DEMONSTRATION OF GAS SWITCHING TECHNOLOGY FOR ACCELERATED SCALE-UP OF PRESSURIZED CHEMICAL LOOPING APPLICATIONS (GASTECH)

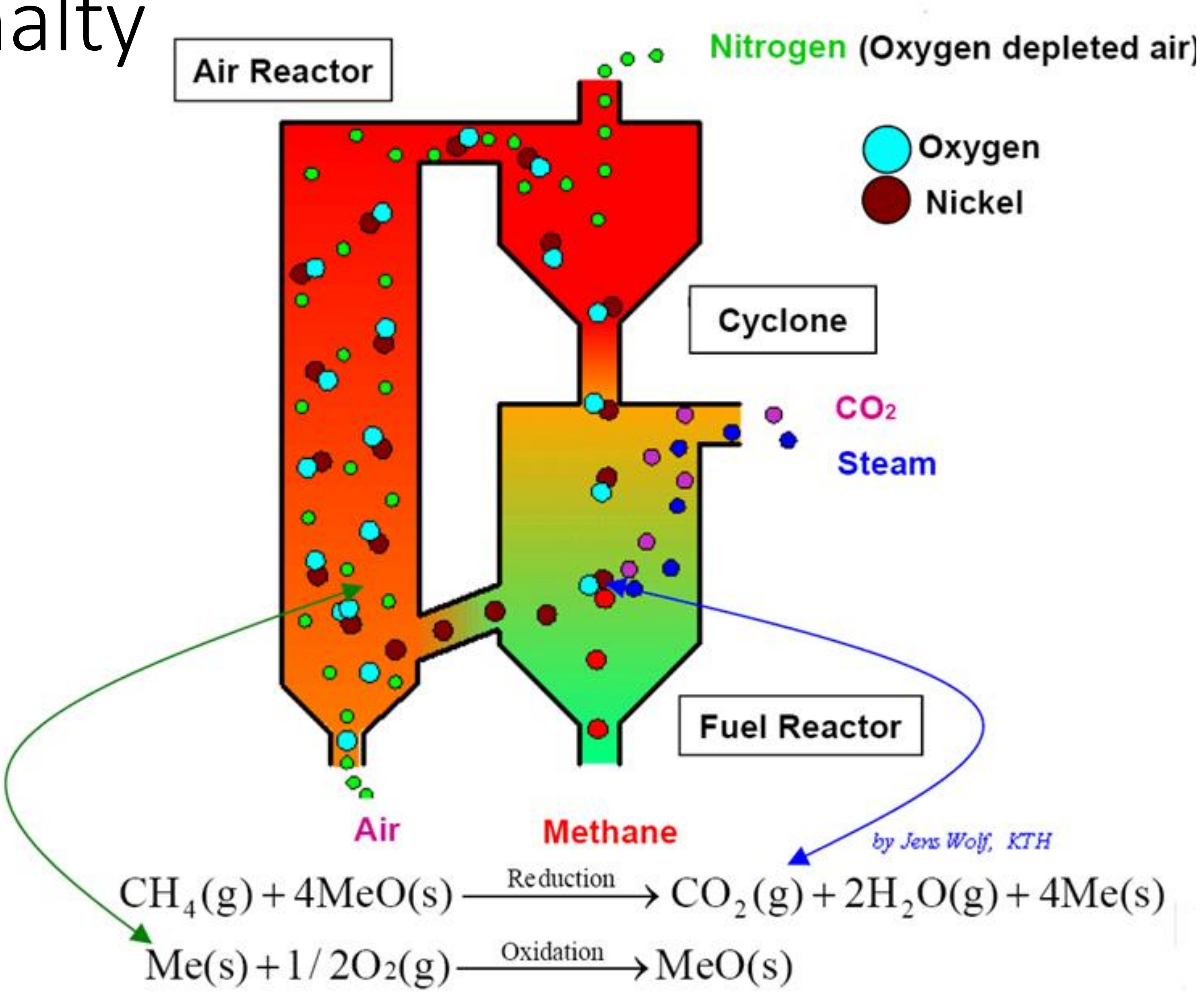
SHAHRIAR AMINI – SINTEF/NORWAY (COORDINATOR)
FELIX DONAT – ETH/SWITZERLAND
ABDEL ZAABOUT – SINTEF/NORWAY
SHAREQ NAZIR – NTNU/NORWAY
CARLOS ARNAIZ– UPM/SPAIN
ANA-MARIA CORMOS – UBB/ROMANIA
FATIH EURGUENY – HAYAT/TURKEY

Project partners

#	Participant legal name	Short name	Type	Country
1	Stiftelsen SINTEF	SINTEF	RTO	NO
2	Norwegian University of Science and Technology	NTNU	UNI	NO
3	Euro Support Advanced Materials B.V.	ESAM	SME	NL
4	Universitatea Babeș-Bolyai	UBB	UNI	RO
5	Hayat	HAYAT	IND	TR
6	ETH Zürich	ETH	UNI	CH
7	Universidad Politécnica de Madrid	UPM	UNI	ES

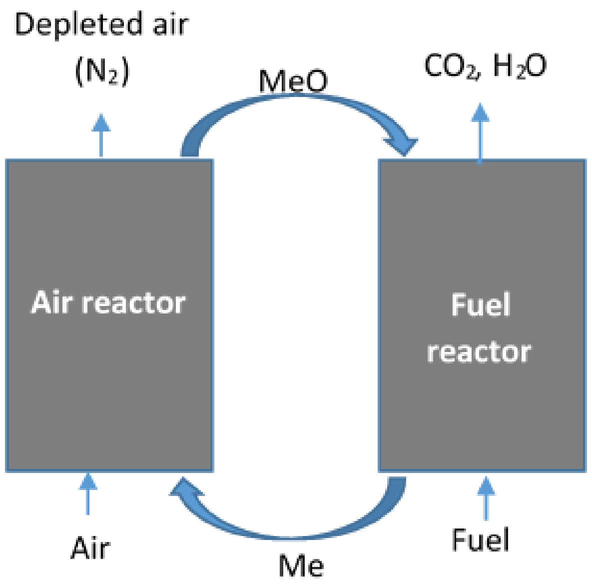
Chemical looping principle for CO_2 capture with no energy penalty

- Pure CO_2 is achieved
- No direct energy penalty
- Metal oxide as a source of oxygen and heat
- No direct contact of air and fuel



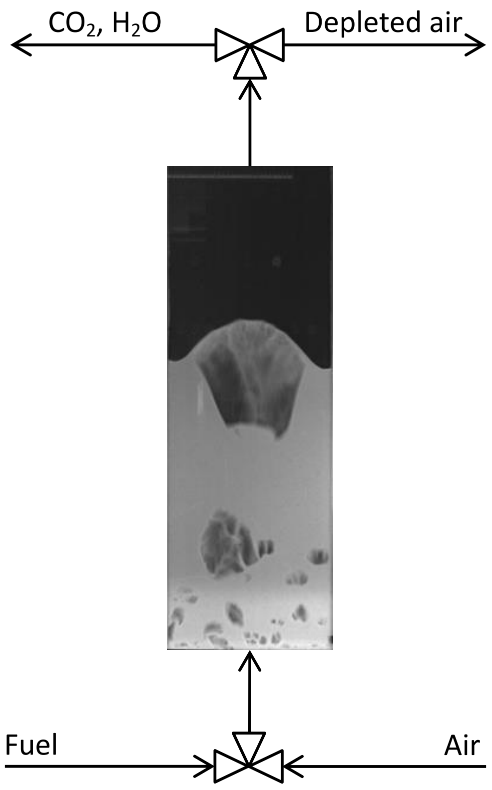
Gas Switching Technology

→ **Based on the Chemical Looping principle**



Process simplification

Gas Switching Reactor



1. Air reactor: Reduced metal (Me) is oxidized with air. High temperature N_2 stream produced
2. Fuel reactor: Metal oxide (MeO) provides the oxygen for combustion in the fuel reactor to produce only CO_2 and steam

- Highly efficient power or hydrogen production with integrated CO2 capture
- No external circulation of solids
- Easy to pressurize and scale up
- High load flexibility

Scope and budget of GaSTech

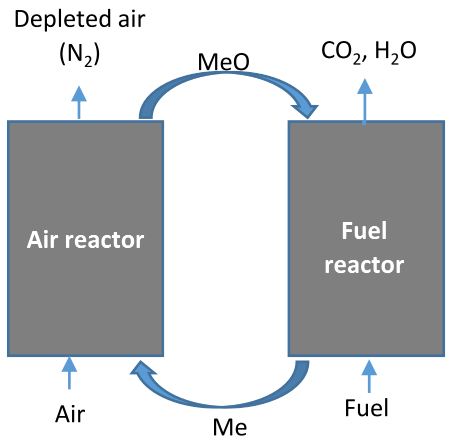
<u>Project objective</u>: *To accelerate the development of gas switching technologies by further technology scale-up through:*

- Lab-scale demonstration (TRL 4) of gas switching reactor concepts
- Large-scale technology implementation studies to evaluate the techno-economic feasibility of process concepts incorporating gas switching reactors
- Business case development
- Budget: 2,602,000 Euro

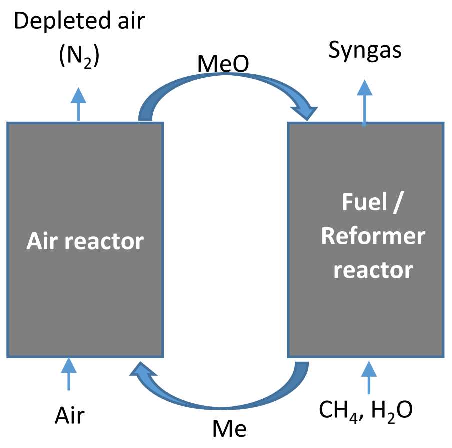
GasTech is applied to different Chemical looping processes:

