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Development of a novel highly efficient energy supply system for energy autonomous multi-family buildings based on biomass gasification coupled with an SOFC and a PV system

Final international project workshop

Online event, 25 March 2026, 14:00-16:30 CET

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Agenda

Time	Topic	Speaker
14:00	Welcome and introductory remarks	Thomas Götz, Wuppertal Institute
14:05	Project overview	Thomas Brunner, BIOS
14:20	Gasification system and tar reforming (BCM)	Christoph Mandl, BIOS
14:35	HCl and H_2S removal	Alexandru Morosanu, Hysytech
14:45	SOFC stack fundamentals	Stefan Megel, IKTS
14:55	SOFC system and process control	Luc Conti, Inergio
15:05	Test run results (BCM)	Christoph Mandl, BIOS
15:20	Test run results (SOFC module) – Part A	Anna Seidl, IKTS
15:27	Test run results (SOFC module) – Part B	Luc Conti, Inergio
15:35	Application of the Micro-Bio-CHP concept in different building types	Klaus Supancic, BIOS
15:50	Environmental and overall impact assessment	Birte Schnurr, Wuppertal Institute
16:05	Q&A session	All
16:25	Closing remarks	Thomas Brunner, BIOS

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Development of a novel highly efficient energy supply system
for energy autonomous multi-family buildings
based on biomass gasification coupled with an SOFC and a PV system

Micro-Bio-CHP
Project overview

Prepared by: Thomas Brunner, Ingwald Obernberger

BIOENERGIESYSTEME GmbH

Final public project workshop

Online

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Project overview

- **Project key data**
- **Overall objectives and concept**
- **The Micro-Bio-CHP approach**
- **Detailed objectives of the project**
- **Project partners and their involvement**

Project key data

Project title:	Development of a novel highly efficient energy supply system for energy autonomous multi-family buildings based on biomass gasification coupled with an SOFC and a PV system
Acronym:	Micro-Bio-CHP
Project no.:	101083409 (EU Horizon Europe)
Duration:	**42 months** (October 2022 – March 2026)

Project consortium:

BIOENERGIESYSTEME GMBH

Catator

Fraunhofer IKTS

HYSYTECH FILLING THE GAP

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Wuppertal Institut

Overall objectives and concept

- **Development of a RES-based concept for heat and electricity supply to achieve an almost energy autonomous multi-family building regarding**
  - space heating
  - domestic hot water supply
  - electricity consumption
  - electro-mobility

- **This shall be achieved by integrating**
  - a novel and highly efficient **biomass micro-CHP technology** based on an **updraft gasifier**,
  - a novel **gas cleaning system**
  - a **solid oxide fuel cell** (SOFC)
  - a state-of-the-art **PV system**
  - appropriate innovative **energy storage** solutions

- **This system shall not only satisfy the energy demands of the building but also distinguish itself by virtually zero emissions of CO, OGC and particulate matter and clearly reduced NO_x emissions compared to other biomass-based CHP technologies**

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The challenge - fully renewable energy consumption of a building under consideration of annual fluctuation in energy demand

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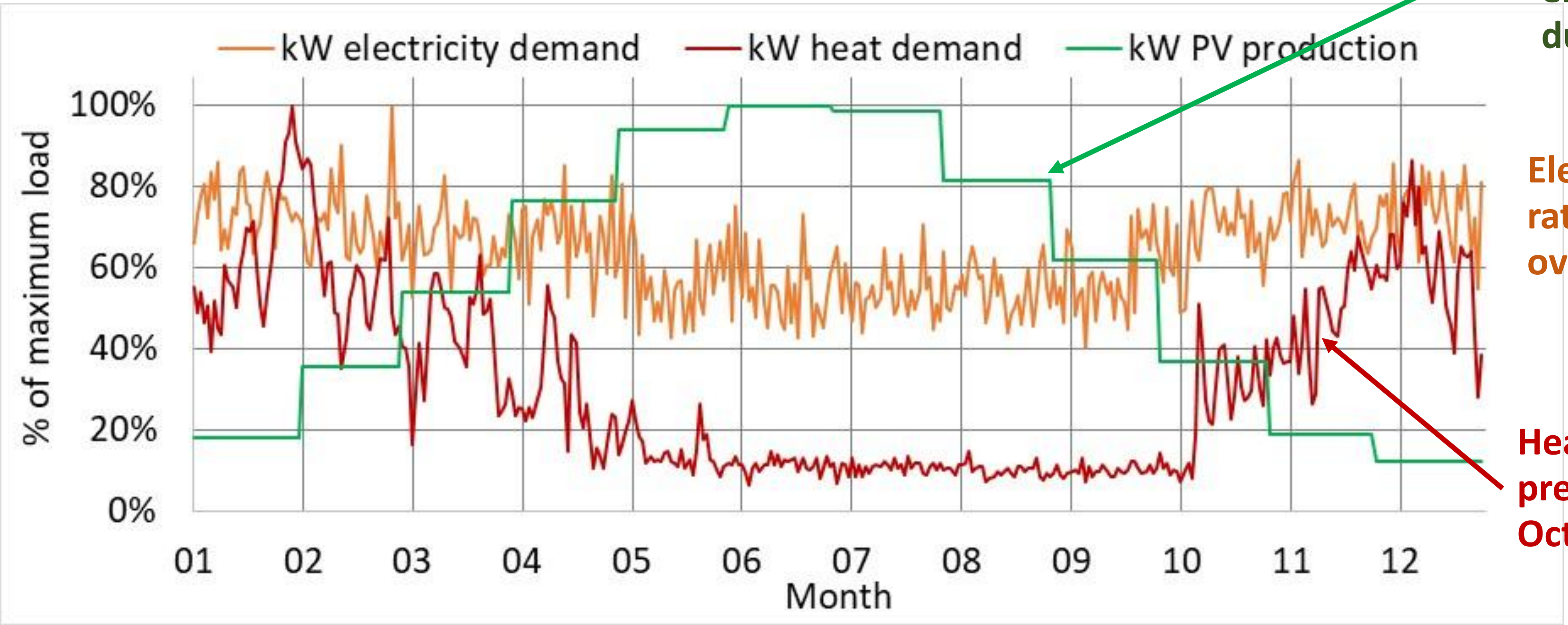
Heat and electricity demand of a typical multi-family house as well as PV electricity production over one year



PV production: highly efficient during summer but low energy production during winter

Electricity demand: rather low fluctuations over the year

Heat demand: predominantly between October and April

Explanations: **Data from a long-term energy monitoring** of a **multi-family house** with 9 apartments, 19 occupants and an average apartment size of 65 m², located in the alpine region (i.e.: AT)

Building type: new house fulfilling the Austrian building standards for low energy buildings; spec. heat demand: 42 kWh/m²/year

Energy demand:

- Annual heat demand (space heating and DHW supply): 38,700 kWh
- Annual electricity demand: 23,200 kWh

The innovative Micro-Bio-CHP approach

- **Micro-Bio-CHP system based on pellet gasification and an SOFC, which**
  - maximises electric efficiency and annual full load operation hours of electricity production from biomass
  - provides flexibility regarding heat production.
- **During the period between May and September**
  - CHP operation is not efficient and meaningful due to the low heat demand.
  - Electricity production of a **PV system** shows an opposite yearly trend with low production during wintertime and maximum production during the summer months.
- **Consequently, a combination of an appropriately designed biomass CHP system and a PV system seems to be very suitable to cover the energy demand of a building over the whole year.**
- **From this combination also an electricity surplus can be expected which can be used to provide electricity for e-mobility of the occupants.**

Implementation of the Micro-Bio-CHP approach (I)

- A fixed-bed updraft gasifier fueled with wood pellets forms the basis for biomass conversion.
- A partial flow of the product gas is extracted above the fuel bed, and after gas cleaning is led to the SOFC system for highly efficient electricity production (target: η_{el} of 44% related to the NCV of the product gas).
- Gas cleaning of the extracted product gas flow involves
  - High-temperature thermal and catalytic tar reforming
  - High-temperature particle filtration
  - H_2S and HCl removal
- The remaining product gas is combusted in a low-emission product gas burner located directly downstream the fuel bed.
- The flue gas from the gas burner as well as the off-gases of the SOFC system are directed to a heat recovery unit (boiler and a flue gas condenser).

Implementation of the Micro-Bio-CHP approach (II)

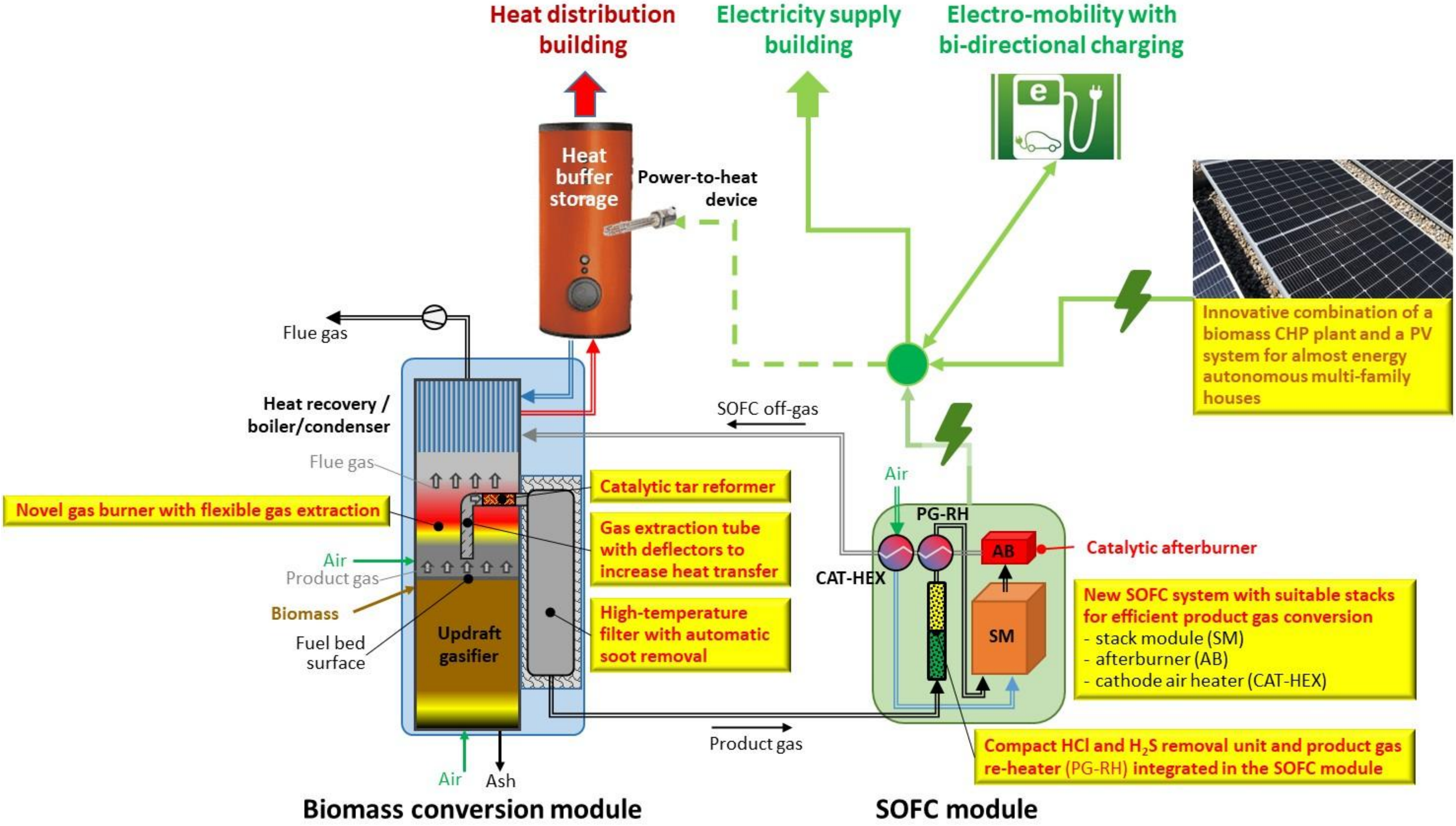
- **The product gas flow extracted to the SOFC shall be in a range, which allows for a continuous high load SOFC operation also during transitional seasons with maximum electricity production at minimum product gas burner load (i.e. heat production).**

- **During the cold seasons (rising heat demand)**
  - the fuel power is increased
  - the product gas flow to the SOFC remains at its range for maximum SOFC load
  - the gas flow over the burner is increased thus supplying the heat recovery section with more energy

- **Combination two functionalities within one system**
  - a **base load CHP system** providing electricity and off-heat over the whole operation period
  - an **additional product gas burner system** covering increased heat demand and peak load phases

- **The configuration also allows for a "heat-only" mode which supplies the building with heat even if the SOFC module is not in operation.**

Scheme of the whole Micro-Bio-CHP system



Innovative combination of a biomass CHP plant and a PV system for almost energy autonomous multi-family houses

Novel gas burner with flexible gas extraction

Catalytic tar reformer

Gas extraction tube with deflectors to increase heat transfer

High-temperature filter with automatic soot removal

Catalytic afterburner

New SOFC system with suitable stacks for efficient product gas conversion
- stack module (SM)
- afterburner (AB)
- cathode air heater (CAT-HEX)

Compact HCl and H_2S removal unit and product gas re-heater (PG-RH) integrated in the SOFC module

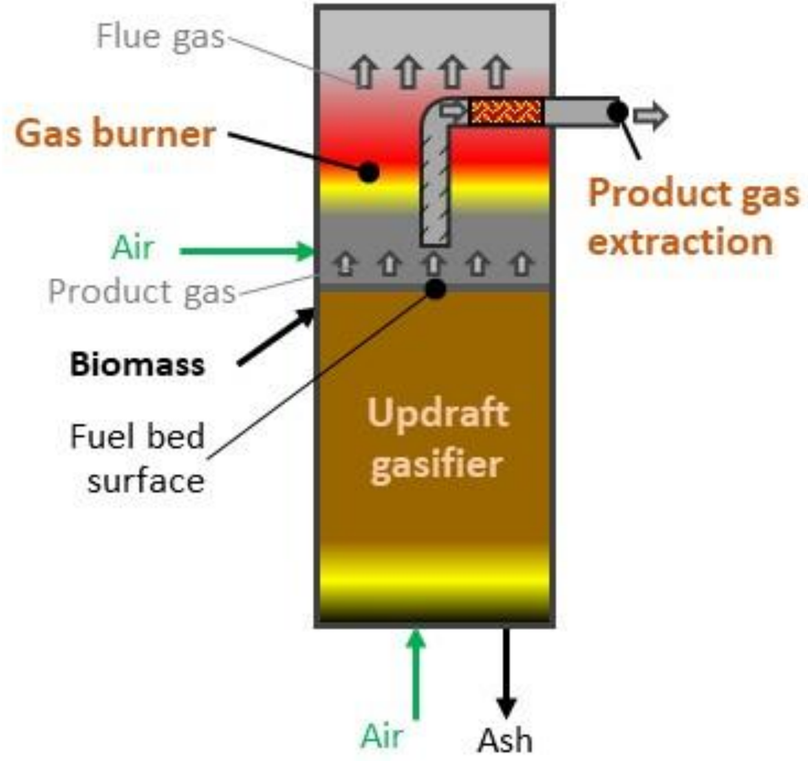
Detailed objectives to develop the overall CHP technology (I)

Detailed objectives regarding the development of the Biomass Conversion Module (BCM)

- Development of a **biomass updraft gasifier** for a **capacity range of 10-18 kW** (fuel power related to the NCV of the fuel) operated with **pellets (A1-quality) as fuel.**

- Development of a **novel product gas burner** directly coupled to the gasifier which fully oxidises a part of the product gas from the gasifier at **almost zero CO, OGC and PM emissions** at full and minimum load and additionally supplies energy for heating up product gas which is extracted for electricity production in the SOFC.

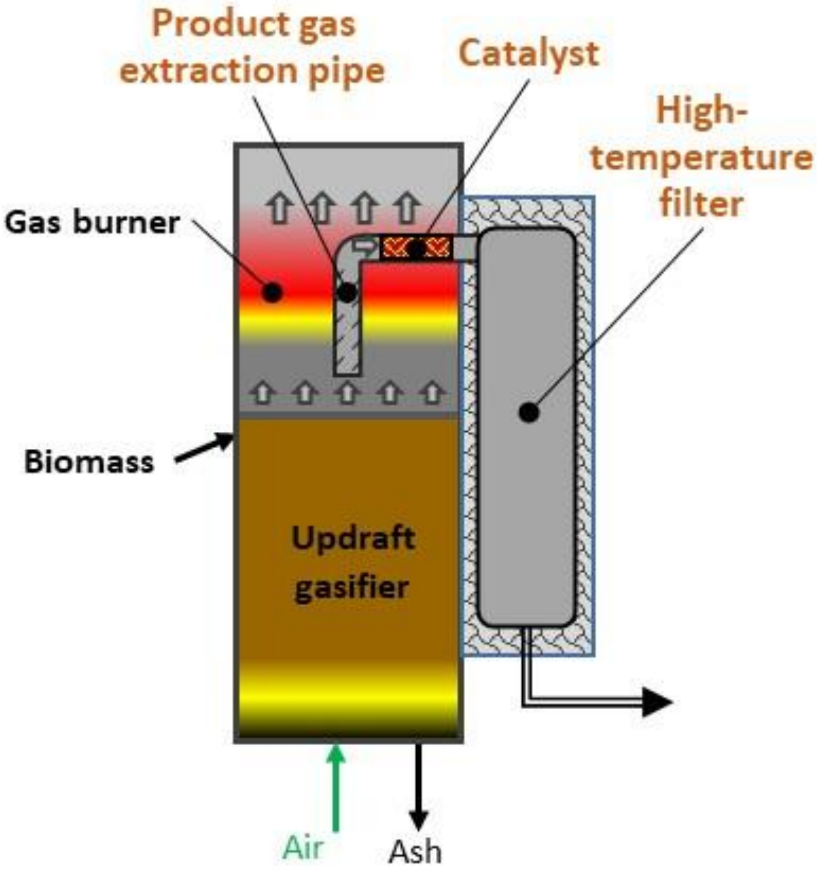
- **The share of the extracted product gas** on the whole gas stream from the gasifier **shall be flexible**, amounting between zero (heat only operation) and about 50% at minimum thermal load operation.



Detailed objectives to develop the overall CHP technology (II)

Detailed objectives regarding the development of the BCM (continued)

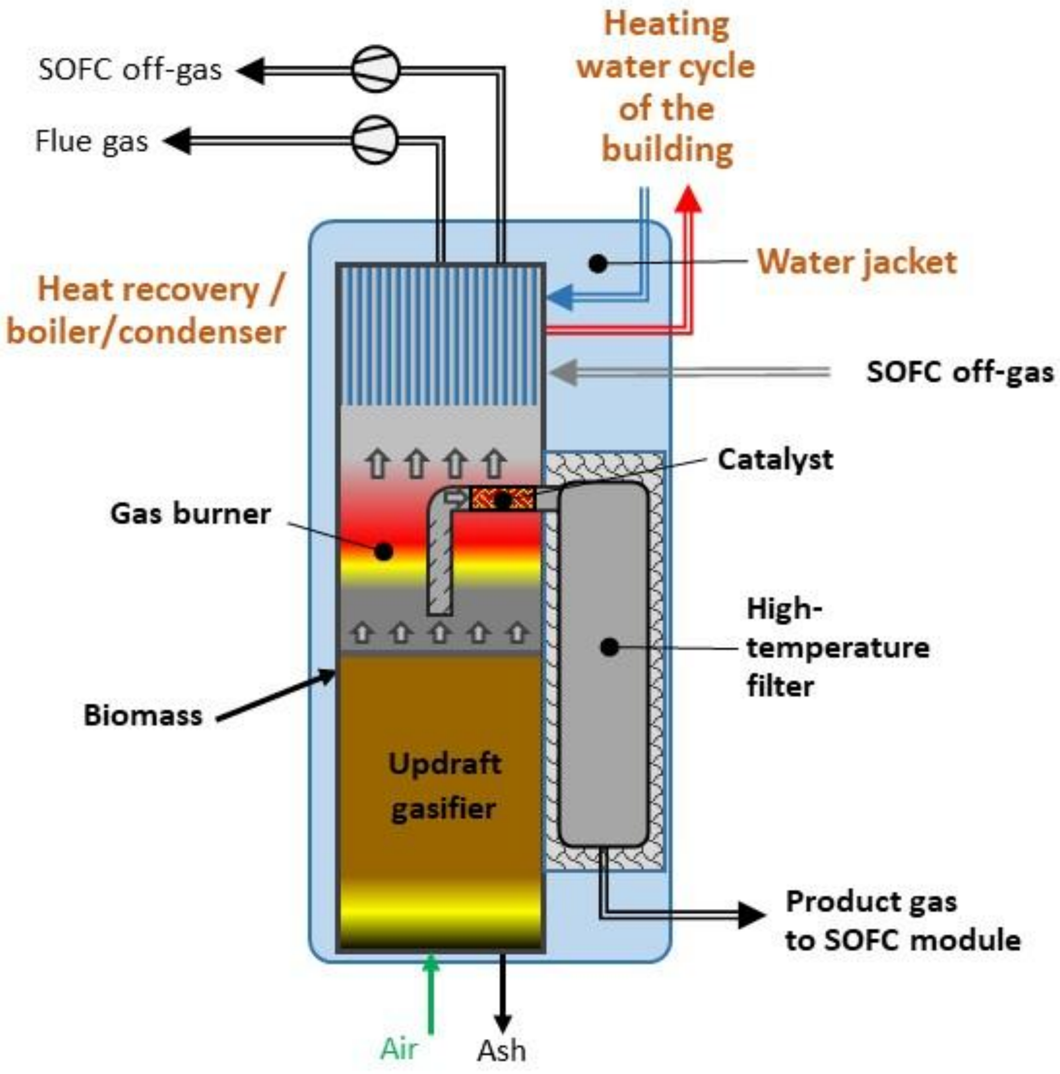
- Development of a **special product gas extraction pipe**
  - Extract a part of the product from above the fuel bed
  - Heat it on its way through the product gas burner to more than 900°C
- Development of a **suitable tar reforming catalyst** for application in the product gas extraction pipe at 900°C.
- Development of a **hot gas filter for particle removal to levels below 1 mg/Nm³**, placed downstream the product gas extraction tube.



Detailed objectives to develop the overall CHP technology (III)

Detailed objectives regarding the development of the BCM (continued)

- **Design of a heat recovery system** consisting of
  - a **water jacket** around the gasifier and the product gas burner,
- **Design of a boiler and a condenser unit** to recover the off-heat of the product gas burner and the SOFC system efficiently.
- **An overall plant efficiency of more than 90%** (related to the NCV of the biomass fuel supplied) shall thereby be achieved.



Detailed objectives to develop the overall CHP technology (IV)

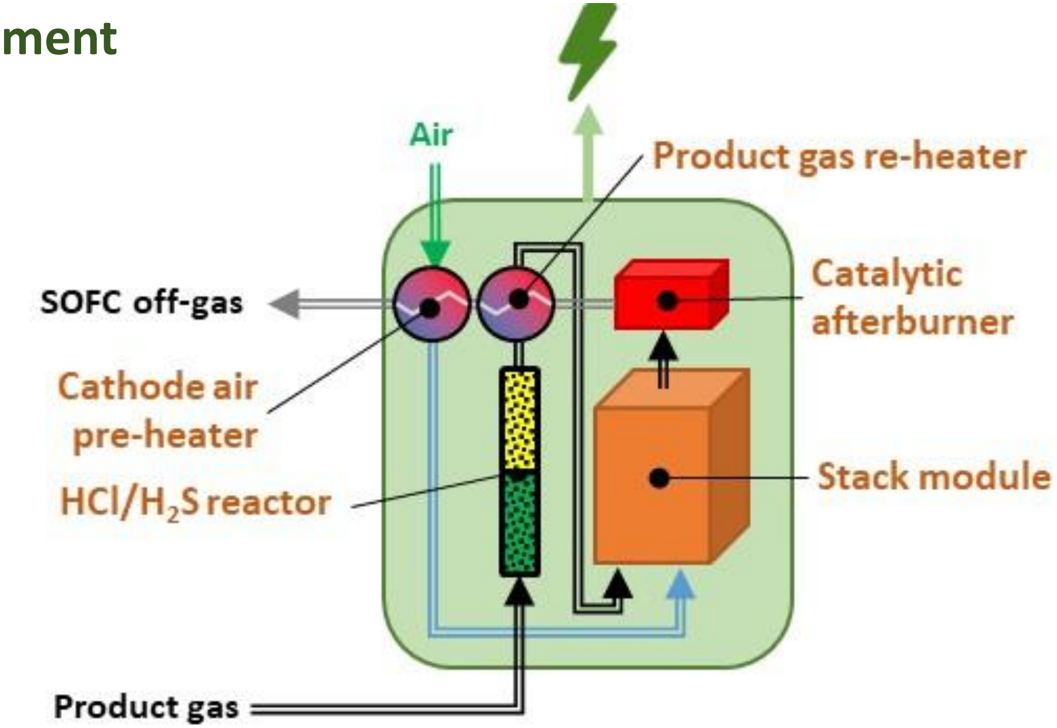
Detailed objectives regarding the development of the SOFC-Module

- Development and design of a **compact and easily maintainable sorption reactor for HCl and H_2S removal**. Target values: <5 ppm HCl and <1 ppm H_2S at SOFC inlet
- **Further development and optimisation of SOFC stacks** for operation with product gas from biomass updraft gasification and of the **SOFC process control** to
    - identify parameters responsible for **stack degradation**
    - **eliminate** the **risks** for rapid degradation
    - achieve an as **homogeneous** as possible **gas flow** through the stacks
    - achieve a **well-controlled and save operation** avoiding scenarios which may enhance stack degradation
    - achieve an **enhanced life-time** of the stacks
    - **achieve high fuel utilisation of about 75%** and high electric efficiencies on stack level of **more than 44%** (related to the NCV of the product gas entering the stack)

Detailed objectives to develop the overall CHP technology (V)

Detailed objectives regarding the development of the SOFC-Module (continued)

- **Integration of all relevant components in a compact SOFC module** consisting of
  - HCl/H_2S sorption reactor
  - stack unit
  - cathode air pre-heater
  - product gas re-heater
  - catalytic afterburner
  - process control
- **Implementation of an appropriate process control able to communicate with the process control of the BCM via a master controller.**



Detailed objectives to develop the overall CHP technology (VI)

Detailed objectives regarding the overall system

- **Development of an overall process control** for the biomass micro-CHP system.
- Construction of a **testing plant of the CHP system.**
- **Performance of testing campaigns** at this testing plant including accompanying measurements and analyses as well as stepwise optimisation of the testing plant.
- Definition of a **final system design** including design **studies for larger multi-family houses as well as of the system with the lowest possible nominal capacity.**
- Performance of **accompanying risk and safety analyses**, **environmental and social impact assessments** as well **as techno-economic analyses** to support the development of a technically optimised, environmentally capable and economically sound system.

