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3rd Doctoral Colloquium Bioenergy, 18th September 2020, Leipzig

# Development of a pellet boiler for micro-CHP with an organic Rankine cycle

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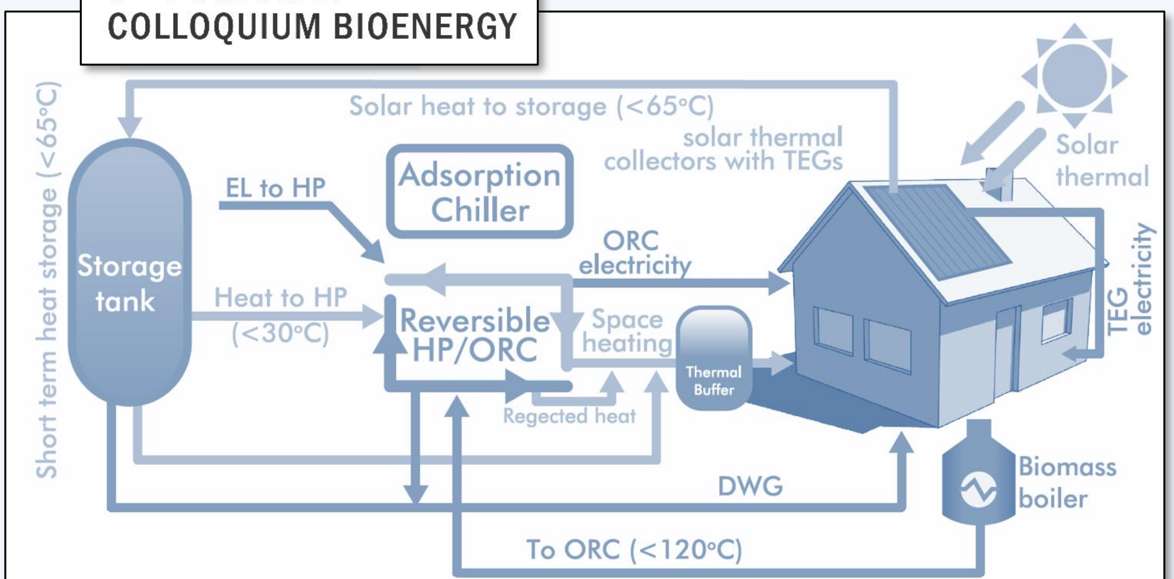


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1. Objectives of the EU-project SolBio-Rev

2. Pellet boiler concept for micro-CHP

3. Test results with primary measures

4. Summary and outlook

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# Motivation

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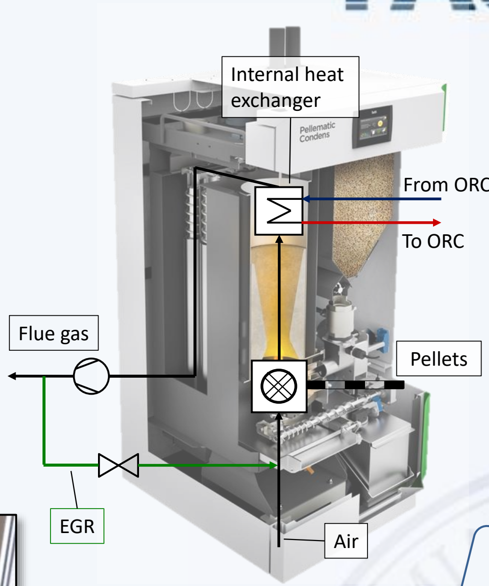
- **Micro-CHP (combined heat and power) with biomass** is considered to still have a **large unused potential**
- Organic Rankine Cycles are an established technology for generating power from low temperature heat sources




*Scheme of an ÖkoFEN pellet boiler with internal heat exchanger and EGR*


*Set-up of the pellet boiler with the flue gas analyzers in the EVT lab*

## Key challenges

- Reduction of specific investment costs
- Increase of cogeneration efficiency
- Reduction of emissions

## Main goals

- Development of a flexible and efficient small-scale unit for CHP
- Contribution to the reduction of emissions
- Decentralization of energy systems

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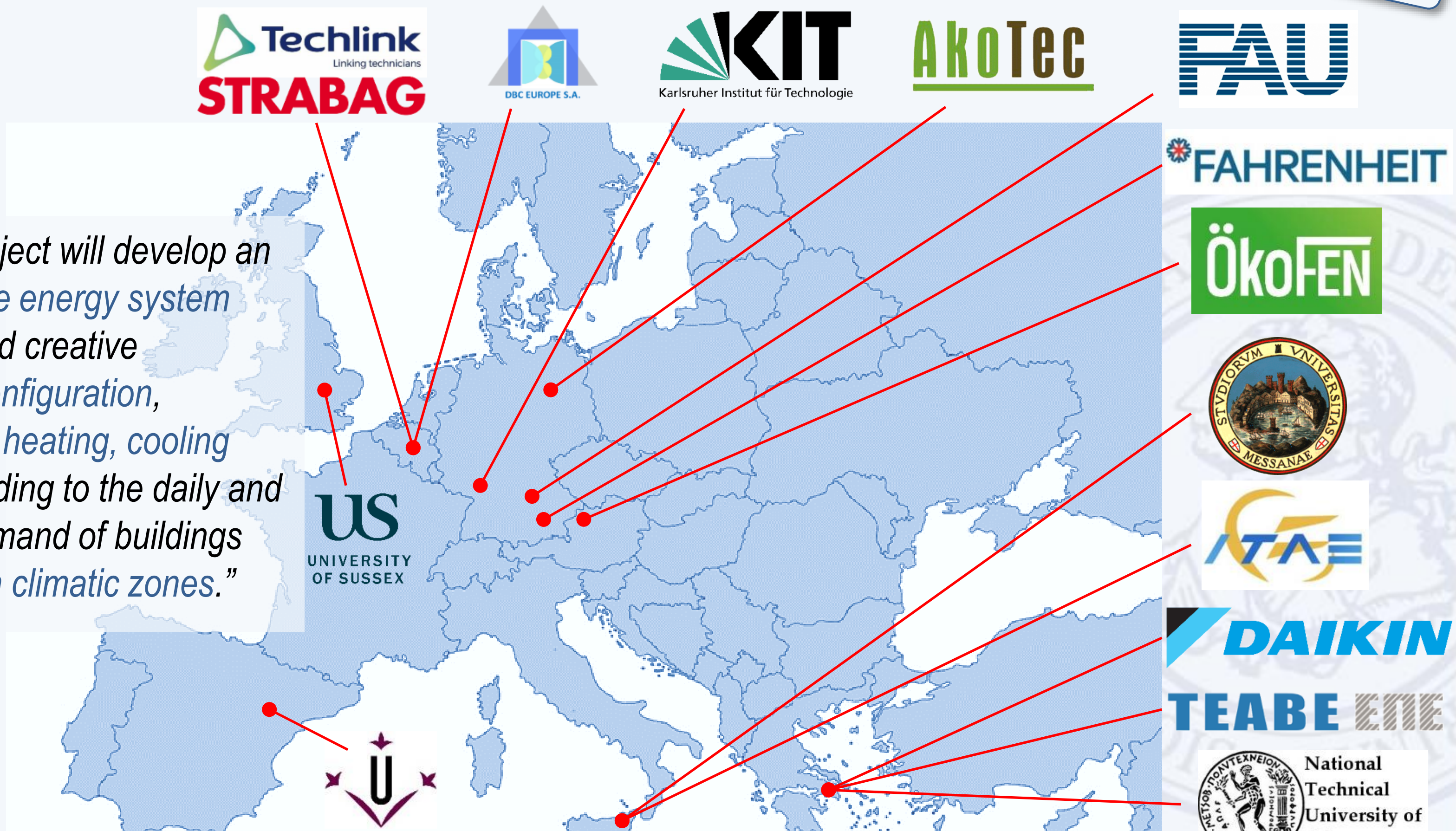
# The EU-project SolBio-Rev

