# PROFESSORSHIP OF ENERGY PROCESS ENGINEERING | EVT


Institute of Energy Process Engineering and Chemical Engineering | IEC

TU Bergakademie Freiberg

Prof. Dr.-Ing. Martin Gräbner


TUBAF The University of Resources. Since 1765.

DBI Virtuhcon

Fraunhofer IKTS

INSTITUTE OF ENERGY PROCESS ENGINEERING AND CHEMICAL ENGINEERING

ELECTRICIANS

BUSINESS ADMINISTRATORS

MECHANICAL ENGINEERS

# TEAM

PROCESS ENGINEERS

MATHEMATICIANS

CHEMICAL ENGINEERS

MATERIAL ENGINEERS

PSYCHOLOGISTS

MINERALOGISTS

CHEMISTS

CONTROLLER

PHYSICISTS

MEDIA DESIGNERS

INDUSTRIAL ENGINEER

ASSISTANCE

COMPUTER SCIENTISTS

ELECTRONIC TECHNICIANS

PLANT OPERATOR

TECHNICIANS

METALLURGISTS

LABORATORY ASSISTANTS

# Content

# Mission

The education and R&D profile of the Professorship of Energy Process Engineering (EVT) focus on the electrification of circular carbon and hydrogen technologies via the $e^-CH_2T$-Concept:

$e^-$ Integration of electricity via plasma discharge, conduction, induction, radiation or generation of auxiliary substances (e.g. $O_2$, $H_2$) in chemical reactions

C Closing of the carbon cycle through chemical recycling, utilization of biogenic waste and the development of $CO_2$ sources (e.g. for e-Fuels or e-Chemicals)

$H_2$ Production of hydrogen on the basis of biogenic waste, pyrolytic splitting of hydrocarbons and reforming/partial oxidation with integrated $CO_2$ management

T Development of technologies – building on classic thermochemical conversion processes (i.e. gasification and pyrolysis) and supported with life-cycle and techno-economic assessments – for industrial applications

# R&D Topics

## #CHEMICAL RECYCLING

Chemical recycling – also known as feedstock recycling – is based on the conversion of carbon-containing waste into basic chemical building blocks to enable the manufacturing of new chemical products from them. As a result, waste becomes a resource within the circular economy as carbon is incorporated into new products instead of being emitted as $CO_2$, as is the case with waste incineration.

In this context, we look at the primary thermochemical conversion of a wide variety of waste and residual materials by pyrolysis and gasification, including peripheral processes, as well as the technical, socio-ecological and economic evaluation of the entire process chains from feedstock to product. One focus is on the integration of electricity and hydrogen from renewable sources.

## #SUSTAINABLE HYDROGEN

Hydrogen plays a central role in the realization of a climate-neutral economy. To achieve this, the supply of hydrogen itself must be climate-neutral and thus sustainable.

Our research focuses on hydrogen production via electrothermal or thermochemical conversion processes. These include the pyrolytic cracking of methane, which produces so-called „turquoise" hydrogen, and the gasification or reforming of biogenic waste and residual materials with subsequent maximization of the hydrogen yield.

## #$CO_2$-NEUTRAL MOBILITY

The use of $CO_2$-neutral synthetic liquid fuels is a climate-friendly complement to electric- and hydrogen-based mobility. Not only can they directly replace fuels from fossil sources, but they can also be mixed with them in any ratio (drop-in capability) as well as serve as a global energy carrier. This enables a continuous transition to these synthetic fuels, including the use of existing infrastructure for distribution and sales. While defossilizing the exisiting vehicle fleet, the future fields of application will be in particular aviation but also shipping and heavy duty transport.

The focus of our research is the synthesis of $CO_2$-neutral fuels based on methanol from laboratory to pilot scale including performance optimization and process chain evaluation.

## #KEY CONVERSION TECHNOLOGIES

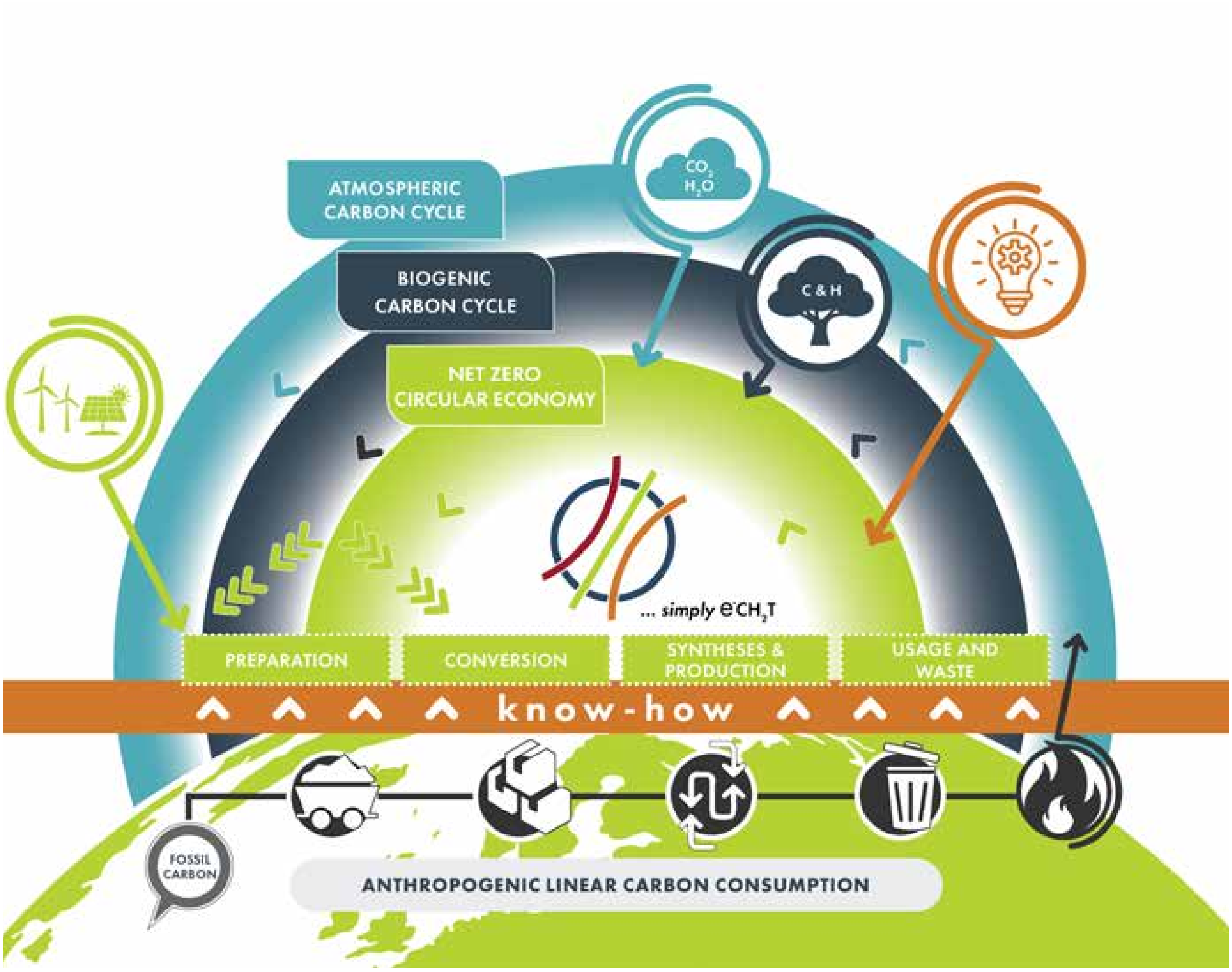
**Gasification**

In thermochemical conversion by gasification, carbon carriers are converted into a gas containing $H_2$ and CO at temperatures above 700 °C using a gasification agent. This synthesis gas serves as a C1-building block for the chemical industry and the origin for a wide range of products. In addition to hydrogen and synthetic fuels, platform chemicals such as alcohols, paraffins, olefins and ammonia can be produced from it. Gasification is attractive for the recycling of waste materials due to its high flexibility and scale-up potential. Electrification of the process allows minimization of the $CO_2$-footprint.

**Pyrolysis**

Pyrolysis is the thermal decomposition of carbonaceous materials into oil, char and gas at temperatures of 400 - 600 °C in the absence of oxygen. Integration of electrical power holds the potential to simplify the process and lower $CO_2$ emissions. It is an established thermochemical process for the production of liquid hydrocarbons as well as for waste processing, e.g. for the recovery of metals and fibers from composite materials. The use of the waste-based pyrolysis oil in refinery processes as a naphtha-substitute is a preferred process route for the chemical recycling of used plastics in particular.