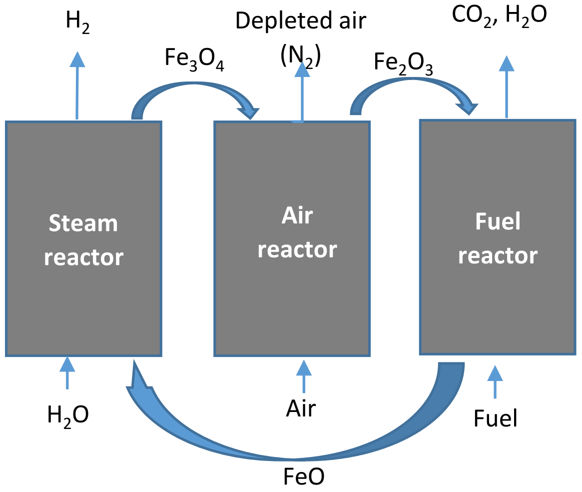
- Combustion (cluster of reactors)
- Reforming
- Water splitting
- Oxygen production

Gas Switching Combustion (GSC)

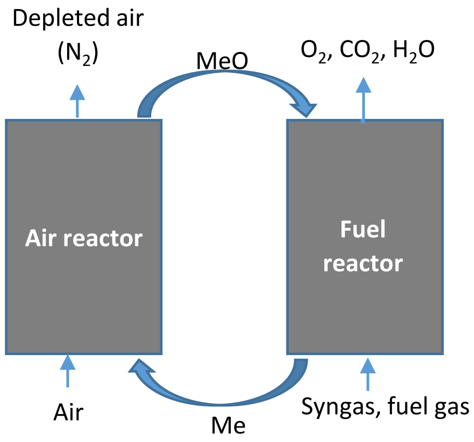


Gas Switching Reforming (GSR)





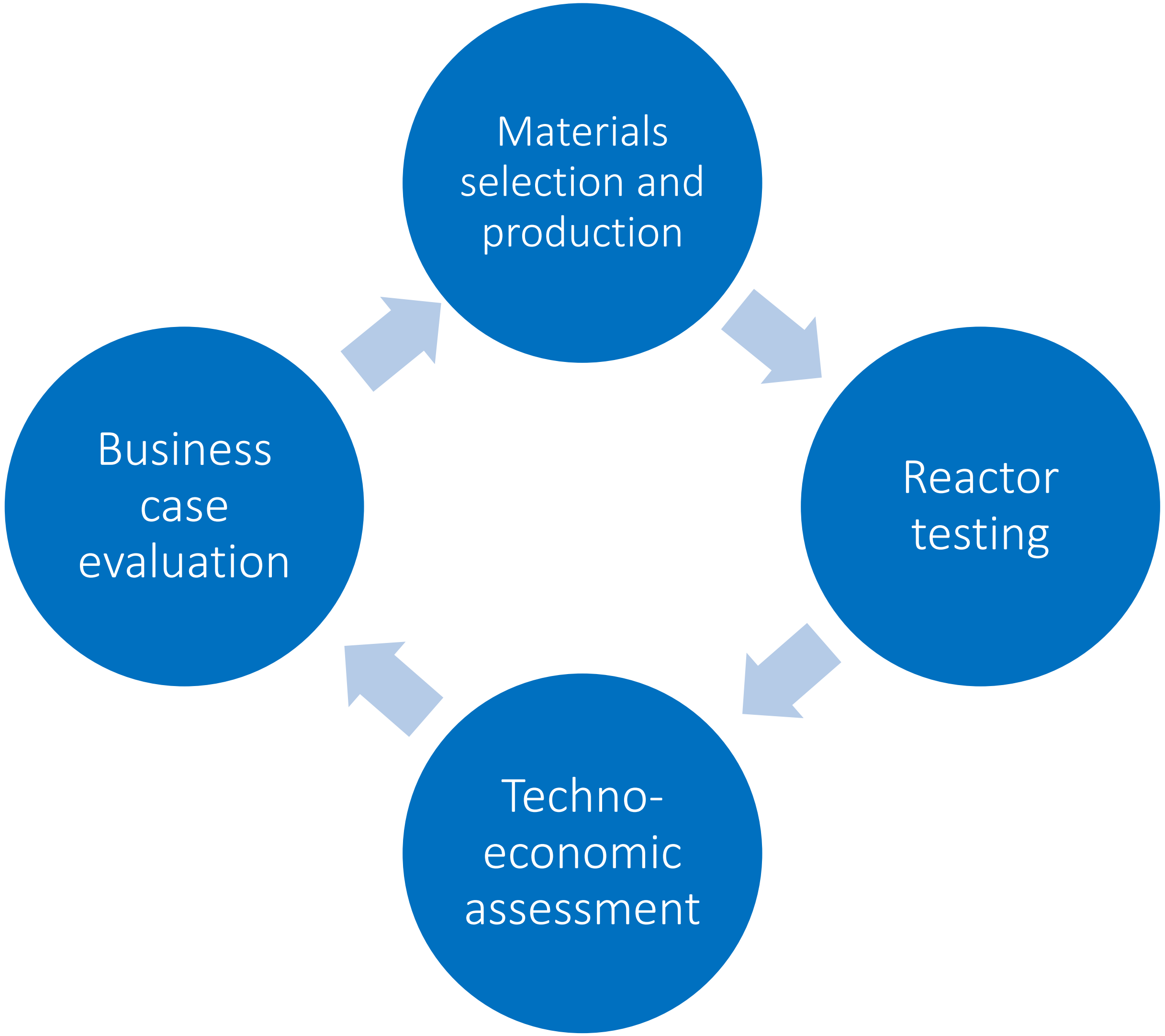
Gas Switching Water Splitting (GSWS)



Gas Switching Oxygen Production (GSOP)

Work packages

WP No	WP title	Lead	Participants
WP1	Materials selection, testing and manufacturing	ETH	ESAM
WP2	Demonstration of pressurized GSC, GSR, GSWS and GSOP operation	SINTEF	NTNU
WP3	Large-scale process simulation of gas switching technology	NTNU	UPM SINTEF NTNU
WP4	Economic assessments of gas switching technology	UBB	ESAM
WP5	Business case	HAYAT	All partners
WP6	Management and dissemination	SINTEF	All partners



Materials selection and production
Reactor testing
Techno-economic assessment
Business case evaluation

Expected project outcomes

- Materials production

  - Development of suitable oxygen career materials for all four processes and their successful production via spray-drying for scale-up

- Reactor test

  - Successful auto-thermal operation in the gas switching reactor incl. cluster operation

- Techno-economic assessment

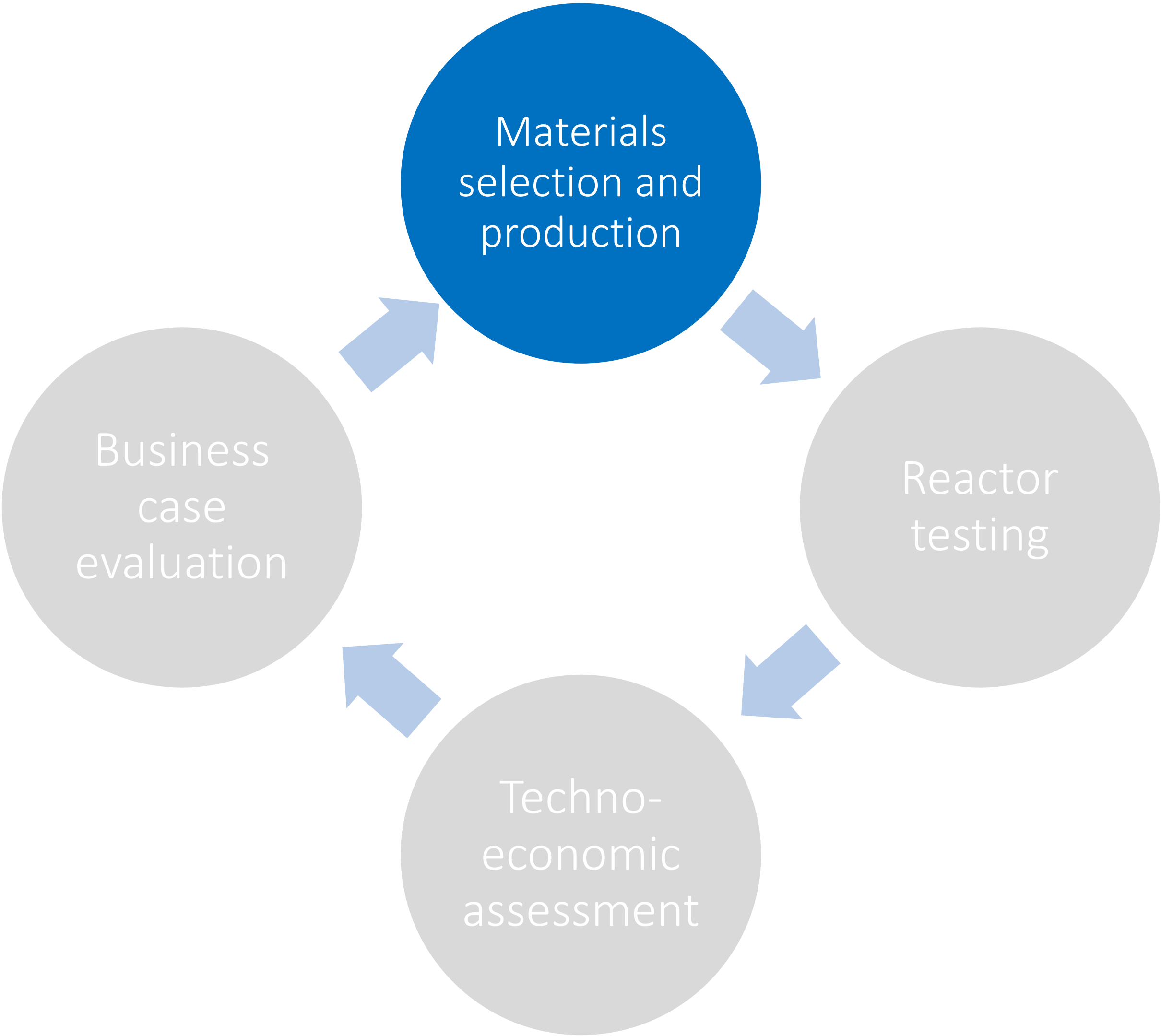
  - Successfully modelled gas switching process configurations that clearly outperform benchmarks in terms of efficiency and economics (power production and H_2 generation relative to conventional carbon abatement technologies)