**Solar** **Biomass** **Reversible System**

Term: May 2019 – April 2023

*"The SolBio-Rev project will develop an innovative renewable energy system based on a novel and creative heat pump-based configuration, for the production of heating, cooling and electricity according to the daily and seasonal energy demand of buildings in different european climatic zones."*

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# The idea of SolBio-Rev

Solar Biomass Reversible System

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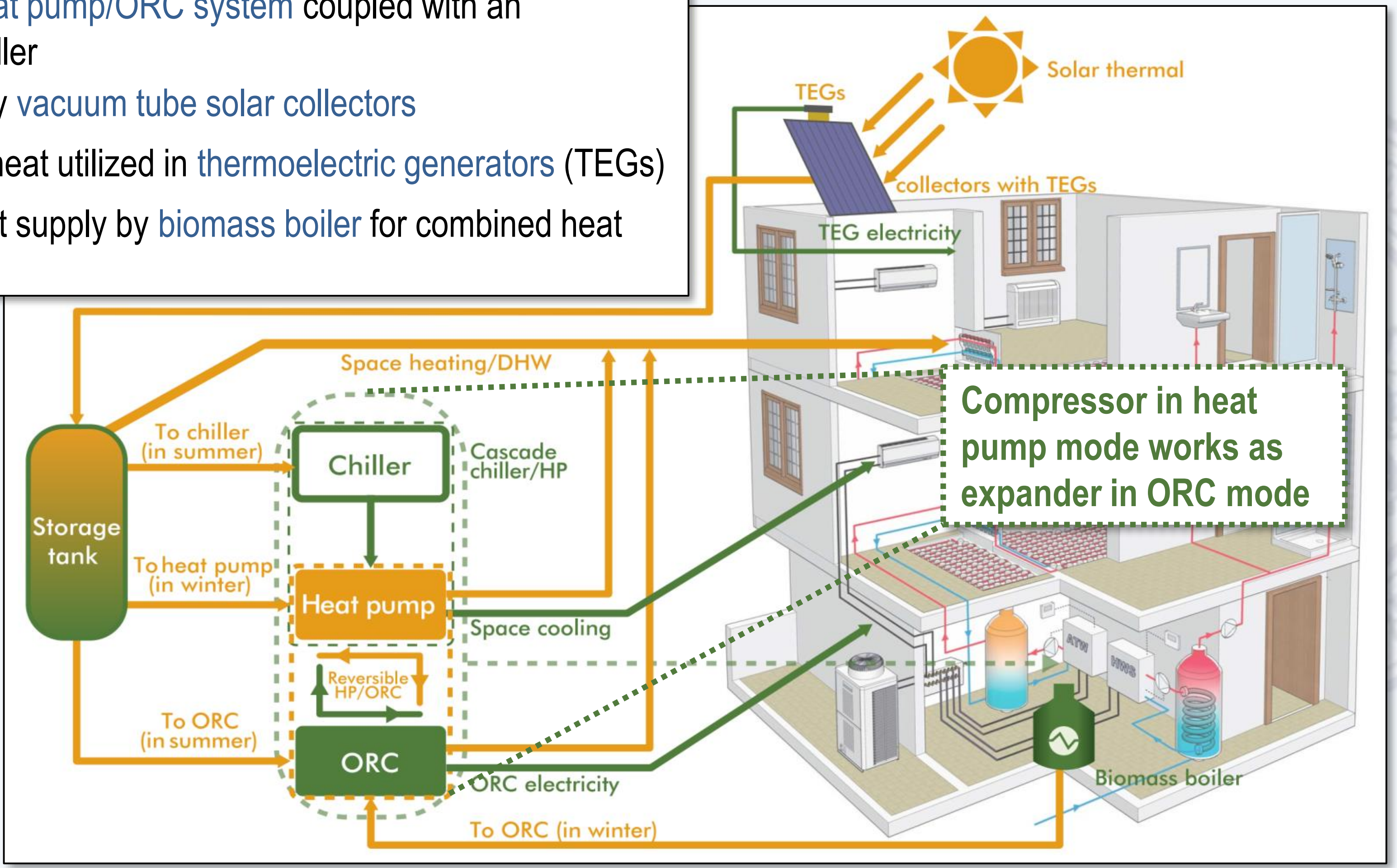
### Technology overview

- Reversible heat pump/ORC system coupled with an adsorption chiller
- Heat supply by vacuum tube solar collectors
- Excess solar heat utilized in thermoelectric generators (TEGs)
- Additional heat supply by biomass boiler for combined heat and power

