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DEVELOPMENT OF A HIGHLY EFFICIENT MICRO-SCALE CHP SYSTEM BASED ON FUEL-FLEXIBLE GASIFICATION AND A SOFC

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ABSTRACT: During recent years comprehensive work has been done on the development of small-scale solid biomass based combined heat and power generation technologies but still only few systems are available, their efficiencies are rather moderate, their fuel flexibility is restricted and their market penetration is poor. Against this background, the on-going Horizon 2020 project FlexiFuel-SOFC aims at the development of a new, highly efficient and fuel-flexible micro-scale biomass CHP technology for a capacity range of 25 to 150 kW (fuel power). The technology consists of an updraft gasifier, a gas cleaning system and a solid oxide fuel cell (SOFC). The new technology is developed with a main focus on (i) the further development of a small-scale fixed-bed updraft gasifier technology towards higher fuel flexibility and integration into the SOFC based CHP system, (ii) the development of a novel and compact gas cleaning unit and (iii) the further development of a SOFC system (stack efficiency of ~40 % with product gas from the updraft gasifier). A first testing plant has been designed, constructed and is presently taken into operation.
Keywords: biomass, gasification, gas cleaning, fuel cell, combined heat and power generation (CHP)

1 INTRODUCTION

Biomass is a locally available energy source that should preferably be utilised in decentralised (small-scale) heat controlled CHP applications due to transport and logistic reasons. However, in this capacity range, only few technologies are presently available and due to their restrictions regarding electric efficiency and fuel flexibility, their market coverage is still poor. Against this background, the Horizon 2020 project FlexiFuel-SOFC (Grant Agreement No. 641229, 05/2015-04/2019) aims at the development of a new, highly efficient and fuel-flexible micro-scale biomass CHP technology consisting of a small-scale fixed-bed updraft gasifier, a compact gas cleaning unit (GCU) and a solid oxide fuel cell (SOFC). Within the project, the technology is developed for a capacity range of 25 to 150 kW (fuel power related to the NCV of the fuel) and thus shall be applicable for decentralised CHP applications.

2 OBJECTIVES

Within the project the new technology shall be developed, two generations of testing plants (a basic and an optimised one) shall be constructed and within comprehensive test runs the new systems shall be tested and validated. To reach this overall goal the project focuses on several specific objectives, which are related to the single plant units, the overall system design as well as the economic and environmental evaluation of the new CHP technology. Therefore, the detailed objectives of the work performed are as follows.

Within previous projects the partners Windhager and BIOS developed a small-scale updraft fixed-bed gasifier technology known as the PuroWIN, which is applied in combination with a burner and a boiler for heating purposes [1]. This technology has been successfully commercialised and models in the nominal capacity range between 24 and 60 kW_{th} are available on the market. Since one of the outstanding features of the PuroWIN technology is its very low dust emissions (in combustion mode below 1 mg/MJ for softwood chips), this gasifier represents the optimum basis for the development of the new CHP technology. Within the project this gasifier will be further developed to enhance fuel flexibility and integrated into a SOFC-based CHP system. Thereby, the further enlargement of the fuel spectrum applicable from softwood pellets and wood chips to wood chips from short rotation coppice (SRC, e.g.: willow, poplar) and selected agricultural fuels such as olive stones, nut shells and agro-pellets plays a central role.

Moreover, a compact gas cleaning concept covering particle precipitation, removal of HCl, H_2S and other sulphur compounds and tar cracking will be developed by

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TU Delft and HyGear. The aim is to provide a product gas with no PM, H_2S contents <1 ppm, HCl contents <5 ppm and to upgrade the tar rich product gas by cracking specific tar compounds which cannot be converted by reforming in the fuel cell system.

Last but not least, a SOFC technology enabling operation at nearly atmospheric pressure in a defined temperature range of the product gas (700 to 800 °C), a high power density of the SOFC stacks and a high electric efficiency (stack efficiency of about 40 % with product gas from the updraft gasifier) shall be developed. A SOFC stack design shall be applied which will in future also be used in other branches such as SOFC CHP based on conventional fuels (e.g. natural gas) and for H_2-generation by electrolysis (SOEC). Thus, a considerable reduction of investment costs by mass production is expected. The SOFC system related tasks of the project are covered by AVL and Fraunhofer IKTS.