- Business case

  - Building a pilot

Partner roles

- Selection and pre-testing of the oxygen carrier materials by **ETH** to be manufactured by **ESAM**
- Experimental demonstration of Gas Switching by **SINTEF** and **NTNU**
- Modelling of large-scale gas switching reactor by **SINTEF** to provide input to process simulations done by **NTNU** and **UPM**
- Economic assessments for the different processes by **UBB**
- Evaluation of the business case based on the main project results by **HAYAT**

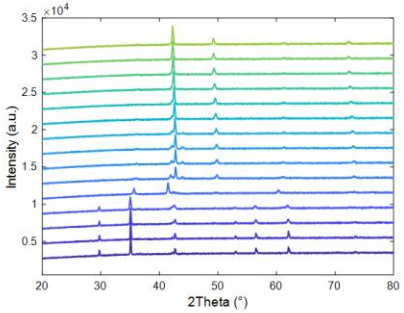

Materials selection and production
Reactor testing
Techno-economic assessment
Business case evaluation

Materials selection, testing and manufacturing

- Development of suitable oxygen storage materials ("oxygen carrier") for the four GaSTech processes for combustion, reforming, water splitting and oxygen production
- Material selection largely based on previous research in the context of chemical looping

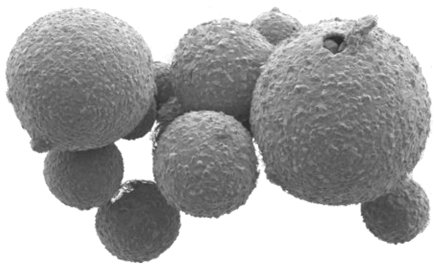
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

- State-of-the-art equipment for material synthesis, testing and characterization
- Focus on chemical, compositional stability and fluidized bed operation



euro support

- Production of oxygen carrier spheres via spray-drying
- 15-20 kg of particles per batch
- Relatively cheap raw materials
- Particle size ~150 µm



Gas Switching Combustion (GSC)

- Power generation with inherent CO_2 capture
- Expertise from previous EU-funded projects (INNOCUOUS, SUCCESS) has been very **useful**
- Oxygen carrier $CaMn_{0.775}Mg_{0.1}Ti_{0.125}O_3$ found to be **highly reactive** for the combustion of natural gas for power generation with inherent CO_2 capture
- **High cyclic stability** and sinter-resistance in fluidized bed experiments
- > 50 kg of oxygen carrier for operation in the cluster of three reactors **successfully produced via spray drying**

Gas Switching Water Splitting (GSWS)

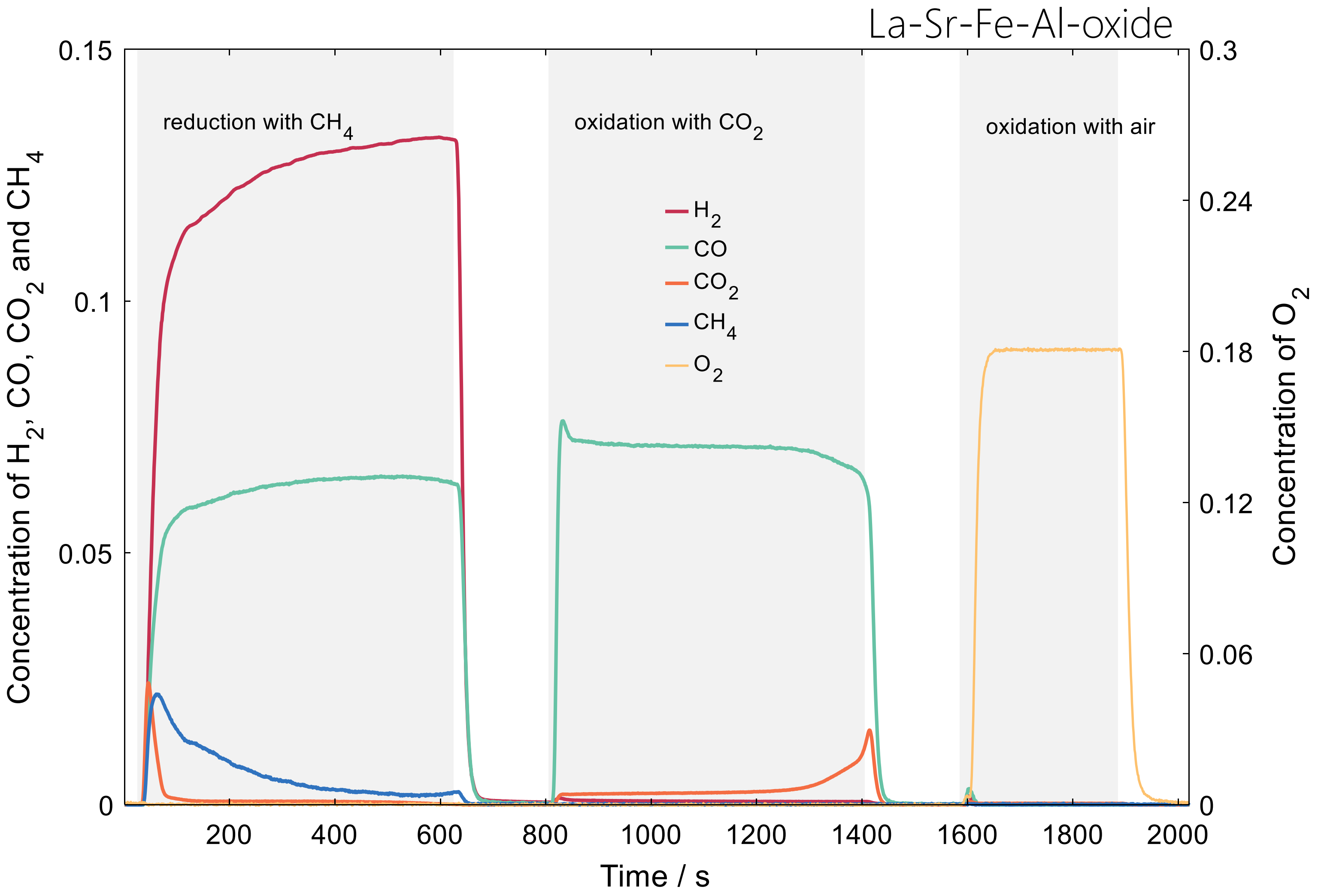
- Inherent CO_2 capture during reduction, H_2 production during oxidation
- Oxygen carriers need to possess a high oxygen storage capacity (>20 wt.%) for competiveness with combined moving bed / circulating fluidized bed reactors
- Highly reactive oxygen carrier $Mg(Fe_{0.9}Al_{0.1})_2O_4$ doped with CuO tested
- Very challenging due to **agglomeration and coke deposition**
- Realistically **no prospects** for GSWS

Gas Switching Reforming (GSR) / Gas Switching Partial Oxidation (GSPOx)

- Redox reactions with the oxygen carrier supply heat to the endothermic steam-methane reforming reaction to produce a H_2-rich syngas with inherent CO_2 capture
- CH_4 reforming requires catalysts, which are either expensive or toxic, and sinter at T > 900°C
- Alternative: "**non-catalytic route**" via the partial oxidation of CH_4
  → Gas Switching Partial Oxidation (GSPOx)
- Syngas production during reduction, H_2 and/or CO production during oxidation

- Long-term stability: **6 weeks of continuous testing** (~3000 redox cycles) of the oxygen carrier $La_{0.85}Sr_{0.15}FeO_3$ doped with Al_2O_3 without problems
- <u>Potential applications</u>: H_2 production for gas turbines, production of chemicals based on syngas (methanol, Fischer-Tropsch)