Energy sources:
solar heat
and pellets



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# The idea of SolBio-Rev

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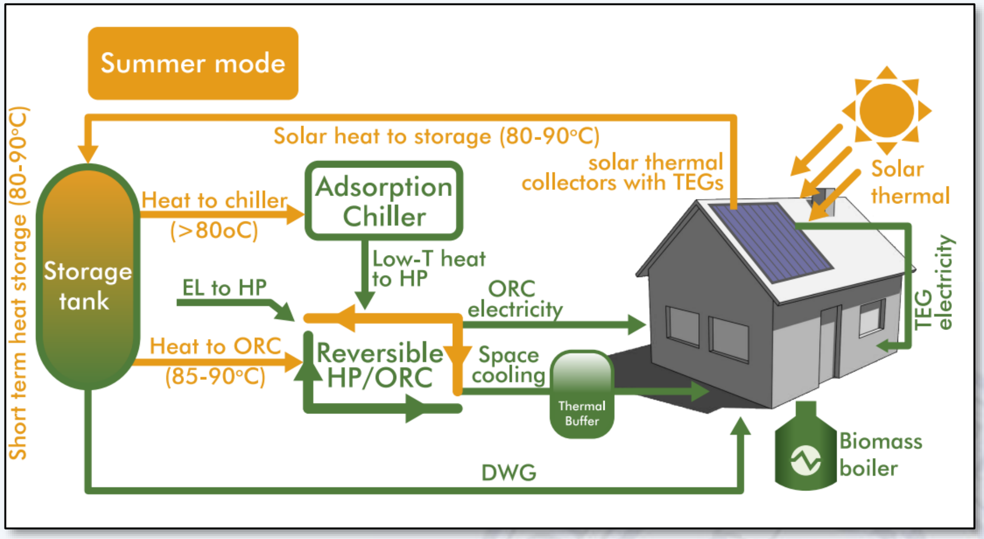
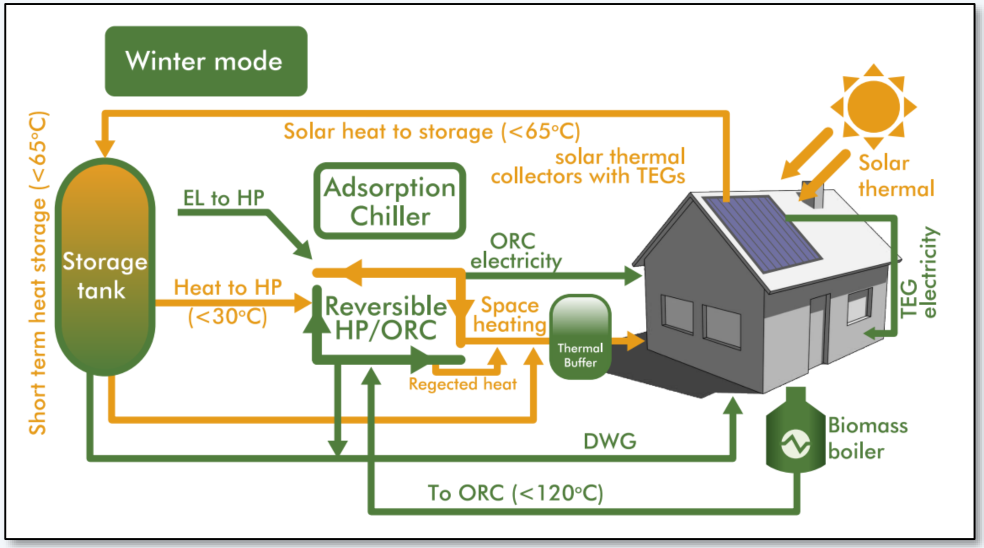
## Summer mode

- Solar heat stored in short term storage
  → Supply of domestic hot water demand
- Priority: space cooling
- Excess heat used for electricity production




Energy flow scheme of the SolBio-Rev system in summer mode




Energy flow scheme of the SolBio-Rev system in winter mode

## Winter mode

- Solar heat used for domestic hot water and space heating
- Low temperature heat supplies the heat pump
- In case of no solar energy:
  biomass boiler for CHP

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# Pellet boiler concept

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## Development and lab-testing of a pellet boiler coupled with an ORC for combined heat and power (CHP)

### 1. Exhaust Gas Recirculation (EGR)

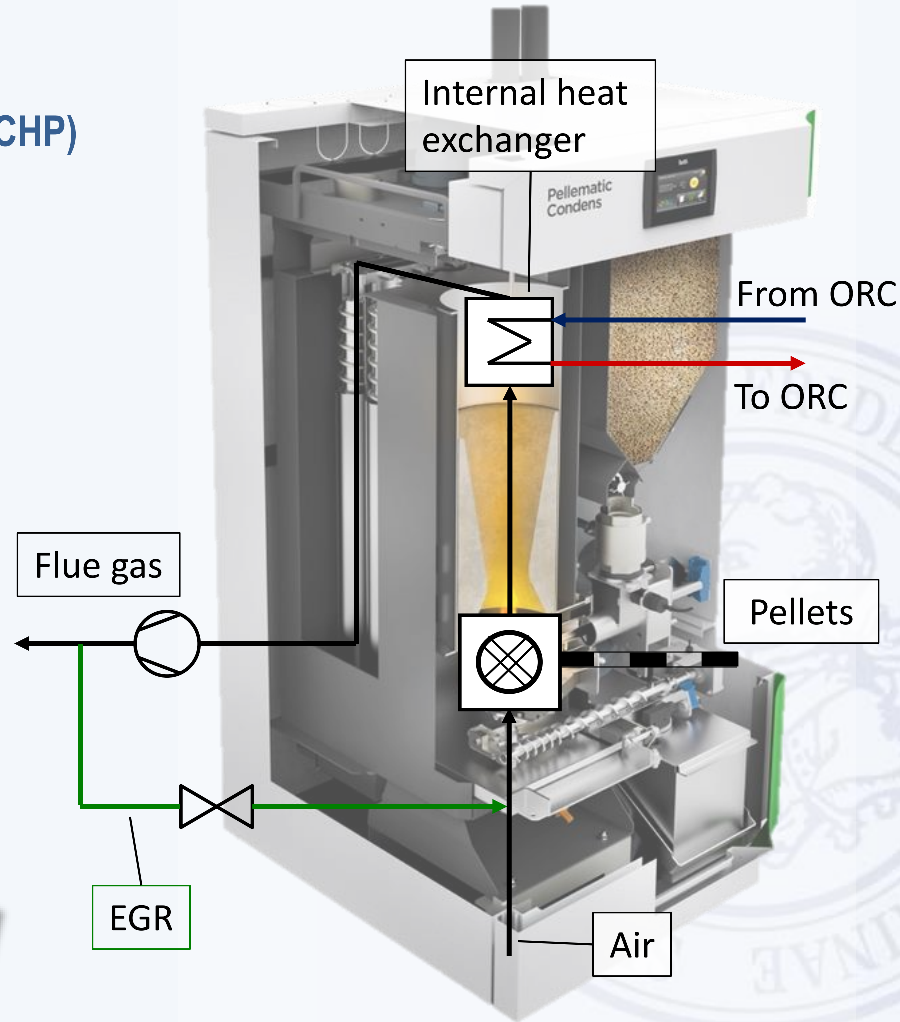
- Avoidance of hot spots and ash melting
  → reduced emissions
- Air-to-fuel ratio closer to stoichiometric
  → increased combustion efficiency

