staxera:

Your Heart of Energy

Systems and System Components

Contents

sunfire powered by staxera

Challenge

sunfire's mission is to provide technologies for an energy supply in a closed carbon cycle by converting renewable electricity, carbon dioxide (CO_2), and water (H_2O) into clean fuels to power cars and planes, as well as sunfire's Gas-to-Power technology

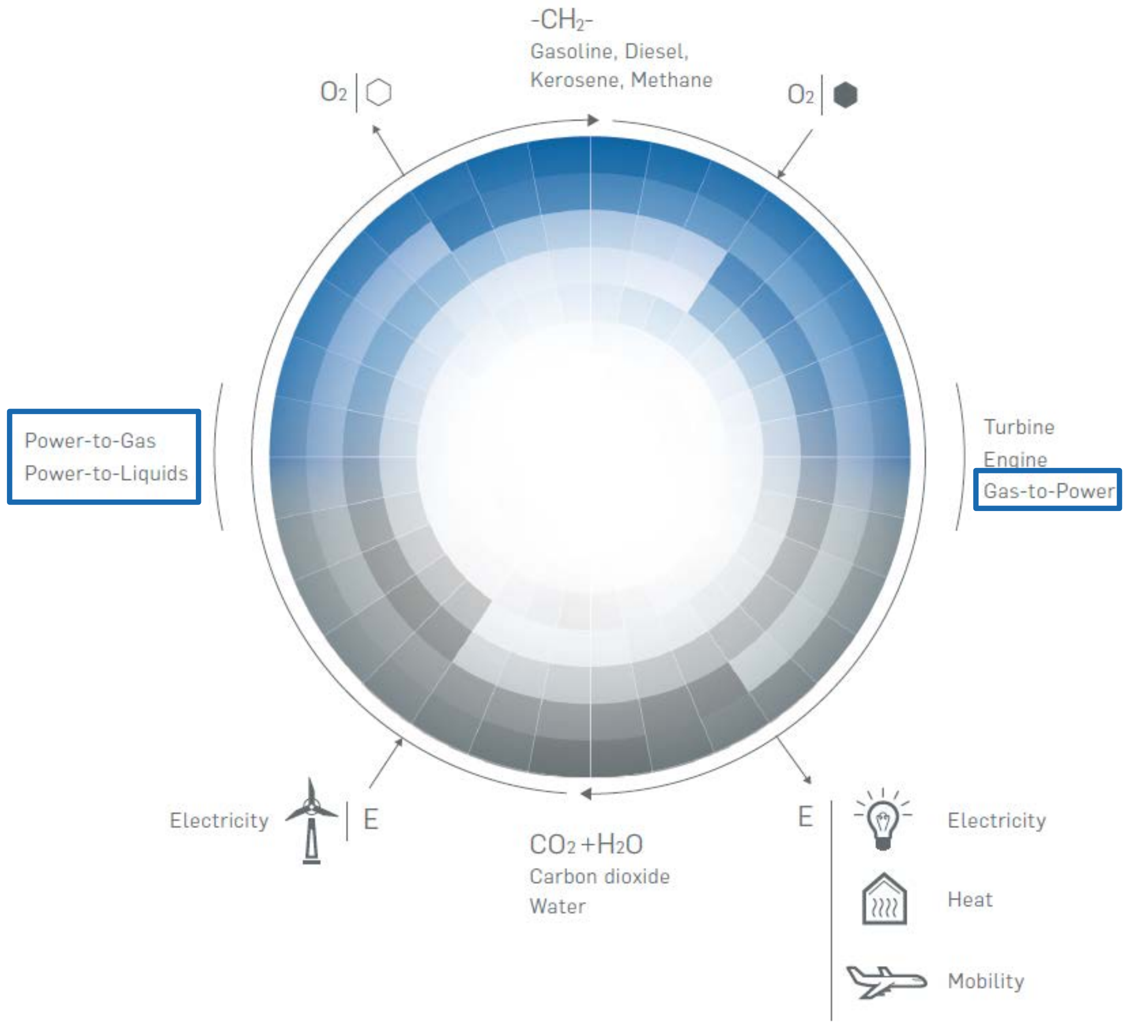
Challenge / Solution

- Limited fossil resources
- Renewable liquid fuel from CO_2

- Intermittent electricity supply
- Energy storage/ grid load compensation

- Increasing CO_2 level
- CO_2-recycling (CCS-alternative)