## TOWARDS A NET-ZERO CIRCULAR CARBON ECONOMY



# R&D Structure

INSTITUTE OF ENERGY PROCESS ENGINEERING AND CHEMICAL ENGINEERING

Institute Director

Professorship of Energy Process Engineering (EVT)

Division Head (Freiberg) Energy and Process Engineering –
Circular Carbon Technologies –
Fraunhofer Institute for Ceramic Technologies and Systems (IKTS)

Director of the Center for Efficient High Temperature Processes
and Materials Conversion, Freiberg

**SUBJECT MATTER EXPERT**
Prof. Dr.-Ing. Bernd Meyer

## eTC electro- & Thermo-chemical Conversion

**HEAD OF DEPARTMENT**
Dr.-Ing. Steffen Krzack

**DEPUTY OF DEPARTMENT**
M.Sc. Stefan Thiel

*We investigate the properties of carbonaceous feedstock and their behavior in thermochemical conversion processes with regard to mechanisms, balances and kinetics for the development and application of advanced processes.*

## GS Gasification Systems

**HEAD OF DEPARTMENT**
Dr.-Ing. Stefan Guhlt

**DEPUTY OF DEPARTMENT**
Dr.-Ing. Ronny Schimpke

*We develop and optimize solid fuel gasification in fixed-bed, fluidized-bed, entrained- flow and plasma-assisted systems, with particular focus on understanding the challenges associated with inorganic compounds.*

## CCT Circular Carbon Technologies

**HEAD OF DEPARTMENT**
Dr.-Ing. Jörg Kleeberg

*We develop and commercialize carbon conversion technologies focusing on pyrolysis to drive the circular carbon economy via chemical recycling.*

## ST Syngas Technologies

**HEAD OF DEPARTMENT**
Dr.-Ing. Peter Seifert

**DEPUTY OF DEPARTMENT**
M.Sc. Michaela Scheithauer

*We optimize and scale-up advanced partial oxidation technologies for liquid and gaseous feedstocks with $CO_2$ integration as well as synthesis processes for the production of $CO_2$-neutral synthetic fuels from methanol.*

## TA Technology Assessment

**HEAD OF DEPARTMENT**
PD Dr. rer. pol. Roh Pin Lee

**DEPUTY OF DEPARTMENT**
M.Sc. Florian Keller

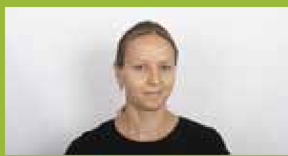
*We utilize an integrated approach to evaluate technologies and process routes along social-technological-ecological-economical-political dimensions to support decision-making and socio-political dialogues at the nexus of science, technology and society.*

Prof. Dr.-Ing. Martin Gräbner

**ASSISSTANCE**
Jeanett Schumann

## Laboratory

**LABORATORY MANAGER**
Dr. rer. nat. Marcus Schreiner



**DEPUTY LABORATORY MANAGER**
Dr. rer. nat. Anja Guhl

« We analyze solid, liquid and gaseous samples along the process chain using standardized as well as advanced and unique proprietary analysis methods. »

## Plant Operation

**HEAD OF DEPARTMENT**
Dipl.-Ing. Olaf Schulze

**DEPUTY OF DEPARTMENT**
Tilo Peissig

*« We operate a full range of bench-scale and pilot-scale facilities to support technology development and optimization as well as validation of developed solutions. »*

## Controlling

**HEAD OF DEPARTMENT**
Dipl.-Wirt.-Sin. (FH) Kristin Wieczorek

**DEPUTY OF DEPARTMENT**
B.A. Stephanie Opitz

*« We support the timely and smooth execution of public-funded and industry projects. »*

## DBI-Virtuhcon GmbH (spin-off/an-institute)

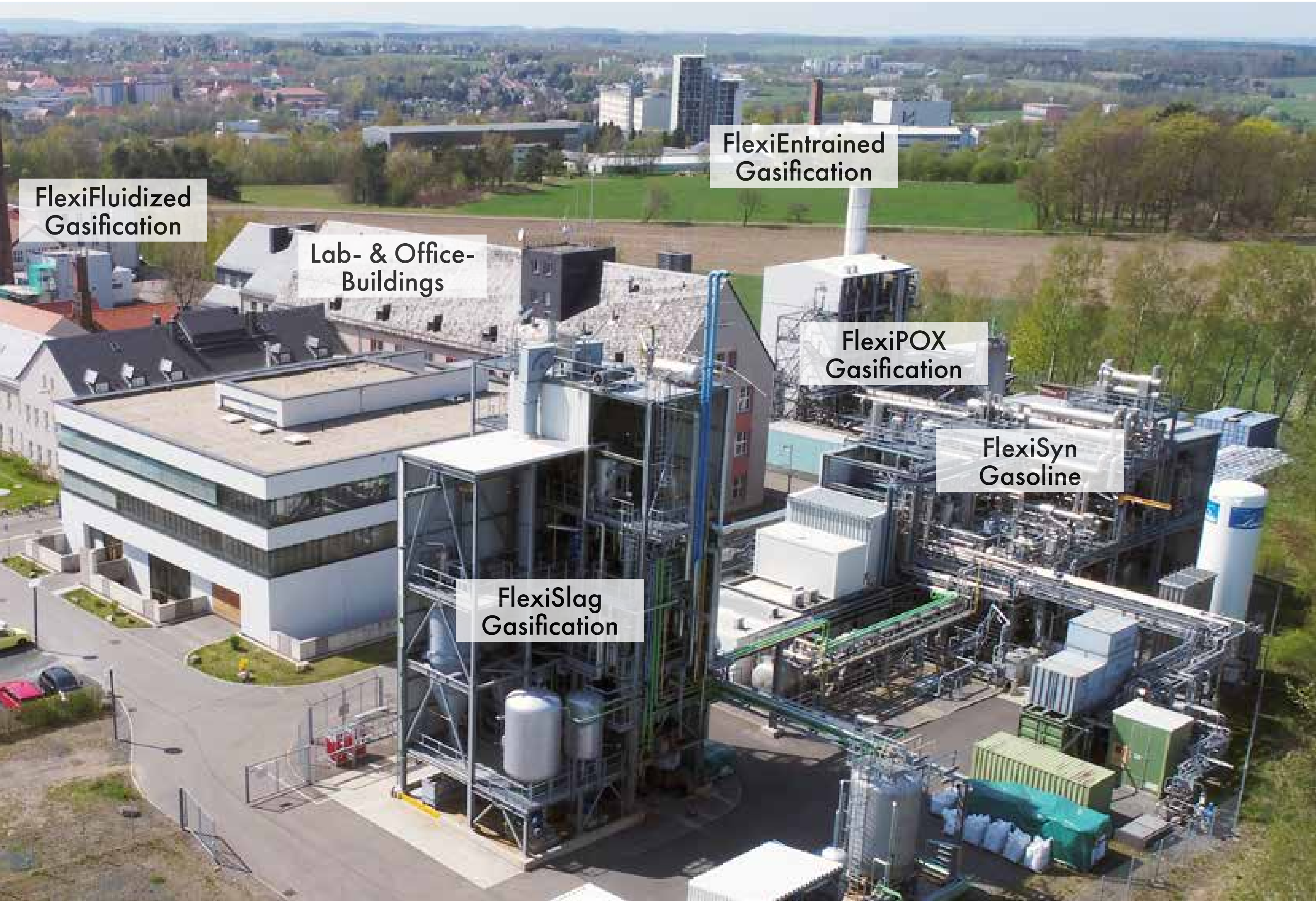
*« We facilitate the timely and efficient transfer of our rich expertise, experience and know-how in the fields of thermochemical conversion. »*

## ZeHS Center for Efficient High Temperature Processes and Materials Conversion

*« We investigate and develop efficient high temperature conversion processes using an interdisciplinary approach and capitalizing on the expertise and know-how of multiple professorships and institutes at the TU Bergakademie Freiberg. »*

# Infrastructure & Equipment

## PILOT FACILITIES



## Highlight

Enables mixed, contaminated and challenging carbon-containing waste materials which are not suitable for mechanical recycling and pyrolysis to be used as secondary raw material for chemical production.

### FlexiSlag Gasification Plant

The FlexiSlag is a next generation fixed-bed slagging gasifier designed for high feedstock flexibility. It offers variable gas qualities for hydrogen application, syngas application (i.e. low dust, tar and phenols-free, low CxHy), or SNG and liquid products application (i.e. low dust, rich in light oil and CxHy). Additionally, it also exhibits high thermal and cold gas efficiency, low oxygen and steam consumption and practically no carbon loss. Furthermore, it has minimal environmental impacts as contaminants are contained in vitrified i.e. glassy slag.

**Key Facts**

- Thermal capacity: 10 MW
- Pressure: 40 bar(g)
- Throughput: up to 1.4 t/h solid carbon feedstock
- Gasification agents: $O_2$ max. 430 m³(STP)/h; Steam max. 450 kg/h
- Gas output: max. 2300 m³(STP)/h

**Feedstock**

- Coal (char coal, lignite, anthracite), petcoke, waste coke from thermal treatments
- Biomass (wood chips, torrefied pellets, straw pellets, ...)
- Different types of waste (MSW, mixed plastic residues, sewage sludge, carbon-fiber and glass fiber composites, automotive shredder, ocean waste, ...)
- ...