These three main components shall be integrated into the overall CHP system. Within the system design a strong focus shall be put on fully automated operation of the whole system and on smart solutions to utilise internally available waste heat streams to cover the heat demand of certain plant components. It is the objective to finally run the CHP system without any need from auxiliary heating sources during plant start-up and continuous operation. Moreover, remaining waste heat shall be recovered in a highly efficient heat exchanger system to provide heat for space heating and warm water supply.

This new CHP technology shall enable an almost equal-zero emission (regarding CO, OGC, NO_x, HCl, SO_x, PAH and PM and due to the utilisation of biomass also regarding CO_2) fuel-flexible heat and power generation with an overall efficiency of close to 90 %.

Two testing plants, a basic (first) and an advanced one shall be developed, manufactured and assembled. The performance and evaluation of test runs with different biomass fuels at these testing plants shall form the basis to achieve an optimised system design at project end. Accompanying risk assessments, safety analyses, techno-economic and environmental impact assessments and market studies shall assure that the new technology resulting from the project also is market competitive. These assessment-related tasks are covered by Utrecht University, Wuppertal Institute and BIOS.

3 APPROACH

Micro-scale CHP systems are presently mainly based on fossil fuels such as natural gas and heating oil fired applications for block heating, Stirling engines and steam expansion machines. Attempts to couple these technologies with biomass combustion processes have not led to marketable products so far. Moreover, the electric efficiencies of such applications would be rather low (typically 8 to 14 % related to the biomass input power) [2, 3, 4, 5].

An alternative option to combustion based CHP technologies are gasification based micro-scale CHP technologies. Such systems have already been introduced into the market. They are usually based on downdraft or multi-stage gasification systems coupled with gas cleaning systems and gas engines. They exhibit higher electric efficiencies (~25 %) but limited overall efficiencies (65-75 %) due to intermediate gas cooling steps. Other disadvantages are the high fuel quality requirements (usually only high-quality wood chips with low moisture contents and well defined particle sizes can be utilised), high efforts for gas cleaning and rather complex process schemes [6, 7, 8, 9, 10].

To overcome these problems and to develop a highly efficient and fuel-flexible micro-scale biomass CHP technology a new approach has been chosen. The technology is based on a fixed-bed updraft gasifier coupled with a 2-stage gas burner and a hot water boiler (see Fig. 1). A part of the product gas is extracted from above the fuels bed and supplied to a modular gas cleaning unit (GCU) through a side stream while the remaining product gas is burned in the gas burner. The cleaned product gas then passes through the SOFC system for electricity production. Hot off-gases from the SOFC-system are partly used to heat the GCU and are then supplied together with gases from the gas burner to the heat recovery system (boiler). Suction fans downstream of the heat recovery system are used to overcome the pressure losses of the single units, thus the plant is operated at underpressure.

The operation of the GCU and the SOFC system in a side stream of the gasifier thereby brings significant advantages compared to an utilisation of the full product gas stream in the SOFC system. For example, from an application point of view, small-scale CHP systems must always be operated in a heat-controlled mode. This would result in a limited partial load operation capability of the whole system if the entire product gas flows to the SOFC system.

The partial load operation capability of the gasifier is very good and allows for operation down to less than 30% of its nominal power. By using a side stream of the gasifier, the SOFC can run at full load even if only low heating power is requested from the heat consumer. As soon as the heat demand increases, the gasifier load is also increased. This leads to an optimised number of full load operation hours of the SOFC system. Thereby, high overall electricity production per year can be achieved and, due to the cheaper (since smaller) SOFC system, the income from the electricity production is optimised and the payback time reduced.

A heat-only operation (in case of unexpected shutdowns due to failures in the GCU and the SOFC system) or very low load demands can be realised without additional components.

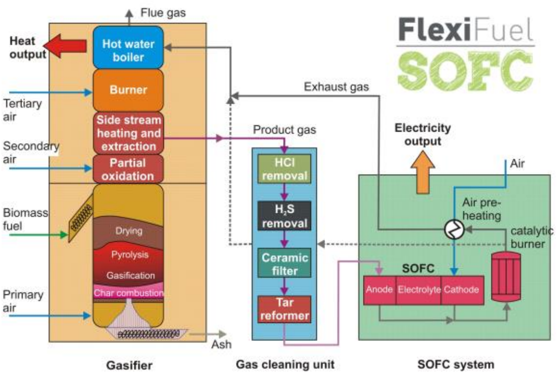

Figure 1: Basic scheme of the novel micro-scale biomass CHP technology

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Operation of the SOFC in a side stream of the gasifier also allows for a start-up procedure without the need for auxiliary (electric) energy for pre-heating the GCU and the SOFC system. During start-up this energy is provided from flue gas extracted from the product gas combustion in the gas burner. Moreover, the number of complicated start-up and shut down processes can significantly be reduced due to the high load flexibility of the gasifier.