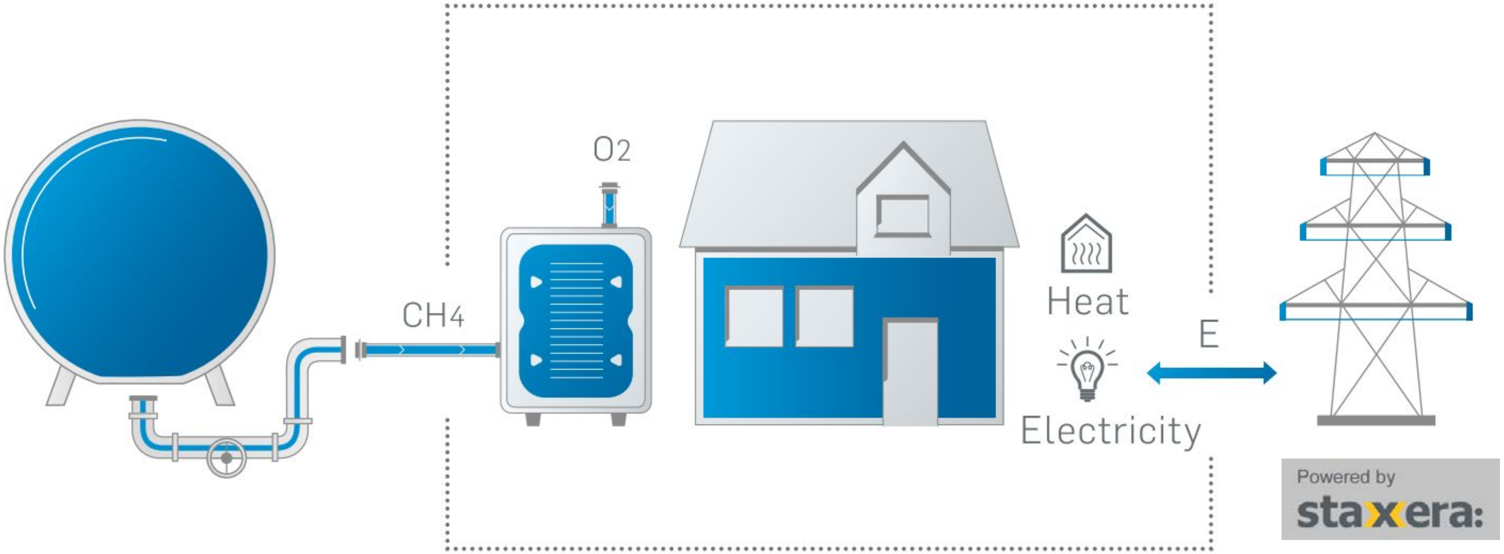
- Inefficient energy conversion
- Combined heat and power (CHP)



Gas-to-Power (Electricity and Heat Generation)

Based on the staxera technology, sunfire manufactures and sells high-temperature fuel cell stacks (SOFC) and fuel cell solutions for efficient heat and electricity generation. For that sunfire cooperates with strong strategic partners in the relevant market segments and local markets.

