combined cycle concepts with the Viking-SOFC system were investigated, adding machinery down-stream of the SOFC. At very small-scale, a Sterling engine and organic Rankine cycle (ORC) was found to be effective, with the ORC showing high electric efficiency at 54-62%. Larger systems at 8-10MW_e using Kalina, steam and gas turbine cycles down-stream of the SOFC showed as the ORC very high efficiencies at 48-58%. These studies also revealed that the SOFC operating temperature and fuel utilization is of great importance when designed combined cycle plants.
Thermoeconomic analysis was carried out for the Sterling egine- and steam injected gas turbine-system (STIG). The Viking-SOFC-Sterling system proved to be cost competitive for electricity generation if used directly in e.g. building as hotels, malls, households. Producing power for the grid proved infeasible at current prices. The Viking-SOFC-STIG plant proved to be infeasible at current prices. Increased capacity of the plant concept might reduce specific costs. Both studies found that the main barrier for commercialization for Viking-SOFC plants was the SOFC investment costs.

Near future tests are planned for the experimental setup, where extended operating periods are expected in order to investigate the longevity of the SOFC with the Viking gasifier. These tests will show the SOFC's ability to operate under slightly unstable conditions and tolerances to particle, tars and inorganics.
The knowledge obtained in this project will be explored further in other projects by some of the same partners. Future projects with operation of the Viking and SOFC are planned and will further investigate the gasification-SOFC platforms potential for power generation.

The Viking-SOFC platform has shown able to produce power and heat at very high efficiencies. These results are demonstrated experimentally as well as theoretically in this project. The Viking-SOFC plants are technically competitive with regards to efficiency, while economic analysis shows that only some niche markets may be feasible at current prices. The main barrier for commercialization are found to be further long-time tests of SOFC's with product gas and the investment price of SOFC's.