A scheme of the technology showing the single plant units is presented in Fig. 1.

4 METHODOLOGY

As the description of the technological approach shows, the FlexiFuel-SOFC technology consists of highly interlinked system components which are combined in a technologically and economically efficient way. Therefore, the project demands for an appropriately interlinked approach, thus the overall methodology consists of a technology development component as well as a technology assessment component.

Technology development is based on process simulations, lab-tests with single components, computer aided unit and system design, test plant construction, the performance of comprehensive test runs and their evaluation. In parallel, technology assessment in form of risk assessments, techno-economic evaluations, environmental and overall impact assessments and market studies takes place in order to secure an economically and environmentally meaningful direction and market orientation of the technology development.

5 RESULTS ACHIEVED SO FAR

During the first 18 months of the 4-year project, the work focused on the development of the single plant components, the overall system design and the design, manufacturing and assembly of a first generation testing plant.

As an initial task, the operating conditions for the single plant components and the interfaces between them have been defined. Moreover, a detailed plant concept has been worked out and appropriate mass and energy balancing tools have been developed to optimise the system design. Based on these data the work regarding the single plant components has been initiated.

Besides these technical tasks, a strong focus has also been put on economic, environmental and market related issues. The compilation of a comprehensive market study regarding the market potentials and future trends for micro-scale biomass CHP systems in several European countries has been initialized in order to identify the most relevant future markets for the new technology. Preliminary techno-economic analyses have been performed in order to check the economic viability of the new technology and to define cost targets for the single plant components. Moreover, work on preliminary environmental, economic and societal assessments has been started.

5.1 Gasifier design

The work has started with the development of an integrated product gas extraction and heating unit, through which the product gas is led towards the GCU, and of a flue gas extraction from downstream the burner for SOFC and GCU pre-heating. In Fig.2 a scheme of the gasifier, the burner and their interfaces to these components is presented. Moreover, the gasifier was further developed in order to allow also the utilisation of biomass fuels with comparatively low ash melting temperatures (such as agro-pellets) thus achieving significantly better fuel flexibility. Therefore, experimental studies at an adapted PuroWIN-gasifier and comprehensive CFD (computational fluid dynamics) simulations have been performed focussing on ash related problems, i.e. ash sintering, ash melting and K-release. In a first step, pre-evaluations based on experience from gasifier operation with different wood fuels, gasifier modelling and the performance and evaluation of thermodynamic high temperature equilibrium calculations regarding ash formation and K-behaviour have been made. These evaluations indicated that especially for ash rich fuels with comparably low ash melting temperatures, de-ashing and fuel bed temperature control play an important role. Therefore, the following measures were implemented to increase fuel flexibility (see Fig. 2):

- Primary air humidification as a measure for fuel bed temperature control
- Implementation of a double grate system which is less sensitive to ash sintering or slagging
- Ability to adjust the de-ashing intervals to the ash content of the fuel

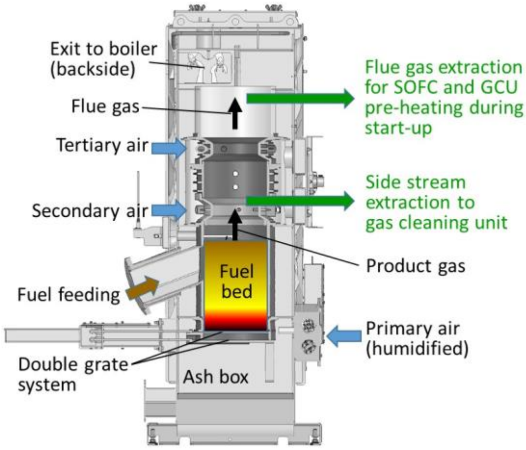

Figure 2: Scheme of the fuel-flexible gasifier developed and interfaces to GCU and SOFC units