**R&D Focus**

- Process validation of different carbon feedstock and blends
- Influence of fuel preparation and fluxing agents on ash/slag behavior
- Influence of variation of gasification conditions and agents on carbon conversion rate and syngas quality
- Variation of yield and composition of tars, oils, SNG, CO+$H_2$ in syngas
- Development of processes and components
- Determination of performance indicators for upscaling
- ...

**Operation**

- Since 2015

Test Campaign in the FlexiSlag

## Highlight

Project DeCarTrans (Demonstrating a Circular Carbon Economy along the Value Chain) 2023-2026: Production of about 380,000 litres of synthetic gasoline from renewable methanol for material, emission and car fleet tests by project partners/ selected end users

### FlexiSyn Gasoline Plant

The "FlexiSyn Gasoline" is a plant designed to demonstrate the production of high-octane gasoline. Originally, the synthesis route was separated into two steps: conversion of syngas (generated via ATR treatment of natural gas) into methanol followed by the subsequent innovative isothermal synthesis process of methanol to gasoline (MtG). Today, only the gasoline production operates using renewable methanol. Technology partner is the CAC Engineering GmbH (former Chemieanlagenbau Chemnitz GmbH).

**Key Facts**

- Gasoline synthesis: 5 bar to 7 bar
- Stabilized gasoline output: up to 1000 litres/day @ RON 93-95

**Feedstock**

- Bio-methanol or e-methanol

Test Campaign in the FlexiSyn Gasoline

**R&D Focus**

- Improvement of operating conditions, process efficiency and gasoline quality
- New catalysts to increase selectivity
- Optimization of product treatment
- Demonstration of long-term operation
- ...

**Operation**

- Since 2010

## FlexiPOX Partial Oxidation Plant

The FlexiPOX plant is designed for high pressure partial oxidation of gaseous and liquid hydrocarbons. It can be operated in the autothermic catalytic reforming (ATR) mode, or as autothermic non-catalytic partial oxidation mode for natural gas (Gas-POX) or liquid hydrocarbons such as oil residues from refineries or pyrolysis oil from chemical recycling (MPG or Oil-POX).

### Key Facts

- Thermal capacity: 5 MW
- Pressure: up to 100 bar(g)
- Temperature: up to 1500 °C
- Throughput: 500 $m^3$(STP)/h gaseous feedstock or 500 kg/h liquid feedstock
- Gas output: 1500 $m^3$(STP)/h syngas

### Feedstock

- Natural gas
- Oil residues
- Pyrolysis oil

### R&D Focus

- Variation of steam-to-feed ratio
- Influence of pressure and temperature on syngas quality
- Analysis of product streams including trace components
- Energetic, exergetic and material balancing
- Development and test of innovative burners
- Optical device for flame assessment and validation of CFD-calculations
- ...

### Operation

- Since 2004

## Highlight

Unique optical devices enable real time determination and verification of flame conditions under high temperature and high pressure operating conditions using customer designed burners.

## Highlight

Technology is widely implemented commercially for coal-to-chemicals today. Over 60 carbon feedstocks (including different types of waste materials) were tested in over 100 test campaigns in the Freiberg facility.

### FlexiEntrained Gasification Plant

The FlexiEntrained (GSP gasification process) is an entrained-flow gasifier with a water-cooled cooling screen, a full spray water quench for gas cooling, a Sulferox plant for desulfurization as well as a waste water treatment plant. It operates with pulverized or liquid (slurry) feedstock. The generated syngas is free of hydrocarbons with very low amount of methane. It is able to convert a broad variety of carbon feedstock into a high-quality tar-free syngas and vitrified slag which is environmentally neutral. Furthermore, it features a pneumatic feeding test rig of commercial scale.

**Key Facts**

- Thermal capacity: 5 MW
- Pressure: 26 bar(g)
- Gas output: 1000 m³(STP)/h syngas
- Throughput: up to 450 kg/h of pulverized solid feedstock or slurry
- Gas treatment: desulphurization unit (Sulferox), COS hydrolysis, HCN hydrolysis
- Waste water treatment plant
- Test rig for solid fuel feeding up to 300 t/d

DBI Virtuhcon

**Feedstock**

- Coal (lignite, hard coal, anthracite) and petcoke
- Biomass
- Sewage sludge
- Torrefied residue derived fuels from MSW
- Slurries
- ...

**R&D Focus**

- Process validation of different carbon feedstock and mixtures
- Influence of fuel preparation and fluxing agents on ash/slag behavior
- Influence of variation of gasification conditions and agents on carbon conversion rate and syngas quality
- Process optimization and test of components (innovative burners, measurements, ...)
- Optical probe systems
- ...

**Operation**

- Since 2018 (in cooperation with DBI-Virtuhcon)

## LTG Pyrolysis Plant

The low temperature gasification (LTG) plant is a continuous mode pyrolysis plant to convert different carbon-rich biomass or waste into pyrolysis coke and tar-/oil-containing pyrolysis gas. It can be operated fully electric in allothermal mode or autothermal with agents to provide heat for pyrolysis. The LTG plant is part of the Fraunhofer IKTS pyrolysis platform.

### Key Facts

- Temperature: 250-550 °C
- Pressure: atmospheric pressure
- Throughput: 125 kg/h

### Feedstock

- Biogenic waste and agricultural residues
- MSW/RDF
- Mixed plastic waste

### R&D Focus

- Allothermal as well as autothermal (future expansion) process
- Feedstock flexibility
- Production of tar-free char (biogenic coke)
- Production of pyrolysis gas for further applications
- Torrefaction

### Operation

- 2023

## Highlight

The IKTS pyrolysis platform serves both: the conversion of feedstock to char or to liquid products at a relevant scale.

## CTC Pyrolysis Plant

The catalytic tribo-chemical (CTC) pyrolysis technology is used to convert different carbon-containing wastes into pyrolysis oil as steam cracker feedstock. Technology partner is Carboliq GmbH. The CTC plant is part of the Fraunhofer IKTS pyrolysis platform.

### Key Facts

- Temperature: < 400 °C
- Pressure: atmospheric pressure
- Throughput: 20-30 kg/h
- Oil output: 10-15 kg/h

### Feedstock

- Biomass
- MSW/RDF
- Mixed plastic waste
- Biogenic waste

### R&D Focus

- High oil yield
- Feedstock flexibility
- High degree of heat coupling by frictional heat input
- Low emissions (no dioxin and furan)
- In-situ neutralization of halogens

### Operation

- 2023

Fraunhofer IKTS

# BENCH-SCALE FACILITIES

## Gasoline Synthesis Plant (STF+)

The Gasoline Synthesis Plant enables the synthesis of high-octane gasoline from methanol at bench scale. Operation conditions can be varied within a wide range. The test facility is also suitable for operation in the methanol-to-olefins mode.

**Key Facts**

- Temperature: 320-400 °C
- Pressure: 4-6 bar
- Throughput: 2-5 l/h methanol
- Reactor: catalyst-filled tube, height 3 m, volume 1.8 l
- Temperature control: molten salt
- 4 levels of sampling points

**Feedstock**

- Methanol (pure or diluted)

**R&D Focus**

- Optimization of operating conditions to increase gasoline quality
- Catalyst tests and benchmarking
- Optimization of catalyst regeneration procedures

## FlexiFluidized Gasification Plant

The FlexiFluidized plant is a fluidized-bed gasifier developed and designed by IEC-EVT. It combines an internal circulating fluidized bed with a moving bed gasification zone to achieve high carbon conversion rates for fine as well as coarse particles. It is especially suited for feedstocks with high ash content.

**Key Facts**

- Thermal capacity: 125 kW
- Wall temperature: 1100 °C
- Pressure: atmospheric pressure
- Throughput: max. 20 kg/h of solid carbon feedstock
- Gasification agents: $O_2$, $H_2O$, $CO_2$
- Gas treatment: warm gas ceramic candle filter
- Online sampling ports for gas and solids at various stages

**Feedstock**

- High ash lignite
- Sewage sludge
- Biogenic waste and residues
- Different types of waste
- ....

**R&D Focus**

- Investigation of the internal circulation gasification principle for diverse carbon feedstock
- Optimization of process design for waste/biomass and high-ash feedstock
- Improved mass and energy balances based on various online measurements and sampling ports
- Generation of validation data for advanced modelling (CFD and flowsheet) to support upscaling
- ...

## MultiFeed Gasification Plant

The MultiFeed is an entrained-flow gasification test plant with optical access on multiple levels. It is designed to operate with gaseous (e.g. natural gas) as well as liquid (e.g. gasoil) and solid feedstock (e.g. coal) and is equipped with a refractory lined reactor vessel and a subsequent quench section.