Project partners I

- **BIOS BIOENERGIESYSTEME GmbH, AT**
  - Project coordinator
  - Overall system design
  - Development of the BCM
  - Engineering, CFD-simulations
  - Performance of test runs, measurements and analyses
  - Techno-economic assessments
- **Catator AB, SE**
  - Tar reforming catalyst development
  - Development of the catalytic afterburner and the high-temperature heat exchangers of the SOFC module
- **Fraunhofer IKTS, DE**
  - Stack and stack-module development
  - Stack module testing and assessment

Project partners II

- **HYSYTECH SRL, IT**
  - H_2S and HCl removal reactor development and manufacturing
- **INERGIO Technologies SA, CH**
  - SOFC-module development (balance-of-plant)
  - SOFC process control development
  - Performance of test runs
- **Wuppertal Institut für Klima, Umwelt, Energie gGmbH, DE**
  - Impact assessment
  - Overall environmental assessment
  - Coordination of dissemination related issues

Thank you for your attention

https://microbiochp-project.eu

BIOS
BIOENERGIESYSTEME GmbH

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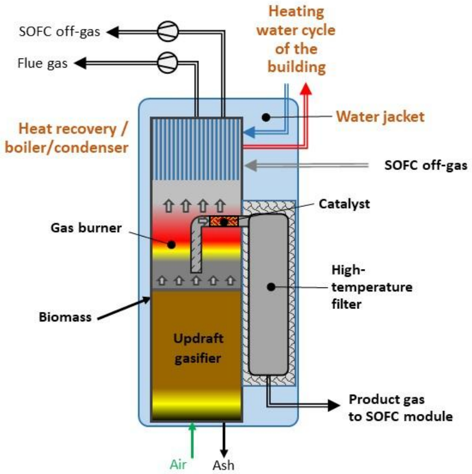
Gasification system and tar reforming
(Biomass conversion module)



Prepared by: Christoph Mandl, Ingwald Obernberger, Thomas Brunner

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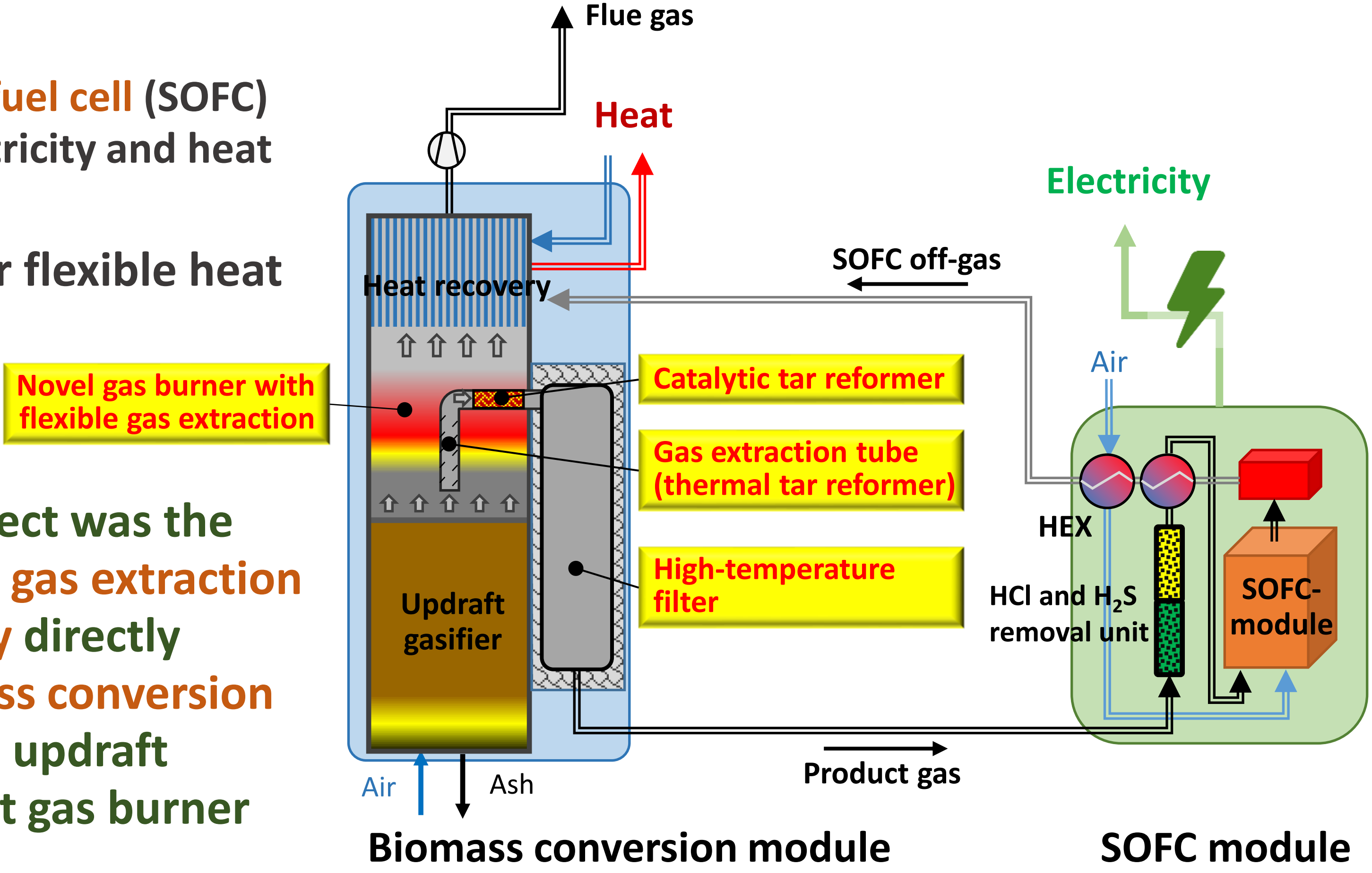
Content

- The Micro-Bio-CHP approach
- Technological approach
- Development of the biomass conversion module
- Design of the BCM
- Conclusions

The Micro-Bio-CHP technology

- Novel biomass CHP system based on updraft gasification with dual product gas utilisation:
  - As fuel in a solid oxide fuel cell (SOFC) for highly efficient electricity and heat generation
  - Direct combustion for flexible heat generation
- One key aim of the project was the development of a novel gas extraction and cleaning technology directly integrated in the biomass conversion module consisting of an updraft gasifier with subsequent gas burner
- Efficient heat recovery from flue gas and SOFC off-gas

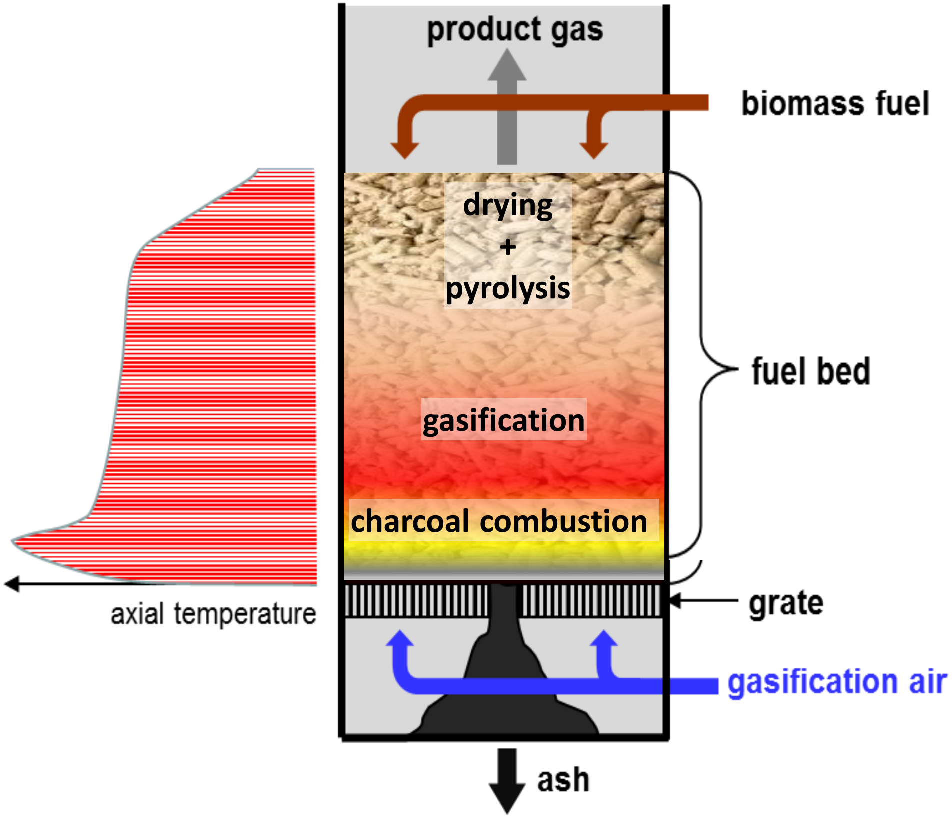


Technological approach

- Development of a concept for the biomass conversion module (BCM)
- Conceptual design of the gasifier
- CFD aided development of the product gas burner and its optimisation
- CFD aided integration of the gas extraction unit with thermal and catalytic tar reformer in the gas burner
- Integration of the single components in the biomass conversion module and design of a 15 kW testing plant

Biomass conversion module – Conceptual design of the gasifier

- The **fixed-bed updraft gasifier** forms the basis for biomass conversion and has been adapted to meet the requirements for Micro-Bio-CHP



- Fuel is fed from above
- Extreme air staging concept: primary air passes upwards through the fuel bed with a very low air ratio (λ ~ 0.2 - 0.3)
- A high fuel bed results (10 times higher fuel bed compared to conventional biomass boilers)
- Zones with different conversion processes
  ➔ pronounced temperature profile
  - Fuel drying and pyrolysis
  - Charcoal gasification
  - Charcoal combustion (~1,000°C)

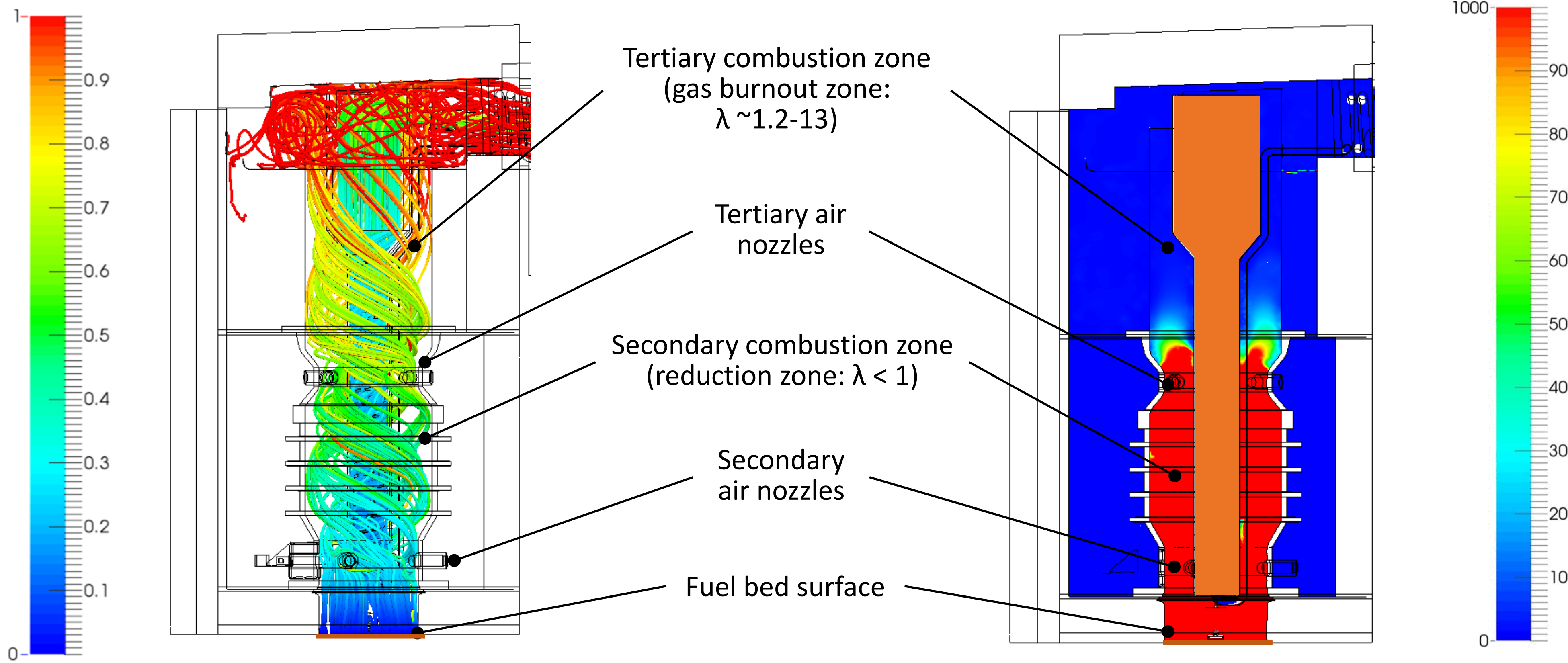
→ The fuel bed acts as a filter

→ Almost dust free product gas due to very low contents of released aerosol forming elements (mainly K) and low product gas velocities

Biomass conversion module – CFD based development of the gas burner

Streamlines of the flue gas along the gas burner

CO concentrations along the gas burner



Tertiary combustion zone (gas burnout zone: λ ~1.2-13)

Tertiary air nozzles

Secondary combustion zone (reduction zone: λ < 1)

Secondary air nozzles

Fuel bed surface

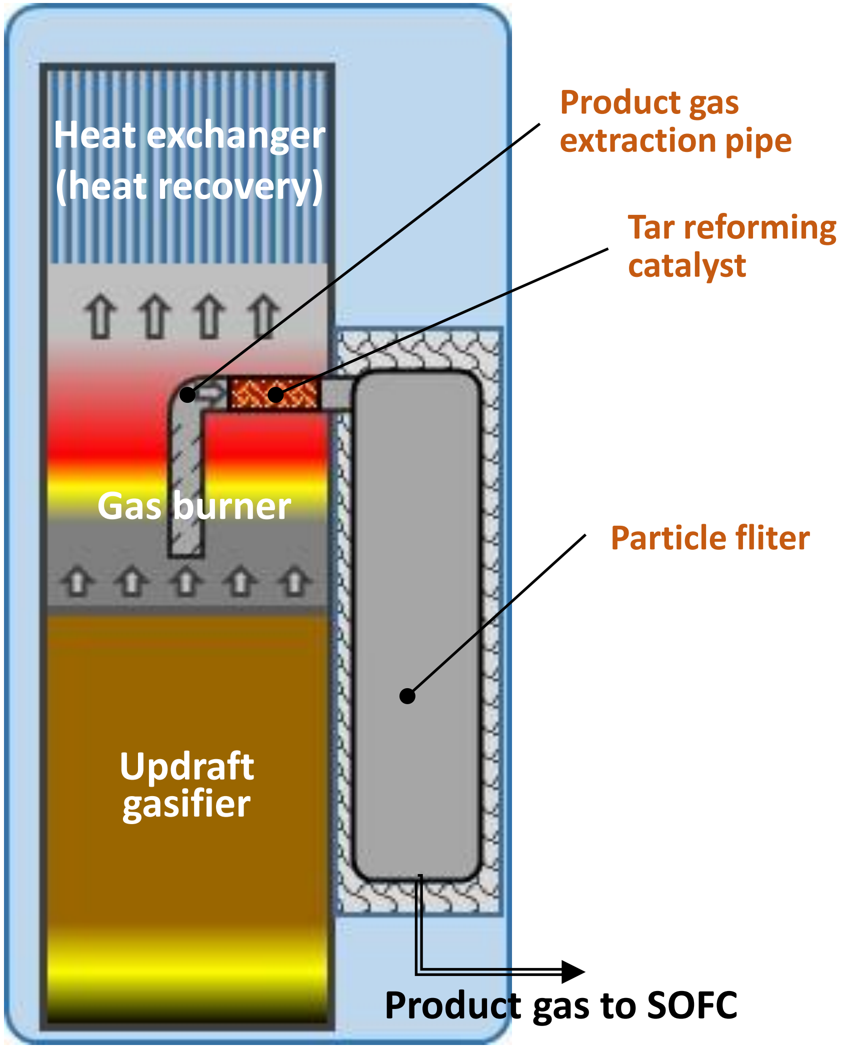
→ **optimised air-staging (Low NO_x) and low excess air (improved efficiency)**

→ **complete flue gas burnout by improved mixing (optimised secondary and tertiary air nozzles and burner geometries)**

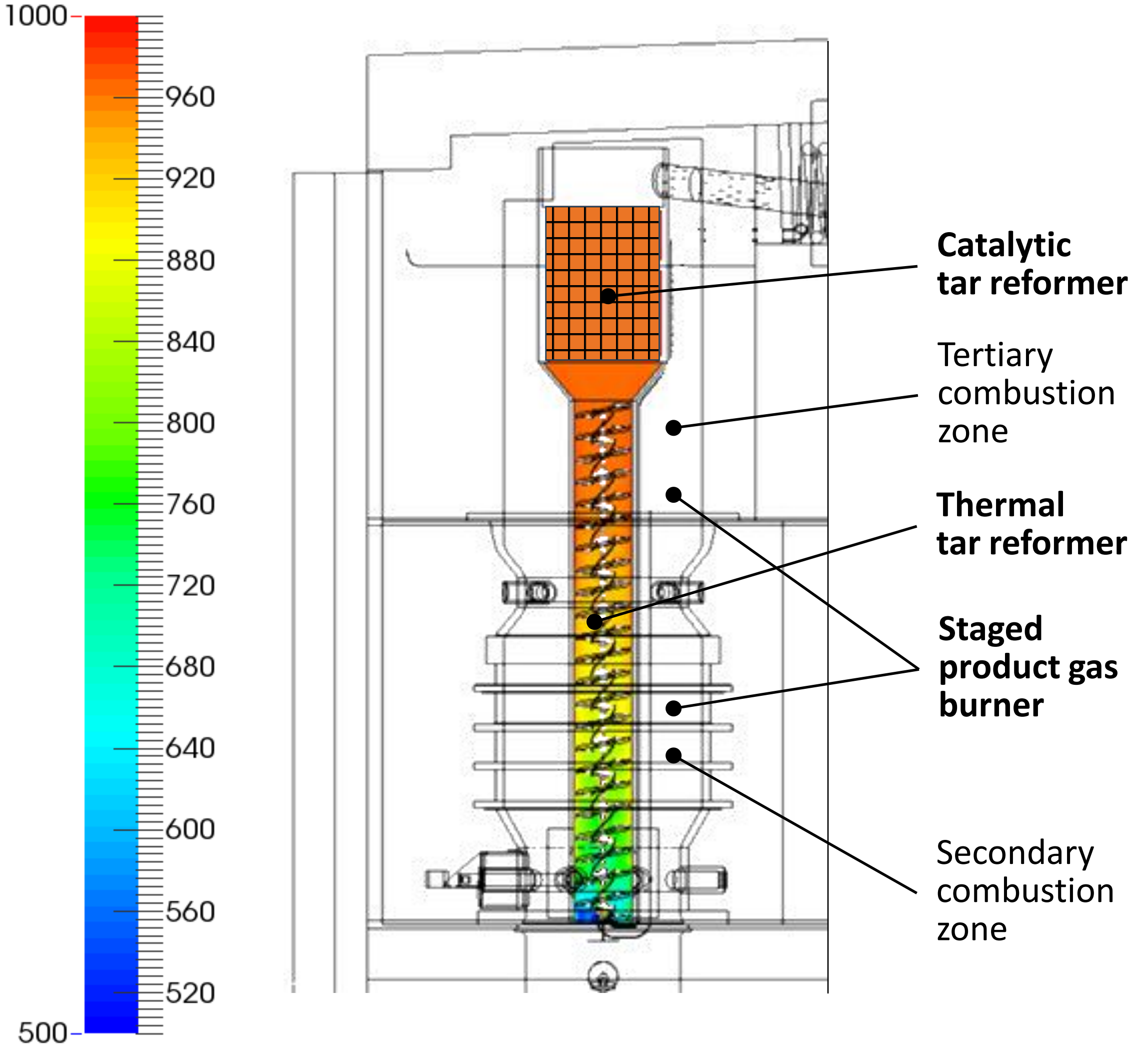
Explanations: flue gas flow coloured by residence time [s]; right … Iso-surfaces of CO concentrations [ppmV]; orange: gas extraction and tar reforming section

Biomass conversion module – Gas cleaning concept

- **Product gas extraction pipe**
  - extracts a part of the product from above the fuel bed
  - heats it on its way through the product gas burner to more than 900°C
- **Tar reforming catalyst**
  - integrated in the product gas extraction pipe
  - operation at ~900°C
- **High temperature particle filter**
  - for particle removal to levels below 1 mg/Nm³
  - placed downstream the product gas extraction tube



Biomass conversion module – CFD aided integration of the gas extraction unit



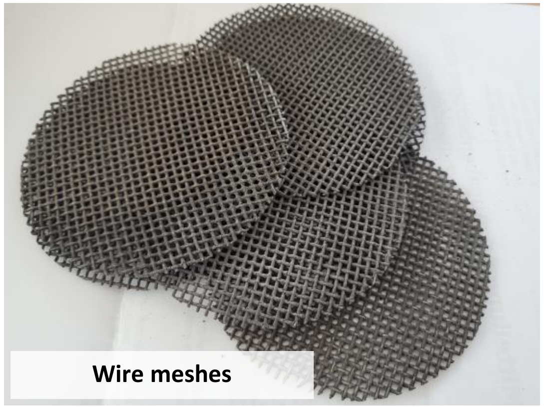
- → detailed gas phase reaction mechanism (detailed POLIMI_BIO [1]) applied for CFD simulations to evaluate the hydrocarbon conversion
- → sufficient energy transferred from the flue gas to heat the extracted product gas in the extraction tube up to 900-950 C at inlet to the catalytic tar reformer
- → basis for an efficient tar reduction by thermal reforming given

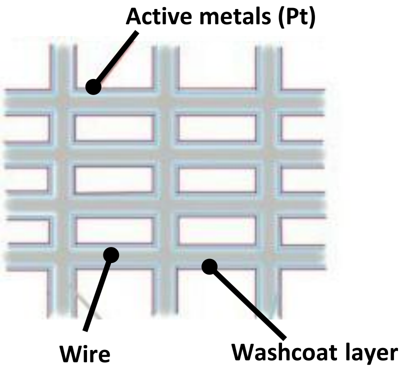
<u>Explanations</u>: gas temperature in °C; [1] … E. Ranzi, M. Corbetta, F. Manenti und S. Pierucci, „Kinetic modeling of the thermal degradation and combustion of biomass,“ Chemical Engineering Science, Bd. 110, pp. 2-12, May 2014

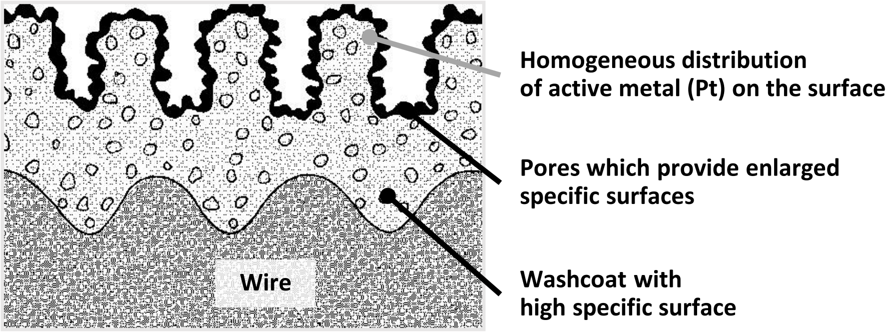
Biomass conversion module – Development of the tar reforming catalyst

- The tar reforming catalyst has been developed and manufactured by project partner CATATOR.

Wire-mesh based tar reforming catalyst



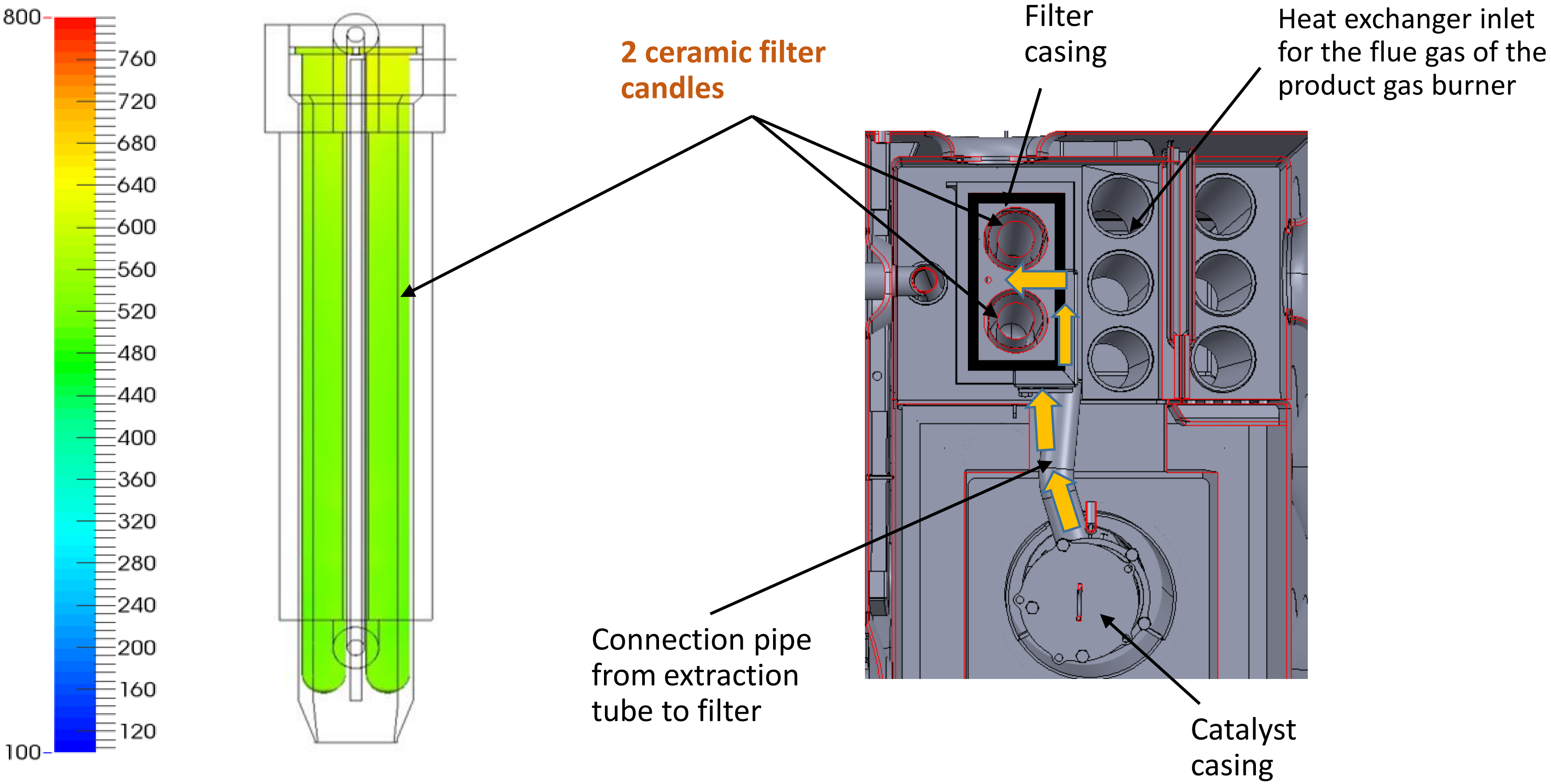




→ **Suitable tar reforming catalysts** have been evaluated at a lab-scale reactor at BIOS with a synthetic gas mixture close to the one expected according to CFD simulations at different temperatures between 700 and 1,000°C and at different gas loads

→ With the **finally selected Pt-based catalyst** a benzene (model tar compound) reduction rate of more than 99% at temperatures of >900°C could be achieved

Biomass conversion module – Development of the high temperature particle filter



2 ceramic filter candles

Filter casing

Heat exchanger inlet for the flue gas of the product gas burner

Connection pipe from extraction tube to filter

Catalyst casing

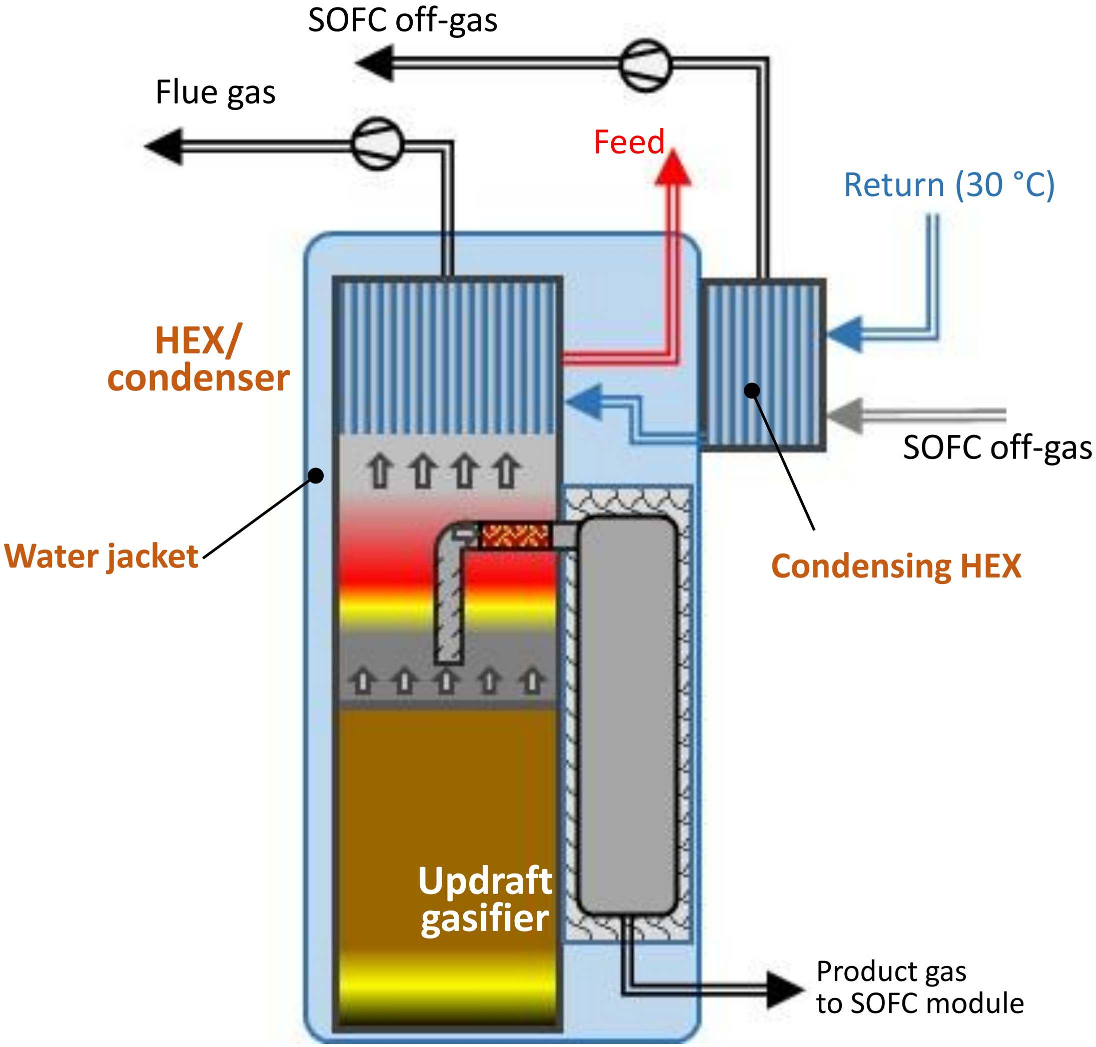
→ direct integration of the particle filter into the boiler casing