In order to experimentally validate the implemented measures and gain practical experience with their application, a comprehensive series of test runs has been performed with an adapted PuroWIN updraft gasifier directly coupled with a staged gas burner and a boiler. Five different biomass fuels (conventional wood chips, miscanthus pellets, olive stones of premium and standard quality, poplar chips and straw pellets with the fuel additive kaolin) have been tested. This fuel selection covers fuels with a broad range of ash contents, ash melting temperatures and fuels which show typical Ca-K-dominated ash chemistries (wood fuels and olive stones) and fuels with a Si-Ca-K-dominated ash chemistry (miscanthus and straw). Therefore, all project-relevant aspects of ash formation and fuel flexibility could be covered. During each test run comprehensive measurements, sampling and analyses have been performed to gain data regarding gaseous emissions,

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product gas compositions (especially regarding S and Cl-compounds) temperature profiles over the fuel bed, pressure losses and operation stability. Moreover, fuel ash and fly ash emission samples have been analysed. Based on these results and plant operation data, mass, energy and element balances over the plant have been calculated. The latter have been applied to investigate ash formation and K-release processes.

For all fuels, primary air humidification has been proven to be an effective measure for efficiently cooling the charcoal combustion zone of the gasifier. The high temperatures typically observed in this zone could be reduced to about 900 °C (a reduction of more than 200 °C). This has also been the reason why even when utilising fuels with rather low ash melting temperatures (e.g. miscanthus, agro-pellets) ash melting did not occur and only some sintered ash agglomerates could be found in the grate ash. Besides this effect, primary air humidification also reduces the risk of coking in the product gas ducts between the gasifier and the GCU.

Based on the results of this work, the new gasifier for the first testing plant has been constructed.

5.2 Gas cleaning unit design

Basic experimental lab-work, process modelling and chemical equilibrium calculations have been employed in order to develop the different reactors needed and to select appropriate sorbents for HCl and H_2S removal and catalysts for tar reforming. Table I shows the product gas composition above the fuel bed of the updraft gasifier for the fuel wood chips (with a moisture content of 30 wt% w.b.) according to gasifier simulation results which have been used as a basis for the design of the GCU (as well as the overall CHP plant).

Table I: Product gas composition (simulated) above the fuel bed of the updraft gasifier for the fuel wood chips (w.b. … wet basis)

Fuel		wood chips
Fuel moisture content	[wt% w.b.]	30
Product gas composition		
CO	[wt% w.b.]	13.4
CO_2	[wt% w.b.]	17.0
H_2	[wt% w.b.]	1.0
H_2O	[wt% w.b.]	25.3
CH_4	[wt% w.b.]	0.8
C_2H_4	[wt% w.b.]	0.7
Gravimetric tar	[wt% w.b.]	9.1
N_2	[wt% w.b.]	32.7

The main aim of the GCU is to provide a product gas stream with an HCl concentration lower than 5 ppm, an H_2S concentration lower than 1 ppm and a particulate matter (PM) concentration lower than 0.1 mg/Nm³. Moreover, the GCU is also expected to upgrade the tar species coming from the gasifier.

The GCU has been designed on the basis of the worst case scenario in terms of total contaminants to be removed, which is the utilisation of S and Cl-rich agro-pellets. The expected S and Cl-levels in the product gas have thereby been calculated from the test runs with the present PuroWIN gasifier mentioned in section 5.1.

The resulting design for the first GCU is based on state-of-the-art sorbents and catalysts; it is composed of four stages:

1. HCl removal using a K_2CO_3 based sorbent
2. H_2S removal using a Zn-based sorbent
3. Particulate filtration with a ceramic candle filter
4. Tar reforming using a Ni-based catalyst

5.3 SOFC system and SOFC stack design

A stationary SOFC system tailored to the gas composition of the cleaned and reformed product gas from the gasifier has been developed. Therefore, the stack module itself has been modified with respect to the product gas properties (new MK352 stack module of Fraunhofer IKTS - see Fig. 3) and the balance of plant components have been newly developed for integration into the whole plant concept.

Calculated gas compositions were used to estimate the SOFC stack module performance based on calculations performed by Fraunhofer IKTS. The performance of the stack module with different gas compositions was calculated with an existing prognosis tool from Fraunhofer IKTS and validated by testing different gas compositions under laboratory conditions [11]. Fig. 3 shows the design of the stack module and results from validation tests with simulated product gas. These tests have revealed that the envisaged power range of 6 kW_{el} can be achieved with the product gas from the gasifier at the target electric efficiency.