**Key Facts**

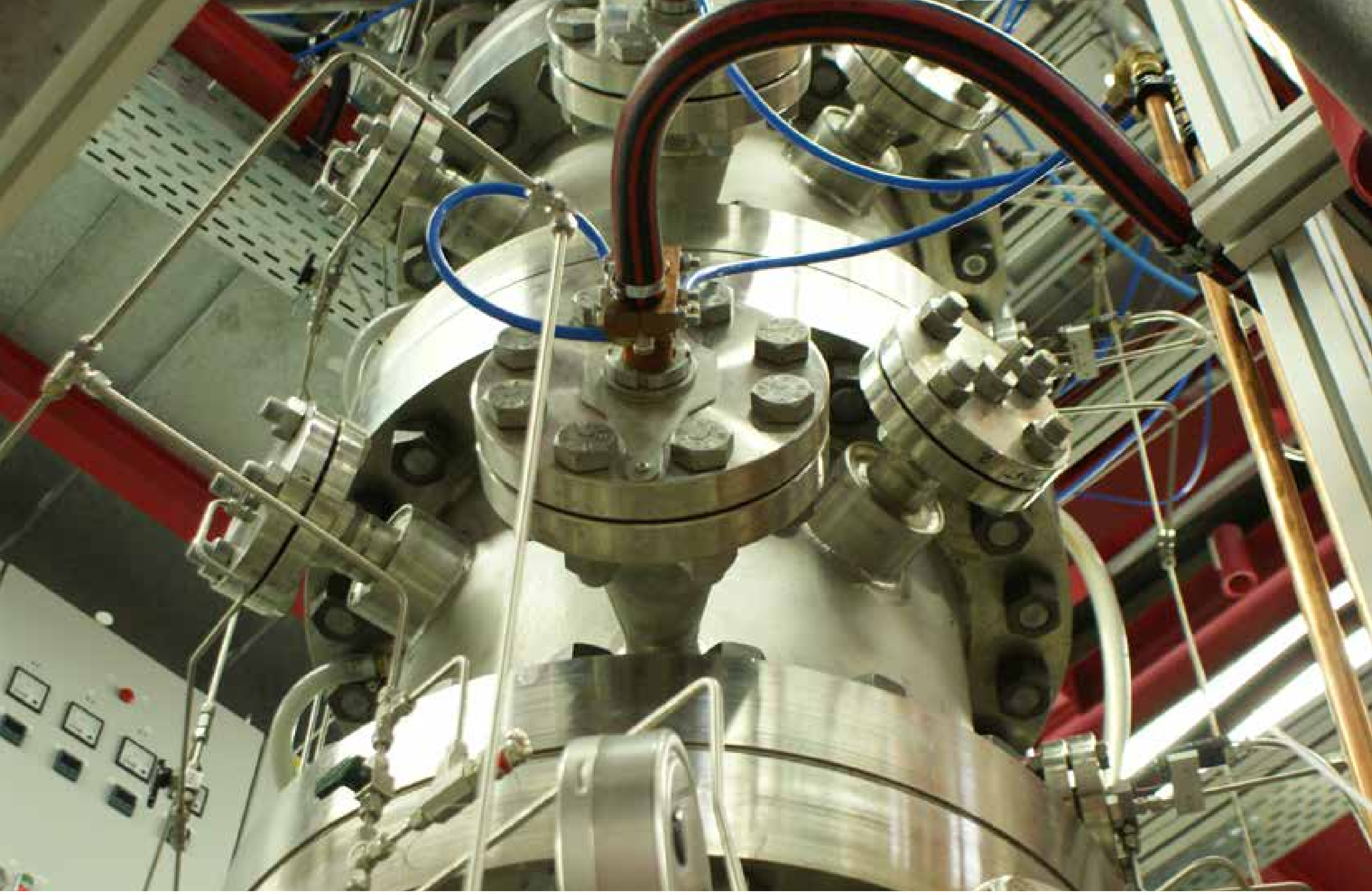
- Temperature: up to 1600 °C
- Pressure: atmospheric pressure
- Throughput: 100 kg/h solids , 70 l/h liquids, 100 $m^3$/h gases (natural gas equivalent)

**Feedstock**

- Solids
- Liquids
- Gases

**R&D Focus**

- Online optical detection and analysis of entrained-flow burner flame
- Burner development
- Validation of CFD models (e.g. flame shape)
- Tests of refractory material (e.g. towards reactor atmosphere related intrusion)
- Development and test of optical devices
- ...



## KIVAN Gasification Plant

The KIVAN gasifier is a high-pressure drop tube gasification reactor, especially designed for the determination of reaction kinetics and residence time behavior.

**Key Facts**

- Temperature: up to 1100 °C
- Pressure: up to 100 bar
- Throughput: char ≤1 mm, max. 1.5 kg/h
- Gasifying agents: up to 300 l(STP)/min of $CO_2$ and up to 14.4 kg/h of steam
- Other gases: $N_2$ or Argon, $H_2$ and CO possible
- Electrically heated
- Heating length of 2.8 m and ID = 70 mm
- 4 levels of gas sampling points and optical ports over the heated length
- 12 gas sampling points for concentration profile

**Feedstock**

- Coal char
- Biomass char
- Char from different types of waste
- ...

**R&D Focus**

- Determination of high pressure heterogeneous gasification kinetics including diffusion controlled regime and inhibition effects
- Particle residence time

## Catalytic Steam Reformer/Methane Pyrolysis Plant

The Catalytic Steam Reformer/Methane Pyrolysis Plant is a highly flexible bench-scale plant for various applications such as catalytic steam reforming, methane pyrolysis, ammonia cracking and other homogeneous gas reactions or gas-solid reactions. Further applications are exposure tests of diverse materials (e.g. refractory, metals, catalysts) and the determination of reaction kinetics.

### Key Facts

- Temperature: 1350 °C
- Pressure: atmospheric pressure
- Heated tube length: 2 m
- Inner diameter: 90 mm
- Tube material: SiSiC/graphite (further materials available)
- Operation modes: countercurrent moving, moving fluidized or fixed bed
- Continuous solid feed and discharge: 30 kg/h
- Gas supply: Ar, CO, $CO_2$, $CH_4$, $H_2$, $N_2$ with up to 6.0 $m^3$/h (STP) each gas
- Hydrogen produced: 12 $m^3$(STP)/h

ZENTRUM FÜR EFFIZIENTE HOCHTEMPERATUR-STOFFWANDLUNG

Center for Efficient High Temperature Processes and Materials Conversion (ZeHS)

### Feedstock

- Coal char (lignite, hard coal, anthracite) and petcoke
- Biomass char
- Torrefied residues
- Methane


## Plasma Gasification Equipment

### Fixed Bed Plasma Gasification Plant

**Key Facts**

- Temperature: up to 5000 °C
- Pressure: atmospheric pressure
- Throughput: max. 15 kg/h solid feed
- Plasma forming gases: steam, $N_2$, air, $CO_2$
- Electrical power: 65 kW (Plasma torch)
- Gas output: syngas max. 30 $m^3$(STP)/h

**Feedstock**

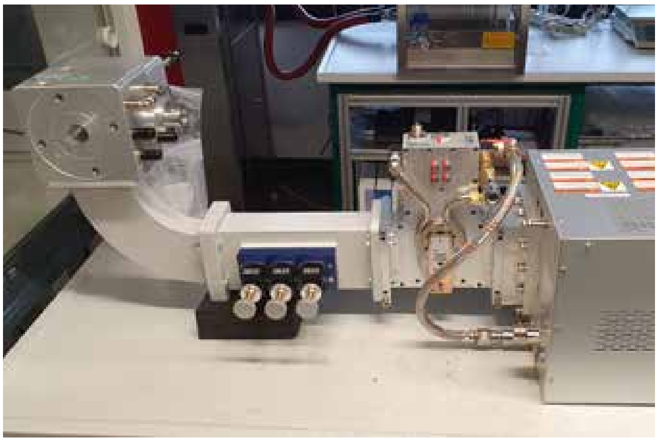
- Sewage sludge
- Plastic-containing waste
- Carbon- and glass-fiber reinforced waste materials
- ...

**R&D Focus**

- Eco-friendly utilization of challenging waste
- Hot gas cleaning using plasma-assisted tar cracking
- Mass and energy balancing for different feedstock
- Development and testing of new plasma torch electrodes
- ...

### Microwave Plasma Gasification

Two microwave plasma torches for plasma-integration into bench-scale gasification plants are available at the IEC. They can be applied for either direct conversion of a raw feedstock into high-grade syngas or to upgrade a low-quality gas, e.g. a tar-loaded pyrolysis gas.