### 2. Internal heat exchanger

- Determining factor for ORC efficiency: supply with high temperature heat (> 100°C)
- Flexible heat supply at defined temperature level

**Key advantages**

1. High cogeneration efficiency
2. Increased electrical output
3. Reduction of boiler emissions




*Scheme of an ÖkoFEN pellet boiler with internal heat exchanger and exhaust gas recirculation*

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# Set-up in the laboratories of EVT

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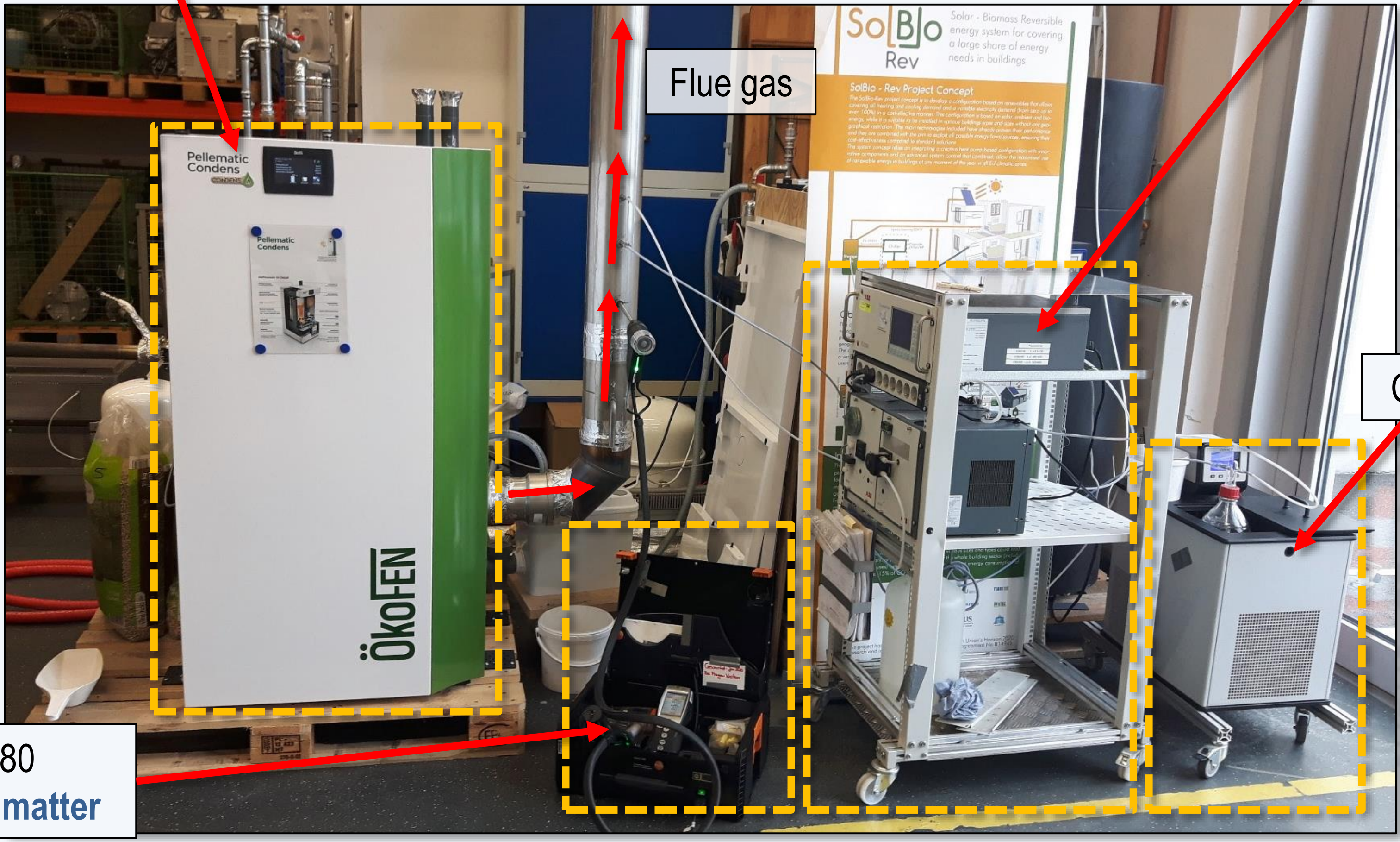
**ÖkoFEN**
**Pellematic Condens**
**14 $kW_{th}$**