→ uniform temperature distribution over filter important for lifetime of the filter candles and efficient soot oxidation during backburning (cleaning)

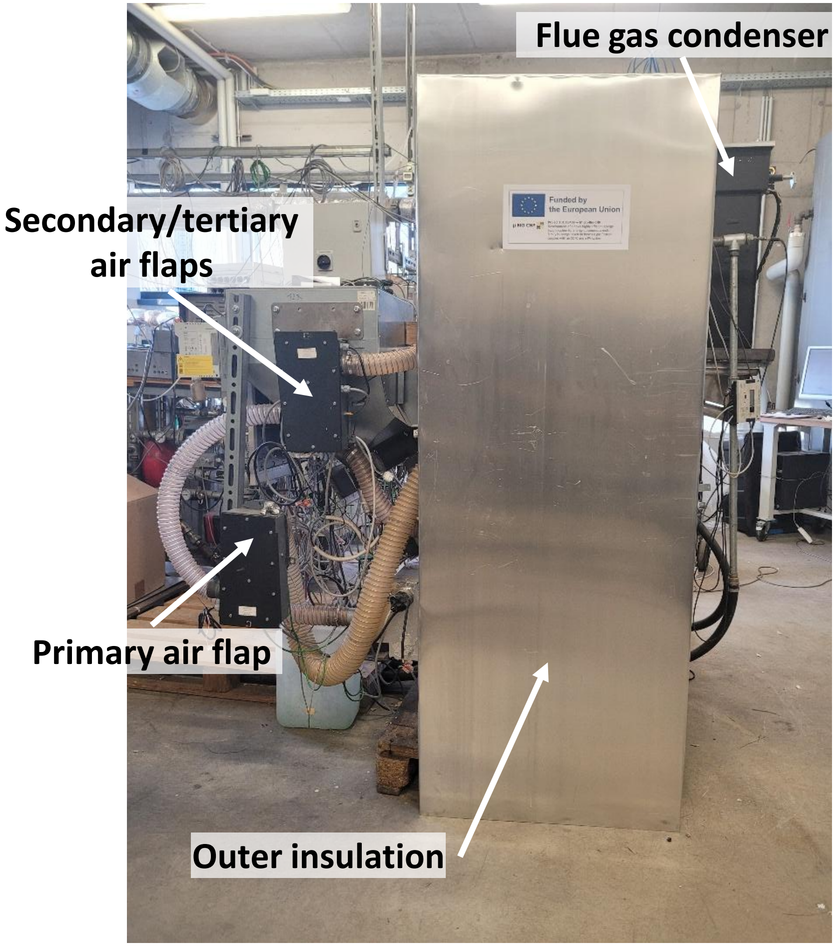
Explanations: gas temperature in °C (results of CFD simulations)

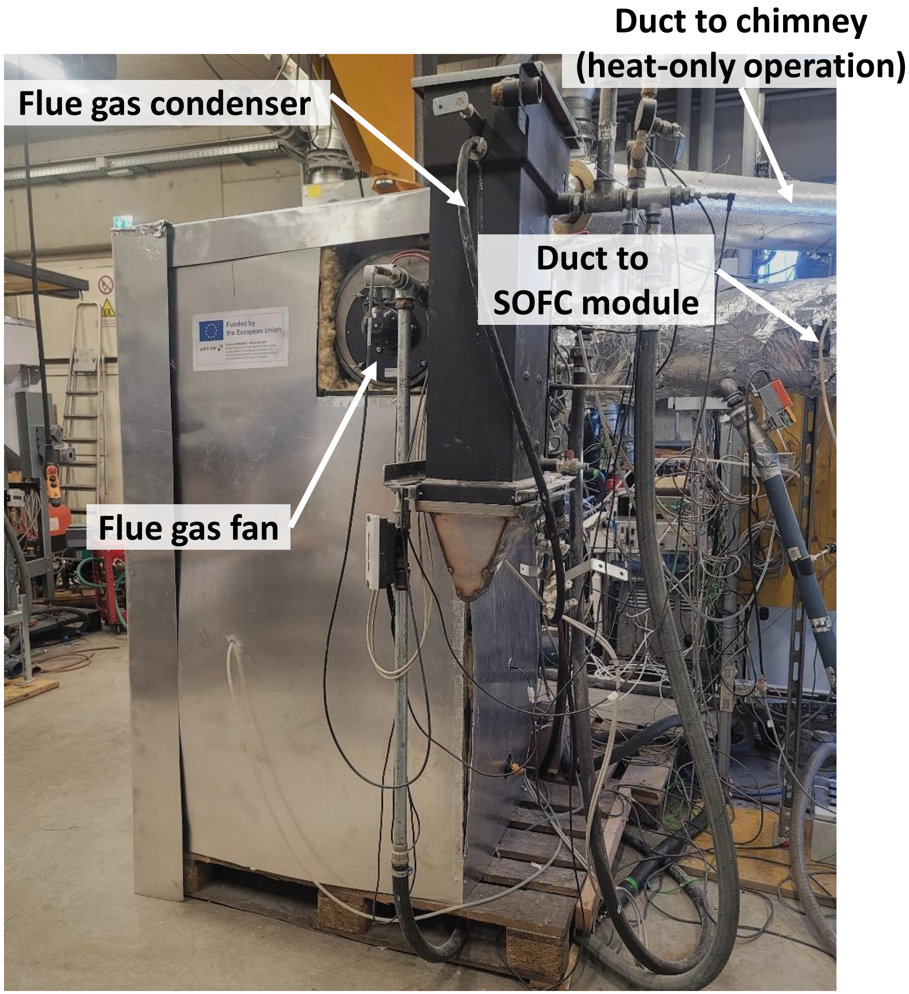
Development of the biomass conversion module – Heat recovery system

- The **heat recovery system** of the **BCM** consists of
  - a **water jacket** around the gasifier and the product gas burner,
  - a **convective heat exchanger (HEX)** for heat recovery from the flue gas downstream the gas burner and
  - a **flue gas condenser**
- **Condensing heat exchanger** to recover the off-heat of the **SOFC system** efficiently
- **An overall plant efficiency of more than 90%** (related to the NCV of the fuel) shall be achievable



Construction of the BCM – Pictures of the BCM installed at BIOS





Conclusions

- The gasifier has been successfully adapted to meet the requirements for Micro-Bio-CHP
- The product gas burner has been successfully developed
  - Complete gas burnout for nominal and partial load operation îs expected
  - Operation conditions are defined in a way that the material temperatures can be kept below the defined maximum operating temperatures
- The product gas extraction system has been successfully developed
  - Good basis for an efficient tar reduction by thermal reforming given
  - Suitable tar reforming catalysts have been evaluated und most promising catalyst has been selected and manufactured
  - Concept for high temperature particle filter developed and directly integrated in the boiler casing
- An efficient heat recovery system for the flue gas and the SOFC off-gas has been designed and implemented.
- Based on the final geometric concept the BCM has been designed and manufactured.
- The BCM has then been intensively tested and stepwise optimisation and evaluation took place in three phases.

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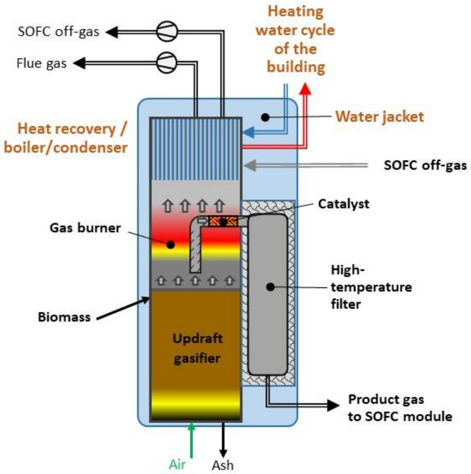
Development of a novel highly efficient energy supply system for energy autonomous multi-family buildings based on biomass gasification coupled with an SOFC and a PV system

Thank you for your attention



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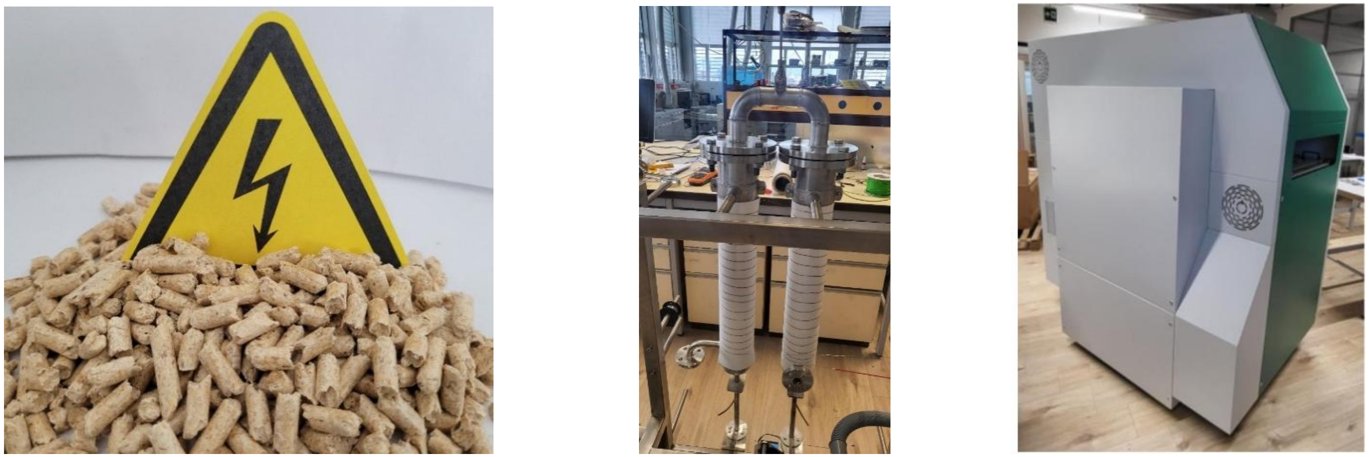
HCl and H_2S cleaning system



Prepared by: Alexandru Morosanu, Davide Di Profio

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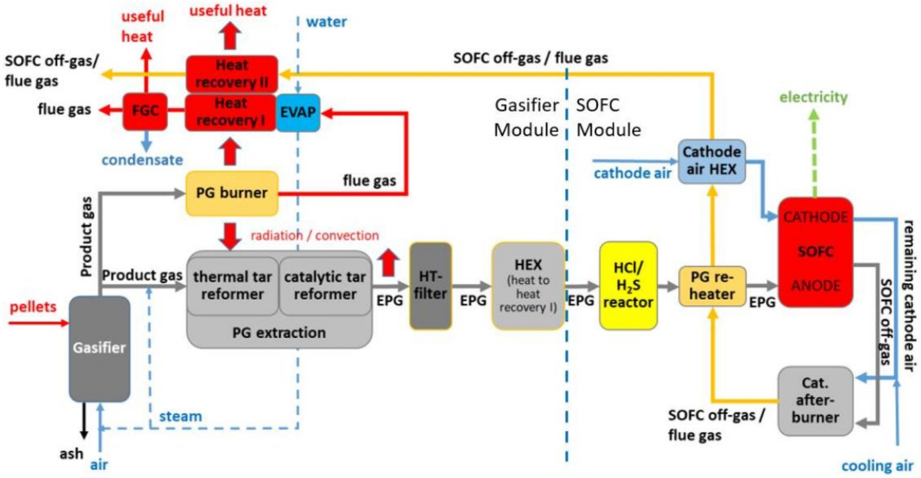
HCl and H_2S cleaning system:
Objectives and technical requirements

Objective

- Purify the syngas from HCl and H_2S using high temperature sorbents before feeding the gas to the SOFC module.

Technical requirements

- $H_2S < 1$ ppm_v and $HCl < 5$ ppm_v
- Sorbent lifetime ≥ 3000 h
- Hot gas operation (no reheating losses)
- Low pressure drop
- Compact design for integration in SOFC hot box
- Easy sorbent replacement
- Use of standard components (low cost)



HCl and H_2S cleaning system:
Material selection

Literature review

- Hydrogen halides removal via dehydrohalogenation using alkali metals > alkaline earth metals > transition metal oxides.
- H_2S removal typically performed with metal oxide sorbents (single oxides, mixed oxides or supported materials).

Review and procurement of commercially available sorbents

- K_2CO_3 – based sorbents for HCl removal from hot syngas.
- ZnO – based sorbents for H_2S removal from hot syngas.

Materials selected based on literature review, commercial availability and Hysytech’s previous operational experience.

HCl and H_2S cleaning system:
Material selection

Selected material for Chloride removal:

- K_2CO_3 on Alumina
- Shape: Spheres, 3 – 5 mm
- Operating temperature: 100 – 400 °C

Advantages

- High chloride absorption capacity
- High sorbent utilization
- High mechanical strength

Selected material for H_2S removal:

- Bulk ZnO sorbent
- Shape: Extrudates, 4 × 9 mm (D/L)
- Operating temperature: 100 – 400 °C

Advantages

- High sulfur removal capacity
- Cost-effective and reliable performance

HCl and H_2S cleaning system:

Reactor preliminary sizing and tests

- **Reactor preliminary sizing criteria**
  - Fluid dynamic considerations:
    - To avoid channeling: $D_R/D_P > 10$
    - To have a stable flow pattern: $L_R/D_R > 50$
    - On the bottom and top of the bed 100 mm of inert material was considered for flow stabilization.
    - Pressure drop was estimated using Ergun’s equation.
  - Two hypothesis were made to proceed with the preliminary design of the filter:
    - Sorbent usage factor: 90 % of dispersed phase sorbents and 30% for bulk sorbents
    - Mass Transfer Zone Length: 30% of overall bed length

HCl and H_2S cleaning system:

Reactor preliminary sizing and tests

HCl and H_2S reactor preliminary design features

- Aspect: U-shape pipes
- Reactor diameter: DN100
- Reactive height: up to 0,65 m for each side
- HCl sorbent: 3.4 kg
- H_2S sorbent: 3.8 kg
- Pressure drop: <6 mbar
- 3 thermocouple wells and a differential pressure transmitter can be installed
- The filter was integrated in the SOFC system prototype

HCl and H_2S cleaning system:

Reactor preliminary sizing and tests

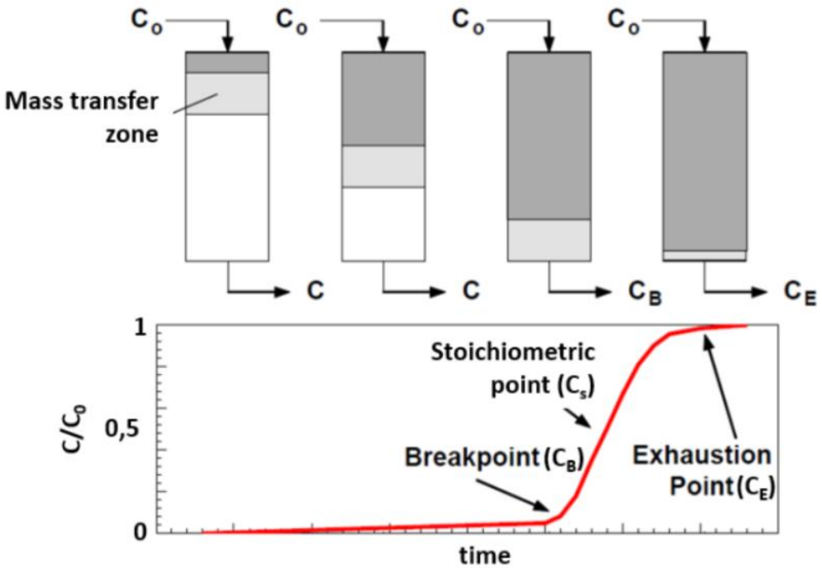
- **Testing at BIOS – Testing phase I and II**
  - Filter operated below design temperature (300 – 400 °C)
  - Stable performance at ~ 250 °C
  - Full compliance with specifications
    - H_2S: nearly complete removal (~ 0.6 ppm w.b.)
    - HCl: well below target (~ 1.2 ppm w.b.)
- **Testing at BIOS – Testing phase III**
  - Sorbent bed temperatures: +50 °C vs. Phase II (improved insulation)
  - Operated well within specifications:
    - H_2S: nearly complete removal (~ 0.4 ppm w.b.)
    - HCl: well below target (~ 0.2 ppm w.b.)

HCl and H_2S cleaning system:

Reactor modelling

Phenomena description

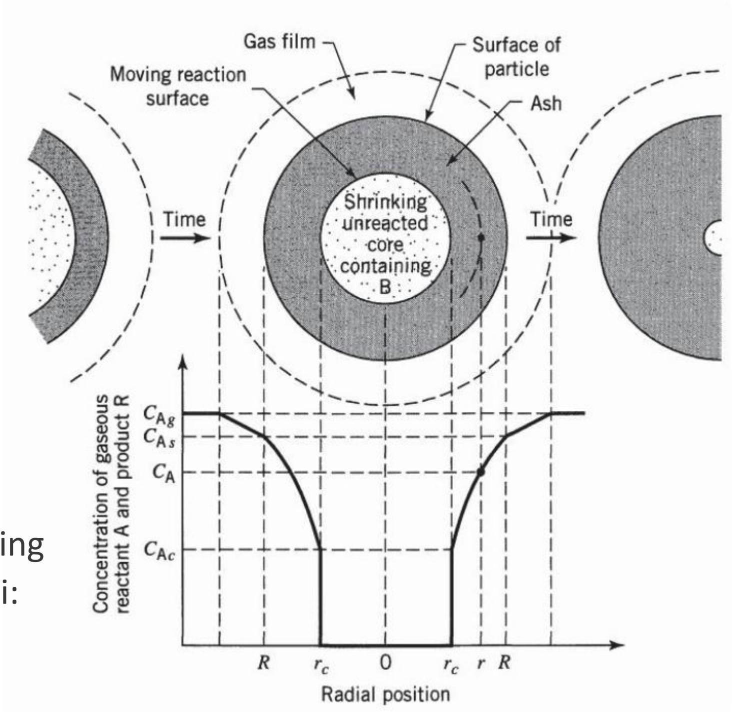
- Adsorption described using the mass transfer zone (MTZ) concept
- Inlet region saturates first, forming an equilibrium zone
- A moving MTZ (concentration front) develops along the reactor
- Front shape governed by diffusion and reaction kinetics
- Breakthrough occurs when the MTZ reaches the reactor outlet → contaminant rises in outlet stream



HCl and H₂S cleaning system:
Reactor modelling

Reactor modelling

- Selected model: Generalized Shrinking Core Model
  - Coupled PDE–ODE system for transient breakthrough simulations (axial plug flow or with axial dispersion if needed):



– Mass balance at the reactor bed level:

$$\varepsilon_b \frac{\partial C_A}{\partial t} + u \frac{\partial C_A}{\partial z} = -n_p \dot{n}_A(C_A, r_c)$$

– Mass balance at the pellet level for a spherical pellets:

$$\frac{\partial r_c}{\partial t}(z,t) = -\frac{\dot{n}_A(C_A(z,t), r_c(z,t))}{4\pi b\, c_{B0} r_c(z,t)^2}$$

Resistance in series (for 1st-order kinetics):

$$\dot{n}_A = \frac{C_{A,\infty}}{R_{film} + R_{ash} + R_{rxn}}$$

For spherical particle:

$$R_{film} = \frac{1}{\boldsymbol{k_g} 4\pi R_p^2}$$

k_g (mass transfer coffecient) determined using transport correlations like Wakao–Funazkri:

$$Sh = \frac{k_g d_p}{D_{AB}} = 2 + 1.1 Re_p^{0.6} Sc^{1/3}$$

$$R_{ash} = \frac{R_p r_c}{4\pi \boldsymbol{D_e} (R_p - r_c)}$$

$$R_{rxn} = \frac{1}{\boldsymbol{k_s} 4\pi r_c^2}$$

D_e (effective diffusivity) and **k_s** (kinetic constant for 1st order kinetics) are experimentally determined parameters

HCl and H_2S cleaning system:

Sorption tests

Test matrix

Parameter	Temperature	Flowrate	Concentration	Composition
ID	A	B	C	D
Unit	°C	Nm^3/h	ppm	-
0 (Low Value Level)	200	0.75	70	in N_2
1 (Medium Value Level)	300	1		
2 (High Value Level)	400	1.25		

HCl and H_2S cleaning system:

Sorption tests

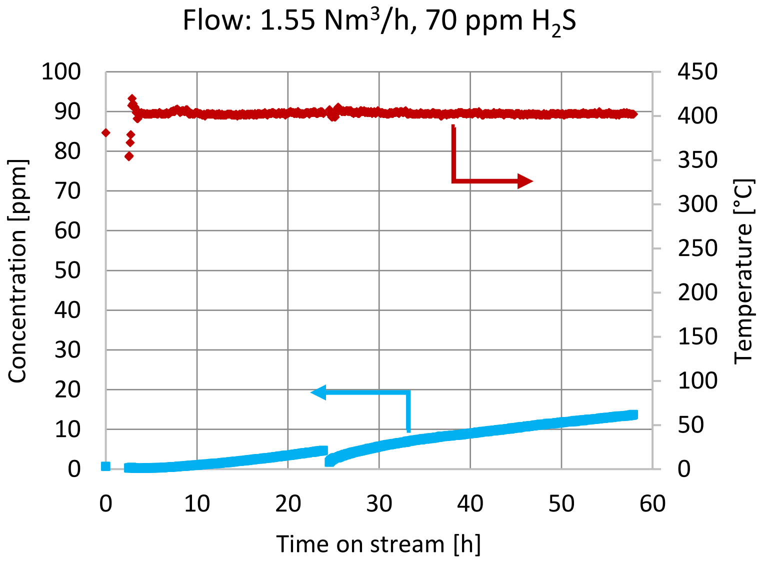
Lab scale testing: setup

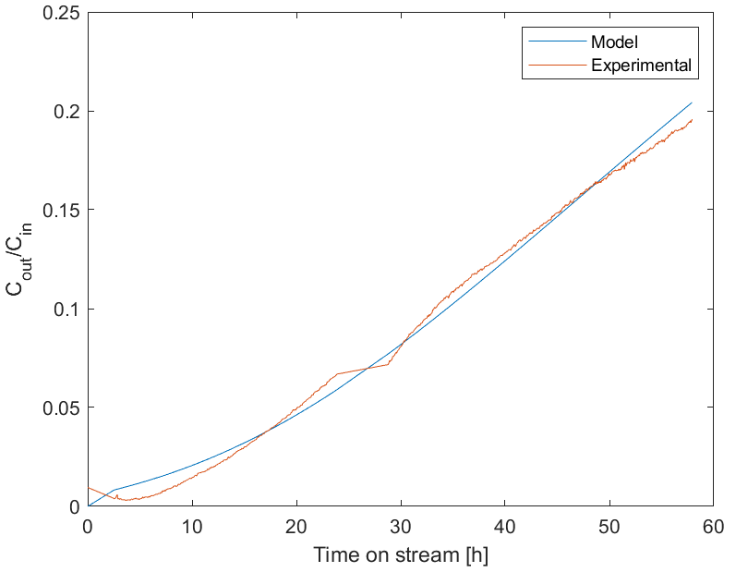
Overall view of the process area

Quartz glass reactor

HCl and H_2S cleaning system:

Sorption tests and modelling


Flow: 1.55 Nm^3/h, 70 ppm H_2S



	Temperature (°C)	$k_s\ (s^{-1})$	$D_e\ (m^2\ s^{-1})$	R^2
H_2S	200	0,0471 ± 0,0025	7,66E-07 ± 1.87E-08	0,988
	300	0,194 ± 0,012	1,90E-06 ± 3.01E-08	0,987
	400	0,409 ± 0,027	8,38E-06 ± 1,41E-08	0,993

HCl and H_2S cleaning system:

Sorption tests and modelling

Model predictions - Literature data for model corrections

- **Effect of other components on sorption behaviour of H_2S**

Based on available literature data, Sasaoka et al. (1994) report that the combined presence of H_2 and H_2O can reduce the H_2S sorption capacity by up to 24.6%. The Shrinking Core Model parameters were adjusted to account for this dependency, allowing us to estimate the breakthrough time at an H_2S concentration of 1 ppm.

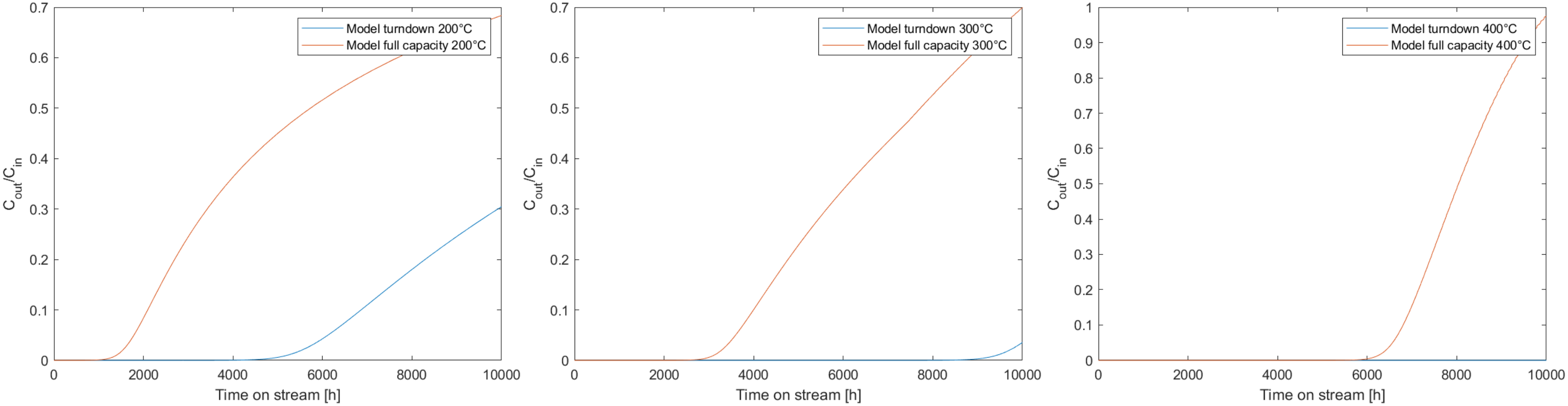
Operating conditions	**Performance delta**
400°C - 500 ppm H_2S - N2	0,0%
400°C - 500 ppm H_2S - 18,1% H_2 - N_2	+4,0%
400°C - 500 ppm H_2S - 18,1% CO - N_2	+3,3%
400°C - 500 ppm H_2S - 18,1% H_2O - N_2	-14,1%
400°C - 500 ppm H_2S - 18,1% H_2 - 18,1% H_2O - N_2	-16,2%
400°C - 500 ppm H_2S - 36,2% H_2 - 18,1% H_2O - N_2	-24,6%

Data adapted from Sasaoka et al.