Natural gas supply	Fuel cell (CHP)	Virtual power plant

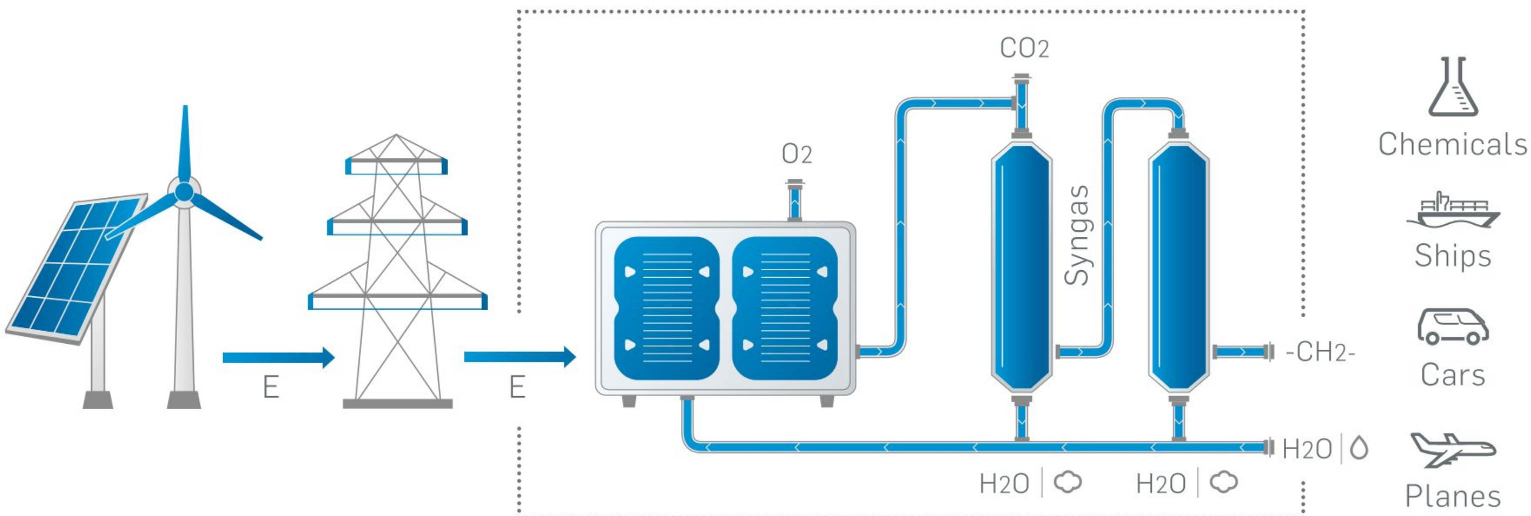


- Decentralized production of energy
- Electric efficiency 35 - 55%
- Overall efficiency > 85%
- Scalability (0.5 kW – 100 kW)
- Robust and reliable stack technology from staxera
- End customer viability proven in “Callux” field test

Power-to-Liquids (Fossil Fuel Replacement)

Climate change and the finite nature of fossil energy reserves demand a switch from fossil to renewable energy sources. Power-to-Liquids (PtL) technology converts renewable electricity into a wide range of liquid synthetic fuels of high quality (i.e. diesel, kerosene).

Renewable electricity	Electrolysis (SOEC)	Conversion	Synthesis

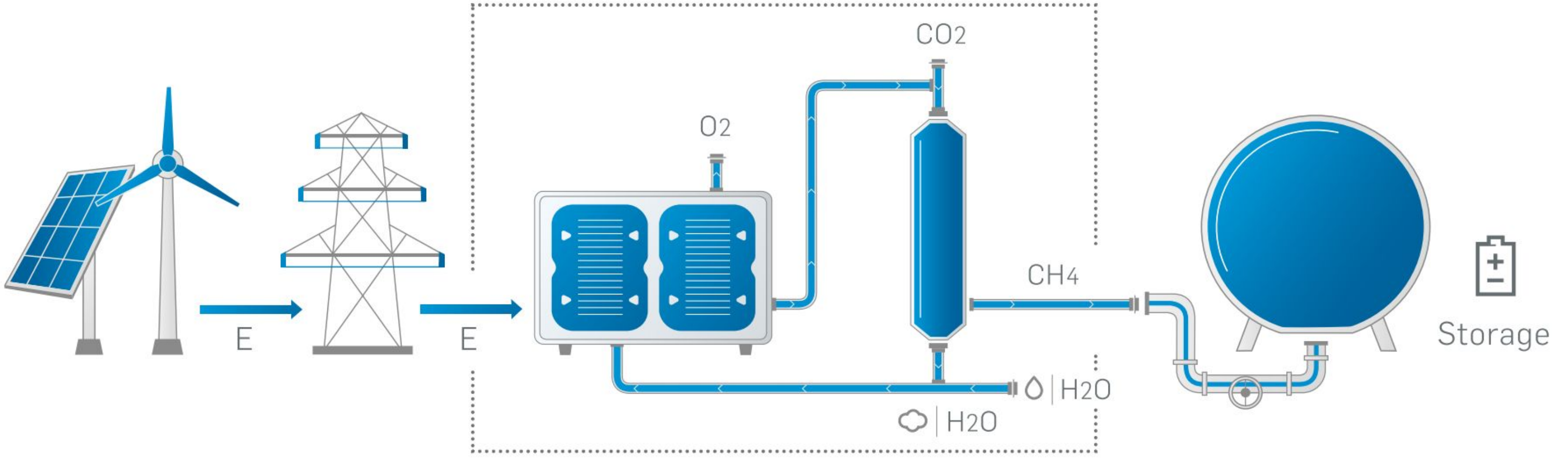


- Process efficiency: ~70%
- GHG-mitigation: >85%
- Production cost (liquids): 1,00 €/l
- High quality fuel
- Fits with existing infrastructure
- Very large production potential