Gas Analyzer
ABB AO2020 (Uras26)
**$CO$, $CO_2$, $NO$**




Testo 380
**particulate matter**

*Set-up of the pellet boiler with flue gas analyzers in the EVT lab*

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# Methodology



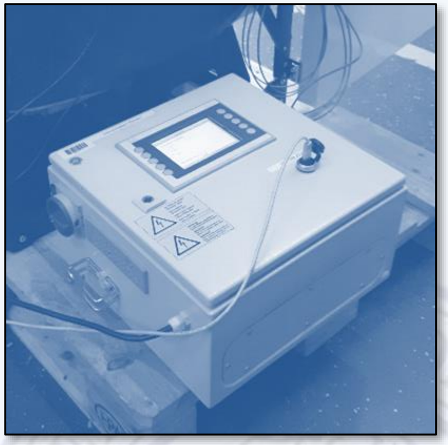
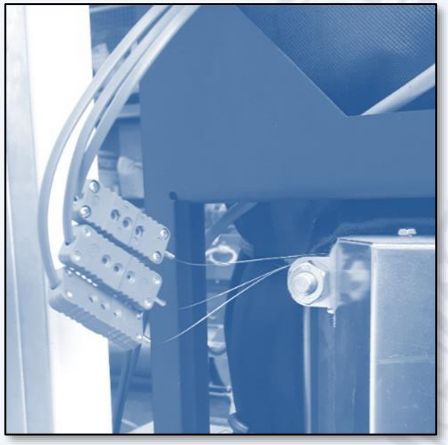
1. Testing with unmodified standard pellet boiler

2. Stepwise retrofitting and testing
   a. Exhaust gas recirculation (EGR)
      *Recirculation of exhaust gas regulated with a control valve*

   b. Air staging
      *Reducing atmosphere in the primary combustion zone and secondary air tube for turbulent secondary combustion*

   c. New approach for control strategy
      *Improved control strategy based on:*
      a. *Combustion calculation*
      b. *Adaption to pellet quality*
      c. *Optimized transients for smooth modulation*

3. Testing with EGR, air staging and new control strategy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# Control strategy

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Temperature boiler → **Control unit** → Modulation stage

*Previous control strategy*

Pressure set → Controller → **ID fan** (feedback: Pressure sensor)

Temperature set comb. chamber → Controller → **Pellet screw** (feedback: Temperature comb. chamber)

*New control strategy*

*Calibrated pellet screw* → Thermal pellet input → *Thermocouples* → Adaption to pellet quality (e.g. bulk density) → **Pellet screw**

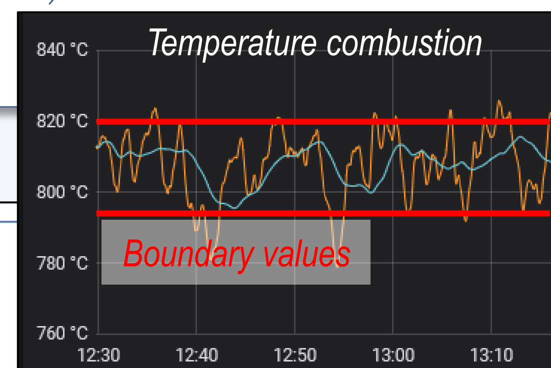
Combustion calculation → *Pressure sensor, Lambda sensor* → Optimized air-to-fuel ratio λ → **ID fan**

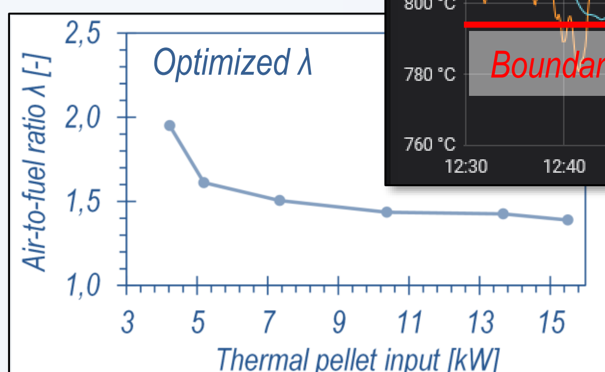
*Smooth transients*

$$C_{\frac{c}{12}} H_{\frac{h}{1}} O_{\frac{o}{16}} S_{\frac{s}{32}} + \left(\frac{c}{12}+\frac{h}{4}-\frac{o}{32}+\frac{s}{32}\right) O_2 \leftrightarrow \frac{c}{12} CO_2 + \frac{h}{2} H_2O + \frac{s}{32} SO_2$$

$$l_{min} = \frac{32}{0{,}232}\cdot\left(\frac{c}{12}+\frac{h}{4}-\frac{o}{32}+\frac{s}{32}\right)$$

$$\lambda = \frac{L}{L_{min}} = \frac{l}{l_{min}}$$



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# Test results – CO

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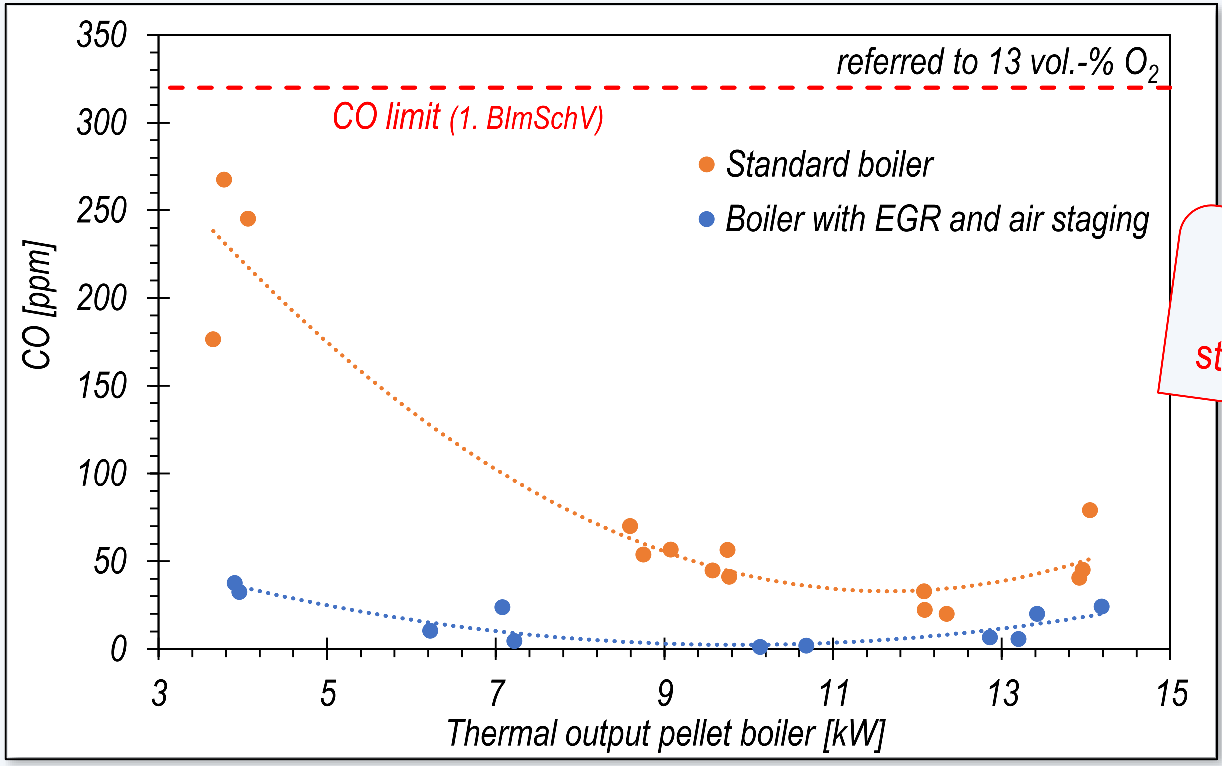
- CO limit *(1. BImSchV)*: 320 ppm/m³
- Minimum of CO emissions shifted from ~12 kW to ~10 kW
  *(increased volume flow and reduced residence time due to EGR)*
- **Part load:** discontinous fuel-feeding (*high variance of air-to-fuel ratio*)
- **Full load:** reduced residence time in hot combustion zone (*increased volume flow due to EGR*)