**Key Facts**

- Temperature: up to 3200 °C
- Pressure: 0-0.5 bar(g)
- Plasma gas throughput: max. 12 $m^3$/h
- Plasma forming gases: $CO_2$, $N_2$, air
- Electrical power: 6 kW (single plasma torch)

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Center for Efficient High Temperature Processes and Materials Conversion (ZeHS)

## Entrained Bed Plasma Gasification Plant

### Key Facts
- Wall temperature: up to 1500 °C
- Pressure: up to 10 bar(g) (depending on plasma system)
- Plasma forming gases: $CO_2$, $N_2$, air
- Electrical power: 12 kW (two plasma torches)
- Syngas output max. 15 $m^3$(STP)/h

### R&D Focus
- Mass and energy balancing of plasma assisted entrained bed gasification
- Benefits and limits of microwave plasma integration
- CFD modeling of plasma gasification processes
- Pyrolysis gas cleaning
- ...

### Feedstock
- Solids: sewage sludge, (torrefied) wood, powdered plastic-containing waste, ...
- Liquids: Tars/oils from pyrolysis, crude oil, ...
- Gases: Reverse water-gas-shift, ammonia splitting, dry reforming, methane pyrolysis, ...

## Lab-Scale Plasma Gasification Unit I

### Key Facts
- Pressure: atmospheric
- Throughput: max. 2 $m^3$/h
- Plasma forming gases: $CO_2$, $N_2$, air
- Electrical power: 1 kW

### Feedstock
- Pelletized solids: sewage sludge, (torrefied) wood, plastic-containing waste, ...

### R&D Focus
- Feedstock suitability characterization
- Gas analysis
- Surface treatment and activation
- Benefits and limits of potential-free plasma incorporation

## Lab-Scale Plasma Gasification Unit II

### Key Facts
- Pressure: atmospheric
- Plasma forming gases: $CO_2$, $N_2$, air
- Electrical power: 6 kW
- Syngas output max. 6 $m^3$(STP)/h

### Feedstock
- Liquids: ethylene glycol to simulate pyrolysis tars/oils
- Gases: Reverse water-gas-shift, dry reforming, methane pyrolysis

### R&D Focus
- Energy and mass balancing
- Benefits and limits of microwave plasma incorporation
- Pyrolysis gas cleaning
- ...

ZENTRUM FÜR EFFIZIENTE HOCHTEMPERATUR-STOFFWANDLUNG

Center for Efficient High Temperature Processes and Materials Conversion (ZeHS)

## Further Gasification Equipment

**R&D Focus**

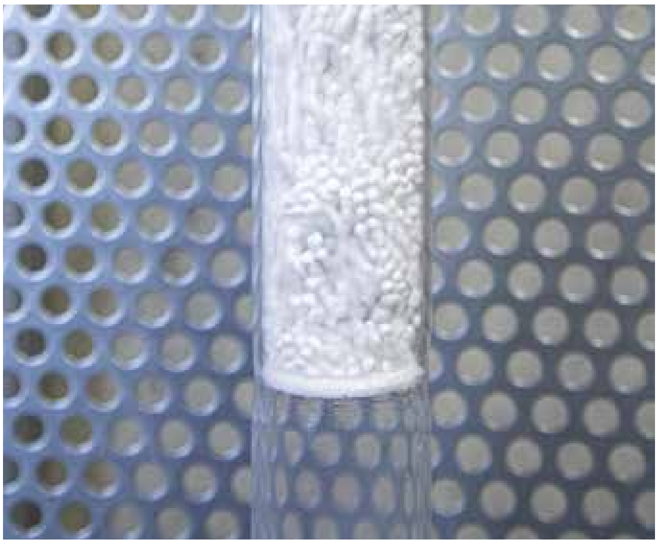
- Heterogeneous reaction kinetics of char gasification, including diffusion controlled regime and inhibition effects
- Investigation of methane pyrolysis

### HTR drop tube reactor

**Key Facts**

- Temperature: ≤ 1450 °C
- Pressure: atmospheric pressure
- Feedstock: ≤ 0.5 mm
- ID = 30 mm (ceramic tube)
- Atmosphere: $CO_2$, $H_2O$, CO, $H_2$, Ar, $CH_4$
- Online gas chromatography (GC)

### Quartz glass reactors



**Key Facts**

- Fixed-bed and fluidized-bed
- Temperature: up to 1000 °C
- Input: 1-10 g char
- Atmosphere: $CO_2$, $N_2$

## PYMEQ Pyrolysis Plant

The PYMEQ is a pyrolysis drop tube reactor with adjustable heated length for the determination of the pyrolysis behavior and the influence of residence time. For a closed balance, the condensable volatiles can be captured and the pyrolysis gas can be analyzed.

**Key Facts**

- Temperature: 800 °C
- Pressure: 100 bar(g)
- Throughput: 10 g/min solid feedstock of 40-100 µm
- Up to 2.5 m heated length with ID = 20 mm
- Purge/reaction gases: 400 l(STP)/h Ar + $H_2$ + $CO_2$ + $CH_4$ + steam
- Inner tube of alumina alloy with movable char collector
- Online gas measurement via mass spectrometer

**R&D Focus**

- Influence of process parameters on pyrolysis behavior of different feedstock qualities
- Mass, element and energy balances
- Char properties
- Chemical composition of tar/oil
- ...

## DPA Pyrolysis Plant

The DPA is a pressurized pyrolysis plant that can be operated in drop tube or fixed bed mode. A multi-stage condensation system is available to capture the condensable volatile products.

**Key Facts**

- Temperature: 800 °C
- Pressure: 30 bar(g)
- Throughput: 30 g/min solid feedstock
- Electrical heating
- 1.5 m heated length with ID = 20 mm
- Purge/reaction gases: 2500 l(STP)/h Ar, 60 l(STP)/h $CO_2$, 1 kg/h steam

**R&D Focus**

- Influence of process parameters on pyrolysis behavior of different feedstock qualities
- Mass, element and energy balances
- Char properties
- Chemical composition of tar/oil
- Drop-in heating/slow heating
- ...

## Pyrolysis Rotary Kilns

**R&D Focus**

- Process development for chemical recycling
- Thermochemical pretreatment of biomass and waste
- Production of carbon adsorbents via pyrolysis, partial gasification or carbon deposition
- ...

### Rotary Kiln (XERION)

**Key Facts**

- Temperature: ≤ 1300 °C
- Pressure: atmospheric pressure
- Electrical heating
- Power: 39 kW
- Feedstock: pulverized or pelletized (≤ 9 kg/h)
- Atmosphere: $N_2$, $H_2O_D$, $O_2$
- Purge gas quantity: 1.2 m³/h (STP)
- Flexible residence time
- Three-stage condensation with heated particle filter
- Complete product recovery for mass and energy balancing
- Gas sampling

### Rotary Kiln (Linn High Therm)

**Key Facts**

- Temperature: ≤ 1200 °C
- Pressure: atmospheric pressure
- Feedstock: ≤ 5 mm
- Atmosphere: Ar, steam, $CO_2$, $C_4H_{10}$
- Batch or continuous mode (7 kg/h)
- Product recovery
- Gas sampling

## Further Pyrolysis Equipment

**R&D Focus**

- Influence of feedstock and process parameters on pyrolysis behavior
- Mass, element and energy balances
- Preparation of large amount of char under defined conditions for further gasification experiences/analyses
- Preparation of carbon adsorbents

### Retort Oven (GERO)

**Key Facts**

- Temperature: ≤ 1100 °C
- Pressure: atmospheric pressure
- Input: ≤ 3 kg
- Atmosphere: $N_2$
- Liquid product recovery
- Gas sampling

### LPA fixed-bed reactor

**Key Facts**

- Temperature: ≤ 800 °C, 1-150 K/min
- Pressure: atmospheric pressure
- Input: 20-50 g solid feedstock ≤ 6 mm
- ID = 20 mm
- Complete product recovery for heat and material balancing

### ALPA fixed-bed or drop-in reactor

**Key Facts**

- Temperature: ≤ 1000 °C
- Pressure: 10 bar
- Input: 150 g solid feedstock ≤ 10 mm
- Atmosphere: Ar and $H_2$
- ID = 20 mm
- Complete product recovery for heat and material balancing

## Further Bench-Scale Equipment

### Simple Particle Disintegrator (SPaltor)

**Key Facts**

- Temperature: ≤ 1550 °C (1600 °C shortly)
- Pressure: atmospheric pressure
- Feedstock: ≤ 3.5 mm
- Atmosphere: Ar, $N_2$
- Images: refresh rate max. 1000 images/s with max. resolution 1280 x 1024 pixel

**R&D Focus**

- In-situ observation of particle behavior in a drop tube under drying and pyrolysis conditions, coupled with a high speed camera

### Large Sample Furnace

**Key Facts**

- Temperature: up to 1800 °C
- Pressure: atmospheric pressure
- Atmosphere: Ar, $N_2$, $H_2$, CO
- Sample space: 500 x 600 mm

**R&D Focus**

- Testing of refractory linings/materials under different gas atmospheres and ash/slag exposure

### Gasification equipment for reduction in fixed bed (GeRix)

**Key Facts**

- Reactor temperature: up to 1850 °C
- Heating rate: up to 10 K/min
- Pressure: atmospheric
- Reactor type: fixed bed
- Feed volume: 3.4 ml
- Gas atmosphere: $H_2$, CO, $CO_2$, $O_2$, Ar, $N_2$