Design basis composition		
CO	[vol% w.b.]	12.65
H_2O	[vol% w.b.]	29.43
CO_2	[vol% w.b.]	11.66
H_2	[vol% w.b.]	29.87
N_2	[vol% w.b.]	16.38
H_2S	[ppmv w.b.]	16.90
HCl	[ppmv w.b.]	11.06

Model predictions

- **Model projections for H_2S sorbent with literature correction**



Temperature (°C)	Lifetime (h)
200	~1,200 @ full capacity ~4,500 @ turndown

Temperature (°C)	Lifetime (h)
300	~3,000 @ full capacity > 8,000 @ turndown

Temperature (°C)	Lifetime (h)
400	>6,000 @ full capacity >> 8,000 @ turndown

HCl and H_2S cleaning system:
Key Conclusions

- **System overview**
  - HCl/H_2S sorption reactor system designed, supplied, and successfully tested in pilot plant
  - The SCM model was derived for performance prediction of the reactors
- **Performance**
  - Effective removal, stable operation, acceptable pressure drop in pilot tests
  - SCM predicts filter lifetime/breakthrough depending on operating temperature:
    - H_2S: very good fit; prediction of reduced performance at 200 °C → ~1200 h; meets target at $\geq$ 300 °C (> 3,000 h)
    - HCl: good fit; less sensitive to temperature than H_2S and gas composition according to literature data → meets target at $\geq$ 200 °C (> 3,000 h)
- **Issues**
  - Issues: low temperatures in pilot unit, heat losses
  - Improvements: heat tracing, enhanced insulation, more compact design for future applications needed

Thank you for your attention

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HYSYTECH Srl

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**Development of a novel highly efficient energy supply system
for energy autonomous multi-family buildings
based on biomass gasification coupled with an SOFC and a PV system**

SOFC stack development

Prepared by: Stefan Megel, Anna Seidl, Sebastian Hielscher

Fraunhofer
IKTS

Final public project workshop

Online

25 March 2026

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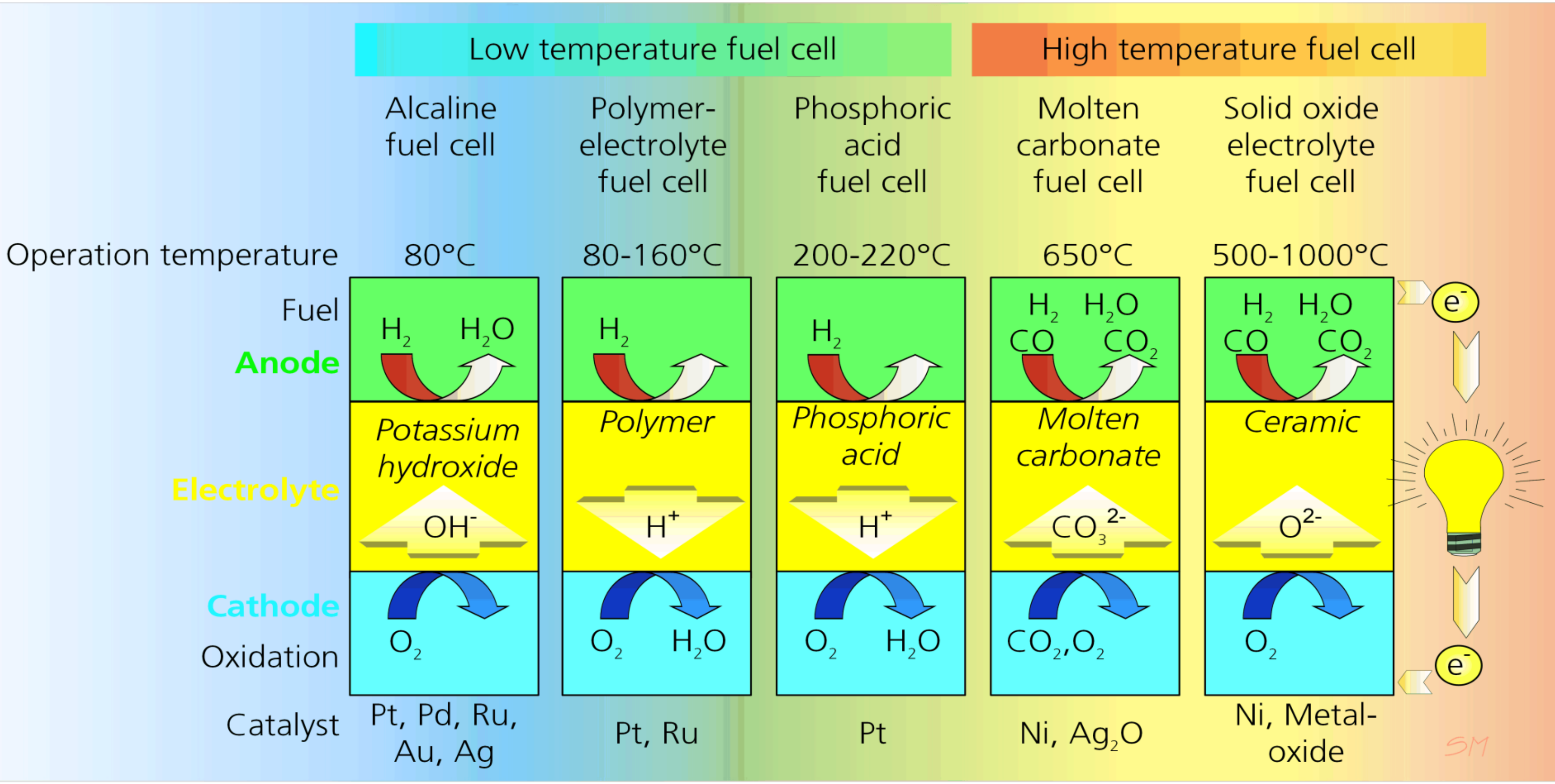
SOFC stack development

1. Introduction
2. Stack assembly MK35x
3. Stack results MK35x
4. Stack module development
5. Conclusion

1. Introduction

Types of fuel cells



	Low temperature fuel cell			High temperature fuel cell	
	Alcaline fuel cell	Polymer-electrolyte fuel cell	Phosphoric acid fuel cell	Molten carbonate fuel cell	Solid oxide electrolyte fuel cell
Operation temperature	80°C	80-160°C	200-220°C	650°C	500-1000°C
Fuel **Anode**	H_2 H_2O	H_2	H_2	H_2 H_2O CO CO_2	H_2 H_2O CO CO_2
Electrolyte	*Potassium hydroxide* OH^-	*Polymer* H^+	*Phosphoric acid* H^+	*Molten carbonate* CO_3^{2-}	*Ceramic* O^{2-}
Cathode Oxidation	O_2	O_2 H_2O	O_2 H_2O	CO_2,O_2	O_2
Catalyst	Pt, Pd, Ru, Au, Ag	Pt, Ru	Pt	Ni, Ag_2O	Ni, Metal-oxide

SOFC stack development

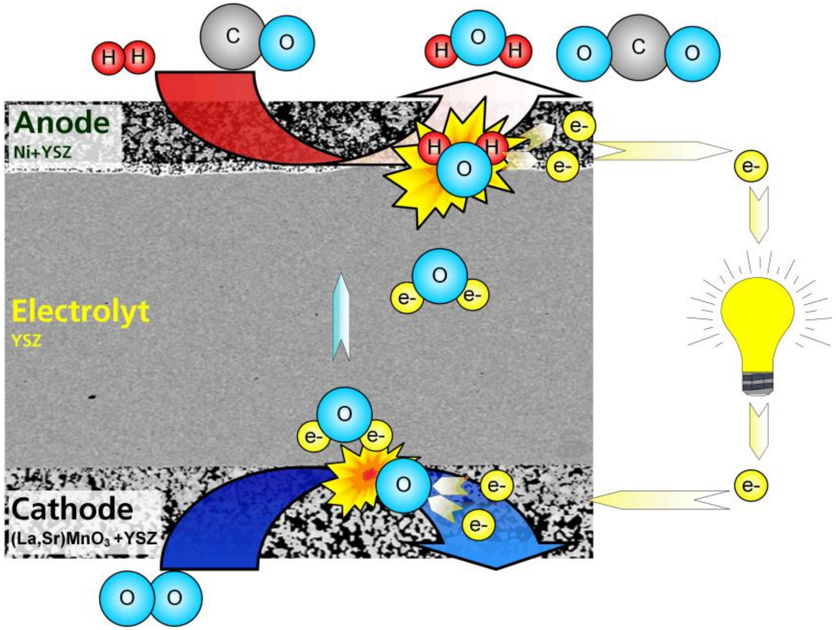
1. Introduction

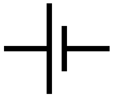
SOFC operation principle

- Gas dense electrolyte
- No noble metals
- Different fuels at anode, air at cathode

→ Chemical potential leads to oxide ion moving

→ Electrical potential

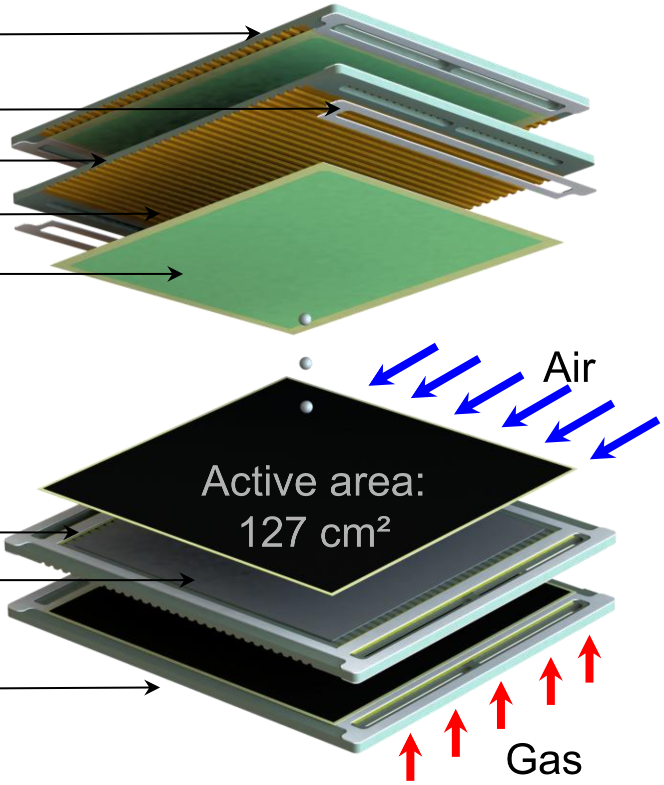




Power per cell: 0.2-0.5 W/cm²

→ Serial connection (n*Ucell)

2. Stack assembly MK35x



End plate BiP

Glass step

Bipolar plate

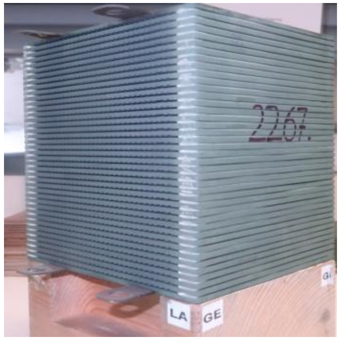
Protection layer

Cell with 10ScSZ electrolyte and contact layer on air side

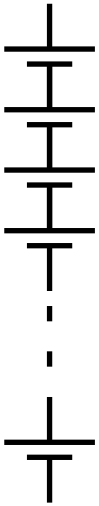
Glass frame

Nickel mesh

Bottom plate BiP



Serial connection of cells



SOFC stack development

2. Stack assembly MK35x

MK355 pilot production facility in Arnstadt developed by IKTS Fraunhofer

Operated by Nucera since mid 2025

→ Capacity 2000 stacks/a

© Fraunhofer IKTS / thyssenkrupp nucera: Paul-Philipp Braun

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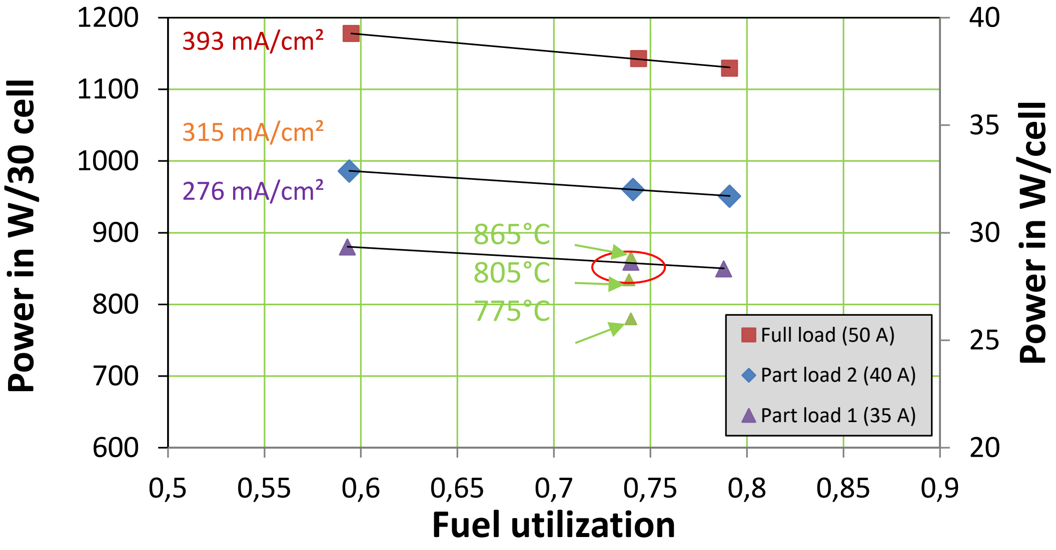
3. Stack results

Performance map 30 cell MK35x stack

Fuel: 40 % H_2 in 5% H_2O and N_2, Air: 100 sl/min, $T_{\_air\_o}$=830°C – 840°C

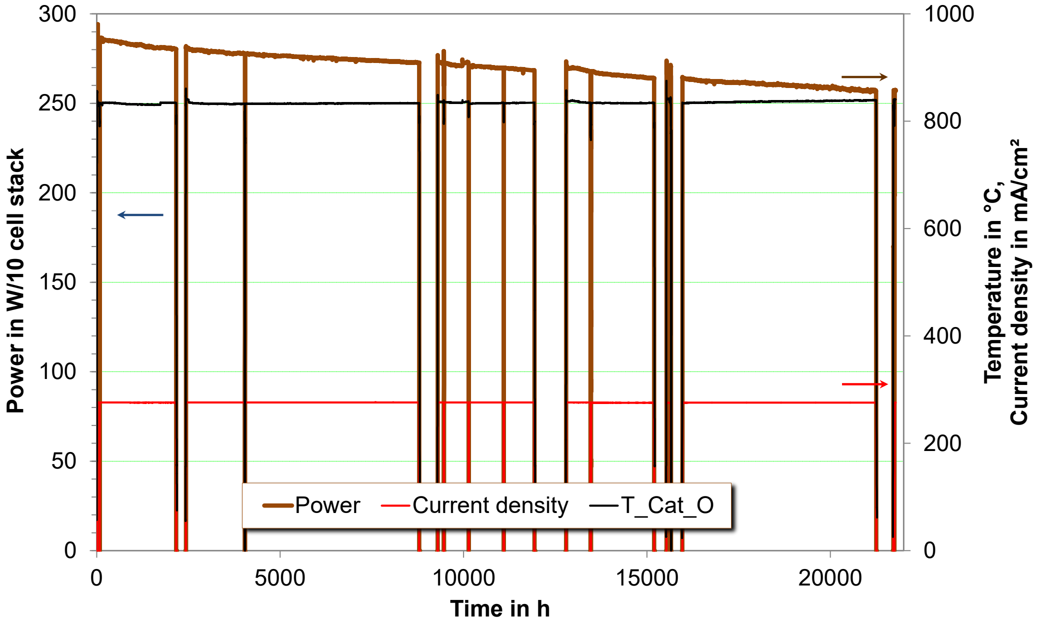
- 850 W/30 cell stack @reference
- Up to 40 W/cell possible
- $\Delta P/P_0$=0.5 %/10 thermal cycles (75 oxidation cycles)
- $\Delta P/P_0$=0.6 %/1,000 h (>20,000 h) (see next slide)



3. Stack results

Durability test 10 cell MK35x stack

Fuel: 40 % H_2 in N_2, Air: 100 sl/min, $T_{\_air\_o}$=830°C – 840°C



- **$\Delta P/P_0$=0.6 %/1,000 h (>20,000 h)** **ΔASR=16 mΩcm²/1,000 h**

SOFC stack development

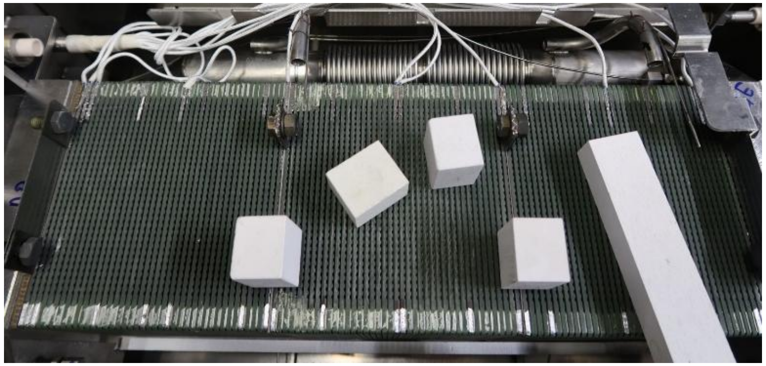
4. Stack module development

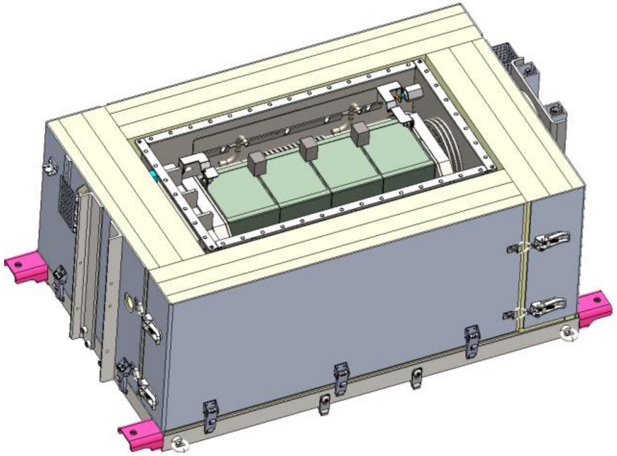
Stack module assembly

- Stacks connected in series
- Insulation and compression system
- Sensing

→ Easy integration into systems

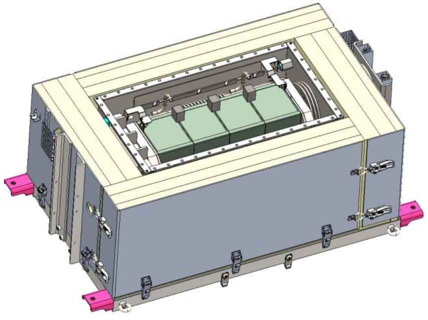
→ Commissioning at IKTS



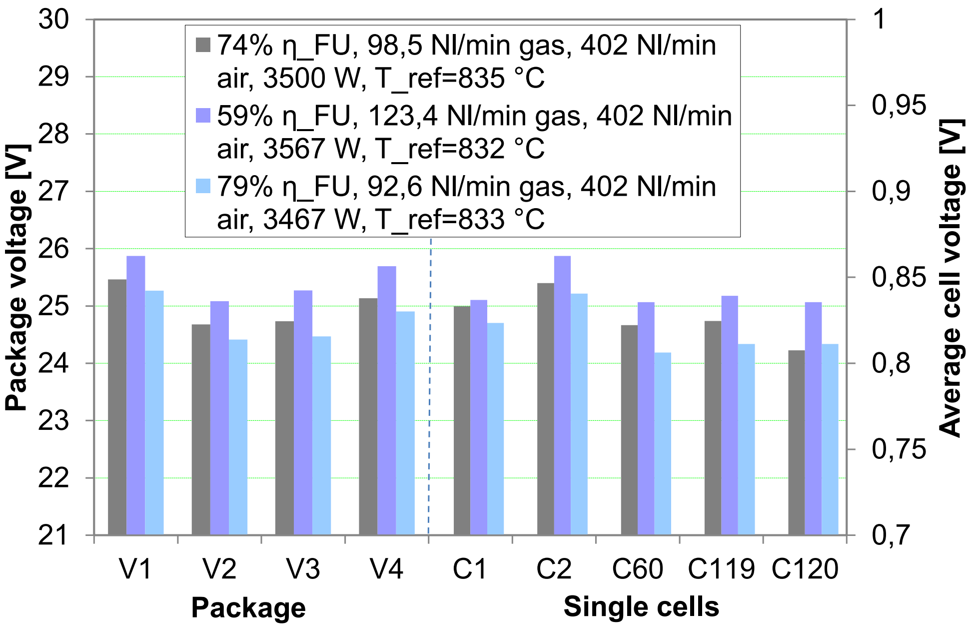


4. Stack module development

Stack module results



- @35 A, 40 % H_2 in N_2, η_{FU}=variation, T_{ref}=835°C, air: 400 Nl/min
- Power in reference point: P_{el}=3.5 kW_{el}
- Homogenous distribution of different fuel utilization in packages → stable performance



5. Conclusion

Stack module results

- **Proofed stack technology MK35x**
  - Available robust stacks
  - Wide temperature range 750°C-900°C
  - Power: 20-50 W/cell depending on temperature and fuel
  - Degradation: $\Delta P/P_{0(835°C)}$= 0.6 %/1,000 h (>20,000 h)
    - RedOx stability: $\Delta P/P_0$< 0.5 %/10 cycles (120 cycles)
- **Assembling to modules >1 kW**
  - 120 cell stack module commissioning test: >3.5 kWel

→ SOFC are the way to efficient power generation with product gas from Biomass gasification

Thank you for your attention

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Development of a novel highly efficient energy supply system
for energy autonomous multi-family buildings
based on biomass gasification coupled with an SOFC and a PV system

SOFC system and process control

Prepared by: Luc Conti

INERGIO

Final public project workshop

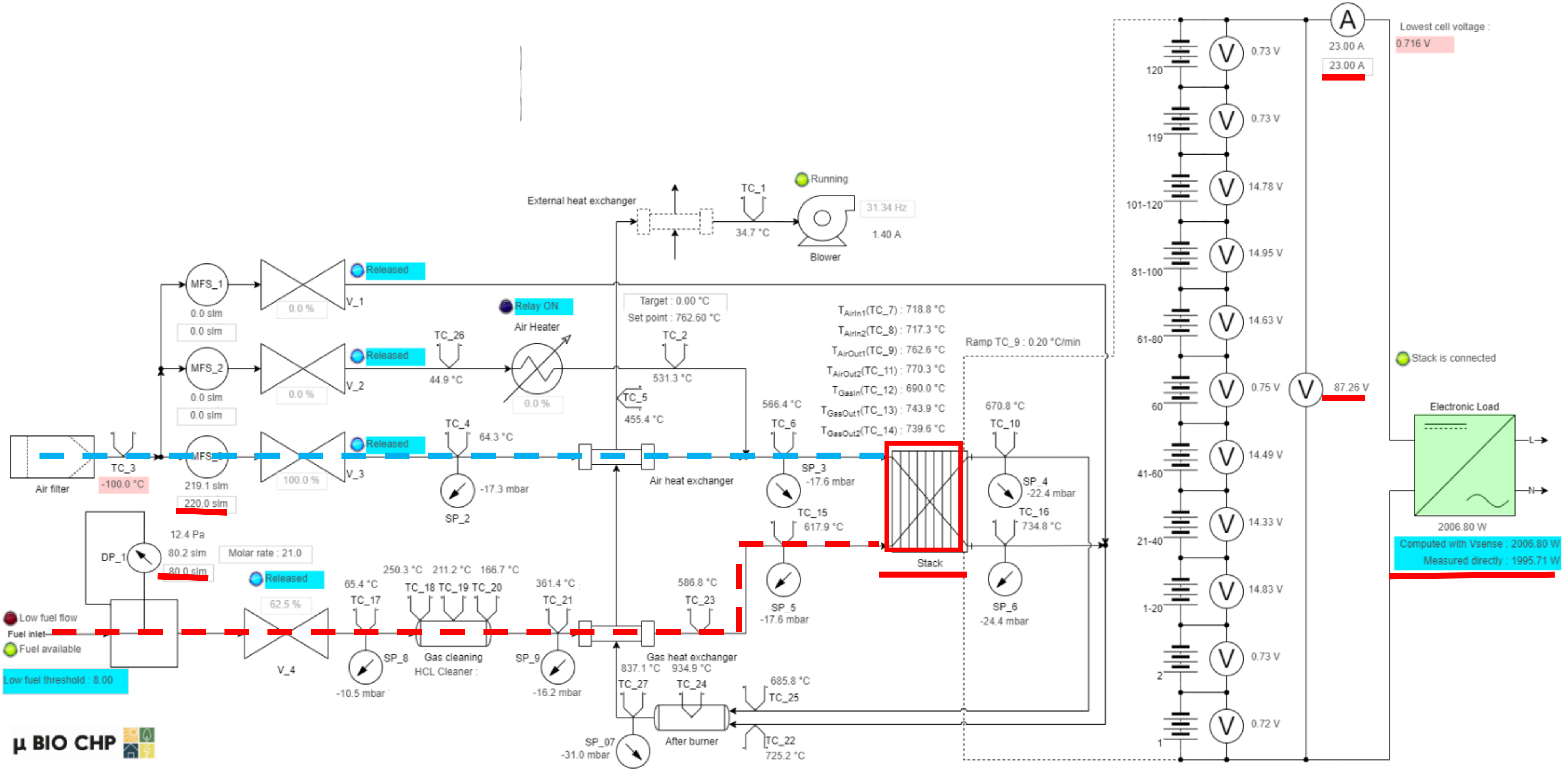
Online

25 March 2026

Content

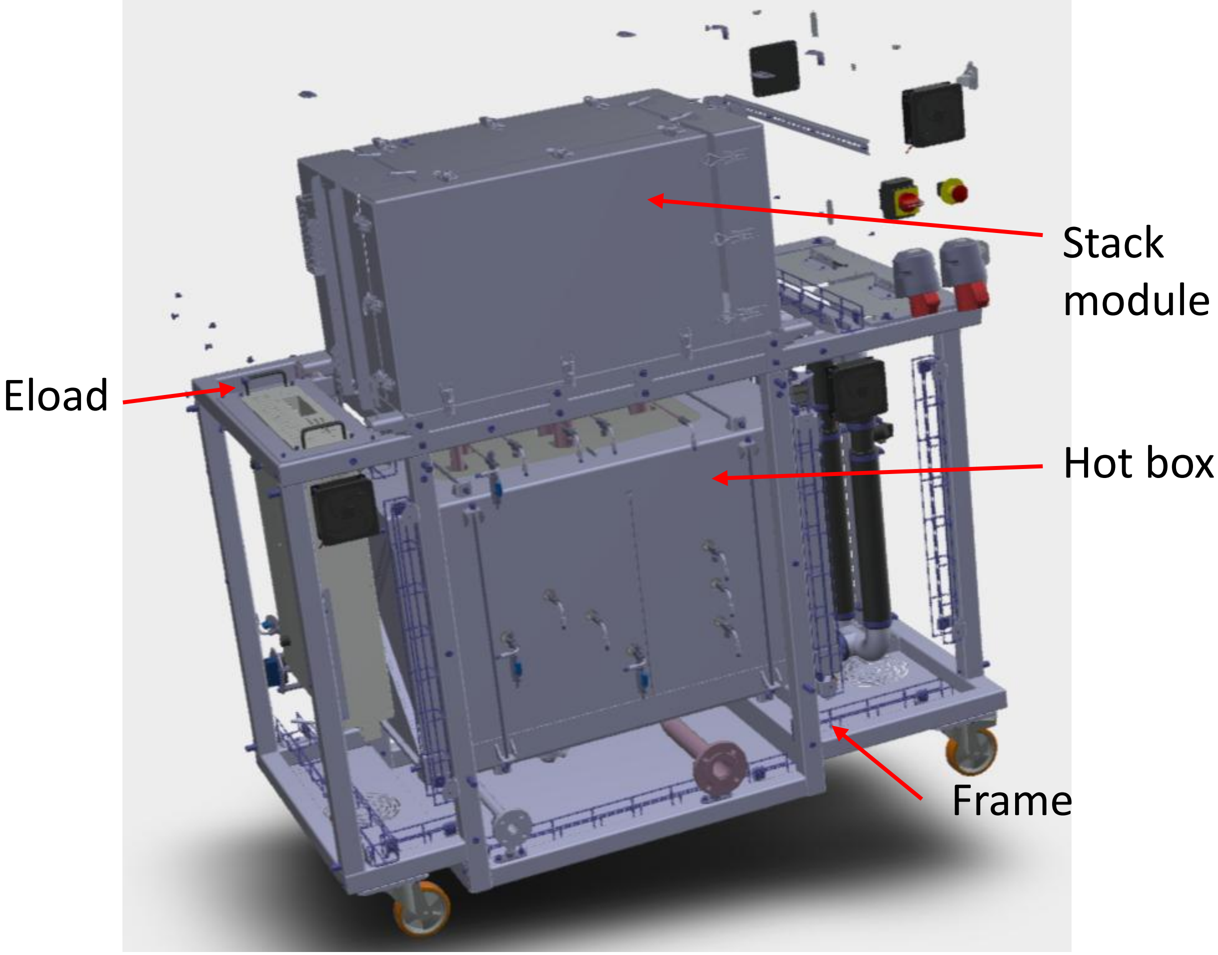
- Diagram and working principle of the SOFC system
- 3D drawings of the system
- Process control used
- Conclusions and outlook