Significant reduction of CO emissions due to EGR, air staging and new control strategy

*CO emissions referred to 13 vol.-% $O_2$ (measured according to VDI 4207-2)*

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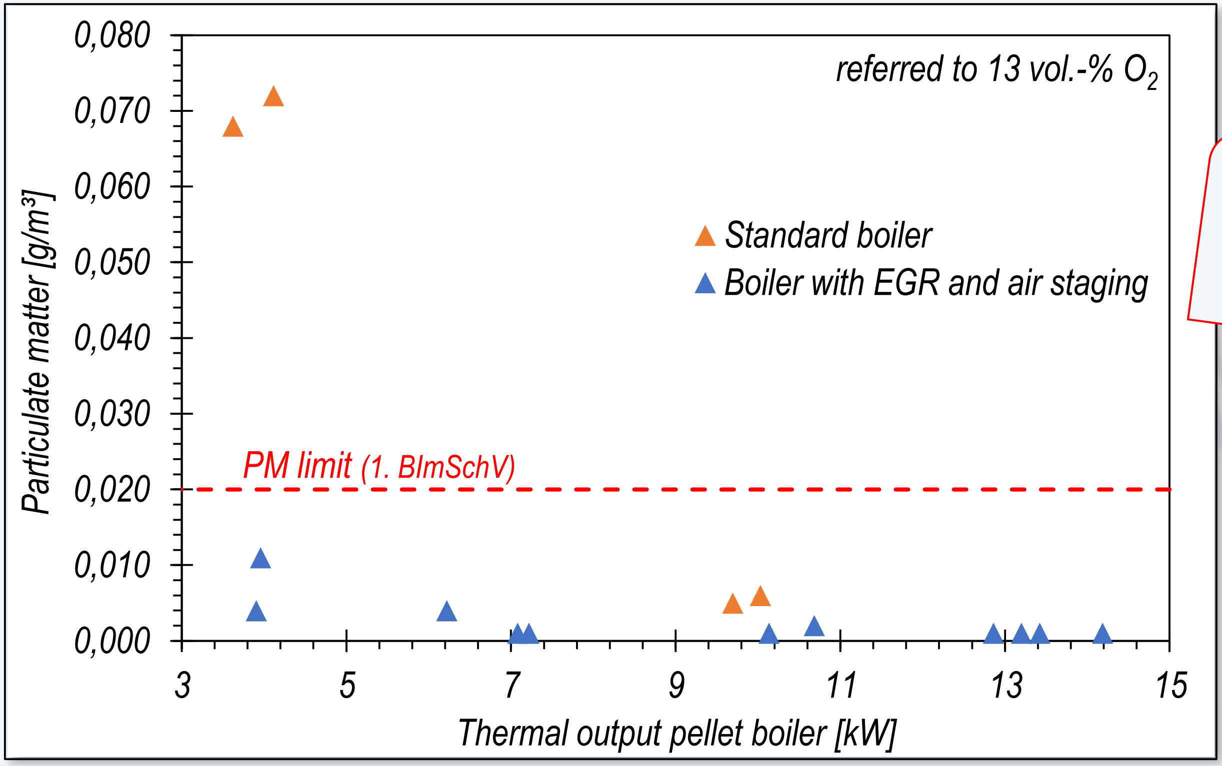
# Test results – particulate matter



- PM limit *(1. BImSchV)*: 20 mg/m³
- Positive correlation between particulate matter and CO emissions
- PM emissions **< 2 mg/m³** for a wide power range
- Slight increase at part load *(due to lower temperatures and incomplete burnout)*




Considerably lower PM emissions after retrofitting of EGR and air staging

*PM emissions referred to 13 vol.-% $O_2$ (measured according to VDI 4207-2)*

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# Test results – X-ray fluorescence ash analysis