Gas Switching Partial Oxidation



Small fluidized bed 950°C, redox cycle with diluted gases

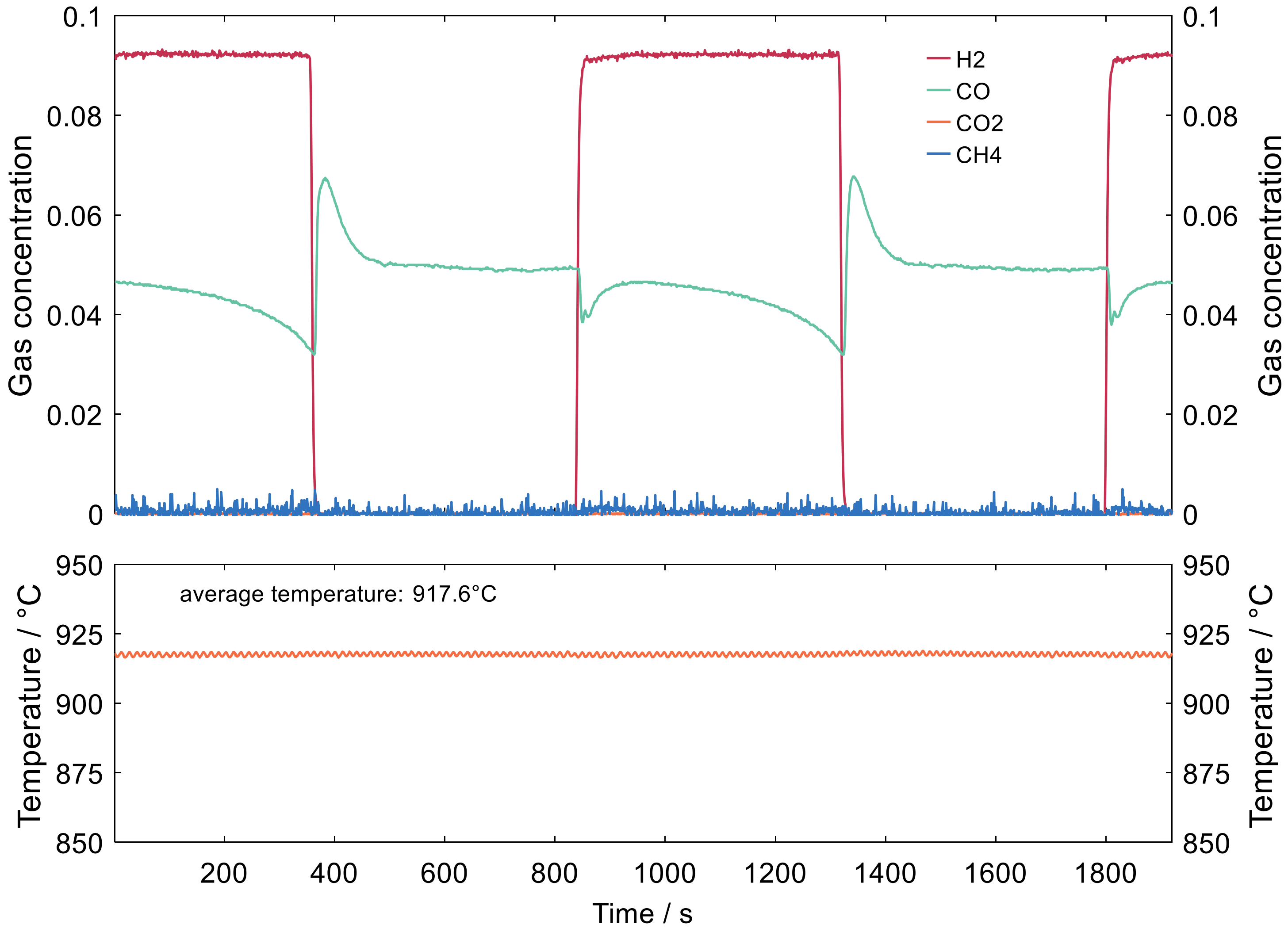
<u>Reduction</u>

- CH_4 conversion: 92%
- Syngas selectivity: 99+ %
- Ratio H_2:CO = 2.00
- Oxygen storage capacity: 8.5 wt.% per g oxygen carrier

<u>Oxidation</u>

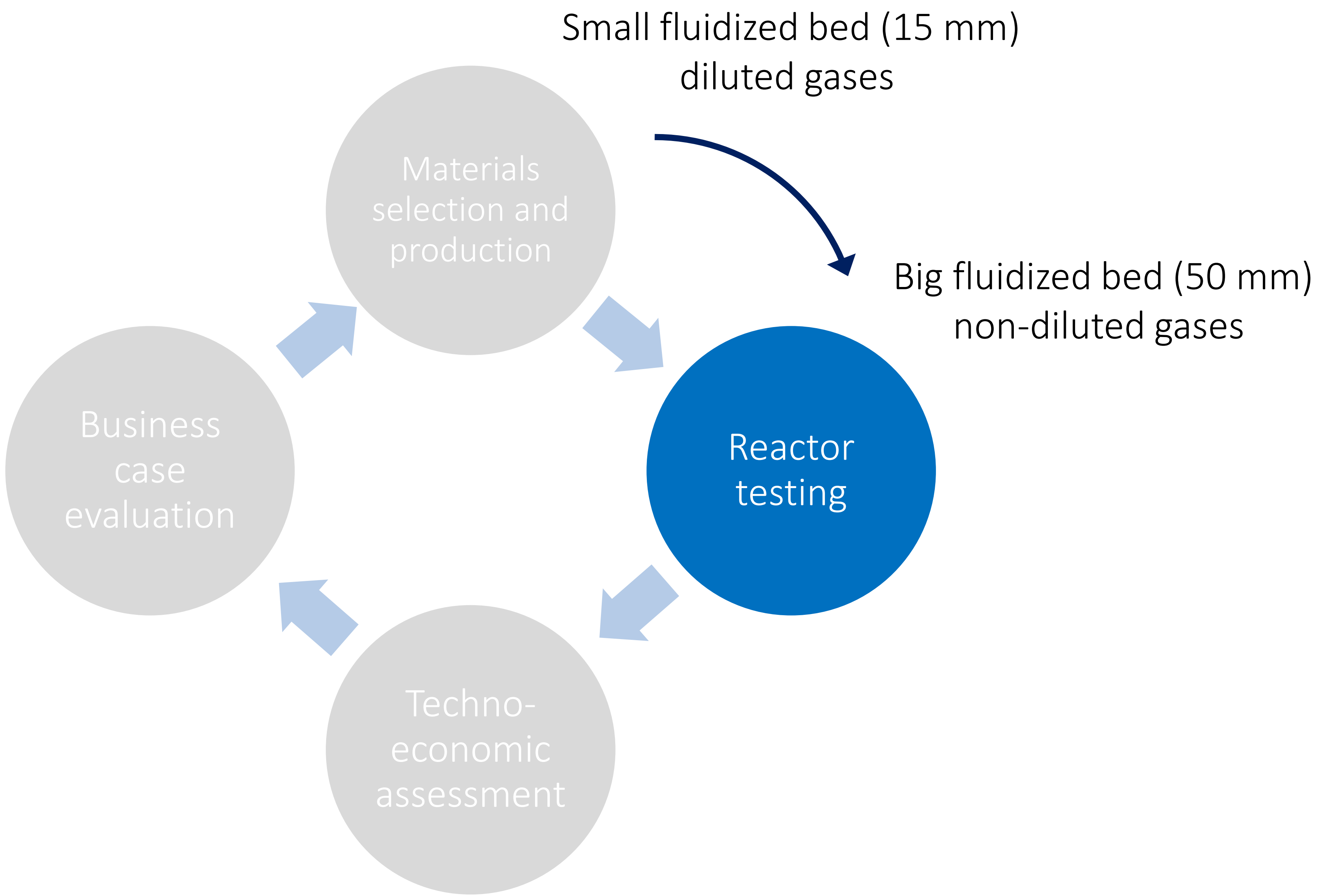
- CO_2 conversion: 97 %
- H_2O conversion: 94 %

Gas Switching Partial Oxidation (new process configuration!)