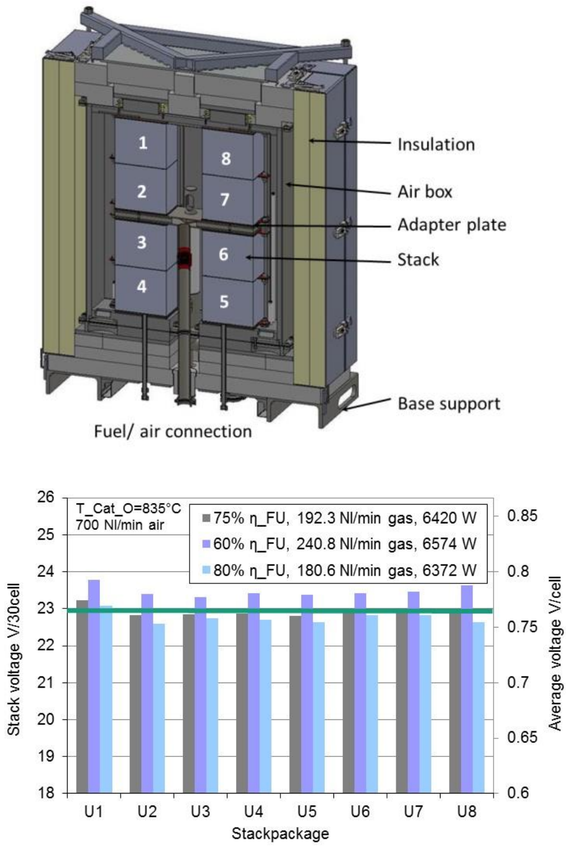

Figure 3: Results from performance tests with the stack module with simulated product gas at 35 A
Explanations: η_FU … fuel utilisation, T_Cat_O … cathode outlet temperature (reference); U1 to U8: single 30 cell stack voltage; green line: performance map of single 30 cell stack at η_{FU}=75%

One of the main improvements of the SOFC system compared to previous generations is the ability to operate at underpressure conditions. This was required to enable the coupling with the biomass gasifier, which runs at almost atmospheric pressure. Therefore, the cathode air blower, typically positioned at the air inlet of the SOFC system, was relocated to the exhaust gas outlet to operate as a suction blower. This leads to less deformation of the high temperature SOFC air box and therefore less internal air by-pass losses, which ultimately improves the stack module performance. A further positive synergy is the use of hot exhaust gas from the gasifier burner to heat the SOFC during start-up, eliminating the need for an additional start-up burner, reducing system complexity and control requirements. A further advantage has been realized by increasing the tar steam reforming temperature up to 750 °C, eliminating the need for an anode gas pre-heater.

A significant design constraint was to keep the overall system pressure drop low to minimise the required suction blower power. The GCU and the SOFC system are the two largest sources of pressure losses, thus considerable attention was paid to minimising pressure losses through these units. Improvements on the SOFC side could be realized by reducing the number of components and a significantly lower pressure drop of the SOFC balance of plant components (e.g. air pre-heater, afterburner). The process design also considers the need to eliminate any mass flow controls at elevated temperatures >400 °C. A sketch of the SOFC system is presented in Fig. 4.

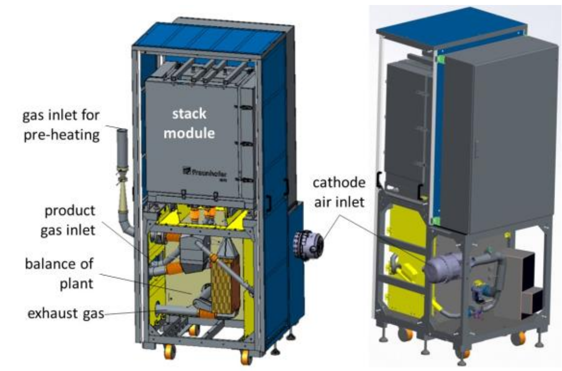

Figure 4: Sketch of the SOFC system

The plant uses one main suction blower, which draws fresh air as well as reformed product gas through the SOFC system. The fresh air is pre-heated before entering the SOFC cathode. Additionally, a bypass air intake is connected directly to the afterburner to prevent overheating. In parallel, the product gas side stream is drawn from the gasifier. The product gas side stream is firstly conditioned in the GCU, before entering the SOFC anode for further electrochemical conversion and generation of electrical power. The anode off gas is mixed together with the cathode off gas in the afterburner to produce heat (hot exhaust gas) for the air pre-heating and the pre-heating of the gas cleaning unit. The hot exhaust gas is then collected and connected to the heat recovery unit, which is integrated in the gasifier.