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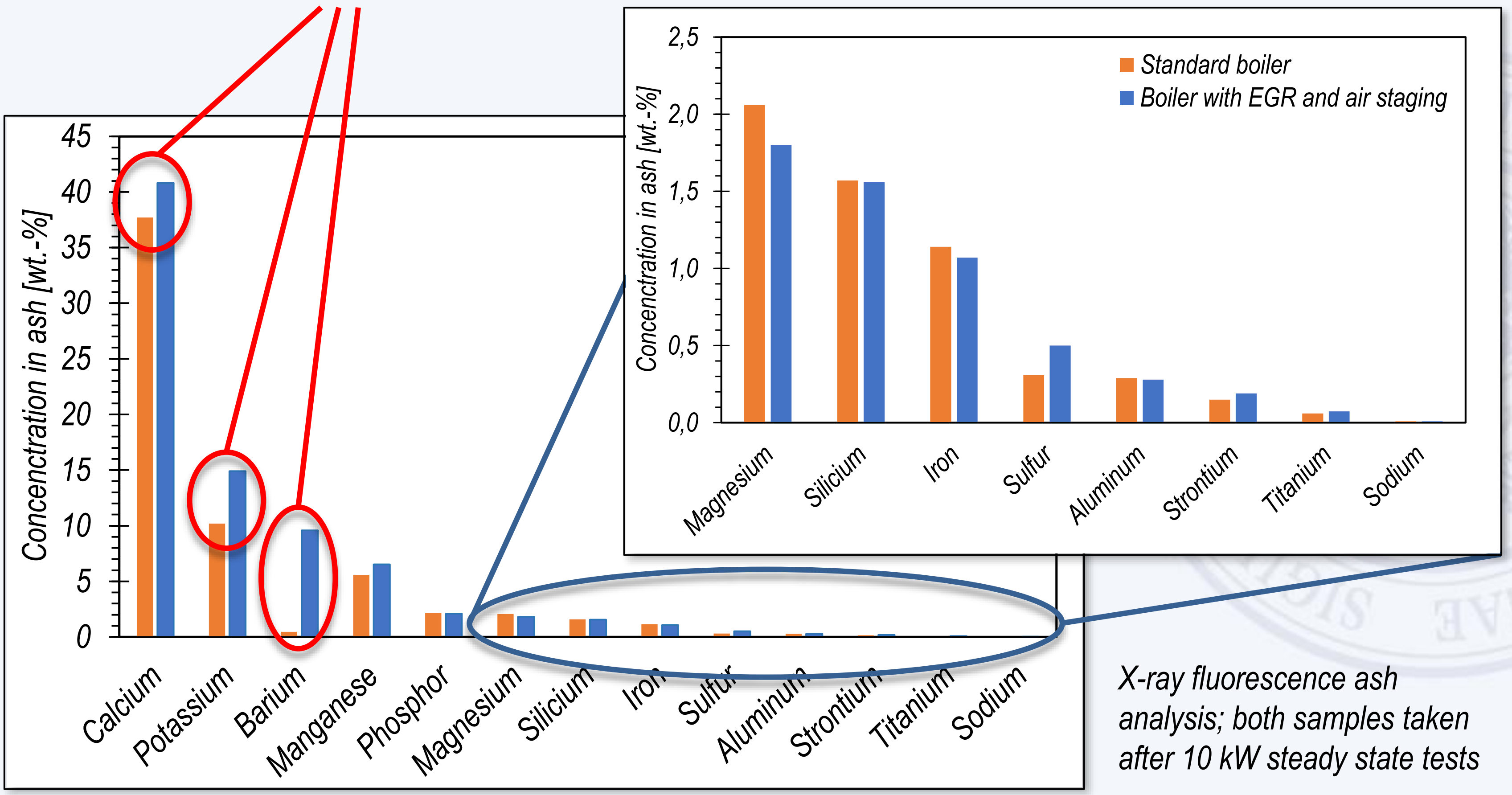
- PM emissions considerably reduced with primary measures
- EGR and air staging lead to lower temperatures at the grate
  → Slightly more anorganic ash compounds (e.g. Potassium) remain in the solid phase
  → Less anorganic compounds emitted as aerosols




*X-ray fluorescence ash analysis; both samples taken after 10 kW steady state tests*

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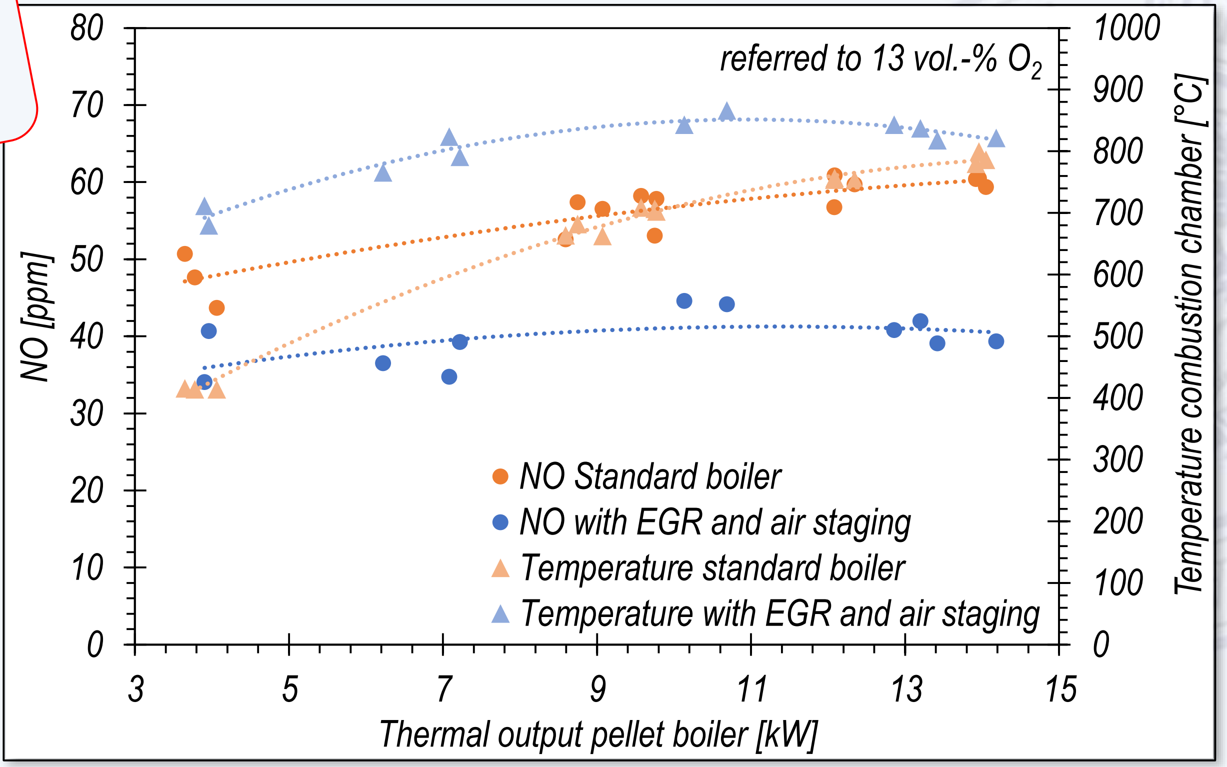
# Test results – NO