Power-to-Gas (Electricity Storage)

Only large-scale storage of intermittent, renewable electricity can reliably secure further growth of solar and wind energy production capacity. Power-to-Gas (PtG) technology converts clean electricity into renewable natural gas that can be stored and transported in the existing gas grid.

Renewable electricity	Electrolysis (SOEC)	Conversion	Gasgrid- and storages



- Efficient storage of fluctuating renewable energy
- Use of existing gas grid for transportation
- Independence from gas imports
- Production cost: < 0,10 €/kWh
- Scalable process
- Supports decentralized energy production (CHP)

Products and business

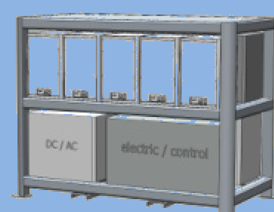
sunfire

Stacks	Systems	Components	Services	Fuel
SOFC stack Integrated stack module (ISM) 1.7 kW ISM * 5.0 kW ISM Customized stack hotbox Powered by staxera:	Demonstrators Test environments Process Gas Modules	Burners Reformers Heat Exchangers Evaporators Desulfurizers Electric gas heaters	Testing Training Engineering „Idea-to-product“	Power-to-Liquids Power-to-Gas System and process technology

* Integrated Stack Module including SOFC stacks

SOFC applications and markets

Market segments

Market segment		Market potential
µCHP **1-10 kW**		• Good market potential in GER, JP, UK, IT, CN • Potential > 10.000 units/yr
off-grid **0.5 – 20 kW**		• Good market potential BRICS (and worldwide) • Potential > 100.000 units/yr
smallCHP **20 – 100 kW**		• Good market potential in industrialized countries • Potential > 10.000 units/yr

Combined heat and power units (µCHP)

staxera:
“inside”

Source: Vaillant

Applications

- Power and heat supply for one- and multifamily homes, small commerce

Efficiencies

- Total efficiency target > 85 %
- Electrical efficiency >45-50(60) % SR, >30-35 % CPOX

Costs targets / payback period

- Very ambitious cost targets <3,000-5,000 € / unit
- Payback period 5 – 10 years (>30,000 operations hours)

Small-size combined heat and power units (smallCHP)

Source: Wärtsilä

Applications

- Apartment houses, district heating, commerce, hotels, hospitals, small industrial applications, decentral biogas units

Efficiencies

- Total efficiency target >85 %
- Electrical efficiency 50-60 % with steam reforming

Cost targets / payback period

- Cost targets: 1750 € / kW @ ≤100 kW; **<1000 € / kW @ ≥500 kW**
- Payback period 10 years: 60,000 operation hours

Off-grid SOFC systems

Applications

- Cell phones, MP3 player, digicams: 2-5 W
- Laptops, video cameras, electric screwdrivers: 20-100 W
- Leisure vehicles (caravans, yachts): 0.1-5 kW
- Portable military generators: 50-200 W
- Autarkic power generators (remote measurement systems, alpine huts): 50 W – 20 kW
- Backup systems – SOFC system as main generator, electr. grid as backup: 5-20 kW
- Auxiliary power units (cars, trucks): 1-5 kW
- Replacement of board electric generator (ships, diesel locomotives, aircrafts): 1-20 kW

Source: eZelleron

Off-grid SOFC systems

Fuels

- LPG, propane, methanol, ethanol, diesel, kerosene

Features

- Very fast start-up times (1-20 min)
- Start-up burner required, mostly battery backed
- High number of thermal cycles and redox cycles

Efficiencies

- >15 % for very small systems
- 25-35 % with CPOX or ATR

Cost targets / payback period

- Applications mostly rather cost tolerant
- 5 W: <200 €; 100 W: <2000 €; 350 W: <2500 €

Customer benefits

- Reduction of noise, range extension, low emissions

Source: eZelleron

Source: new enerday

Auxiliary power units

Applications

- Mostly diesel based power generators for trucks
  → prevents idling of main engine