5.4 First testing plant

At the end of the first project period, the assembly of the first generation testing plant took place. It consists of the following main components:

- 50 kW_{th} fixed-bed gasifier including a 2-stage gas burner and a hot water boiler
- Fully integrated GCU
- SOFC system (6 kW_{el})
- Heat recovery from the SOFC exhaust gas directly integrated in the hot water boiler
- Piping with adequate flow control devices between the main components
- Overall plant control and process data acquisition system

The whole system is highly integrated in order to utilise the heat remaining in the exhaust gas of the SOFC system for GCU heating and for hot water production. Windhager provided the gasifier, HyGear the gas cleaning unit and AVL the SOFC system including the respective piping between the single components.

Besides the main plant components, the overall process control system has also been developed and programmed with special attention to the communication interfaces between the single plant units. The control system has been designed and optimized, especially with regard to start-up and shutdown procedures, safety aspects and failure management. Moreover, a comprehensive process data acquisition system has been installed in order to have all relevant plant operation data from the test runs available for evaluations.

Fig. 5 shows a picture of the assembled first testing plant. All sub-components and the whole plant have been commissioned and pre-tested in the beginning of 2017.

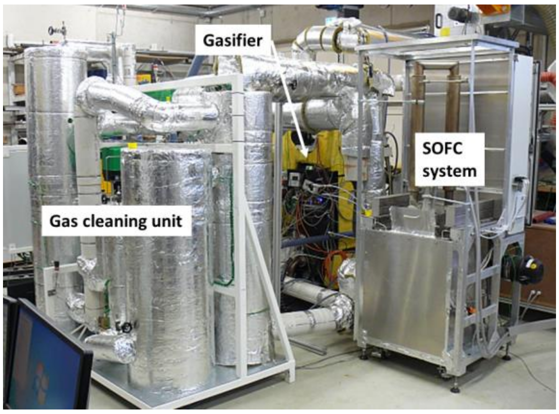

Figure 5: Picture of the testing plant located at BIOS
Explanations: instead of the stack module short cut tubes are mounted for the first test runs

6 SUMMARY AND CONCLUSIONS

During the first period of the 4-year project, the work has focused on the development of the single plant components and the design, manufacturing and assembly of a first generation testing plant of the new technology. As an initial task, the operating conditions for the single plant components and the interfaces between them have been defined. Moreover, a detailed plant concept has been worked out. To achieve a high number of annual full load operation hours of the SOFC also at varying heat demands, only a portion of the product gas from the gasifier is led through the GCU to the SOFC-system while the remaining product gas is combusted in a burner. This strategy enables both constant full-load

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electricity production and flexible heat production. Based on this approach, the work regarding the single plant components has been initiated.

Regarding the gasifier, the work has started with the development of an integrated product gas extraction and heating unit through which the product gas is led towards the GCU. Moreover, the gasifier has been further developed in order to allow the utilisation of biomass fuels with low ash melting temperatures (such as agro-pellets), thus achieving high fuel flexibility. This has been supported by experimental studies on an adapted model of the gasifier and comprehensive CFD (Computational Fluid Dynamics) simulations. Based on the results of this work, the new gasifier for the first testing plant has been constructed.

With respect to the GCU, experimental work, process modelling and chemical equilibrium calculations have been employed in order to develop the different reactors needed and to select appropriate sorbents for HCl and H_2S removal as well as catalysts for tar reforming. These tasks have been completed within the first project period and a first generation GCU has been designed, manufactured and assembled.

Furthermore, a stationary SOFC system tailored to the gas composition of the cleaned and reformed product gas from the gasifier has been developed. Therefore, the stack module itself has been modified with respect to the product gas properties and the balance of plant components have been newly developed for integration into the whole plant concept. First validation tests with the stack module have revealed that the envisaged power (6 kW_{el} for the first testing plant) can be achieved with product gas from the gasifier at the targeted electric efficiency.

Besides R&D on the main plant components also the overall control system has been developed and implemented. At the end of 2016, the assembly of the first generation testing plant took place. Test runs with this plant have started and are ongoing.

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8 ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 641229

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