- $NO_x$ emissions from solid fuels are mainly determined by Fuel-$NO_x$
- Clear correlation between NO emissions and temperature in the combustion chamber *(thermal $NO_x$)*
- EGR and air staging lead to reduced NO emissions
  *(lower temperatures and a reducing atmosphere in the primary combustion zone)*

Reduction of NO emissions after retrofitting of EGR and air staging

→ Reduction by 20-30 %




*NO emissions referred to 13 vol.-% $O_2$*

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# Test results – boiler efficiency

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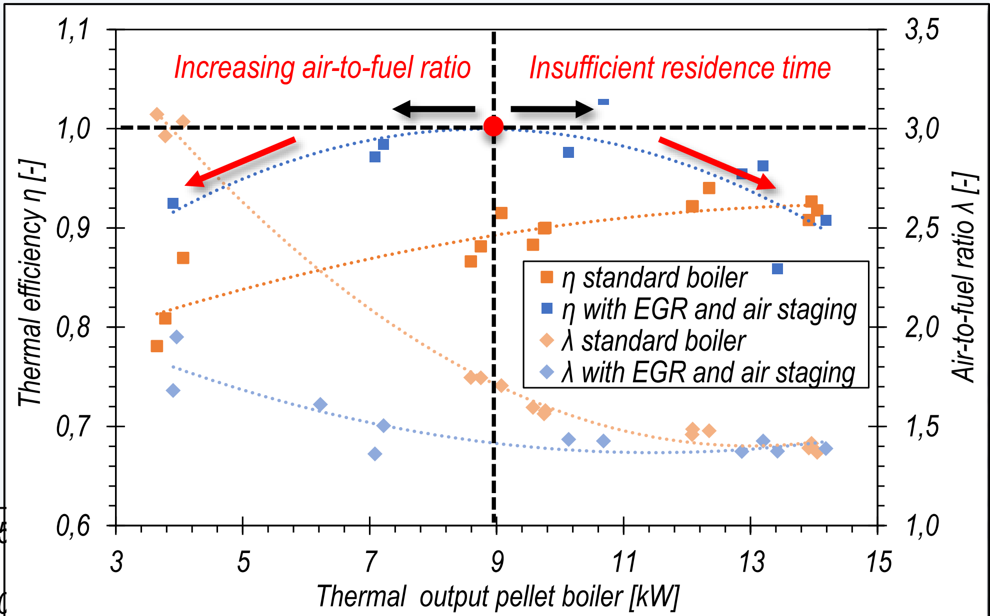
- Condensing boiler efficiency

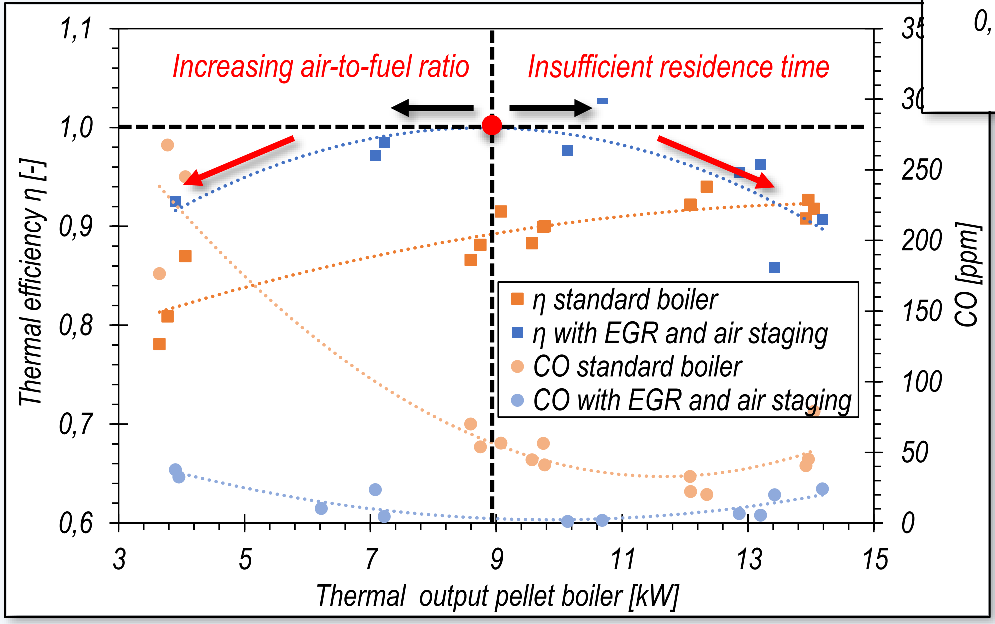
$$\eta = \frac{\dot{m}_{water} \cdot c_p \cdot \Delta T}{\dot{m}_{pellets} \cdot H_u}$$

- EGR and air staging improve pellet boiler efficiency *(reduced air-to-fuel ratio)*

$$\downarrow \dot{Q}_{flue\ gas} = \downarrow \dot{m}_{fg} \cdot c_{p,fg} \cdot T_{fg}$$




*Boiler efficiency and air-to-fuel ratio*




*Boiler efficiency and CO emissions*

- Efficiency maximum correlating to the minimum of CO emissions
- At high thermal outputs with EGR:
  Incomplete combustion due to reduced residence time

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# Summary and outlook

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Kickoff of SolBio-Rev

- Site preparation
- Comissioning of the prototype system
- Integration with a smart system control

Two prototype systems in Nürnberg an Athens

May 2019 → May 2019 – April 2021 → May 2021 – April 2022 → May 2022 – April 2023

**Currently ongoing**

- Development of the SolBio-Rev components
  → Biomass boiler with internal heat exchanger and EGR
- Development of a load-depending control strategy for optimized emissions and efficiency
- Evaluation and manufacturing of different internal heat exchanger designs for CHP with an ORC

ÖkoFEN


- System testing and technology validation
- One year testing to demonstrate advantages

**SolBio-Rev advantages**
- Enhanced flexibility
- Applicability in a large variety of buildings
- High utilization throughout the year
- Reduction of equipment → compactness

**Covering a high share of up to 70% of annual energy needs in a variety of buildings**