P&ID


External heat exchanger
TC_1
34.7 °C
Running
31.34 Hz
1.40 A
Blower
MFS_1
0.0 slm
0.0 slm
0.0 %
V_1
Released
MFS_2
0.0 slm
0.0 slm
0.0 %
V_2
Released
Relay ON
Air Heater
TC_26
44.9 °C
0.0 %
Target : 0.00 °C
Set point : 762.60 °C
TC_2
531.3 °C
TC_5
455.4 °C
Air filter
TC_3
-100.0 °C
MFS_3
219.1 slm
220.0 slm
100.0 %
V_3
Released
TC_4
64.3 °C
-17.3 mbar
SP_2
Air heat exchanger
T_{AirIn1}(TC_7) : 718.8 °C
T_{AirIn2}(TC_8) : 717.3 °C
$T_{AirOut1}$(TC_9) : 762.6 °C
$T_{AirOut2}$(TC_11) : 770.3 °C
T_{GasIn}(TC_12) : 690.0 °C
$T_{GasOut1}$(TC_13) : 743.9 °C
$T_{GasOut2}$(TC_14) : 739.6 °C
Ramp TC_9 : 0.20 °C/min
566.4 °C
TC_6
SP_3
-17.6 mbar
TC_15
617.9 °C
670.8 °C
TC_10
SP_4
-22.4 mbar
TC_16
734.8 °C
Stack
SP_5
-17.6 mbar
SP_6
-24.4 mbar
DP_1
12.4 Pa
80.2 slm
80.0 slm
Molar rate : 21.0
Low fuel flow
Fuel inlet
Fuel available
Low fuel threshold : 8.00
Released
62.5 %
V_4
65.4 °C
TC_17
250.3 °C
211.2 °C
166.7 °C
TC_18
TC_19
TC_20
SP_8
-10.5 mbar
Gas cleaning
HCL Cleaner :
361.4 °C
TC_21
SP_9
-16.2 mbar
586.8 °C
TC_23
Gas heat exchanger
837.1 °C
934.9 °C
TC_27
TC_24
685.8 °C
TC_25
After burner
SP_07
-31.0 mbar
TC_22
725.2 °C
µ BIO CHP
120
0.73 V
119
0.73 V
101-120
14.78 V
81-100
14.95 V
61-80
14.63 V
60
0.75 V
41-60
14.49 V
21-40
14.33 V
1-20
14.83 V
2
0.73 V
1
0.72 V
A
23.00 A
23.00 A
V
87.26 V
Lowest cell voltage :
0.716 V
Stack is connected
Electronic Load
L
N
2006.80 W
Computed with Vsense : 2006.80 W
Measured directly : 1995.71 W

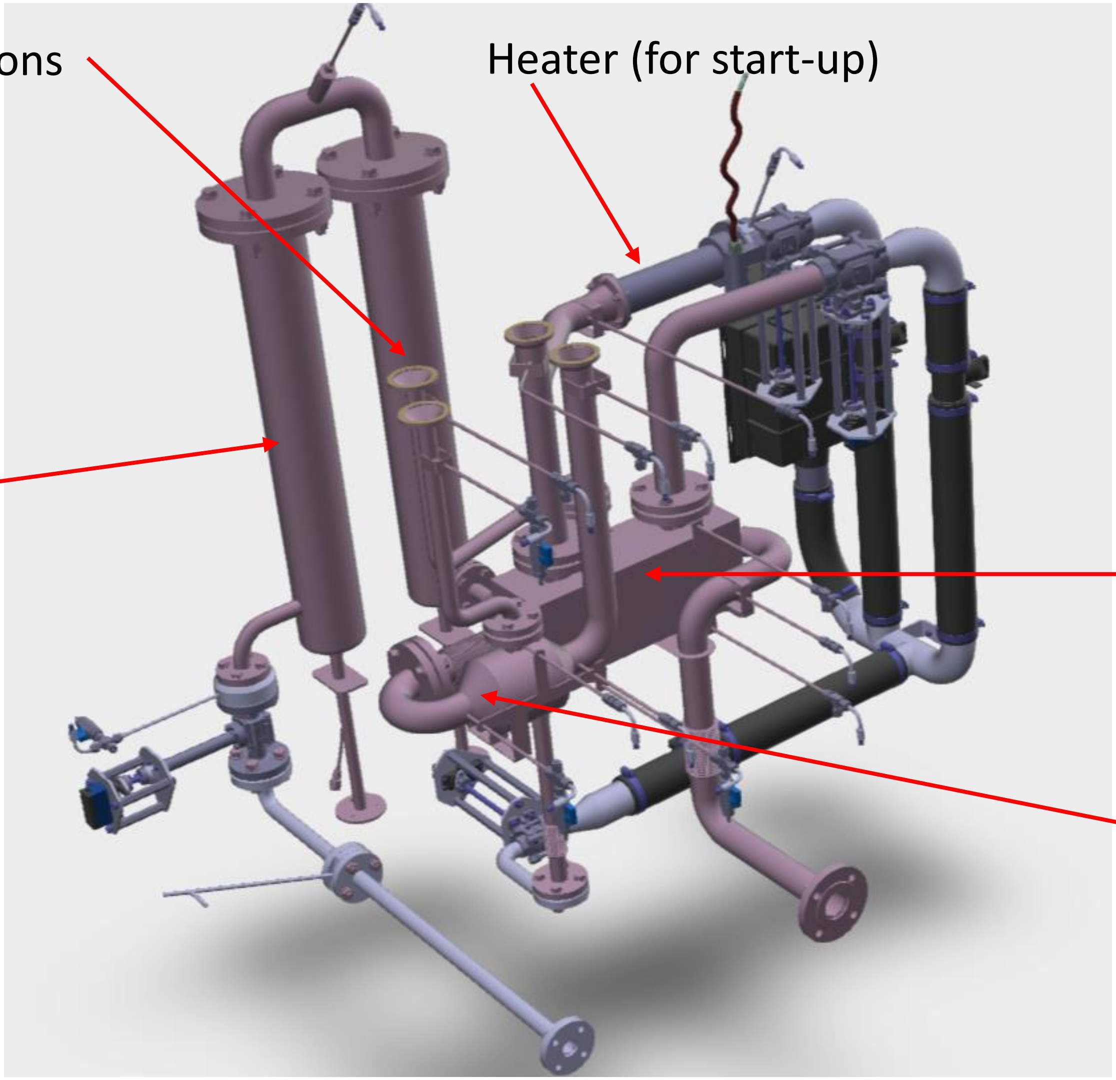
Design of SOFC module

- **Complete design of the SOFC module**



Task 5.3: SOFC system and overall SOFC module development – work performed (II)

- **Zoom of the different units and interconnections of the SOFC module**



Stack connections

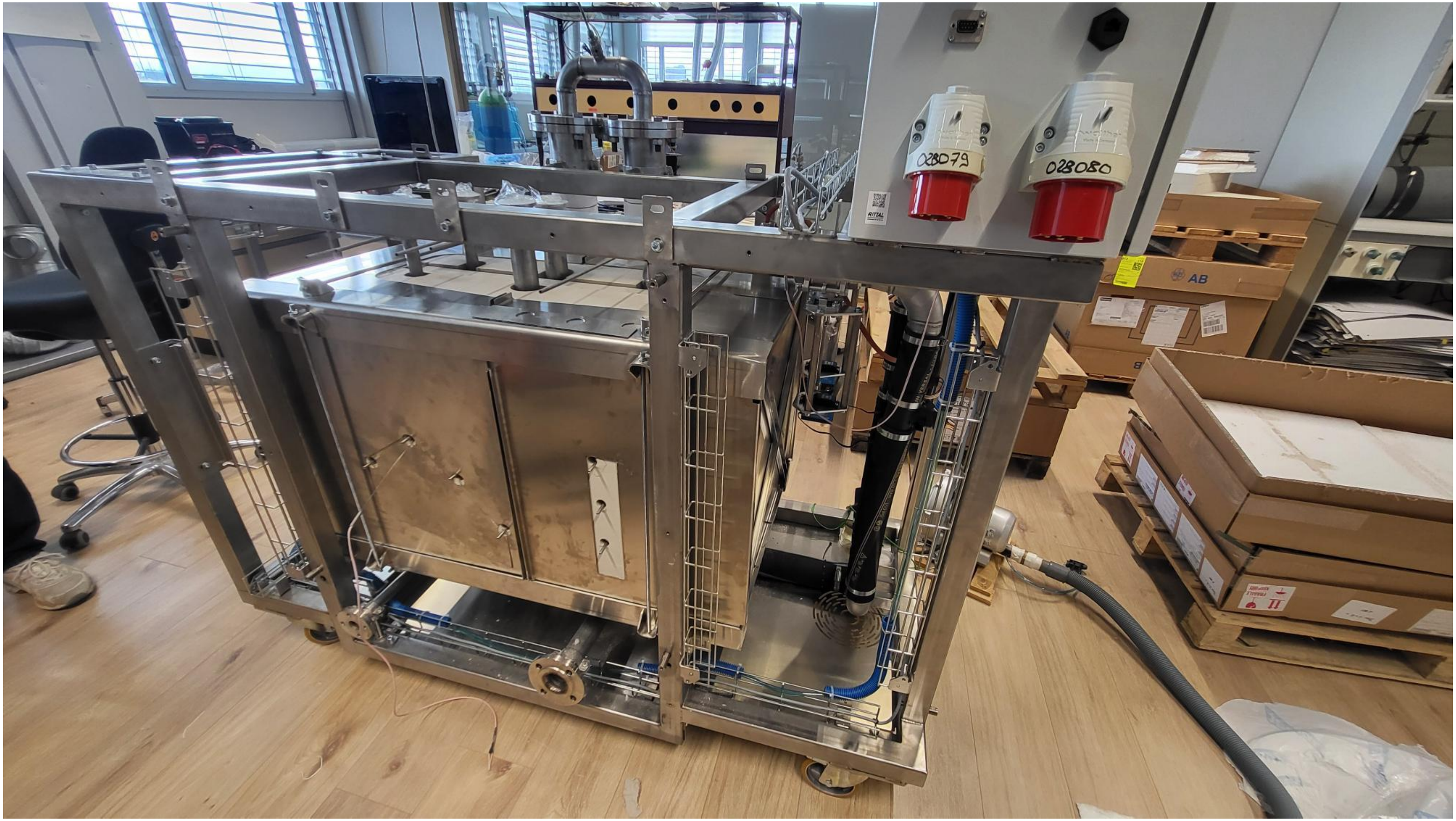
Heater (for start-up)

H2S/HCl
sorption
reactor

Heat
exchanger

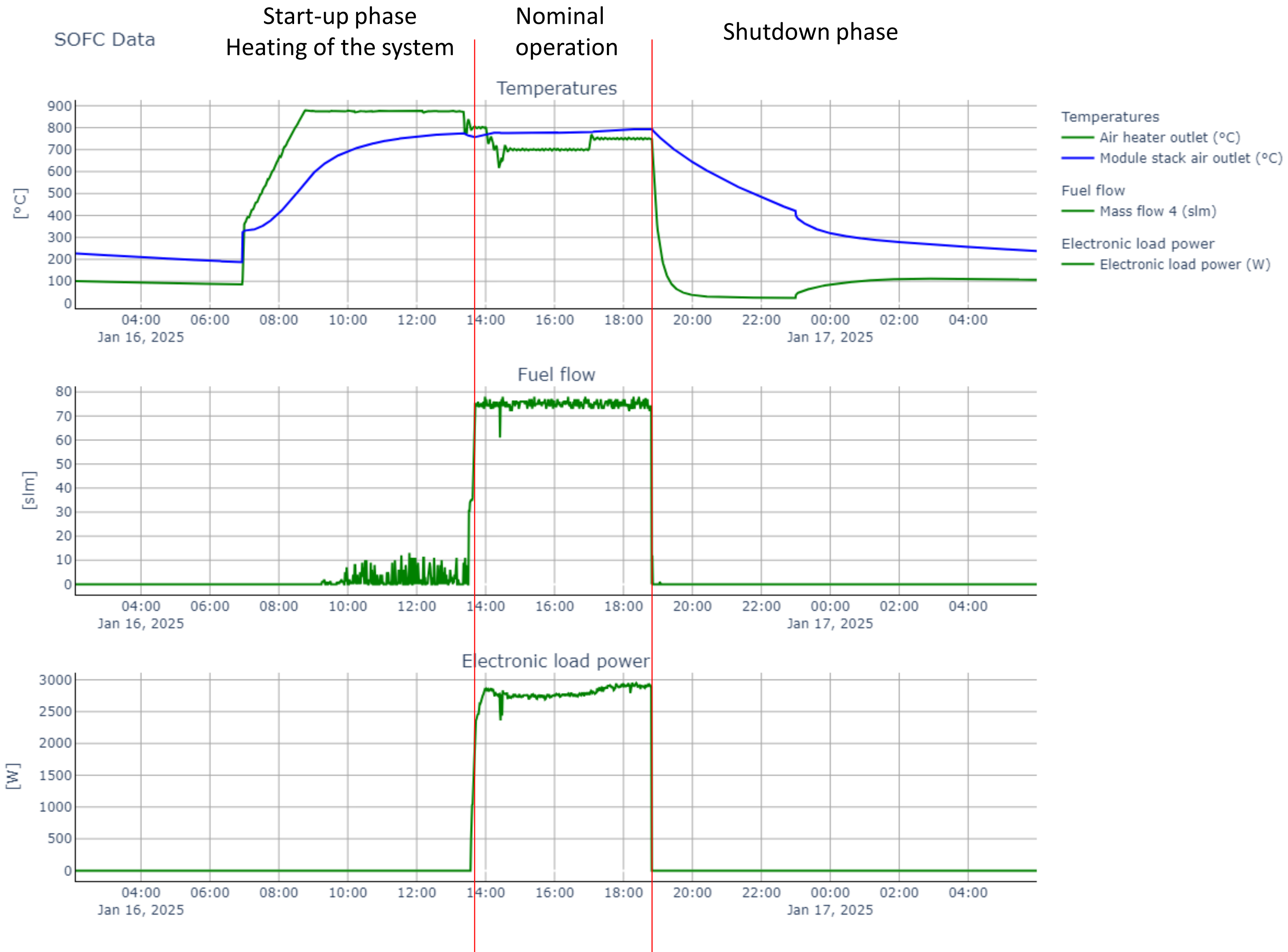
Afterburner

Assembly Pictures (I)



Assembly Pictures (II)

Process control



Start-up phase
Heating of the system

Nominal
operation

Shutdown phase

Conclusions and outlook

- A working SOFC system has been built and tested
- During the project its operation has been optimized
- It's a flexible prototype with parts easily accessible and changeable
- It gives the direction for the design of a commercial unit

Thank you for your attention

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**Development of a novel highly efficient energy supply system
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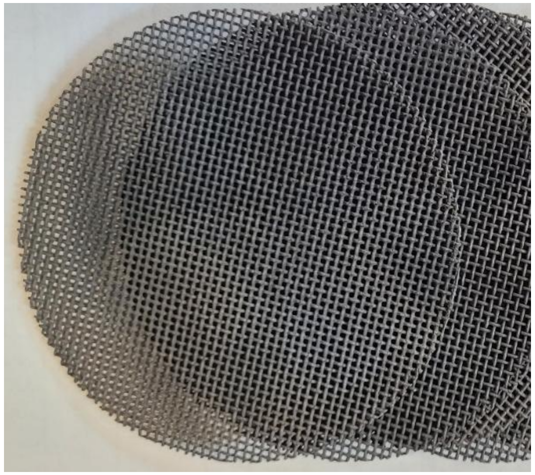
Results of the test runs performed with the biomass conversion module (BCM)



Prepared by: Christoph Mandl, Ingwald Obernberger, Thomas Brunner

BIOENERGIESYSTEME GmbH

Final public project workshop

Online

25 March 2026

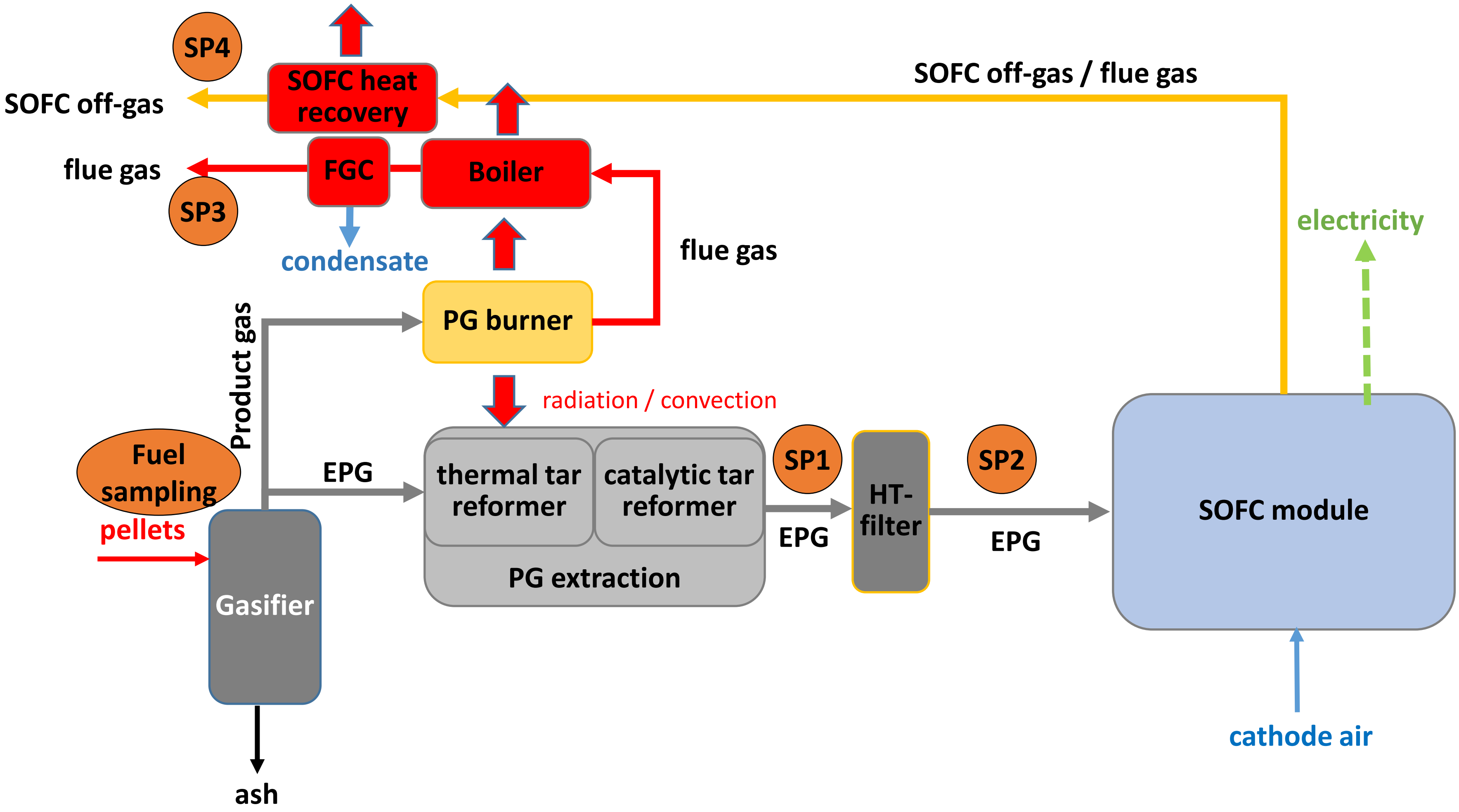
Content

- **Objectives**
- **Methodology of test runs**
- **Selected results of test runs performed**
- **Conclusions**

Objectives

- **The testing campaigns have been dedicated to**
  - the performance of test runs at the testing plant including accompanying measurements and analyses as well as
  - to the evaluation of test runs, the identification of weak points and the formulation of proposals for further improvement
- **At BIOS comprehensive test runs with the entire Micro-Bio-CHP testing plant have been performed at an appropriate test stand.**
- **This presentation focuses on the evaluation of test runs performed concerning the biomass conversion module (BCM):**
  - Evaluation concerning emissions and efficiency
  - Evaluation of the composition of the extracted product gas
  - Evaluation of the tar reforming catalyst
  - Evaluation of the high temperature particle filter
- **In addition, relevant results of the overall evaluation of the testing plant concerning emissions and efficiency will be presented.**

Methodology – test stand set-up for measurements



SP … sampling point for measurements/analyses; PG … product gas, HT … high temperature; HEX … heat exchanger; Cat … catalytic; FGC … flue gas condenser; EVAP … evaporator; EPG … extracted product gas; Heat recovery I+II … heat exchangers (gas/water)

Methodology – Measurements, sampling and analyses

Measurements performed

- Continuous measurements – gas analyses equipment – **flue gas (SP3) and SOFC off-gas (SP4)**
  - Emerson NGA 2000: O_2 (paramagnetism); CO_2, CO, NO (ND-IR)
- Discontinuous measurements – equipment and methods – **flue gas (SP3)**
  - Equipment according to VDI 2066: determination of the total dust content (TSP) in the flue gas downstream BCM
- Continuous measurements – gas analyses equipment – **EPG (SP1+SP2)**
  - Emerson NGA 2000: O_2 (paramagnetism)
  - ABB EL3020: CO_2, CO, H_2, CH_4
  - FTIR (Ansyco DX-4000): H_2O, hydrocarbons
- Discontinuous measurements – equipment and methods – **EPG (SP1+SP2)**
  - Gravimetric tar content using a method referring to CEN TC BT/TF 143 WICSC 03002.4; 2005).
  - Dust content with a high temperature filter with special high temperature seals according to VDI 2066
- Fuel sampling and subsequent fuel analyses

Results from test runs –
Test run fuel applied

		softwood pellets		
		testing plant	BIOS database	
			mean value	s
Ash content	[% d.b.]	0.35	0.37	0.05
Moisture content	[% w.b.]	6.65	6.88	1.05
C	[% d.b.]	50.06	49.81	0.60
H	[% d.b.]	6.16	6.25	0.19
N	[% d.b.]	0.06	0.08	0.03
S	[mg/kg d.b.]	29.00	58.50	9.97
Cl	[mg/kg d.b.]	43.00	30.33	14.54
Ca	[mg/kg d.b.]	1,030.00	945.51	115.82
Si	[mg/kg d.b.]	300.00	178.34	110.79
Mg	[mg/kg d.b.]	130.00	123.04	12.61
Al	[mg/kg d.b.]	18.20	20.71	20.00
Na	[mg/kg d.b.]	3.50	14.05	5.97
K	[mg/kg d.b.]	390.00	421.53	52.88
Zn	[mg/kg d.b.]	<10	11.05	1.94
GCV	[MJ/kg d.b.]	20.24	20.25	0.41

Explanations:
w.b. ... wet basis; d.b. dry basis; s ... standard deviation; BIOS database ... values of fuel database of BIOS for softwood pellets

- **The test run fuel is in general well comparable with the database values from BIOS.**
- **The test run fuel is representative for softwood pellets.**

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Results from test runs – General plant performance (I)

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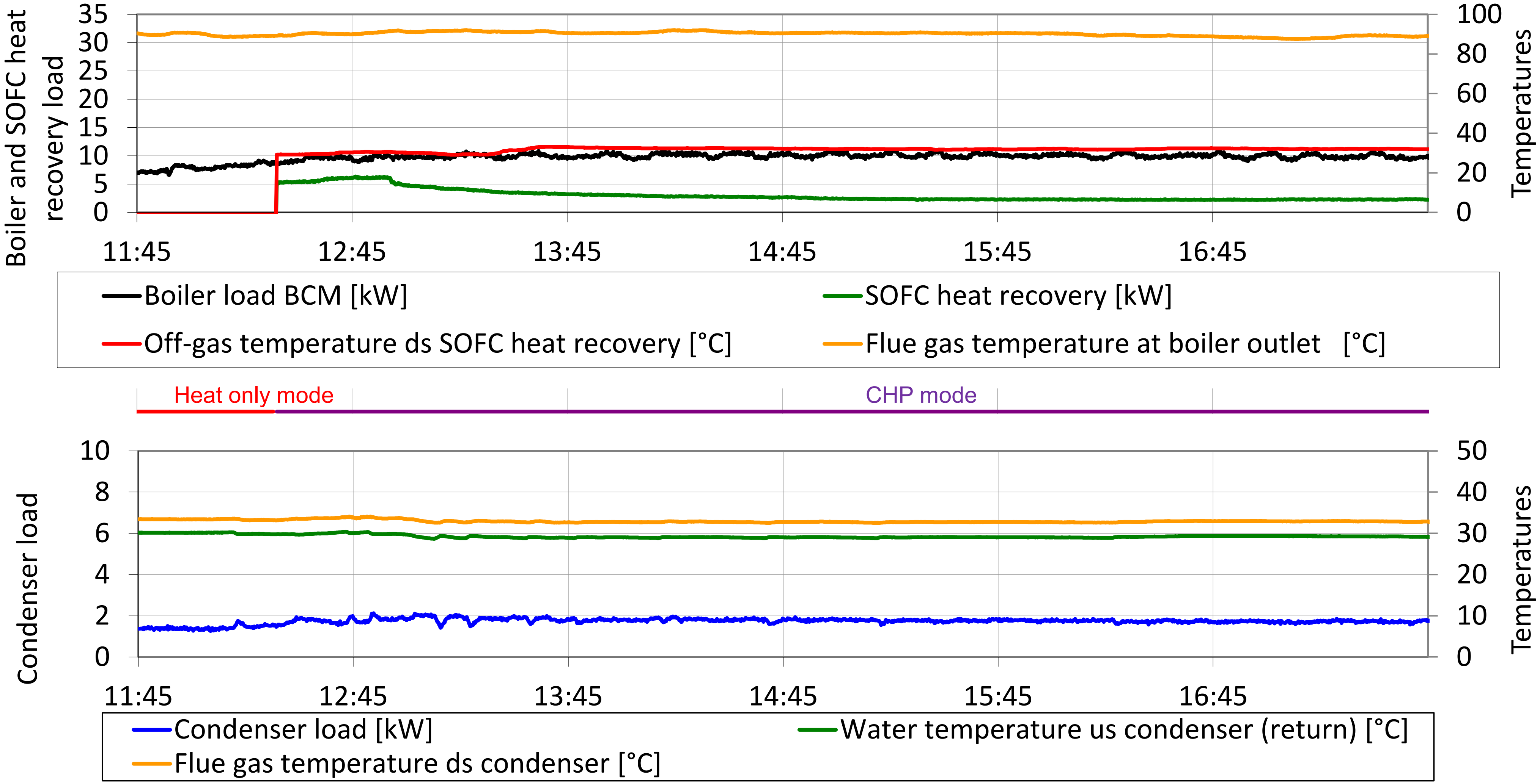
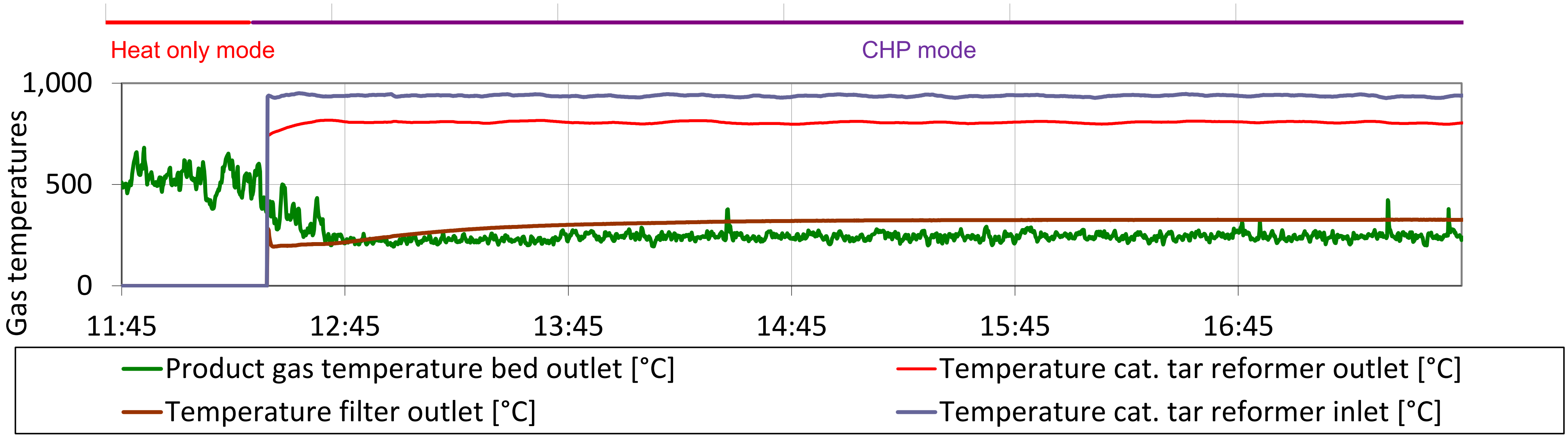
- **Selected results – operation stability and heat recovery**