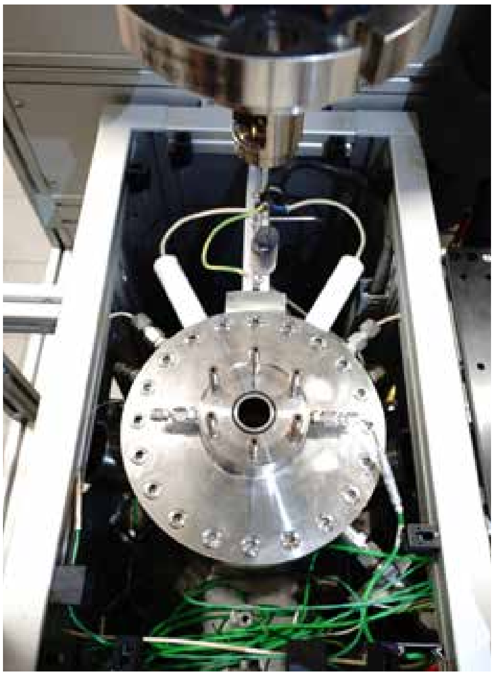
**R&D Focus**

- Transfer of phosphorus into the gas phase via gasification
- Separation of gaseous phosphorous from raw gas
- ...

## High Temperature Quench Furnace

### Key Facts
- Temperature: ≤ 1800 °C
- Pressure: atmospheric
- Atmosphere: $N_2$, CO, $CO_2$
- Feedstock: slag samples

### R&D Focus
- Melting the slag up to a defined temperature under reducing atmosphere
- Freezing the slag state (crystallization of slag components) at appropriate temperature for further analysis (i.e. super cooling effects)



## Pressurized Thermogravimetric, Thermographic and Spectroscopic Analysis (HITECOM)

### Key Facts
- Temperature: ≤ 1300 °C
- Pressure: ≤ 30 bar
- Atmosphere: Ar, $N_2$, CO, $CO_2$, $O_2$, $H_2$, $H_2O$ (steam)
- Feedstock: single particle: ≤ 4 g, maximum particle size: 15 mm
- 4 optical ports (perpendicular to the flow direction)
- In-situ measuring technology (thermogravimetry, thermography, spectroscopy)

### R&D Focus
- Spatial and time resolved characterization of thermochemical conversion of single particles in directed flow
- Fundamental research and advanced CFD validation
- Temperature map on the particle surface
- Temperature and concentration profiles in the boundary layer around particles

## Universal Electron Beam Facility

The electron beam facility consists of two separate units for application-oriented and innovative R&D in the field of high-temperature materials and their material systems for application in thermochemical conversion processes such as plasma gasification.

### Key Facts

Unit 1 (Wire-feed process)

- Beam generation: 150 kV
- Max. beam power: 0.5-30 kW
- Working chamber: approx. 4 $m^3$

Unit 2 (Powder-based process):

- Beam generation: 60 kV
- Max. beam power: 0.5-6 kW
- Working chamber: 150x150x150 mm

### Materials

Steels, non-ferrous metals, high alloys, refractory metals, high-entropy alloys, ODS materials

### R&D Focus

- High-temperature materials and their material systems via powder-based or wire-feed additive manufacturing
- Development and investigation of function-integrated materials and structures using electron beam technology


ZENTRUM FÜR EFFIZIENTE HOCHTEMPERATUR-STOFFWANDLUNG

Center for Efficient High Temperature Processes and Materials Conversion (ZeHS)

# LABORATORY FACILITIES

## Overview of Laboratory Equipment

**Sample Preparation Lab**
- Sieve analysis
- Camsizers (particle size distribution)
- Sample dividers
- Mills (cutting mill, impact mill, ultracentrifugal mill, freezer mill)
- Tablet/pellet press
- high-temperature microwave pressure digestion

**Solid Feedstock Lab**
- ETV-ICP OES – electrothermal vaporization – inductive coupled plasma – atomic emission spectroscopy for multi-element-analysis, temperature dependent element release in combination with elemental speciation
- Elemental (ultimate) analyzer (for solids and liquids)
- Combustion calorimeter (for solids and liquids)
- Karl-Fischer titrator (for solids and liquids)
- Direct mercury analyzer (for solids and liquids)
- Coke reactivity index (CRI) and coke strength after reaction (CSR)
- Dilatometer (high temperature/Ruhr)
- Gieseler plastometer

**Pore Structure and Adsorption Lab**
- Surface area measurement ($N_2$ and $CO_2$ isothermes)
- Mercury porosimetry
- Helium pycnometry
- Density measurement
- Adsorption test facility for Hg and $SO_2$

**Gas and Liquid Lab**
- Gas chromatography (various micro gas chromatographs with different columns and detectors)
- Ion chromatography
- GCxGC-TOF-MS with pyrolyser
- GC-FID with headspace sampler
- ICP-OES
- Viscometer (temperature controlled up to 200 °C)
- Density measurement
- DHA with SimDist

**Ash/Slag Lab**
- Plasma ashing device
- X-ray fluorescence analysis: XRF
- X-ray diffractometry XRD with in-situ temperature/pressure chambers
- Electron microscopy (SEM, FIB-SEM)
- Thermo-optical measurement systems for surface tension and characteristic ash melting temperatures (TOMAC, TOMMI)
- High-temperature slag viscometers
- Leitz heating microscope (LEM) for investigations of ash melting behavior (oxidizing or reducing atmosphere)

**Thermal Analysis Lab**
- Thermogravimetry (TG) for ambient & elevated pressure (up to 100 bar)
- Differential thermo-analysis (DTA)
- Differential-scanning calorimetry (DSC)
- Simultaneous analysis coupled with mass spectroscopy: TG-DTA-MS, TG-DSC-MS

## HIGHLIGHTS OF LAB EQUIPMENT

### X-Ray Fluorescence (XRF) and X-Ray Diffraction Analysis (XRD)

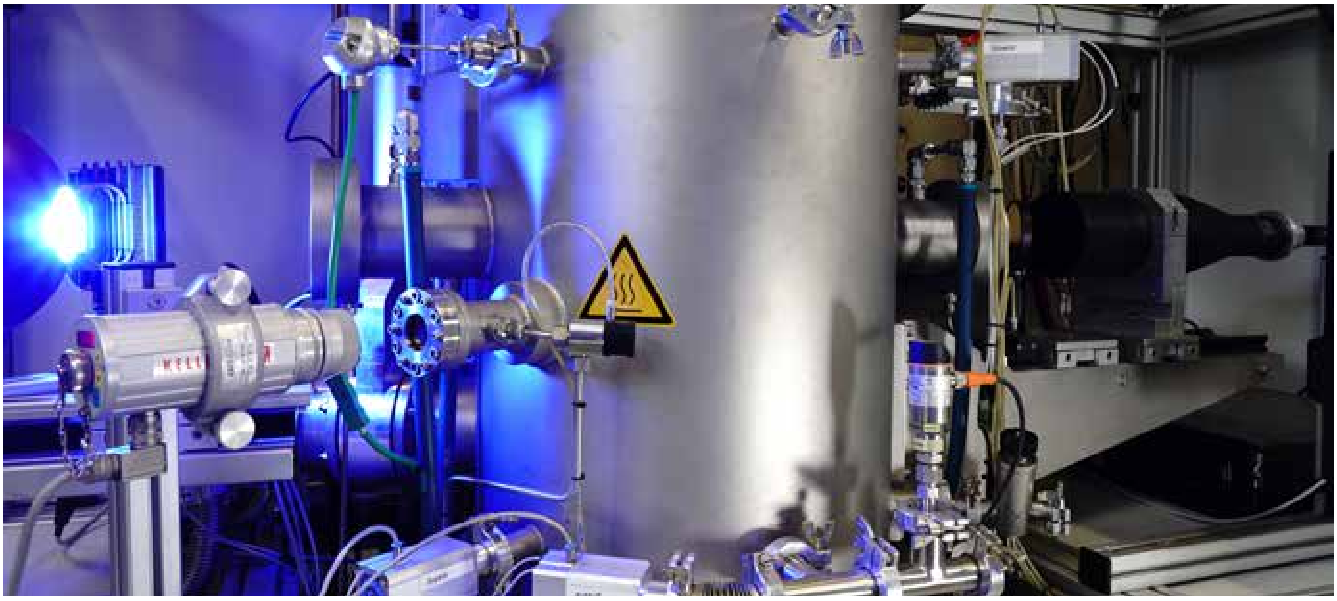
**Key Facts**
- Temperature: up to 1600 °C (three different chambers)
- Pressure: high vacuum to 20 bar (@ 1100 °C)
- Atmosphere: Air, $N_2$, $N_2 + H_2$
- Cu + Co radiation (standard diffractometer)