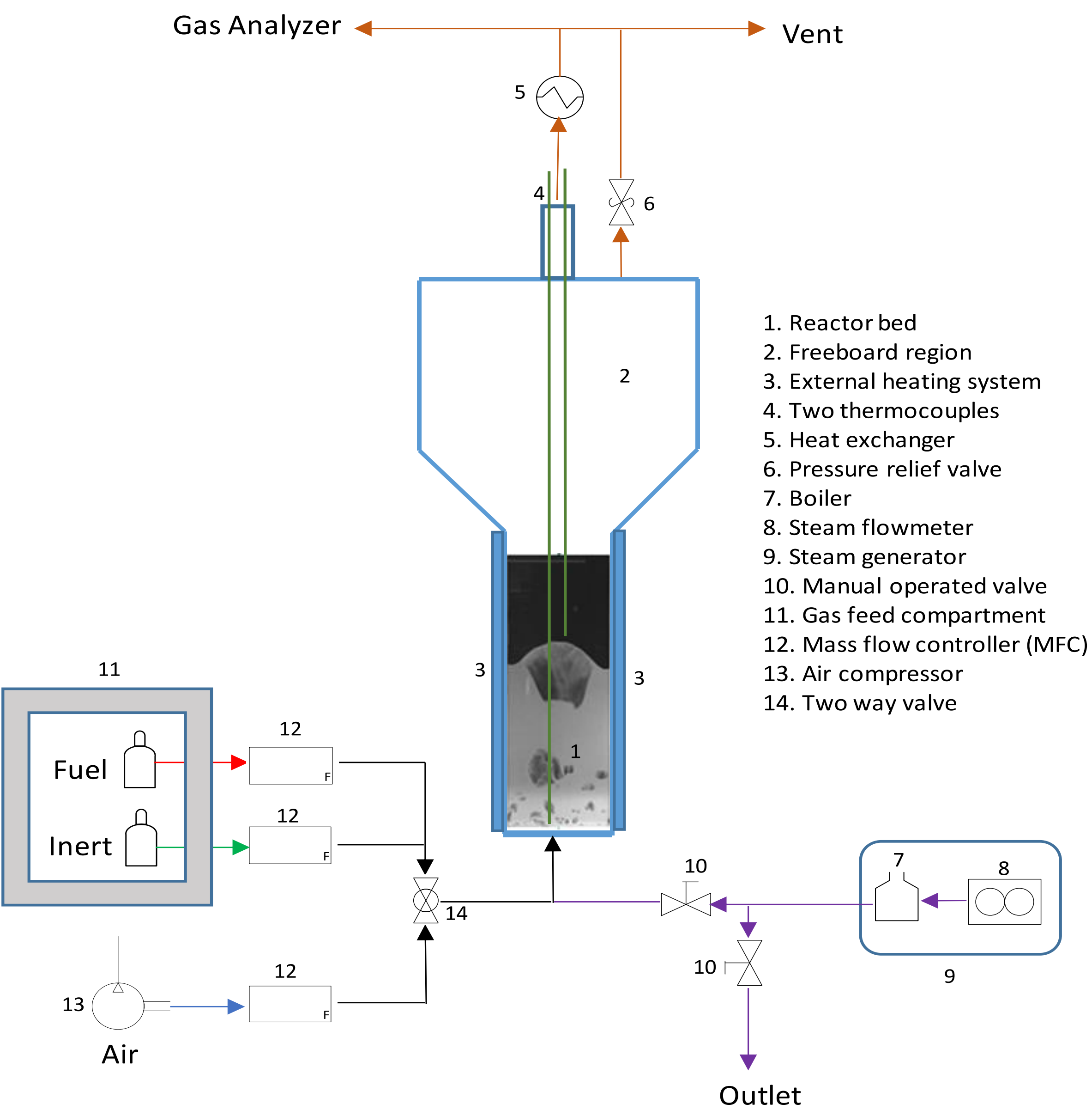


- Continuous operation without purge (reduction/oxidation) under **packed bed conditions**
- **Complete** conversion of CH_4 to syngas
- **Near complete conversion** of CO_2 to CO (or H_2O to H_2)
- No CO_2 generation
- Ratio H_2:CO can precisely be set through the choice of the oxidant (CO_2 or H_2O)

- Elimination of mixing effects in the gas switching reactor


Small fluidized bed (15 mm)
diluted gases
Materials selection and production
Big fluidized bed (50 mm)
non-diluted gases
Business case evaluation
Reactor testing
Techno-economic assessment

Experimental Demonstration in a larger reactor



- Fluidized bed reactor
- 5 cm diameter, 50 cm height
- Reactor vessel can withstand up to 12 bar and 1000°C
- Undiluted gases
- Online gas composition, temp. and pressure measurements

Completed experimental campaigns

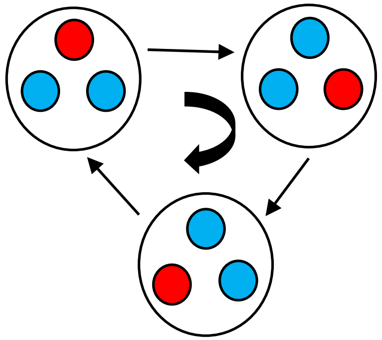
S/N	Process	Description	Oxygen Carrier	Temp.	Pressure	Application
1	GSC	2-stage process that produces high temperature gas stream with integrated CO_2 capture	$CaMnO_{3-\delta}$-based	850 - 1000°C	1-15 bar	• Power generation
2	GSR	Syngas with H_2/CO ratio between 2-4	Fe-based	700 - 850°C	1 -5 bar	• H_2 production • GTL processes
3	GSR	Syngas with H_2/CO ratio between of approx. 1	Ni-based	700 - 850°C	1-5 bar	• GTL processes
4	GSOPX	2-stage process that produces syngas in 1st stage and utilizes CO_2/H_2O to produce H_2/CO in the 2nd stage	La-Sr-Fe-based	800 - 1000°C	1-10 bar	• GTL processes • H_2 production • CO production
5	GSWS	2-stage process for H_2 production with integrated CO_2 capture	Fe-based	700 - 850°C	1-5 bar	• H_2 production

Process currently investigated: GSOP

- GSC: Gas Switching Combustion
- GSR: Gas Switching Reforming
- GSWS: Gas Switching Water Splitting
- GSOP: Gas Switching Oxygen Production
- GSPOX: Gas Switching Partial Oxidation

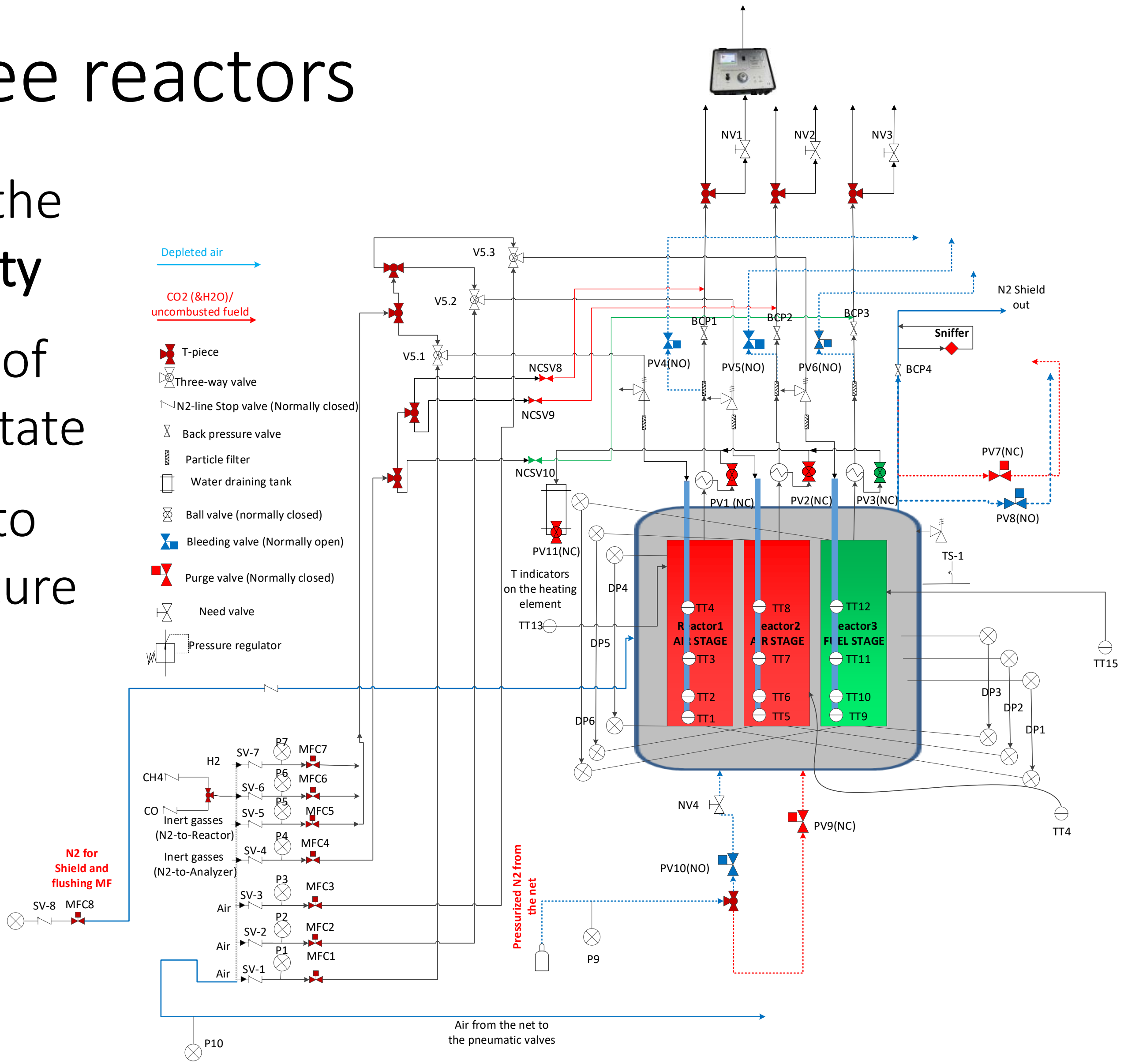
Design of a cluster of three reactors

- Demonstrate the continuous operation of the Gas Switching Combustion at **60 kW capacity**
- Design and validate the operation strategy of multiple reactors in the cluster for steady state
- Advance the state-of-the art operation up to **15 bar** in pressure and **1000 °C** in temperature