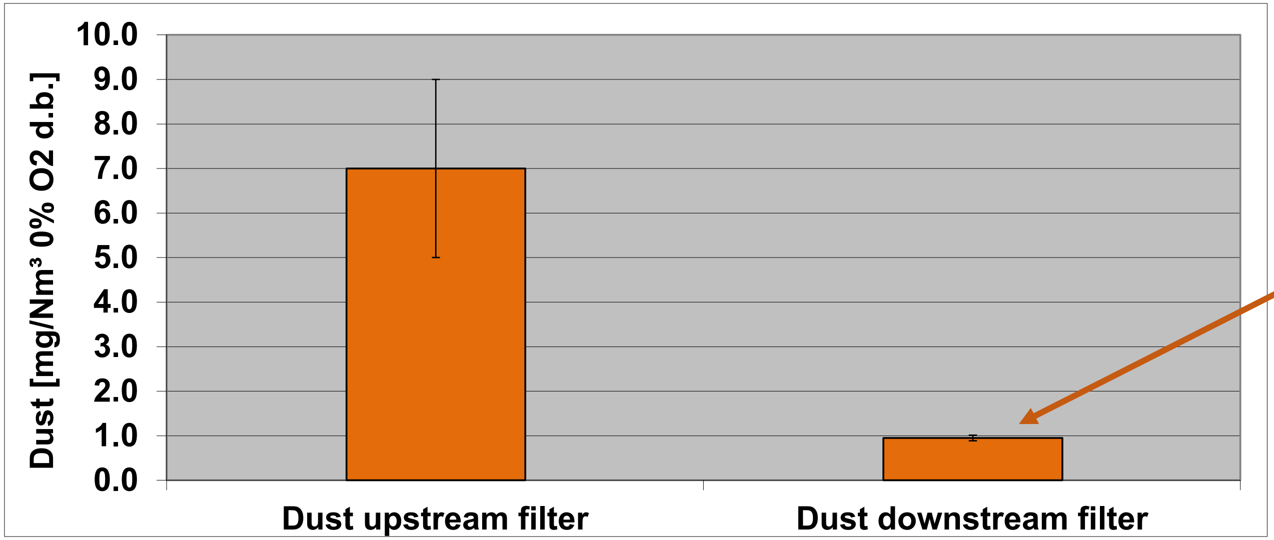


Explanations: us … upstream; ds … downstream

Results from test runs – General plant performance (II)

- **Selected results – tar reformer and high-temperature particle filter**





Results from test runs –
Evaluation of the tar reformer

- **Product gas characterisation along its pathway based on test run results**

		EPG tube inlet	EPG uspstream CTR	EPG downstream CTR
			mean values	mean values
Tgas	[°C]	~400	930	~820
CH_4	[vol% w.b.]	1 - 1.5	3.4	0.2
CO_2	[vol% w.b.]	7 - 8	9.7	9.4
CO	[vol% w.b.]	8 - 11	14.2	16.9
H_2O	[vol% w.b.]	44 - 47	32.6	27.0
H_2	[vol% w.b.]	8 - 10	12.5	29.8
Benzene	[ppm w.b.]	n.d.	2130	280
Naphthalene	[ppm w.b.]	n.d.	700	11
Gravimetric tars	[g/Nm³ d.b.]	100.0	2.7	0.6
NCV	[kJ/kg w.b]	5.2	5.6	6.4

→tar reduction of >99% (benzene reduction ~90%) achieved

→increase of NCV due to endothermic hydrocarbon reforming reactions

Explanations: EPG … extracted product gas; Tgas … Temperature of product gas; w.b. … wet basis; d.b. … dry basis; CTR … catalytic tar reformer; NCV … net calorific value; HT-Eq … high temperature equilibrium calculations; n.d. … no data

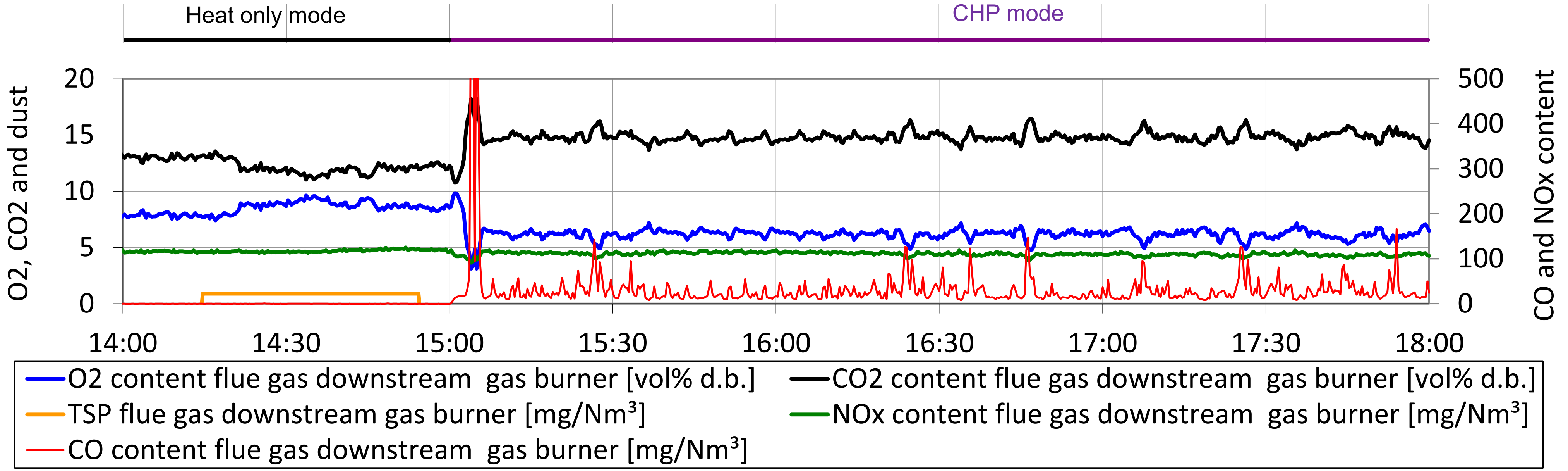
Results from test runs – High-temperature filter – dust and tar reduction

Dust content in the extracted product gas upstream filter (mainly soot particles)	mg/Nm³ dry product gas	5 - 9
Dust content in the product gas downstream the high-temperature filter	**mg/Nm³ dry product gas**	**0 - 1**
Tar content in the extracted product gas upstream filter	mg/Nm³ dry product gas	~ 600
Tar content in the product gas downstream the high-temperature filter	**mg/Nm³ dry product gas**	**240-280**

→ **the high-temperature filter provides the expected efficiency regarding the minimization of the dust content of the product gas to levels below 1 mg/Nm³**

→ **further tar reduction due to reactions of soot particles on filter candle surface with tar compounds**

Results from test runs – emissions downstream the gas burner

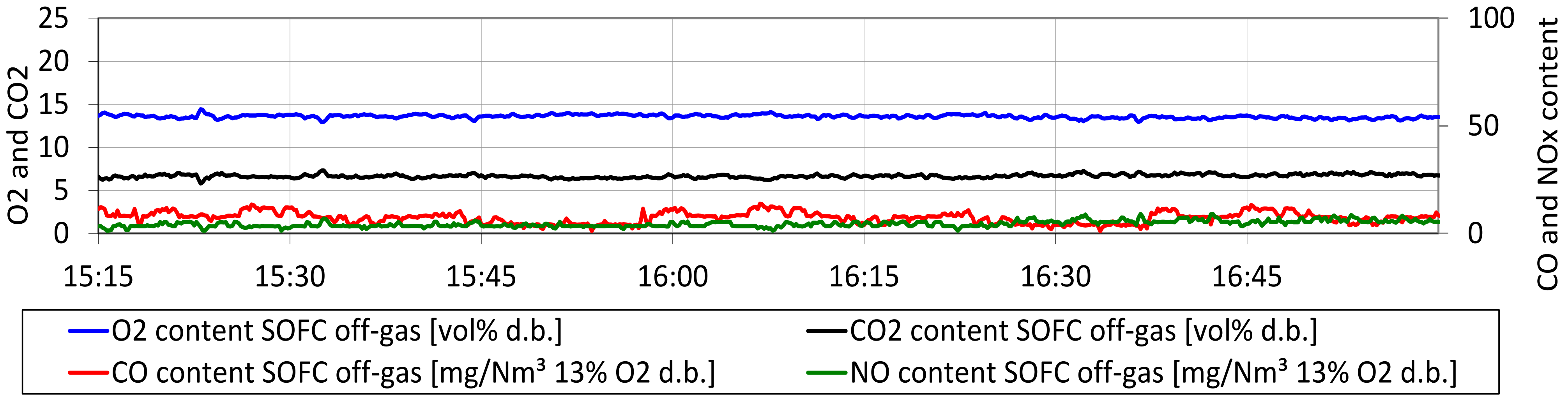


- → **very good burnout quality of flue gas achieved**
- → **low NO_x emissions due to the optimized air-staging in the gas burner**
- → **zero dust emission operation**

		flue gas downstream gas burner
		mean
CO content	[mg/Nm³ 13% O2 d.b.]	20.0
NOx (NO2) content	[mg/Nm³ 13% O2 d.b.]	105.0
TSP (totatl dust)	[mg/Nm³ 13% O2 d.b.]	< 1

Explanations: Emissions related to dry flue gas and 13% O_2; TSP … total suspended particles

Results from test runs – emissions SOFC off-gas



- → **very good burnout quality of off-gas achieved**
- → **almost zero NO_x emissions due to almost complete conversion of NO_x precursors NH_3 and HCN to N_2 in the stack module**
- → **zero dust emission operation**

		SOFC off gas
		mean
CO content	[mg/Nm³ 13% O2 d.b.]	10.0
NOx (NO2) content	[mg/Nm³ 13% O2 d.b.]	5.0
TSP (totatl dust)	[mg/Nm³ 13% O2 d.b.]	< 1

Results from test runs – thermal efficiency BCM and overall testing plant

Energy balance BCM		
Boiler load BCM	[kW]	10.85
O2 content flue gas downstream BCM	[vol% d.b.]	6.02
Flue gas temperature at boiler outlet	[°C]	88.70
Flue gas temperature at condenser outlet	[°C]	32.83
Energy balance boiler		
Input		
Biomass fuel power	[kW NCV]	18.9
Output		
EPG chemical and thermal power	[kW]	8.0
Boiler load	[kW]	9.9
Heat losses - radiation and convection	[kW]	0.5
Heat losses - flue gas	[kW]	0.4
Efficiency boiler (related to NCV)	**[%]**	**94.8**
Energy balance boiler + condenser		
Input		
Biomass fuel power	[kW NCV]	18.9
Output		
EPG chemical and thermal power	[kW]	8.0
Boiler load	[kW]	9.9
Condenser load	[kW]	1.7
Total efficiency incl. condenser (related to NCV)	**[%]**	**104.1**

Energy balance testing plant		
Energy balance		
Input		
Biomass fuel input	[kg/h]	3.9
Biomass fuel power	**[kW NCV]**	**18.9**
Output		
Boiler load BCM	[kW]	9.9
Condenser load	[kW]	1.7
Load SOFC heat recovery	[kW]	2.3
Electronic load power	[kW]	2.6
Total output	**[kW]**	**16.5**
Overall plant efficiency (related to the NCV of the fuel)	**[%]**	**87.3**
Latent heat recovered by condenser/SOFC HEX	[kW]	0.5
Heat losses - flue gas / SOFC off-gas	[kW]	0.5
Heat losses through radiation and convection		
BCM	[kW]	0.5
SOFC module	[kW]	1.8
Connecting pipe BCM - SOFC	[kW]	0.1
Connecting pipe SOFC - heat recovery	[kW]	0.4
Total heat losses - radiation and convection	[kW] / [% of input]	2.8

→ **high thermal efficiencies of 95% (104% including condenser) of BCM achieved**

→ **overall plant efficiency amounts to 87.3 % (related to NCV of the fuel) - slightly lower than the anticipated value of > 90% due to comparatively high heat losses of the SOFC module and connection pipes → can be minimised in a real plant**

Conclusions

- **Stable operating behaviour** and **good burnout quality** of flue gas achieved
- **Dust emissions** downstream BCM are in the range of ≤ 1.0 mg/Nm^3 (related to 13% O_2 and dry flue gas) – **zero dust emission operation** achieved
- **Very low total NO_x emissions** due to **optimized air-staging** in the product gas burner and **almost zero NO_x emissions** of the SOFC
- **Boiler** and **condenser** enable **highly efficient heat recovery**
- Stable and **good EPG quality** obtained - the composition of the EPG regarding the main compounds is in the expected range and targeted fuel power input for SOFC achieved
- A **tar reduction** of **>99 %** to values < 0.5 g/Nm^3 and a **low benzene content** of the extracted product gas could be achieved
- The **high-temperature particle filter** provides the expected precipitation efficiency and **dust contents** in the product gas **below 1 mg/Nm^3**

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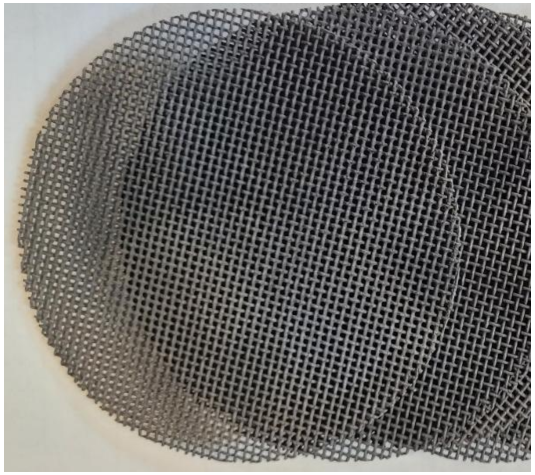
Development of a novel highly efficient energy supply system
for energy autonomous multi-family buildings
based on biomass gasification coupled with an SOFC and a PV system

Thank you for your attention



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Development of a novel highly efficient energy supply system for energy autonomous multi-family buildings based on biomass gasification coupled with an SOFC and a PV system

Test run results – SOFC performance

Prepared by: Luc Conti

INERGIO

Final public project workshop

Online

25 March 2026

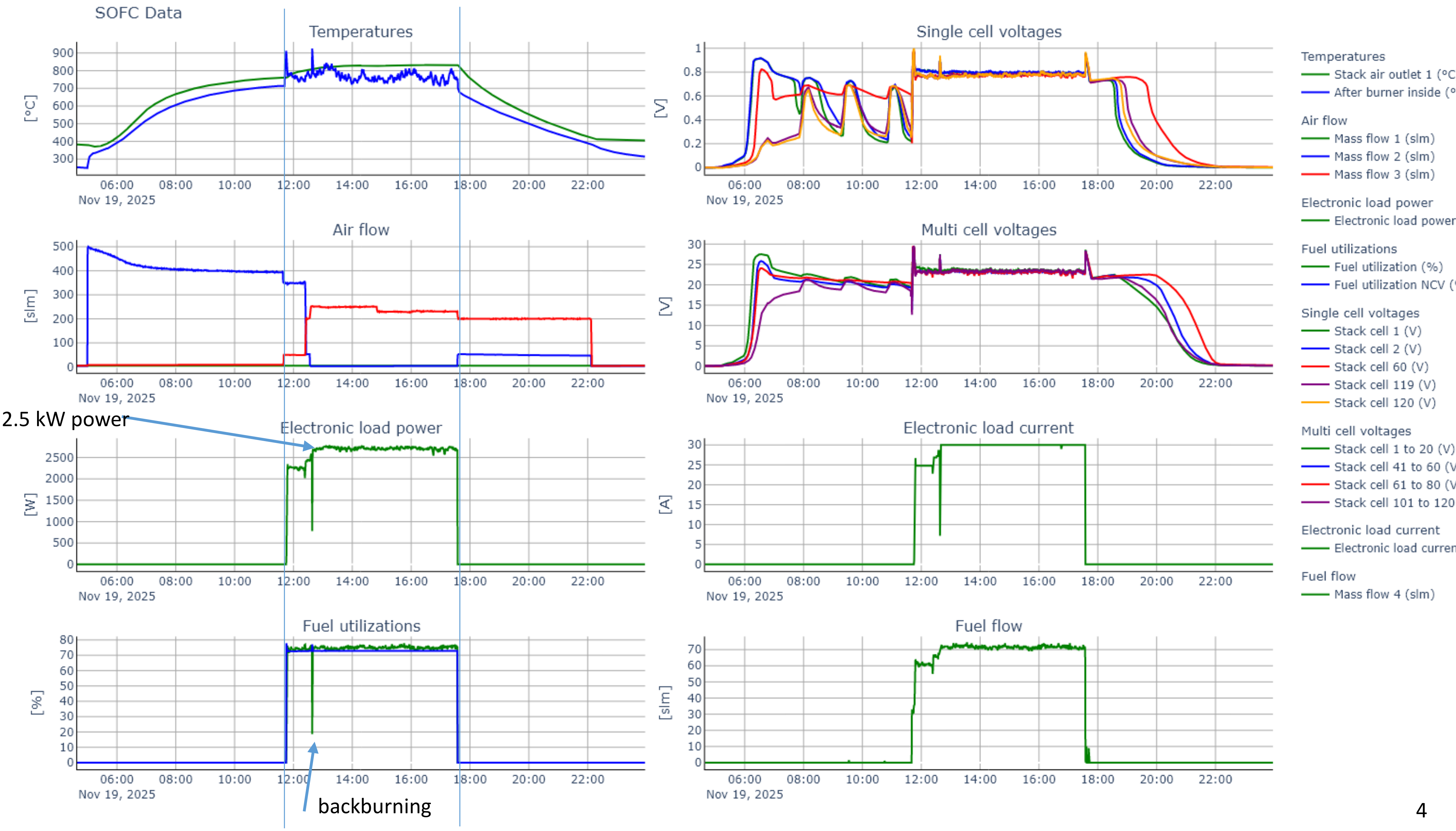
Content

- Objectives
- Results
- Conclusions and outlook

Objectives

- **Extract 2.5 kW of electricity from the SOFC stack**
- **Achieve a net electrical efficiency above 40%**
- **Manage to run the system with minimal degradation**
- **Perform a backburning (catalyst and filter cleaning) without breaking the stack**

Test run results (I)



2.5 kW power

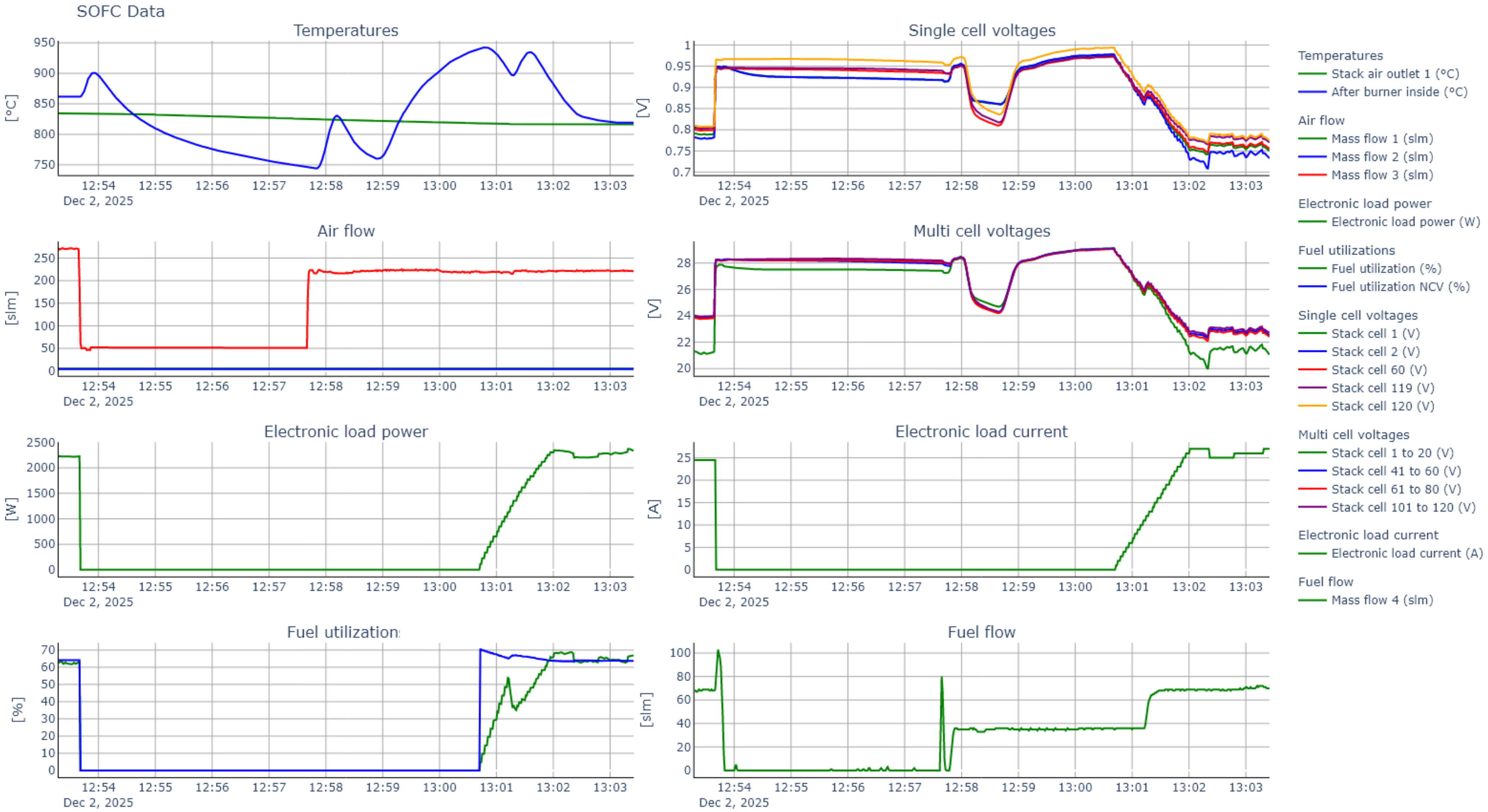
backburning

Test run results (II)

Operation data of stack module

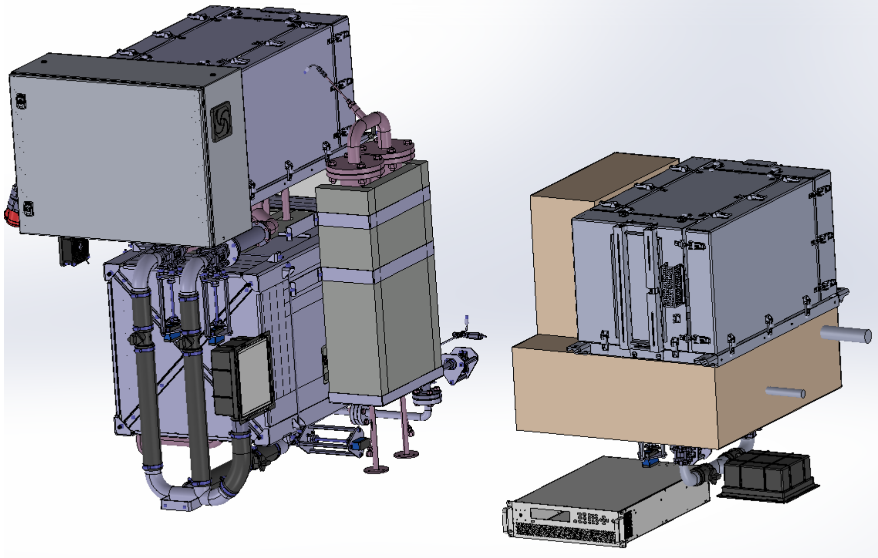
EU-Micro-Bio-CHP-testing plant - November 2025		**Nominal load**	**Nominal load**	**Nominal load**	**Nominal load**	System design
		27.11 12:30:00 27.11 15:00:00	24.11 15:15:00 24.11 16:15:00	20.11 13:00:00 20.11 15:30:00	18.11 17:05:00 18.11 18:02:00	**Nominal load**
Stack module						
Flow rate product gas (PG)	[kg/h]	3.80	3.78	3.73	3.77	4.00
	[Nl/min]	70.43	71.14	70.04	71.74	76.0
Fuel power PG anode in	**[W]**	**6,654**	**6,565**	**6,495**	**6,434**	**6,365**
Air flow stack in	[Nl/min]	249.57	226.54	226.18	217.54	350.00
Air flow stack in	[kg/h]	19.21	17.44	17.41	16.75	27.13
Air stack in (T6)	[°C]	569.80	557.80	553.10	548.09	630.00
Air cathode in	[°C]	761.78	755.65	762.16	745.77	755.00
Air cathode out	[°C]	825.57	818.20	825.85	808.69	835.00
Air cathode out (T11)	[°C]	817.05	809.40	816.40	796.36	835.00
PG stack in (T15)	[°C]	610.68	594.49	586.67	574.55	635.00
PG anode in (T12)	[°C]	720.90	712.03	717.17	697.16	720.00
PG anode out (average)	[°C]	789.60	780.56	787.25	772.49	785.00
PG stack out (T10)	[°C]	722.52	713.05	718.65	707.30	678.00
Stack voltage 1	[V] cell 1	0.80	0.79	0.80	0.79	0.78
Stack voltage 2	[V] cell 2	0.80	0.80	0.80	0.80	0.81
Stack voltage 3	[V] cell 1-30	23.15	23.16	23.25	23.75	24.10
Stack voltage 5	[V] cell 31-60	23.36	23.01	22.96	23.22	23.60
Stack voltage 6	[V] cell 60	0.78	0.77	0.77	0.77	0.79
Stack voltage 7	[V] cell 61-90	23.26	23.05	22.90	23.23	23.70
Stack voltage 9	[V] cell 91-120	23.49	23.24	23.27	23.43	23.80
Stack voltage 10	[V] cell 119	0.79	0.78	0.79	0.77	0.76
Stack voltage 11	[V] cell 120	0.79	0.77	0.79	0.77	0.76
Electronic load voltage	[V]	90.66	89.86	89.88	91.22	94.90
Electronic load current	[A]	28.48	28.49	28.44	28.48	30.00
Electronic load power (W)	**[W]**	**2,582.25**	**2,560.07**	**2,557.02**	**2,598.07**	**2,863.00**
Measured electric efficiency	**[%]**	**39.86**	**40.03**	**40.48**	**40.48**	**44.73**
Fuel utilisation based on current	[%]	68.37	69.54	70.60	70.02	74.50

Backburning phase

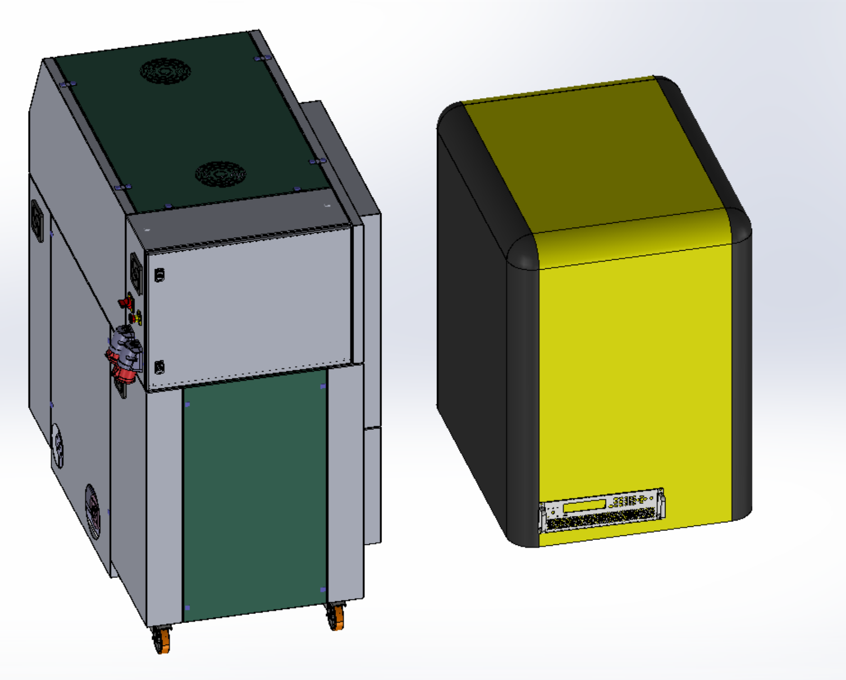


Conlusions and outlook

- TRL 5 achieved: SOFC module was build and the concept of a SOFC system working with product gas from wood pellets gasification has been proven
- Electric efficiency > 40% achieved
- Completely autonomous operation was possible
- Tightness of the system and insulation need further improvement
- It is now possible to move to a higher TRL and develop a machine ready for commercialization



Actual design TRL6-7 concept



Actual design TRL6-7 concept

Thank you for your attention

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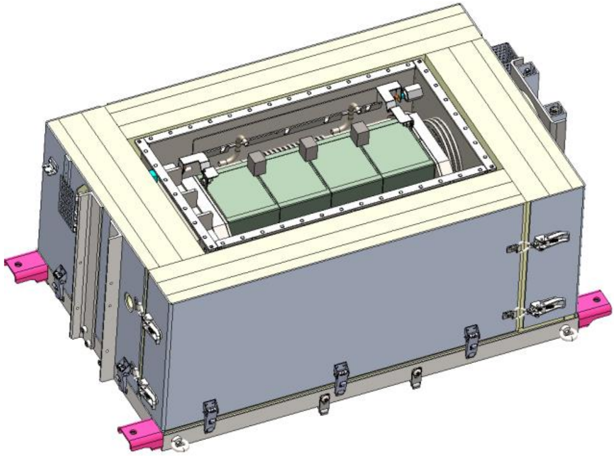
Development of a novel highly efficient energy supply system
for energy autonomous multi-family buildings
based on biomass gasification coupled with an SOFC and a PV system