**R&D Focus**
- XRF enables the elemental analysis of solid and liquid feedstock as well as ash/slag
- XRD enables the determination and quantification of mineral phases as well as estimation of crystalline/amorphous content in ashes and other crystalline materials


### Scanning Electron Microscopy (SEM)

**Key Facts**
- SE, BSE, EDX, WDX detectors
- 3D analysis by "ion milling" (focused ion beam FIB), reconstruction software Avizo Fire
- Heating chambers (1500 °C)
- Gas injection: steam, $CO_2$

**R&D Focus**
- High resolution photographs and microanalysis of different samples



## Thermo-Optical Measurement (TOMAC/TOMMI)

**Key Facts**

- Temperature: 1700/2000 °C
- Pressure: air (TOMMI), vacuum
- Atmosphere: $N_2$, Ar, Ar+$H_2$ (TOM-AC)
- Image recording with shape evaluation
- Load application, weight measurement
- Maximum bubble pressure
- Option for in-situ FTIR

**R&D Focus**

- Slag behavior under high temperatures
- Determination of material properties (e.g. surface tension)

## High Temperature Viscometer

**Key Facts**

- Temperature: 650-1650 °C
- Atmosphere: air, $CO/CO_2$
- Viscosity range: 0.1-1500 Pas
- Heating/cooling rate: 0-10 K/min

**R&D Focus**

- Measurement of slag viscosity at high temperatures under different (gasification) atmospheres and shear rates
- Investigate non-newtonian slag behavior

## Pressurized Thermogravimetric Analysis

### Key Facts

- TGA (DMT Bergbauforschung GmbH)
- Temperature: ≤ 1100 °C
- Pressure: ≤ 100 bar
- Atmosphere: Ar, $CO_2$, $O_2$, $H_2$, CO, $H_2O$ (steam)
- Input: ≤ 1 g
- Heating/cooling rate: ≤ 40 K/min
- Drop in mode (preheated furnace)

### R&D Focus

- Investigate mass loss kinetics of pyrolysis and gasification
- Influence of process parameters and fuel properties

## Thermal Analysis (TG, DSC, DTA, EGA)

### Key Facts

- Devices:
  - TG-DSC
  - TG-DSC-MS
  - TG-DTA-MS
  - drop-DSC
- Parameters:
  - Temperatures: ≤ 600/1300/1650/2000 °C
  - Pressures: atmospheric
  - Atmospheres: Ar, $N_2$, He, $CO_2$, vacuum, air, $O_2$, forming gas
  - Input: ≤ 500 mg

### R&D Focus

- Investigate reaction kinetics and heat requirement
- Heat capacity measurement of solid feedstock
- Determination of phase changes, temperatures and enthalpies
- ...

## Inductive Coupled Plasma Optical Emission Spectroscopy (ETV-ICP OES)


### Key Facts

- Controlled programmable temperature (max. 2800 °C; max. heating rate 800 K/s)
- Atmospheres: Ar (with/without modifier, e.g. $CCl_2F_2$, $CF_4$, $CHF_3$, $NF_3$), $O_2$
- Detect the temperature-dependent decomposition of the sample

### R&D Focus

- Simultaneous quantitative multielement analysis of solids (after electro-thermal vaporization) and liquids (pure or after microwave digestion)

## Comprehensive Gas Chromatography Mass Spectrometry (GCxGC-MS)

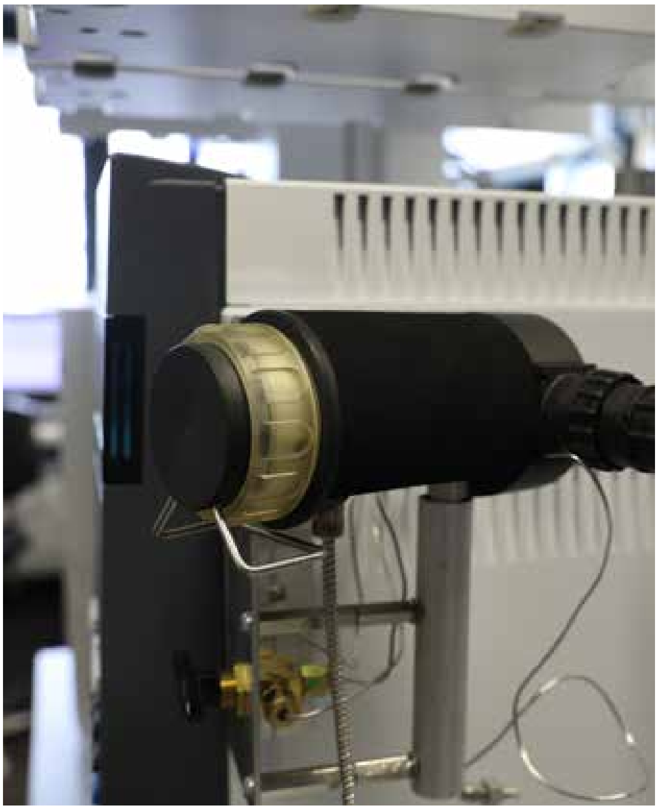
Comprehensive Gas Chromatography is an instrumental-analytical method that is particularly used for the analysis of complex mixtures of organic compounds.

### Key Facts

- High-resolution gas chromatography method
- Structural analysis using a hyphenated time-of-flight mass-spectrometer (TOF)
- Sample application depending on the analyte by liquid injection, headspace (HS) or solid phase microextraction (SPME)
- In-situ analysis of pyrolysis products using a pyrolysis unit directly coupled to the injector

### R&D Focus

Products from various thermochemical processes or syntheses are analyzed using GCxGC-MS. The main application areas are pyrolysis oils from plastics, biomass or coal, as well as the comprehensive analysis of fuels such as synthetic kerosene. In addition, the coupling with an analytical pyrolyzer is used to investigate the chemical reactions occurring at the molecular level of materials such as plastics.



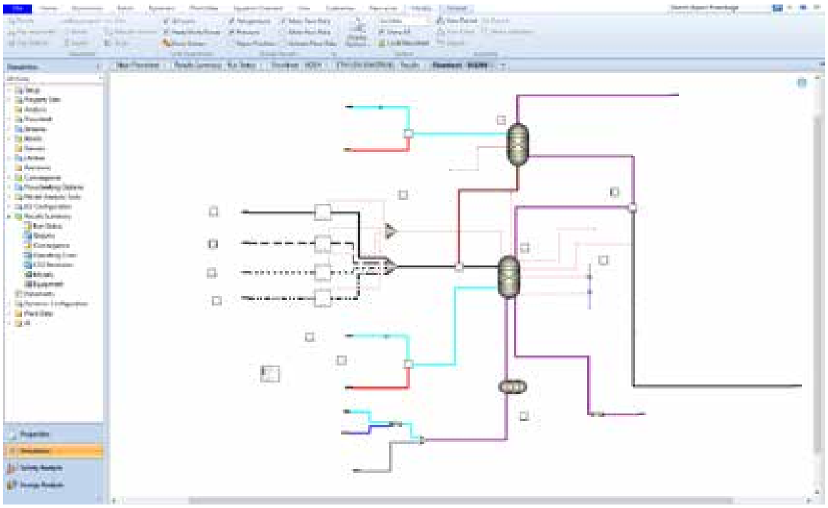
Fraunhofer IKTS

# MODELING & SOFTWARE TOOLS

Various modeling and software tools are available for different research and development activities including in-house code, commercial and open source codes.

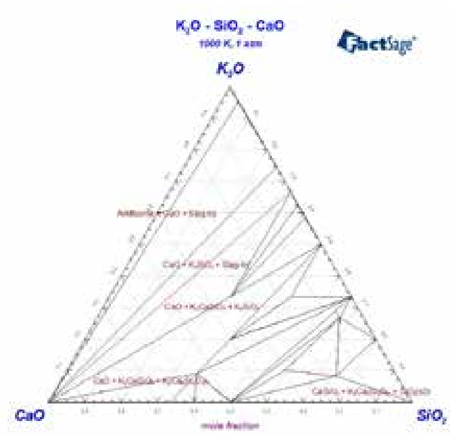
**CAD**
- AutoCAD
- AutoCAD P&ID
- Autodesk Inventor
- SolidWorks

**Flow Sheet Simulation**
- Aspen Engineering Suite: Aspen Plus, Aspen Dynamic, Aspen Custom Modeler, Aspen HYSYS
- Belsim Vali



**Mathematical Tools**
- MathCAD
- MATLAB
- Origin
- Statgraphics
- Python
- MySQL database

**Optimization**
- modeFrontier




**Life Cycle Assessment**
- GaBi

**Thermodynamics**
- FactSage
- SimuSage

In cooperation with Chair MTK:

**CFD Modelling and Mesh Generation**
- ANSYS Fluent
- StarCCM+
- ANSA

# R&D Service Portfolio

We offer a wide range of scientific and applied services that can be tailored to support your R&D goals. Contact us for discussions on a potential collaboration.