= Reduction stage

= Oxidation stage



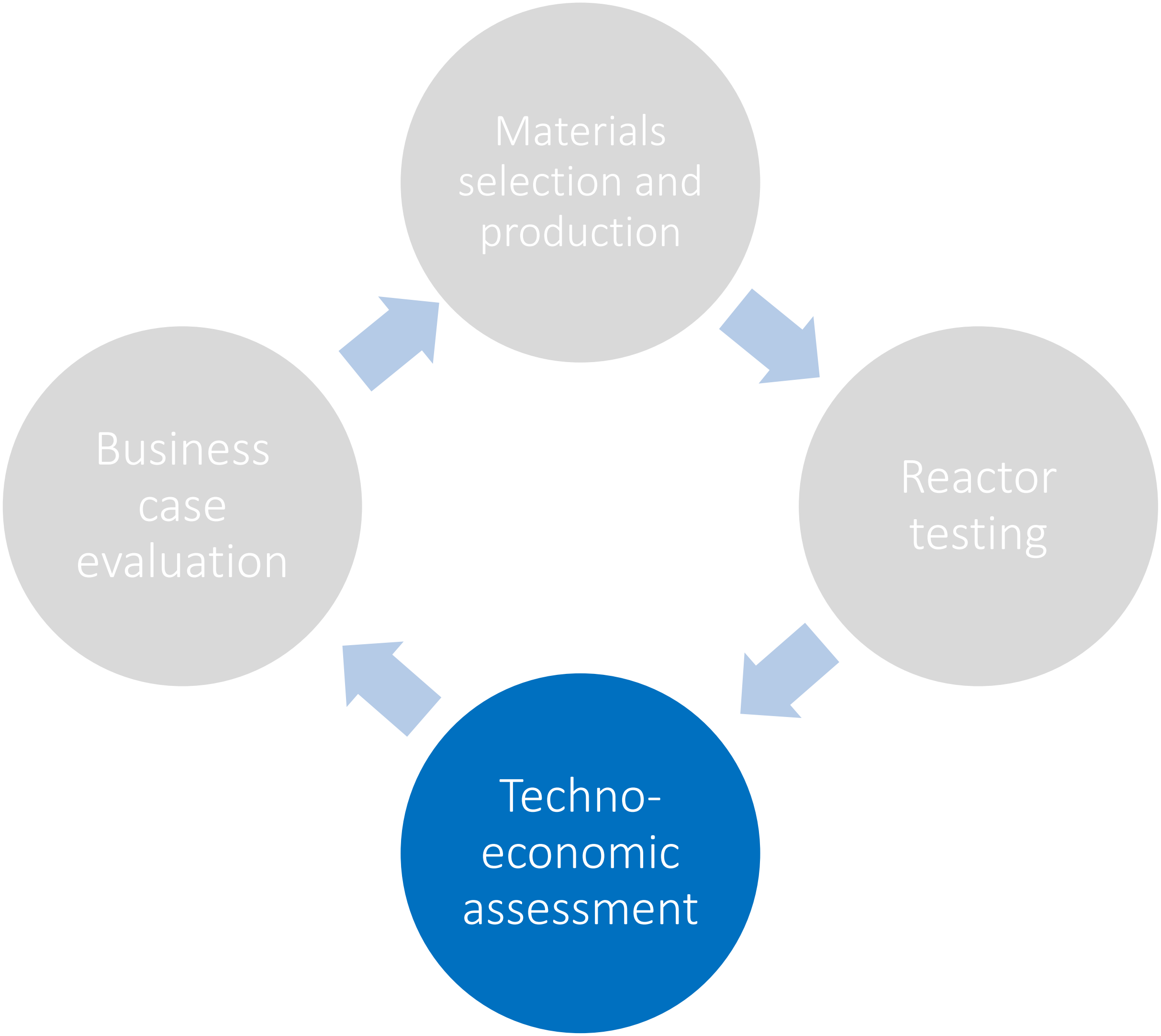


- Three reactors of 10 cm ID and 2 m height
- Designed for 20 bar operating pressure
- 1100 °C operating temperature
- Reactors are placed in a pressure shell
- Autothermal operation

Dissemination materials development and testing

- Journal publications: 4
    1. International journal of Hydrogen Energy
    2. International Journal of Greenhouse Gas Control
    3. Energy Technology
    4. Powder Technology

- Conference presentations: 8
    1. Trondheiem CCS Conference (TCCS 10), Trondheim
    2. Fluidization XVI Conference Guilin, China
    3. PARTEC International Congress on Particle Technology, Germany
    4. GHGT 14 International Conference Melbourne, Australia
    5. 5th International Conference on Chemical Looping Park City Utah, USA
    6. Energy Conference organized by The Research Council of Norway, Oslo
    7. 25th International Conference on Chemical Reaction Engineering, Florence, Italy
    8. International Hydrogen and Fuel Cell Conference Trondheim, Norway


Materials selection and production
Reactor testing
Techno-economic assessment
Business case evaluation

Key project results: Reforming

Process	**Key findings**
Gas Switching Reforming (GSC) – Combined Cycle	**7.2%**-point efficiency penalty relative to conventional NGCC (ca. 10%). GSR-CC gives a **5%** more return on investment in a scenario with 50% variable renewable mix.
Gas Switching Reforming (GSR) – H_2 Production	More than **96%** CO_2 capture and near zero efficiency penalty with respect to SMR plant (without CO_2 capture). H_2 with lower cost than from SMR plant can be produced.

Key project results: Combustion

Power Plant Concept	Power Plant Model	Power Plant KPI		+	-
		Eff. (%)	*Capture (%)*		
Benchmark	Unabated IGCC	47.6	0	*High Efficiency* *GT Modified*	*No Capture*
	Pre-Combustion CO_2	37.8	90.6	*High Capture* *GT modified*	*High Energy Penalty* *H2 Firing*
Gas Switching Oxygen Production (GSOP)	GSOP + GSC	46.6	83.8	*High Efficiency*	*Lower Capture* *2 Clusters* *Valves & Filters* *Gasification*
	Oxygen Production Pre-Combustion (OPPC)	43.9	82.9	*Moderate Efficiency* *GT Modified*	*H2 Firing* *Lower Capture* *Gasification*
Gas Switching Combustion(GSC)	GSC – Combined Cycle	43.6	91.9	*Moderate Efficiency* *High Capture*	*Valves & Filters*
	GSC + Extra Firing	**49.4**	**77.9***	*High Efficiency* *GT Modified*	*Lower Capture* *Natural Gas* *Valves & Filters*
	GSC – Humid Air Turbine	41.6	99.2	*Very High Capture* *Flexibility* *Lower Investment*	*Valves & Filters* *Power Cycle* *Cluster Design*

Economic assessments of gas switching technologies

Processes

Benchmark cases

Gas Switching Reforming (GSR)

- Natural Gas Combined Cycle (NGCC)
- Natural Gas Combined Cycle with Carbon Capture (NGCC–CC)

Gas Switching Combustion (GSC)

- Integrated Gasification Combined Cycle (IGCC)
- Integrated Gasification Combined Cycle with Carbon Capture (IGCC–CC)

Methodology

Installation Cost

- Installation cost of each unit
- Engineering procurement and construction costs
- Process contingency, etc.

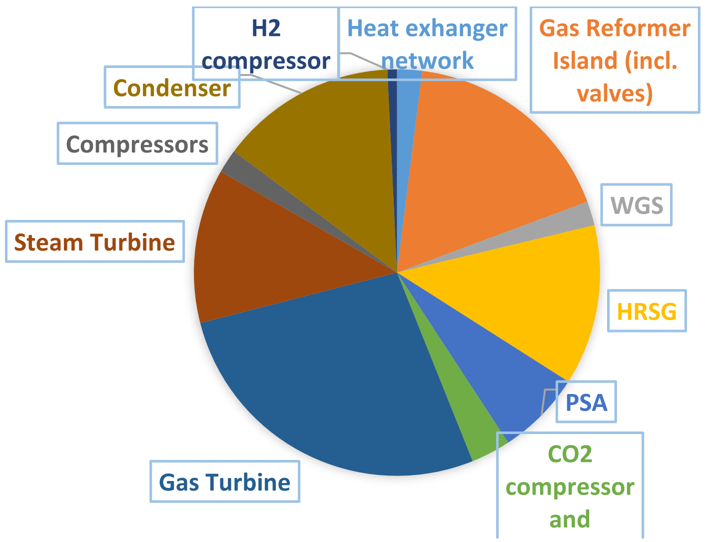
Operational and maintenance costs

- Fixed O&M costs
- Variable O&M costs
- Chemicals, etc.

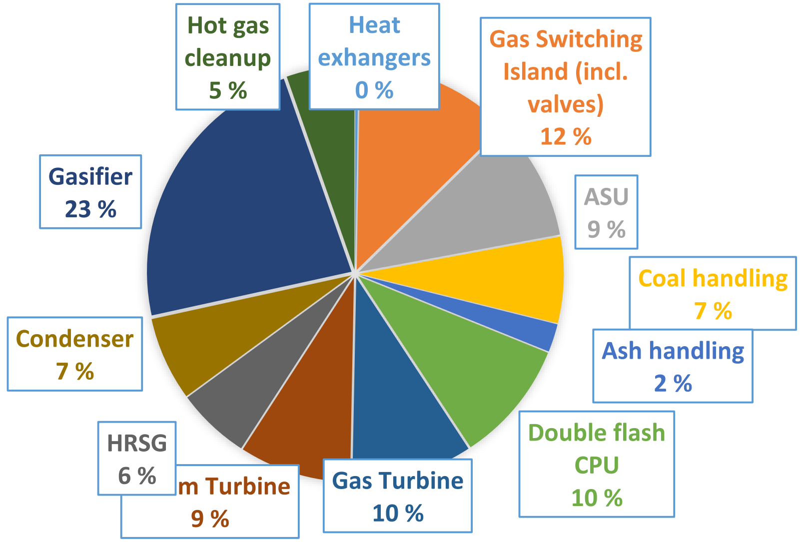
Levelized cost of electricity

Cost of CO_2 avoidance

Capital cost for Gas Switching Reforming / Gas Switching Combustion



Total install cost breakdown for **Gas Switching Reforming**



Total install cost breakdown for **Gas Switching Combustion**

	NGCC	**NGCC-CC**	**GSR**	**IGCC**	**IGCC-CC**	**GSC**	**GSC + NG**
Total Install cost (M€)	382.9	495.8	692.3	605.93	685.40	734.41	805.85
Total overnight cost (M€)	532.6	702.25	1014.1	897.99	1017.09	1264.84	1212.53
Specific investment cost (€/kWe)	**642**	**989**	**1072**	**2209**	**3157**	**2979**	**2085**

	GSR	GSC
Economic lifetime	30 years	25 years
Discount rate	8%	8%
Construction period	3 years	4 years
Capacity factor	85%	85%
First year capacity factor	65%	65%

LCEO - calculated for a net present value (*NPV*) of zero

$$COCA\left(\frac{€}{tCO_2}\right) = \frac{LCOE_{cc} - LCOE_{ref}}{E_{ref} - E_{cc}}$$