Test run results SOFC module – commissioning of stack



Prepared by: Anna Seidl

Final public project workshop

Online

25 March 2026

Fraunhofer
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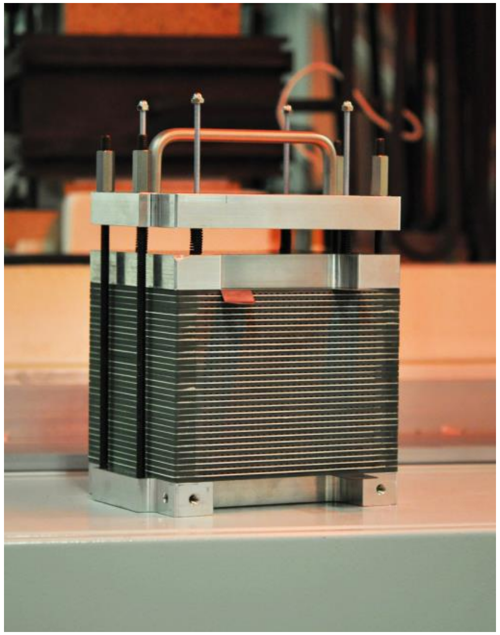
Commissioning results

Outline

- Voltage sensing
- Variation of fuel utilization
- Air variation
- Temperature variation
- Derived operating points

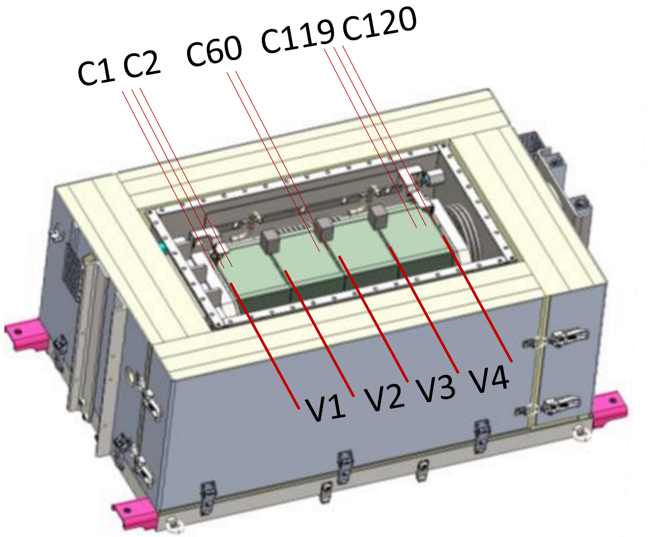


Commissioning results

Voltage sensing

Voltage sensing

- Voltages as primary monitoring of stack performance
- Stack should not be operated below critical value of 0.7 V for longer periods
- Package voltages with 30 cells of each stack (V1, V2, V3, V4)
- Single cell monitoring of two edge cells at each side and in the middle (C1, C2, C60, C119, C120)



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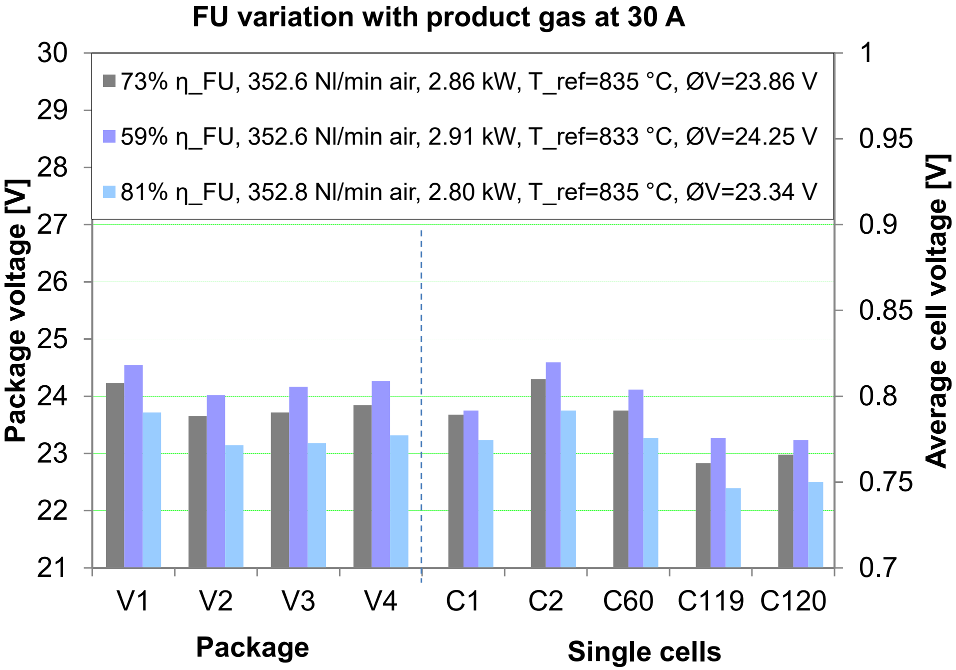
Commissioning results

Variation of fuel utilization

Fraunhofer IKTS

Variation of fuel utilization

- Synthetic gas is mixed at the test stand with a composition corresponding to the product gas from the BCM
- Variation of FU from 73 % to 81 % at 30 A
  → the higher FU the lower the voltages
  → no irregularities
- Power output of 2.86 kW_{el} sufficient for CHP plant (above target value)

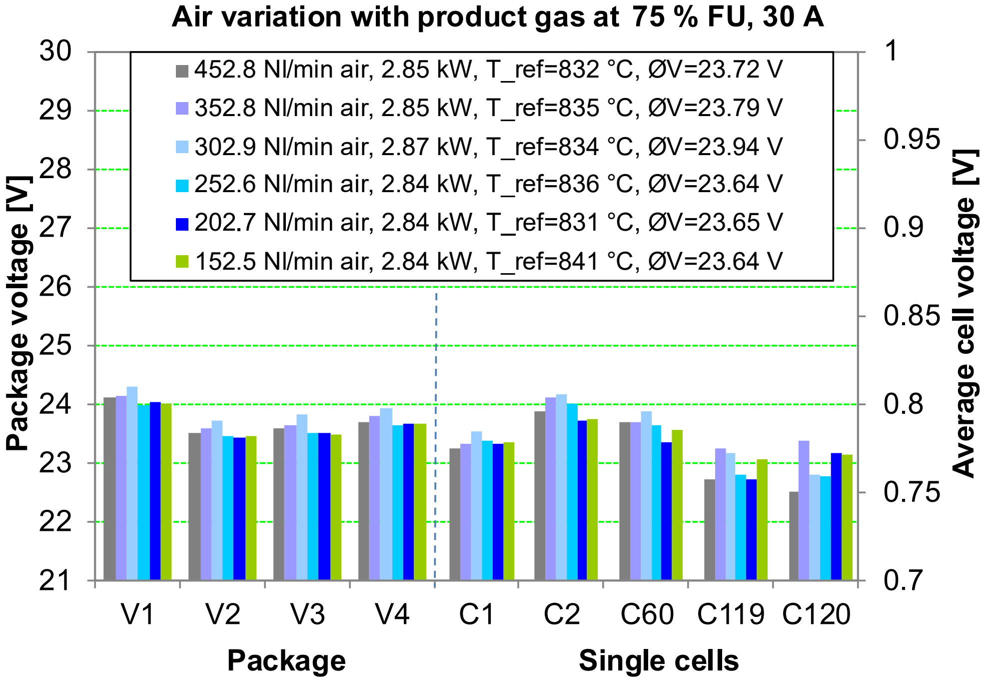


Commissioning results

Air variation

Air variation

- Determination of minimum air flow at full load
- Stable stack module performance at 150 slm
- Difference in voltages due to temperature changes and water dosing

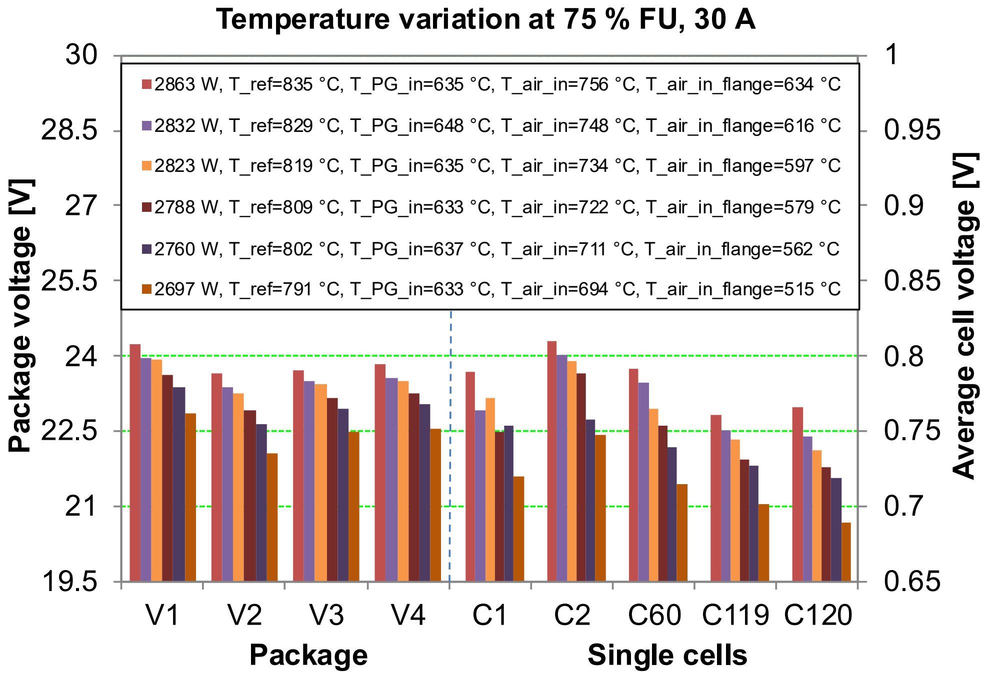


Commissioning results

Temperature variation

Temperature variation

- Operation window for different temperatures of the air outlet from 790 °C to 835 °C
- The lower the temperature the lower the voltages
- Power output still sufficient
- Air outlet temperatures < 800 °C should be avoided due to low voltages of the edge cells



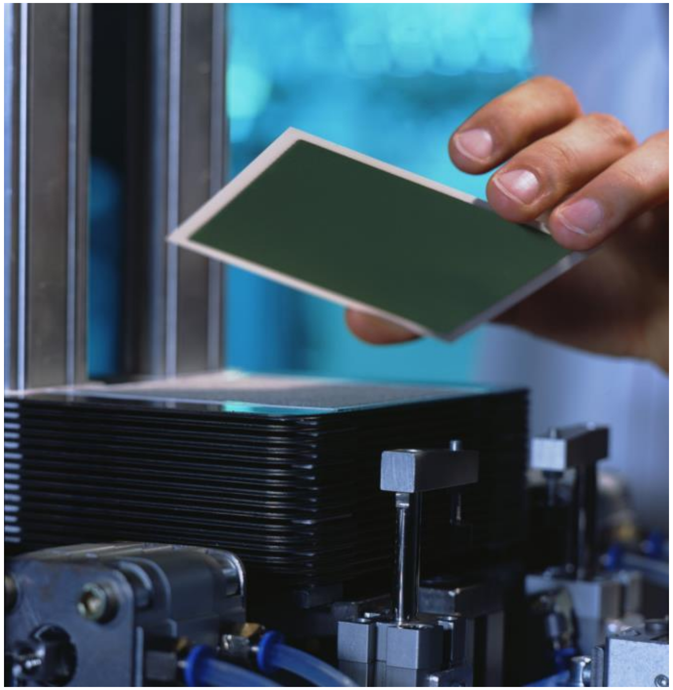
Commissioning results

Operating points

Derived operating points

- $V_{cell} \geq 0.7$ V
- FU ≈ 75 %
- Cathode air flow > 150 slm
- $T_{air\ out} \geq 800$ °C (stack operation temperature)

→ These guiding values derived from the commissioning tests have been used as a basis for process control settings of the SOFC module



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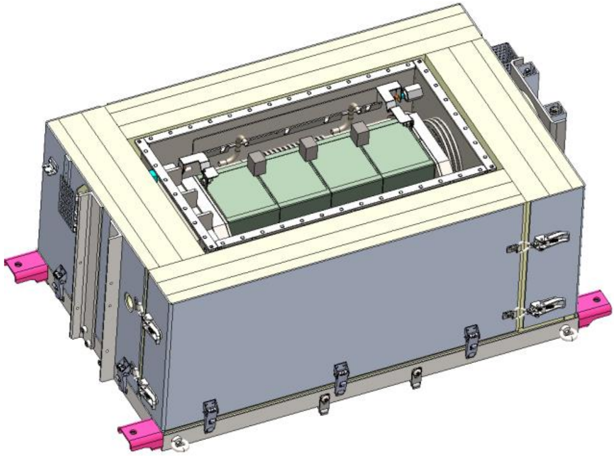

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Application of the Micro-Bio-CHP concept in different building types

Prepared by: Klaus Supancic, Ingwald Obernberger, Thomas Brunner

BIOENERGIESYSTEME GmbH

Final public project workshop

Online

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Content

- Objectives
- Methodology
- Results
- Conclusions

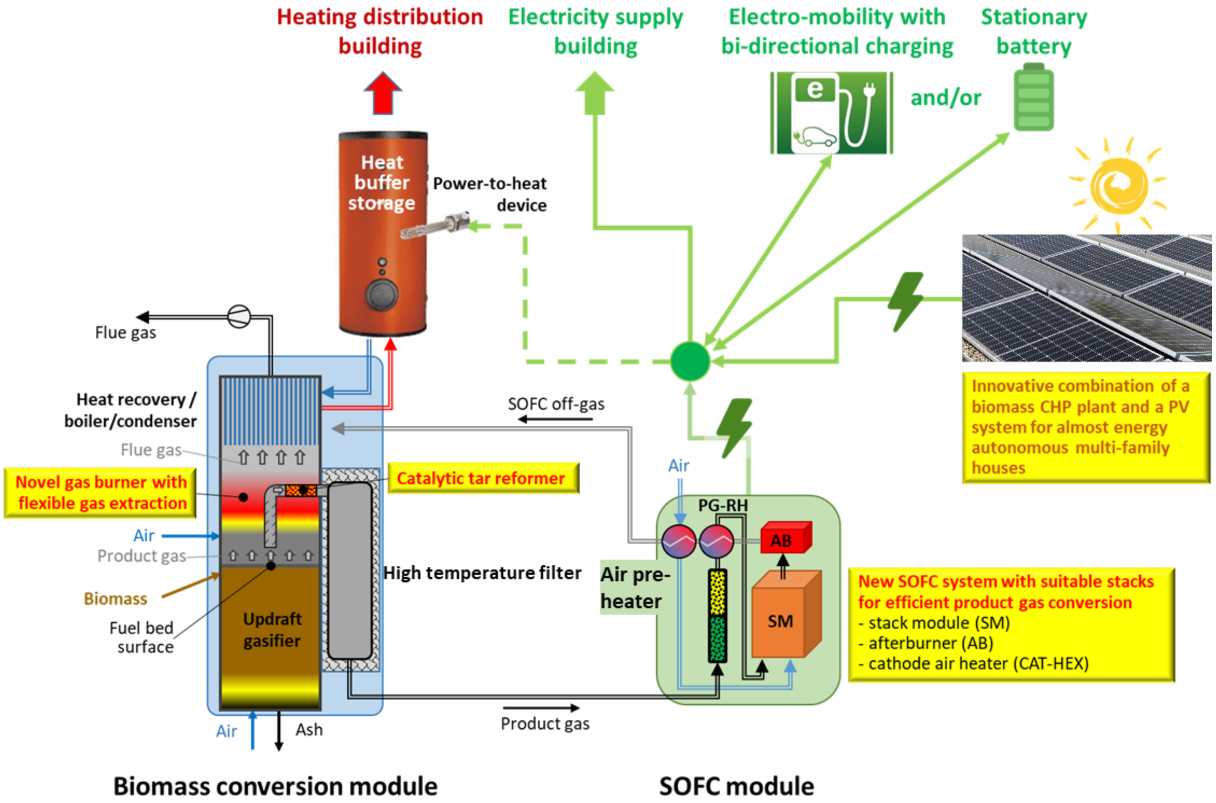
Objectives

- Investigation of the framework conditions for the integration of the µ-Bio-CHP system in residential buildings with different heat and electricity demand profiles over a calendar year.
- Definition of meaningful cornerstones regarding minimum building sizes and regarding cascading options to supply bigger buildings as a basis for scaling up and down the technology.
- The results of these evaluations also helped, in combination with the results of the techno-economic analysis, to define the constraints and demands for the final system design to assure the development of a technically optimized as well as economically competitive solution.

Methodology –
Description of the technology (I)

Process overview

- The µ-Bio-CHP technology shall be coupled with a photovoltaic plant, a battery storage system (electricity) and a buffer storage system (heat). Either a stationary battery system or the batteries of E-cars (bi-directional charging) shall be used as battery storage.



Novel gas burner with flexible gas extraction

Catalytic tar reformer

Innovative combination of a biomass CHP plant and a PV system for almost energy autonomous multi-family houses

New SOFC system with suitable stacks for efficient product gas conversion
- stack module (SM)
- afterburner (AB)
- cathode air heater (CAT-HEX)

SOFC … Solid Oxide Fuel Cell; PG-RH … product gas pre-heater, AB … after burner, SM … stack module

Methodology – Description of the technology (II)

Framework conditions

- The following framework conditions have been considered:
  - Fuel power needed for full load SOFC operation: approx. 14 kW
  - Maximum heat output (incl. condenser): approx. 9.4 kW
  - Maximum gross electricity output of the SOFC: 2.5 kW; considering the own consumption of about 290 W, the net electricity output of the SOFC is approx. 2.2 kW
  - Minimum fuel power for partial load operation (50%) of the SOFC: approx. 10 kW
  - Minimum heat output (without condenser) to operate the SOFC at partial load: approx. 6 kW
  - Net electricity output of the SOFC at 50% partial load: 1.1 kW

Methodology –
Simulation over on e calendar year (I)

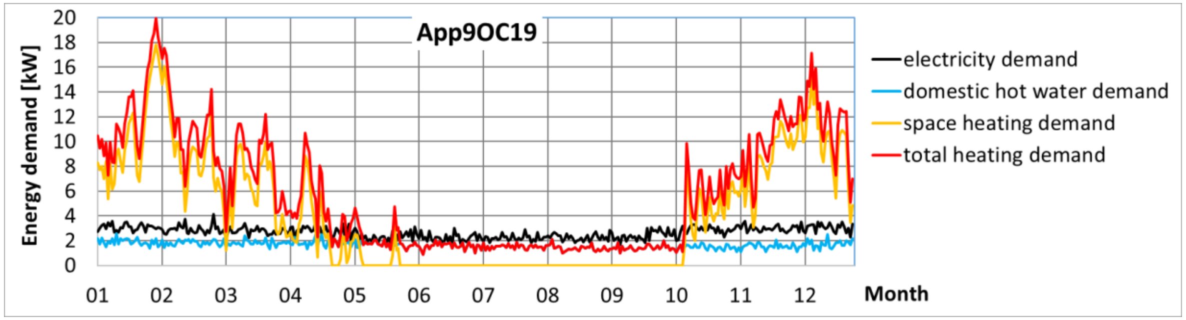
Simulation tool

- BIOS developed a calculation tool based on MS-Excel that simulates the operation of the µ-Bio-CHP system based on the heat demand of selected buildings. The tool features the options to include a buffer storage, a power to heat device, a PV system, a battery system and/or bi-directional charging and the feed-in of excess electricity to the grid.
- At each hourly step, the algorithm
    1. computes building heat and electricity demand;
    2. determines µ-Bio-CHP operation based on heat demand and buffer state-of-charge (SoC) according to the control logic;
    3. derives SOFC electric output from the µ-Bio-CHP thermal set-point;
    4. applies PV generation from the scaled profile;
    5. allocates surplus electricity to stationary storage (subject to limits and efficiencies), then to E-car storage (subject to availability and daily mobility constraints), otherwise to grid export; and
    6. covers deficits by discharging stationary storage, then E-car storage, finally importing from the grid. Power-to-heat (P2H) is activated per thresholds to cover DHW and summer needs. SOFC start-up energy is added to the electricity balance whenever a start event occurs.
- Load profiles originate from prior R&D datasets based on synPRO (Fraunhofer ISE). Profiles include electricity, DHW and space heating at 1-minute granularity for multiple residential archetypes (see next slide).

Methodology –
Energy load profiles

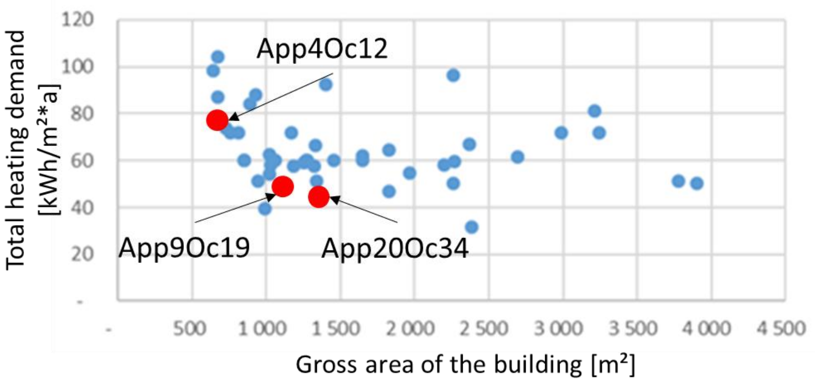
Energy load profile considered

- In this presentation only results for the App9Oc19 building (nine apartments, nineteen occupants) are shown. The specific annual heat demand (without distribution losses) is consistent with typical multi-apartment buildings in the target region (see below); distribution and buffer losses are accounted for separately in the simulation.



Building name		**App9Oc19**
Apartments per building		9
Number of buildings		1
Number of inhabitants per building		19
Annual heat demand DHW	[kWh/a]	14,287
Annual space heating demand	[kWh/a]	36,720
Total annual heat demand	[kWh/a]	51,007
Total annual electricity demand building	[kWh/a]	23,201
Annual electricity demand per apartment	[kWh/a]	2,578
Spec. Heat demand DHW	[kWh/m²*a]	16
	[kWh/a*person]	752
Spec. heat demand space heating	[kWh/m²*a]	40
Total spec. heat demand	[kWh/m²*a]	56
Total living space	[m²]	918
Average living space per dwelling	[m²]	102

DHW … domestic hot water



Methodology – Additional framework conditions (I)

Size of the µ-Bio-CHP system

- Heat output and size of the buffer storage were adjusted to allow for a full coverage of the heating demand and most of the DHW demand during the heating season (October to early April). Outside the heating season or during periods of heat demand peaks the additional demand shall be covered by a power to heat device, powered by electricity from the PV system. Moreover, starts and stops of the SOFC system per year shall be minimized (below 10). Considering these constraints, the following plant specification has been considered for App9Oc19:

Thermal power output (nominal load)	[kWth]	18
Net electricity output	[kWel]	2.2
Buffer storage capacity	[kWh]	240

Size of the PV system

- PV generation uses an annual profile measured on the BIOS office rooftop in Graz (49.1 kWpeak, 268.5 m²) as a basis that was scaled to the needs of the individual buildings.

Methodology – Additional framework conditions (II)

Stationary battery sizing

- Stationary batteries are used to store electricity from PV systems during the day to provide electricity during periods with no sun light (night or bad weather). Two scenarios were investigated:
  - Scenario 1 with 48 kWh useful capacity for App9Oc19
  - Scenario 2 was calculated with half the battery size of Scenario 1, 24 kWh net.
- PV and battery systems operate with DC while consumers in the buildings operate with AC. The conversion from DC to AC and vice versa is done by inverters that feature conversion losses which were considered in the simulations.

Bi-directional charging: assumptions and constraints for App9Oc19

- Generally, the calculations are based on the assumption that each household (i.e. apartment) owns one E-car. For App9Oc19, Scenario 1 assumes that on average 50% of the E-cars are available for BDC (4.5 available E-cars); Scenario 2 halves this to 25% average availability (2.25 E-cars).

µ BIO CHP

Results –
Building and plant configuration evaluated

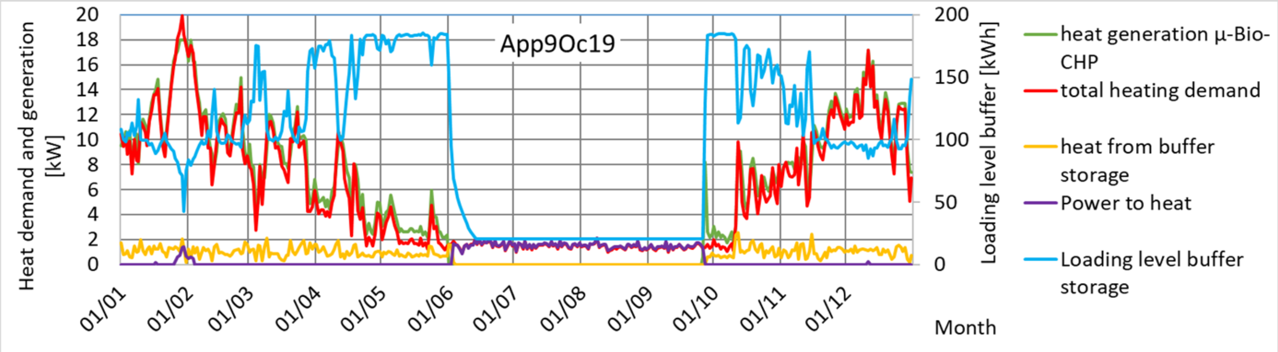
BIOENERGIESYSTEME GmbH

Building and plant configuration for Scenario 1 and 2

Building name		App9Oc19	
Apartments per building		9	
Number of buildings		1	
Number of inhabitants per building		19	
Total annual heat demand	[kWh/a]	51,007	
Total annual electricity demand	[kWh/a]	23,201	
µ-Bio-CHP system			
Heat output	[kWth]	18	
Net electricity output	[kWel]	2.2	
Buffer storage capacity	[kWh]	240	
PV system			
Peak load (kWpeak)	[kWel]	39.3	
Annual electricity generation (after inverter)	[kWhel/a]	40,089	
Battery storage system			
Scenario		*1*	*2*
Usable storage capacity stationary battery	[kWh]	48	24
Number of E-cars considered		4.50	2.25
Kilometres travelled per year and vehicle	[km/a]	13,100	13,100
Kilometres travelled per day and vehicle	[km/d]	35.9	35.9
Electricity demand	[kWh/100km]	21	21
Average daily electricity demand	[kWh/d]	7.5	7.5
Battery capacity per E-car	[kWh]	65	65
Max. discharge to	[kWh]	30	30
Max. available capacity per car	[kWh]	27.5	27.5

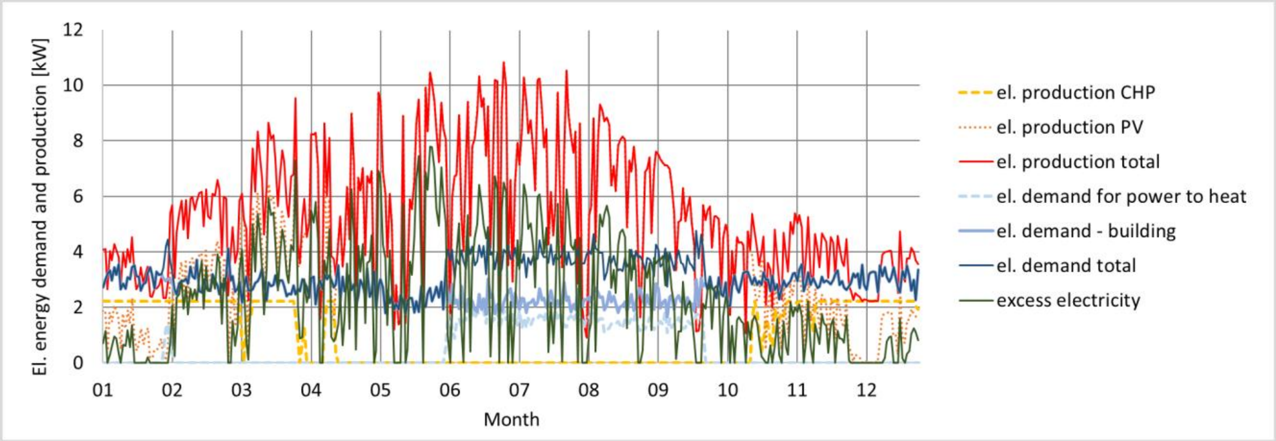
- Due to the limited time available, only the results of Scenario 1 are shown .

Results –
Heat and electricity generation – Scenario 1 (I)



Building name		App9Oc19
Heat generation µ-Bio-CHP	[kWh/a]	51,557.2
Full-load operating hours heat generation	[h/a]	2,864.3
Power to heat (PTH)	[kWh/a]	4,414.5
Storage capacity buffer	[kWh]	240.0
Direct heat use	[kWh/a]	45,140.2
Heat used from buffer storage	[kWh/a]	5,866.8
Heat losses distribution system	[kWh/a]	4,964.8
		9%
Biomass fuel consumption	[kWh/a]	75,318.9
Annual utilisation rate µ-Bio-CHP		79.6%

- The main share (>90%) of the total heat production of 55.3 MWh/a is provided by the µ-Bio-CHP system, a small amount is provided by power to heat, mainly during the summer months.
- About 45.0 MWh/a of the heat generated are directly used in the building, 6.0 MWh/a are provided from the buffer storage.
- The annual utilization rate of the µ-Bio-CHP system (incl. electricity generation) is around 80%.