### 1. Scientific/technology consultancy & technical advisory:

- Due diligence (Probability-criticality analysis)
- Identification and evaluation of alternative conversion routes for carbonaceous feedstock
- Technological evaluation (e.g. conversion process, reactor design, burner design, refractory, components, feedstock preparation, handling of products and by-products)
- Process/technology optimization
- Technology screening
- Independent technology consulting & technical advisory, trouble-shooting
- ...

### 2. Laboratory & analytical services (especially high temperature/pressure processes):

- Feedstock analyses and evaluation
- Thermal analyses and characterization of feedstock
- Pore structure analyses
- Mineral matter analyses and characterization (e.g. slag viscosity)
- Pyrolysis and gasification behavior (kinetics)
- Characterization of feedstock and products
- ...

### 3. Process route evaluations & techno-economic-ecological assessments

- Development and modeling of syngas production routes (XtY)
- Feasibility studies including technology selection and economical evaluation
- Techno-economic & life-cycle impact assessments
- Identify process optimization and site integration opportunities
- Support of different project phases

### 4. Test campaigns:

- Test campaigns for all kinds of carbon feedstock
- Determination of feedstock suitability or process applicability
- Complete elemental and energy balances for main and minor elements including heavy metals, halogens, higher hydrocarbons, tar/oil, ...
- Evaluation of ash/slag qualities and composition of grey water
- Adjustment of different operational parameters for process optimization
- ...

### 5. Joint R&D, technology and process development/optimization

- New gasifier designs
- Robust burners with extended life-span for multiple feedstock
- Equipment/component tests
- ...

### 6. Utilization/transfer of patents for commercialization

# Communication and Knowledge Transfer

## INTERNATIONAL FREIBERG CONFERENCE

11th International Freiberg Conference
on Circular Carbon Technologies
Towards a Net-Zero Carbon Economy
24 – 29 September 2023
Rotterdam, Netherlands

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Since 2005, the IEC has organized the „International Freiberg Conference" – a leading international conference which addresses a wide range of socio-technological-economical-ecological-political topics relating to the thermo-chemical conversion of carbonaceous feedstock and its contribution to decarbonization and zero waste.

Specifically, the event focuses on opportunities, challenges and developments in thermo-chemical conversion of primary and secondary carbon resources into chemical products/hydrogen/fuels for the transition towards a low carbon, circular and hydrogen economy. It provides a high-level interactive discussion forum for specialists, practitioners and stakeholders from industry, science, politics and civic society to exchange information and insights about new developments, current/planned projects and operational experiences along innovative carbon value chains.

Previous conferences have been held in various locations in Germany as well as in Inner Mongolia in China.

In addition to a stimulating scientific conference program, the event also includes exciting on-site and off-site technical tours. During the tours, participants not only obtain first-hand experience of the facilities, they also have the opportunity to engage experts and industry specialists on-site in intensive discussion about their activities.

Last but not least, the conference program also consists of interesting social events (e.g. welcome reception, conference dinner, walking tours) which are dedicated to facilitating networking and interaction between conference participants.


# NETWORK FOR A CIRCULAR CARBON ECONOMY (NK2)

Carbon-containing raw materials are vital resources for the industry and underpin the wealth of numerous nations. A transition towards a circular carbon economy can enable carbon to be retained in the system rather than be emitted as climate polluting $CO_2$ upon combustion/incineration and/or landfilling. This however requires a change from business-as-usual and a coupling of the energy, chemical, engineering, waste management, recycling and other sectors (e.g. processing, lightweight construction and renewables).

To facilitate intersectoral dialogue and collaboration, the Network for a Circular Carbon Economy (in German: Netzwerk Kohlenstoffkreislaufwirtschaft i.e. NK2 Network) was initiated in 2019 by Fraunhofer IMWS and IEC, TU Bergakademie Freiberg. The NK2 Network provides a neutral platform for information exchange, knowledge sharing as well as intersectoral and international networking. Aim is to identify and address socio-technological-economical-ecological-political issues associated with the transition towards a circular carbon economy via workshops, experience exchanges, trainings and conferences, and to actively engage diverse stakeholders from industry, science, politics and civic society and contribute to socio-political dialogues about associated opportunities and challenges.

## Key topics and focuses for NK2:

- Materials, processes and technologies for the conversion of solid carbon resources
- Integration of "green" hydrogen and renewable power
- $CO_2$-neutral, gas-based processes and syntheses for chemical basis materials and synthetic fuels
- New materials, material utilization & process design
- Information technology
- Systems and sustainability for a circular economy
- Political framework and legislations

## NK2 partners include:

- Air Liquide Forschung und Entwicklung GmbH
- BASF SE
- CARBOLIQ GmbH
- CAC Engineering GmbH
- Covestro Deutschland AG
- DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH
- Dow Olefinverbund GmbH
- Eurofins Umwelt Ost GmbH
- Fraunhofer IKTS
- Hallesche Wasser und Stadtwirtschaft GmbH
- Hochschule Merseburg
- IBExU Institut für Sicherheitstechnik GmbH
- INEOS Inovym
- LyondellBasell Polyolefine GmbH
- ROMONTA GmbH
- RWE Power AG
- Sächsisches Textilforschungsinstitut e.V.
- Synthos Schkopau GmbH
- TAF Thermische Apparate Freiberg GmbH
- ...

NK2 Netzwerk Kohlenstoff kreislaufwirtschaft

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# COMPACT COURSES

IEC-EVT offers intensive compact courses in the field of thermo-chemical conversion. Courses provide a detailed introduction to the scientific fundamentals, process routes and technologies of the following topics:

- Chemical recycling
- Pyrolysis/Gasification
- Synthesis gas production
- Synthesis gas purification
- IGCC power plants
- ...

Leading commercialized carbon conversion technologies are presented in detail. The course program also provides introduction to various simulation and assessment software tools (e.g. LCA, TEA).
On-site courses also include technical tours of IEC's extensive laboratory, bench-scale and pilot-scale facilities and optional off-site technical visits.

The courses are targeted at:

- Engineers, technical, management and R&D personnel
- Technology companies and organizations which are engaged in sustainability, circular carbon and decarbonization activities and which would like to update and expand their knowledge on innovative carbon value chains and alternative feedstock and conversion routes

The limited number of participants allows for intensive interactive exchanges with experts providing the course. To ensure a high level of quality, experienced specialists from the industry are invited to present special topics in the courses.

Compact courses are being offered regularly by IEC-EVT since 2005. Employees from leading national and international companies from diverse sectors have participated in previous courses including ArcelorMittal, Alstom, BASF, Covestro, Dow, Ebara, EDL, E.ON, Enerkem, Haldor Topsoe, Hydro Oil and Energy, INEOS Inovyn, Johnson Matthey, Linde, MAN, MOL, RWE, Saint Gobain, Shell, Siemens, Total, VNG,...

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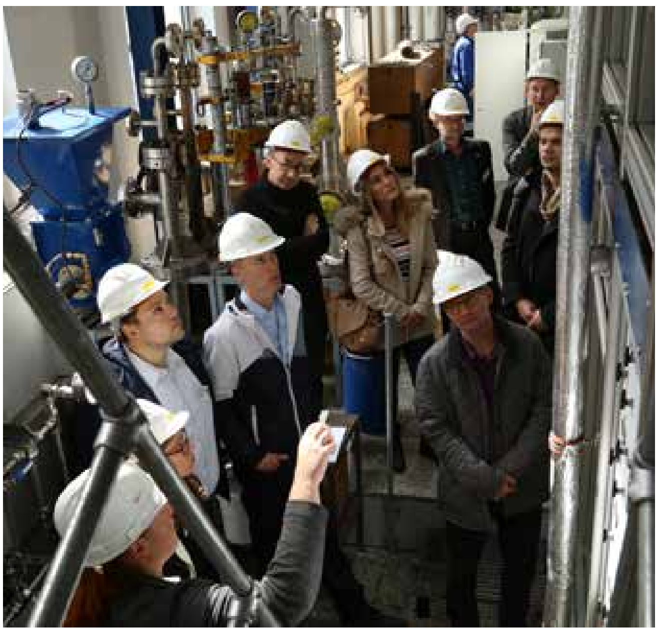


## CARBON DISCOVERY TRAIL

In 2020, IEC launched the Carbon Discovery Trail (in German: Wissensreise Kohlenstoff) at Reiche Zeche in Freiberg, Germany. Aim is to engage the general public to increase their awareness about the carbon challenge, and provide them with insights into how R&D activities in IEC contribute to solutions to address global challenges ranging from climate change, extreme weather, waste crisis, resource depletion to import dependency.

The Carbon Discovery Trail takes visitors on a journey through:

- What is Carbon?
- The Carbon Dilemma
- We Need a Carbon Transition!
- Our Institute
- Carbon Transition Technologies
- Innovations for Sustainable Products

It is open daily from 8:00 to 20:00 and welcome visitors to take a walk through the trail independently, or to contact us to arrange for a guided tour.

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