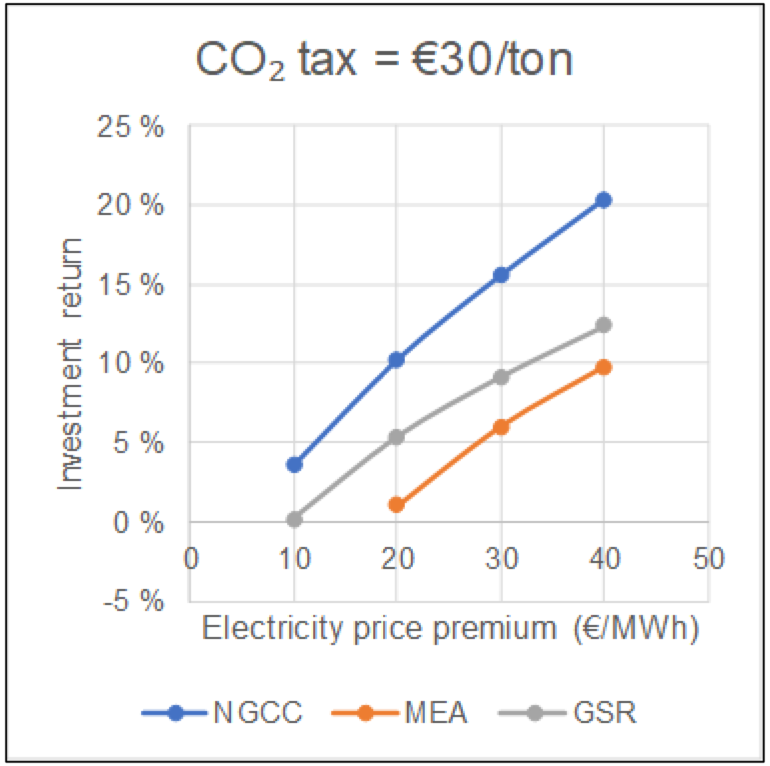
$$NPV = \sum_{t=0}^{n} \frac{ACF_t}{(1+i)^t}$$

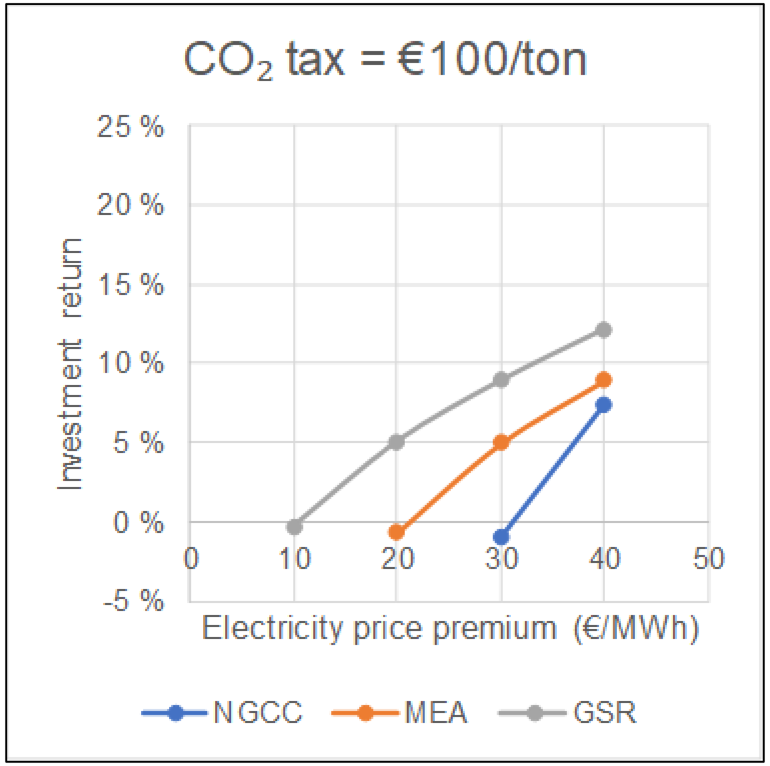
	NGCC	NGCC-MEA	GSR-CC	IGCC	IGCC-CC	GSC	GSC + NG
LCOE [€/MWh]	**53.95**	**73.18**	**74.95**	**60.61**	**92.36**	**84.36**	**72. 45**
COCA [€/ton]	**-**	**60.86**	**60.86**	**-**	**49.53**	**35.82**	**20.03***
Capture rate [%]	-	90.59	91.89	-	90.59	91.89	77.90

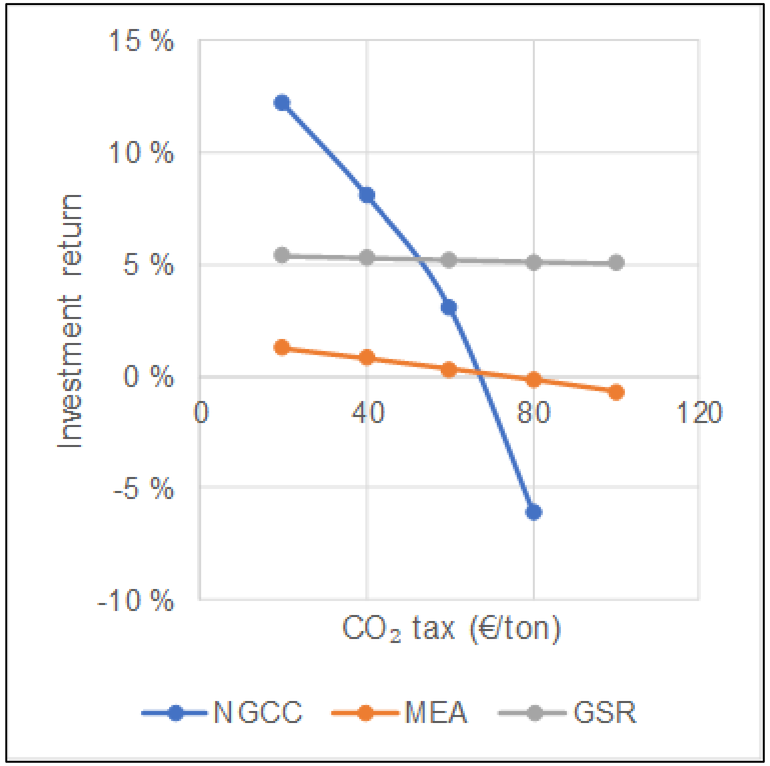
* CO_2 price according to European Trading Scheme: 24-26 [€/ton]

GSR for power production – potential to integrate variable renewables

Annualized return on investment as a function of electricity premium and CO_2 tax



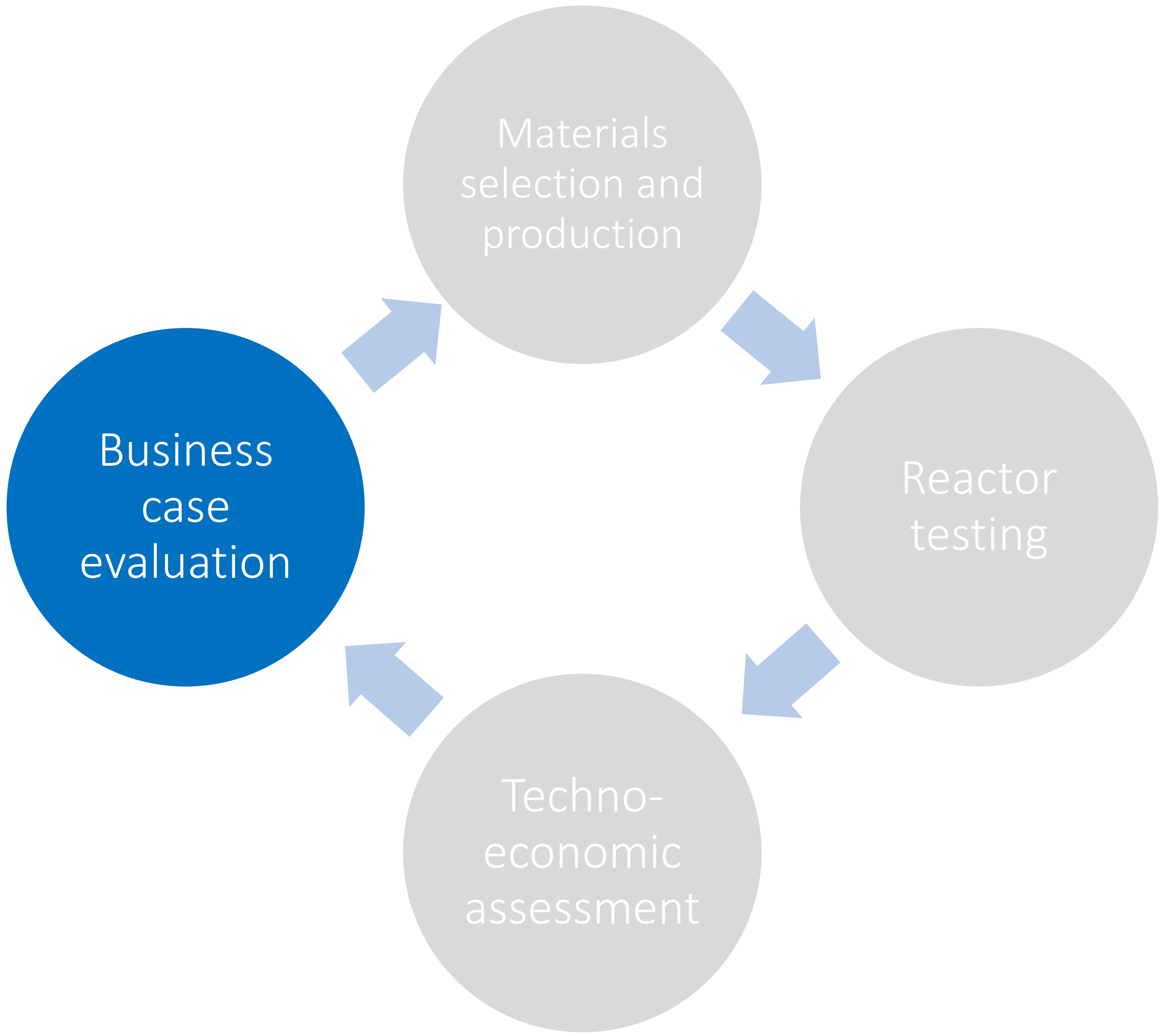




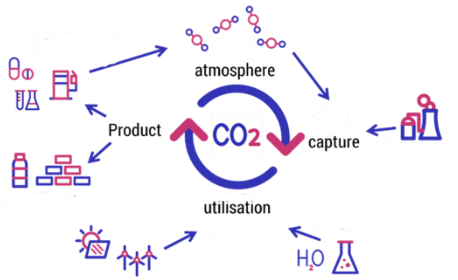
Dissemination techno-economic assessment