Results –
Heat and electricity generation – Scenario 1 (II)

Electricity generation and use, scenario 1, DC coupling – overview:

Building name		**App9Oc19**	**App9Oc19**
Configuration electricity storage system		stationary battery/ stationary battery + bi-directional charging	no electricity storage/ bi-directional charging only
Electricity production µ-Bio-CHP	[kWh/a]	8,418.0	8,418.0
SOFC starts/stops		*7*	*7*
Electricity demand for heating-up during SOFC start	[kWh/a]	175	175
Electricity generation PV system	[kWh/a]	40,089.2	40,089.2
Total electricity generation	[kWh/a]	48,507.2	48,507.2
Annual electricity demand building + Power to Heat	[kWh/a]	27,790.5	27,790.5
Storage capacity stationary battery	[kWh]	60	0
Usable storage capacity stationary battery	[kWh]	48.0	0.0
Direct electricity use [kWh/a]	[kWh/a]	17,232.0	17,232.0
Electricity from stat. battery	[kWh/a]	9,356.6	0.0
System losses stat. Battery	[kWh/a]	859.8	0.0
el. self-sufficiency with and w/o stat. battery		*96.3%*	*62.4%*
Electricity from grid with and w/o stat. battery	[kWh/a]	1,201.8	10,558.5
Excess electricity to grid with and w/o stat. battery	[kWh/a]	21,058.8	31,275.2
Bi-directional charging (BDC)			
Number of E-cars considered		9	9
Battery capacity per E-car	[kWh]	65	65
Max. discharge to	[kWh]	30	30
Max. available capacity per car	[kWh]	27.5	27.5
Average availability of E-cars	[-]	0.5	0.5
Usable electricity for E-cars (net charging)	[kWh/a]	9,972.3	10,069.1
Kilometres travelled per year by net charging	[km/a]	47,487.1	47,947.9
Electricity from BDC to consumers	[kWh/a]	503.1	9,410.3
System losses BDC (charging + discharging)	[kWh/a]	1,012.5	2,319.7
el. self-sufficiency with and w/o stat. battery +BDC		*97.5%*	*95.9%*
Electricity from grid with and w/o stat. battery + BDC	[kWh/a]	698.8	1,148.1
Excess electricity to grid with and w/o stat. batt. + BDC	[kWh/a]	9,570.9	9,476.0

- The electricity self-sufficiency raises from about 63% w/o any electricity storage system to 97.3% (87.6% Sc2) with a stationary battery only and to 96.8% (96.3 Sc2) with bi-directional charging only. The combination of both storage systems increases the self-sufficiency to 97.7% (97.2% Sc2).
- Based on theses findings, the combination of both el. storage systems does not provide a relevant improvement regarding self-sufficiency.
- Less than 10 SOFC starts per year, buffer storage is designed properly.

Results – Heat and electricity generation – Scenario 1 (III)

Comparison stationary battery vs. bi-directional charging

- Comparing the overall system with stationary battery only and bi-directional charging only, the following can be concluded:
  - The amount of electricity used within the system (electricity demand building, power to heat, net E-car loading) is for bi-directional charging higher, as additional electricity can be used in the E-cars.
  - No additional investment costs for bi-directional charging (apart from appropriately adapted loading station) are needed
  - The benefits of bi-directional charging decrease with a decreasing number of E-cars available; considering that on average only between 25 and 50% of the E-cars are available for BDC 1 E-car per apartment is recommended
  - A maximum charging capacity of 11kW per E-car is sufficient to utilize more than 99% of the electricity that is available for E-car charging.
  - If no or not enough E-cars are available a stationary battery can make sense.
  - A higher number of apartments and occupants (consumers) are of advantage as load rates get smoothened and electricity demand rises.

Summary and Conclusions (I)

- **Suitability of the µ-BIO-CHP system to cover the heat and electricity demand of residential buildings:**
  - With a proper design of the system (µ-BIO-CHP plant, buffer storage, PV system and electricity storage system) and an appropriate control strategy the complete heat demand and the main share of the electricity demand of residential buildings with different sizes can be covered.
  - Buildings with a daily average heat demand (space heating and DHW combined) of at least 6.2 kW_{th} during the heating season are suitable for the µ-BIO-CHP system in the configuration evaluated in the simulations. This corresponds to an annual heat demand of around 50 MWh/a.
  - If the daily average heat demand increases above 12.4 kWth, a second µ-BIO-CHP unit can be installed.
  - Bi-directional charging with E-cars is more beneficial than the installation of a stationary battery
    - It increases the electric self-efficiency of the building & provides a significant share of the annual electricity demand of the E-cars per year.
  - However, legal framework conditions do currently not allow bi-directional charging in Austria and Germany. Considering the benefits of bi-directional charging, it is to be hoped that the legal situation will change in this regard soon.

Summary and Conclusions (II)

- **Suitability of the µ-BIO-CHP system to cover the heat and electricity demand of residential buildings (cont.):**
  - To achieve a high electric self-sufficiency and a high internal electricity utilisation rate
    - the size of the buffer storage system shall be in the range of of 4 to 5 kWh/MWh heat demand per year,
    - the size of the PV system shall be in the range of about 1.2 to 1.45 kWpeak/MWh electricity demand per year,
    - a bi-directional charging system that involves as many cars as possible (at least 1 e-car per apartment, if an average availability of the E-cars for BDC of 25 to 50% is considered) with a charging capacity of at least 11 kW (AC charging) shall be implemented (preferred over a stationary battery),
    - as an alternative to bi-directional charging (which is currently not possible in Austria and Germany) a 0.50 – 0.65 $\mathrm{kWh}_{\mathrm{storage}}$/MWh electricity produced per year (smaller values for larger numbers of apartments in a house) battery storage can be installed.

Thank you for your attention

https://microbiochp-project.eu

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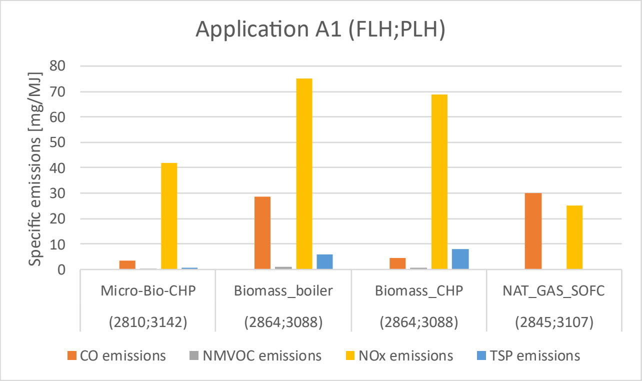
µ BIO CHP

Development of a novel highly efficient energy supply system
for energy autonomous multi-family buildings
based on biomass gasification coupled with an SOFC and a PV system

Environmental and overall impact assessment



Prepared by: Birte Schnurr, Thomas Götz, Jan Kaselofsky

Wuppertal Institut

Final public project workshop

Online

25 March 2026

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Environmental and overall impact assessment

- **Assessment of macro-scale impacts, Austria and Germany (use phase)**
- **Focus of this presentation:**
  - Results for Germany
  - GHG emissions
  - Non-GHG emissions: TSP („total suspended particles“), NMVOC, CO, NO_x

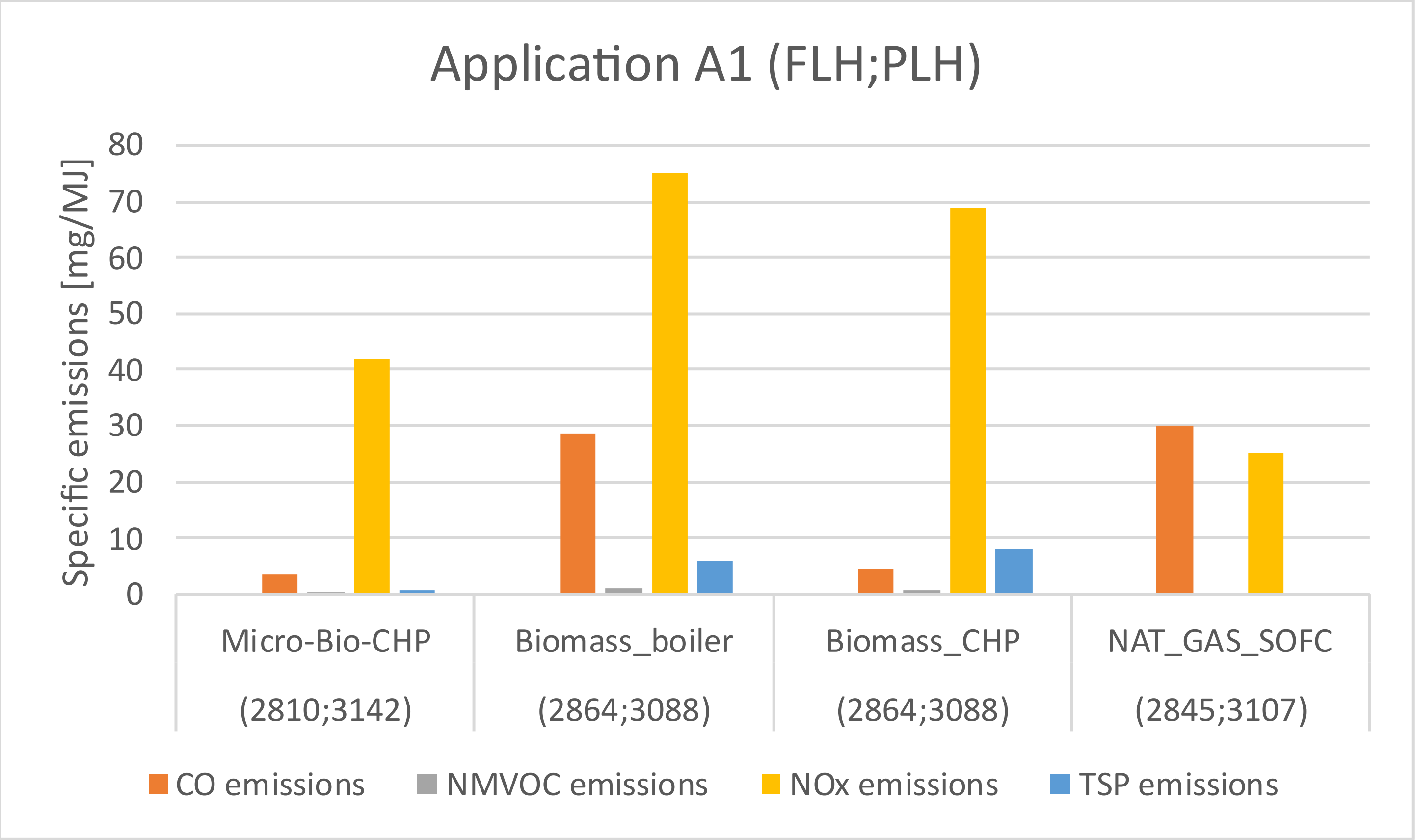
- **Emissions are result of:**
  - Solid fuel gasification and gas conversion/combustion
  - Net electricity consumption (incl. grid electricity effects)

Environmental and overall impact assessment

- **Example application case A1 for this presentation:**
  - MFH with 9 apartments (→ from techno-economic analysis)
    - 36.7 MWh/yr space heating demand
    - 14.3 MWh/yr total domestic hot water demand (70% covered by CHP heat supply, 30% covered by electricity from PV)
    - 52.5 MWh/yr electricity demand, about 50% for e-mobility and around 10% from grid electricity (5.4 MWh/yr)
- **Technology options analysed and compared:**
  - Micro-Bio-CHP
  - Natural gas-based fuel cell (SOA)
  - Micro-scale biomass CHP (SOA)
  - Biomass boiler (SOA)

Environmental and overall impact assessment

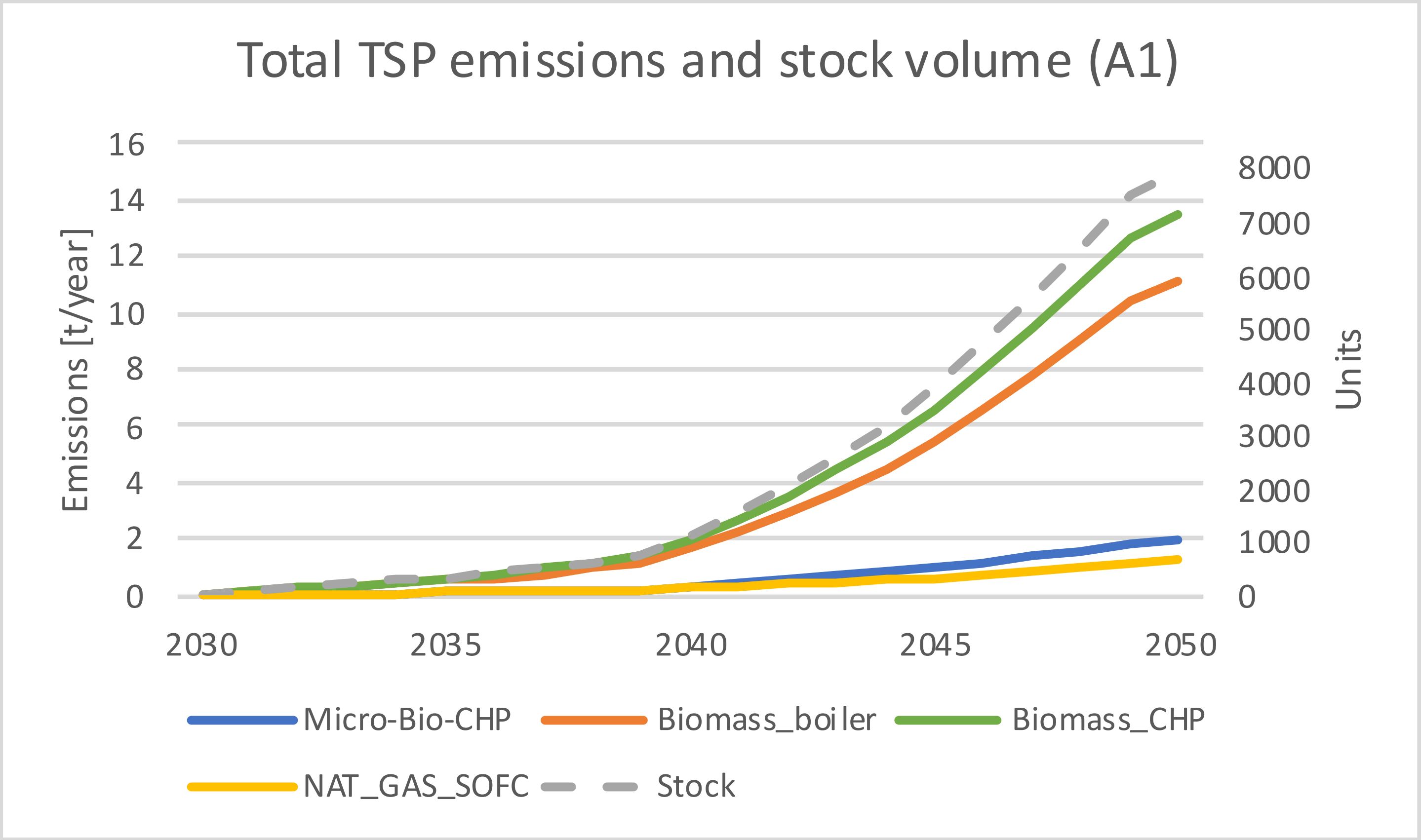
- **Comparison of Micro-Bio-CHP emission levels**



- TSP, CO, NMVOC emissions up to 85% lower than from SOA biomass boiler
- Lower NO_x emissions compared to state-of-the-art biomass systems
- Lowest CO emissions of all systems

Environmental and overall impact assessment

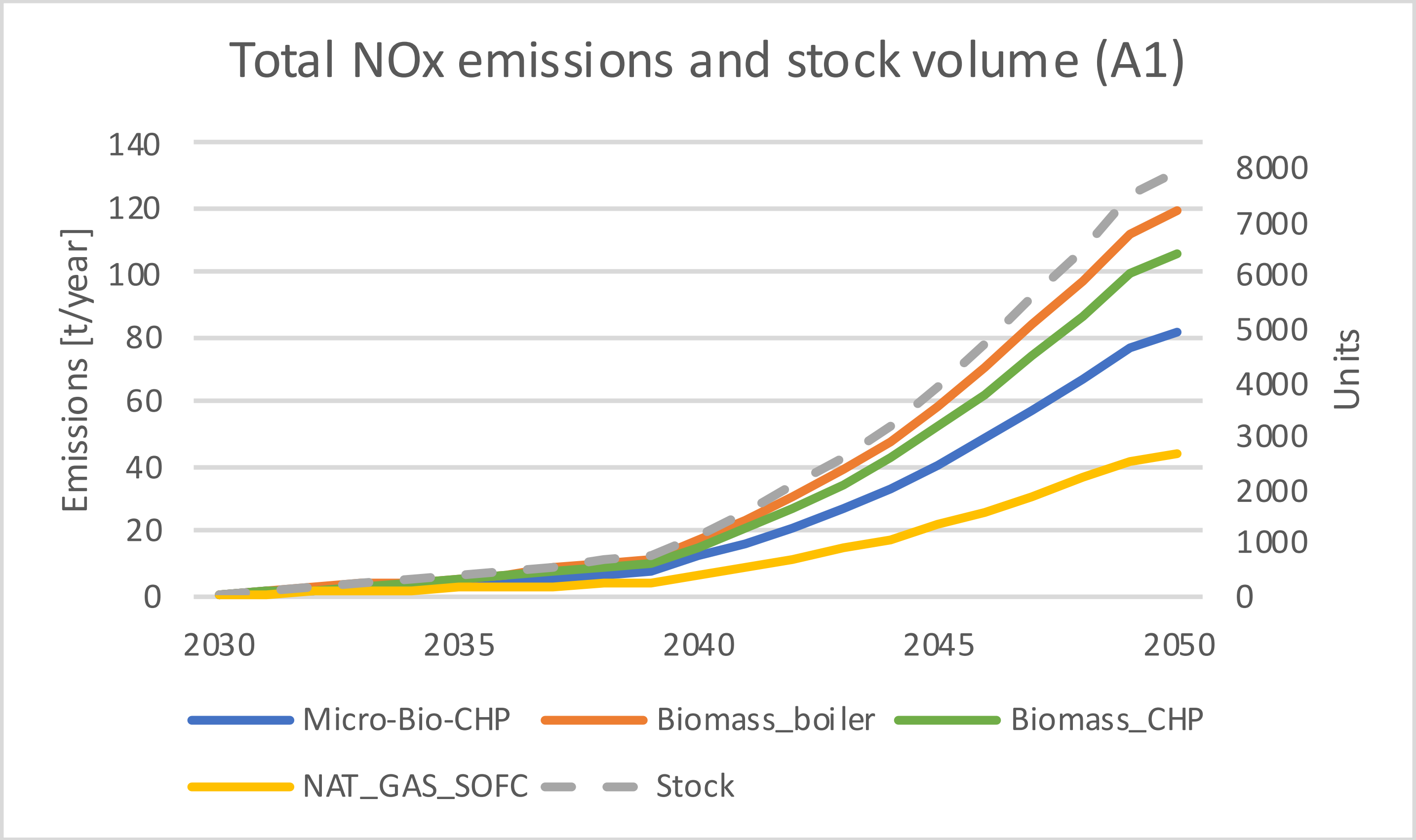
- **Annual TSP emissions and stock volume (Germany)**



- Ramping up of total emissions in 2045 due to assumed increasing sales and stock
- Micro-Bio-CHP TSP emissions significantly lower compared to state-of-the-art biomass systems

Environmental and overall impact assessment

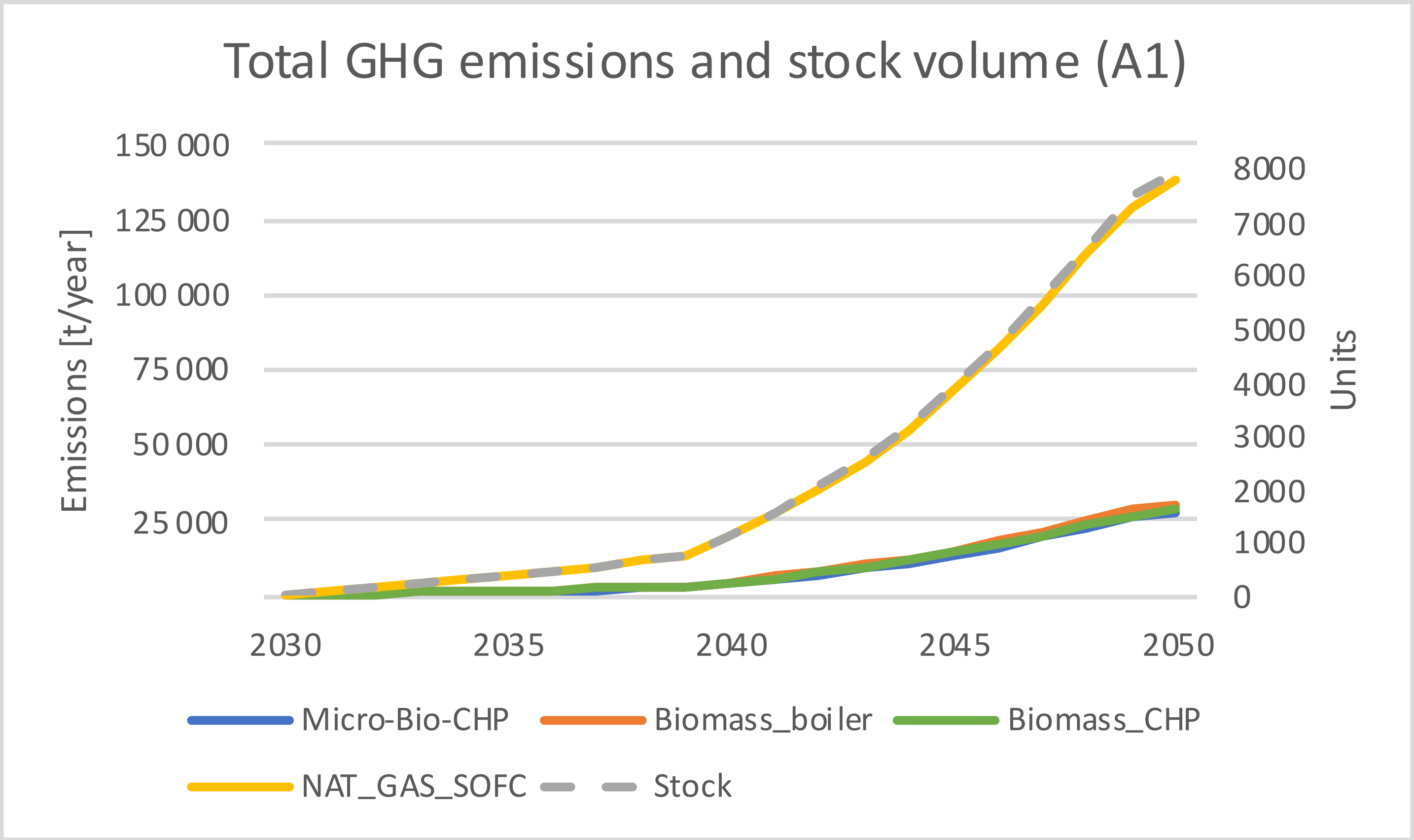
- **Annual NO_x emissions and stock volume (Germany)**



- Significantly lower NO_x emissions of Micro-Bio-CHP compared to state-of-the-art biomass systems

Environmental and overall impact assessment

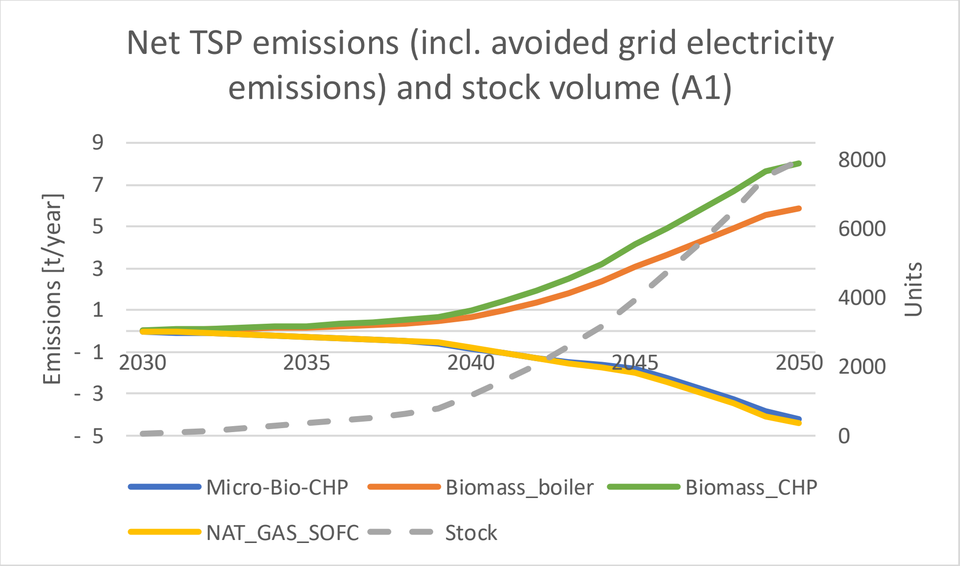
- **Annual GHG emissions and stock volume (Germany)**

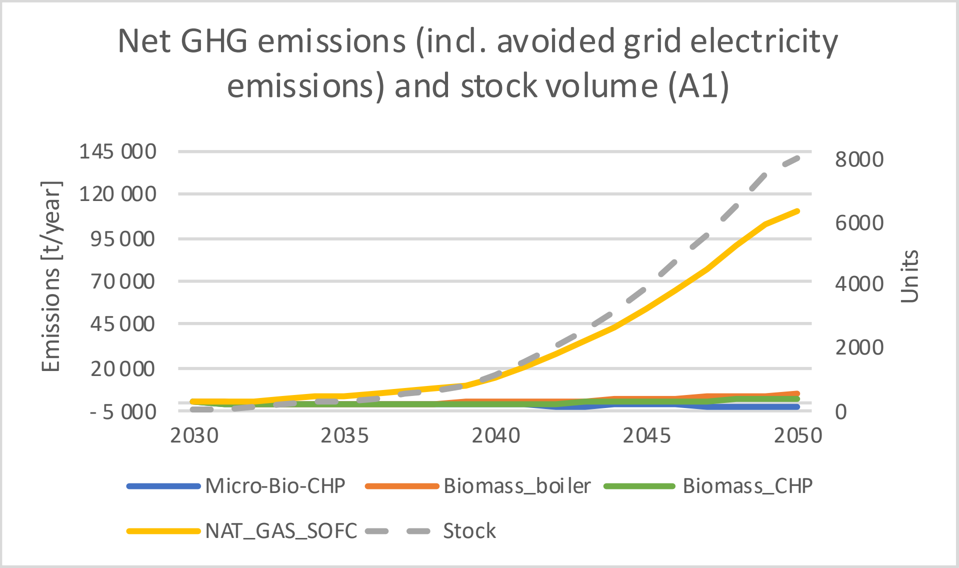


- Significantly lower GHG emissions of all biomass-based vs. natural gas-based systems
- Lowest GHG emissions with Micro-Bio-CHP

Environmental and overall impact assessment

Net TSP and GHG emissions for Micro-Bio-CHP (Germany)


Net TSP emissions (incl. avoided grid electricity emissions) and stock volume (A1)


Net GHG emissions (incl. avoided grid electricity emissions) and stock volume (A1)

- Net TSP and GHG emissions are negative due to grid electricity displacement
- Advantage compared to fossil-based systems and state-of-the-art biomass systems

Summary and Conclusions

Micro-Bio-CHP:

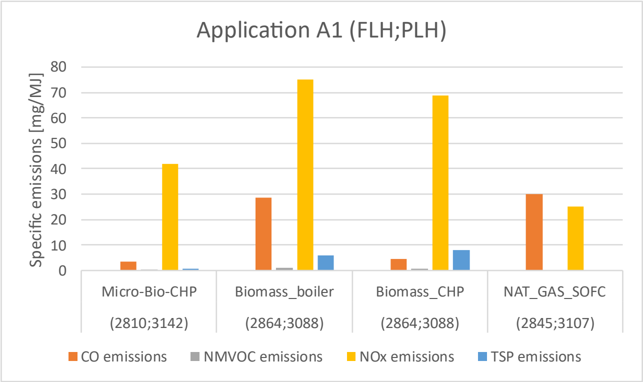
Significant potential for GHG and air pollutant emission reductions

- Substantial GHG emission reductions vs. natural-gas fuel cells and modern biomass boilers
- Significant air pollutant emission reductions (TSP, NMVOC, CO, NO_x) vs. modern biomass boilers, and partly also vs. natural-gas CHP
- Particularly strong improvements for TSP and NO_x
- Supports EU renewable energy, clean air and resilience objectives

µ BIO CHP

Development of a novel highly efficient energy supply system for energy autonomous multi-family buildings based on biomass gasification coupled with an SOFC and a PV system

Thank you for your attention



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