- Journal papers: 10
  - International Journal of Greenhouse Gas Control
  - Energy Conversion and Management
  - International Journal of Hydrogen Energy
  - Process Efficiency Improvement Studies
  - Renewable and Sustainable Energy Reviews
  - Energy
  - Energies
  - Applied Thermal Engineering

- Conference presentations: 12
- Press release: 1


Materials selection and production
Reactor testing
Techno-economic assessment
Business case evaluation

Business case



Potential applications to commercialize Gastech project outcomes:

- **Case 1 – Gas Switching Combustion (GSC) (completed)**

  Methanol or formaldehyde production from captured CO_2 and hydrogen

- **Case 2 – Pressurized GSC (completed)**

  Replacing Hayat's current biomass utilization process (Gasification + Organic Rankine Cycle process) with High Pressurized GSC technology

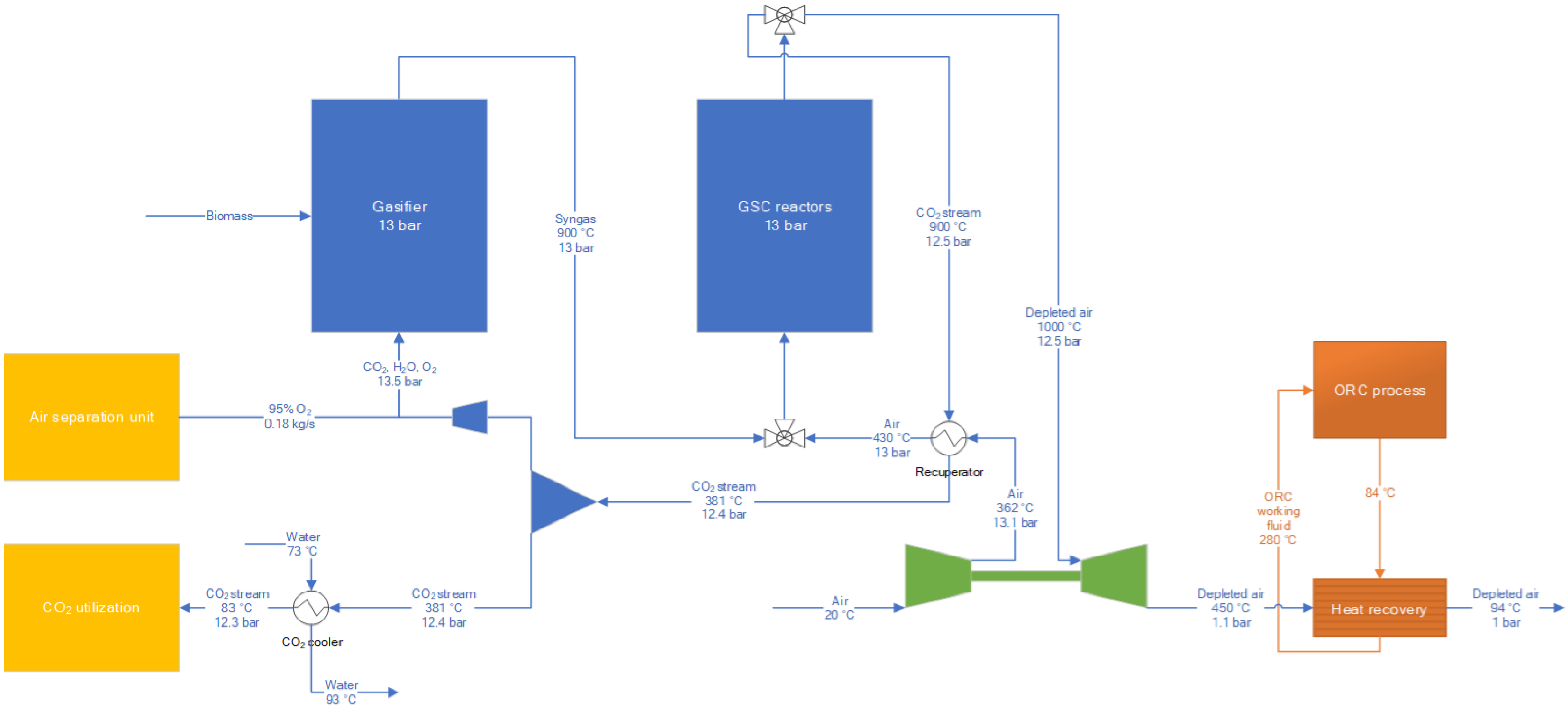
- **Case 3 – Gas Switching Reforming (GSR) (Current assessment)**

  Upgrading Hayat's current biomass utilization process in order to fully utilize the output stream of "CO_2 + H_2" with an additional process step

Industrial site at HAYAT

Business case

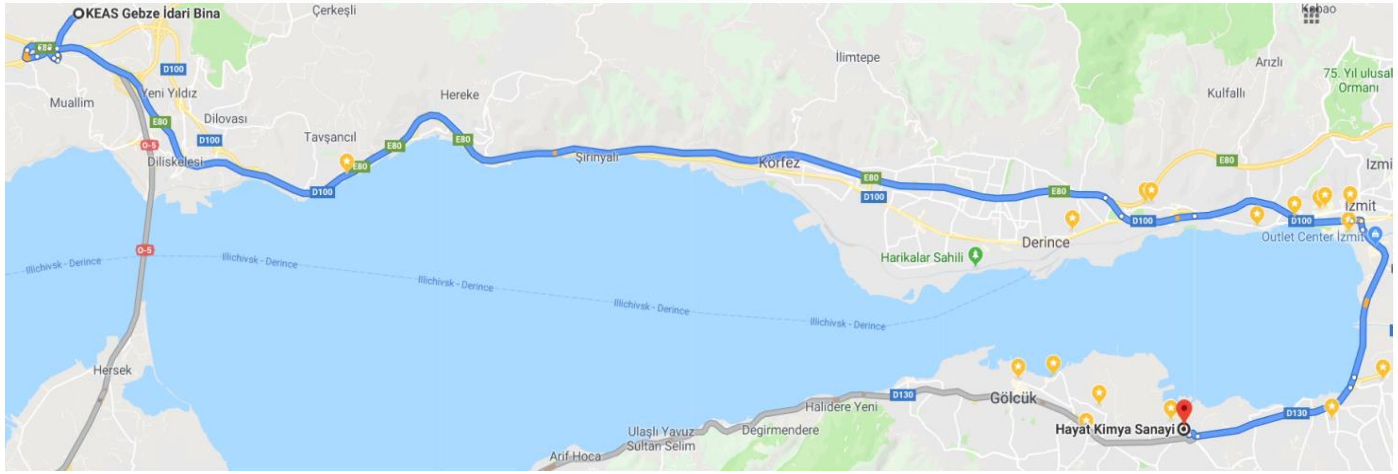
Pressurized GSC Integrated into HAYAT Gasification Plant



Business case

Essentials

INPUT		OUTPUT	
Net electricity output	509 MWh/month	CAPEX	~5.5 Mio. €
Net thermal energy output	2910 MWh/month	Peak Power	3 MW
Maintenance and miscall. costs	1178 €/month	Electricity Output Thermal Energy Output	2.2 MW 3 MW Steam + 3.5 MW Hot Water
Delivered cost of biomass (wood powder & Tissue paper powder)	45.82 € per ton		



PAYBACK TIME
46 months

Business case

Summary

Process	Key Findings	Result
CO_2 → Methanol or Formaldehyde	• Needed H_2:CO_2 ratio is 3:1 • H_2 supply is critical. For lower ratios additional H_2 production must be performed. • Additional H_2 production makes the whole process very expensive compared to the “Natural Gas → Methanol” case.	**Not feasible**
High pressurized GSC	• Electrical and thermal energy outputs are better compared to Organic Rankine Cycle case. • If the whole thermal energy output can be utilized, the payback time can be lowered to 27 months from 46 months.	**Feasible (plan to build a pilot plant in the ACT ERA-NET project)**
High pressurized GSC + GSR	• Utilization of CO_2+H_2 output by using Gas Switching Reforming (GSR) will be investigated further	TBA

Overall project outcomes so far

- Journal publications: 14
- Conference presentations: 20
- Press release: 1
- More journal publications and press release by the end of the project
- Plan to build a pilot plant in Turkey in the Follow-up ACT project

Acknowledgement

- ACT GaSTech Project No 276321
- This project has received funding from funding bodies in the respective countries
  - Research Council of Norway, Norway
  - MINECO, Spain
  - Netherlands Enterprise Agency, Netherlands
  - Department of management and administration of thematic research programmes, Romania
  - TUBITAK, Turkey
  - Swiss Federal Office of Energy, Switzerland
  - European Commission (EC)
- Co-funded by the European Commission under the Horizon 2020 programme, ACT Grant Agreement No 691712