Features

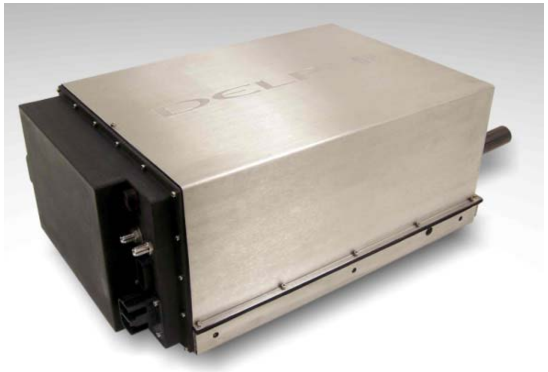
- Electrical power output 3-5 kW
- Start-up time <30 min

Efficiencies

- Electrical efficiency targets 25-35 % with CPOX or ATR

Cost targets / payback period

- Very ambitious: 500 €/kW
- Price depends on competition with diesel engines



Source: Delphi

Fuels and fuel processing

Fuels for fuel cells

- Hydrogen is the basic fuel for all fuel cells, but hydrogen must normally be derived from hydrocarbons
- Advantage of SOFC against other fuel cell types:
  - Higher tolerance against impurities
  - Internal reforming capability

- Fuels can be fossil (coal, diesel, gasoline, natural gas) , from waste (landfill gas, sewage gas, methanol) or from renewables (biogas)
- Preferred fuel depends on application (µCHP, smallCHP, off-grid, APU)
- Nearly all hydrocarbons need some gas processing before entering a fuel cell:
  - Steam reforming (SR), catalytic partial oxidation (CPOX), oxidative steam reforming (OSR)
  - Gasification

Gaseous fuels

	Natural gas	Liquefied Petroleum Gas (LPG)	Biogas
Application	• µCHP • Small CHP • (Off-grid)	• Off-grid • µCHP	• Small CHP
Infrastructure	• Extended gas grid	• Worldwide supply infrastructure	• Mostly countries with biogas subsidies
Reforming	• SR, CPOX, OSR • Composition depends on source	• SR, CPOX, OSR • Varying composition to be taken into account	• SR, CPOX, OSR • Cleaning required
Impurities	• < 5 ppmw H_2S and COS • 5 … 20 ppmw odorant (TBM, THT)	• Up to 120 ppmw sulfur • Odorized with TBM or THT	• Depends strongly on source • High amount of H_2S

Liquid fuels

	Gasoline	Diesel	Kerosene
Application	• Auxiliary power unit (APU) • Range extender for electrical cars	• Auxiliary power units • Range extender • Off-grid power supplies	• Auxiliary power units for aircrafts • Military applications
Infrastructure	• Worldwide supply infrastructure • Varying quality depending on source and refinery		
Reforming	• SR possible, but risk of catalyst deactivation • CPOX challenging: carbon formation, catalyst deactivation • Most promising: OSR with anode off-gas recirculation		
Impurities	• Up to 80 ppm sulfur (average 30 ppmw) • **Dibenzylthiophen** • Additives, complex hydrocarbons	• Standard on sulfur content: 10 ppmw (EU), 15 ppmw (US) • **Dibenzylthiophen** • Additives, complex hydrocarbons	• Sulfur content 500-1500 ppmw • **Dibenzylthiophen** • Additives, complex hydrocarbons

Oxygenated fuels

	Ethanol	Methanol	Dimethyl ether (DME)
Application	• Renewable fuel • Off-grid application	• Produced from renewables or waste • Off-grid application, smallCHP	• Renewable fuel • Off-grid application • Replacement of LPG for µCHP?
Infrastructure	• No general infrastructure (some countries with 100 % ethanol at gas station) • Delivery via tank truck	• No infrastructure, but delivery via tank truck • Small canisters for off-grid (Smart Fuel Cells)	• No infrastructure, but delivery via tank truck
Reforming	• CPOX very easy • Steam reforming with soot formation risk → pre-reforming	• SR, CPOX, OSR • Low reforming temperatures	• SR, CPOX, OSR • Methanation to be considered
Impurities	• No sulfur	• Halide ions • No sulfur	• No sulfur

Reforming types

Steam reforming (SR)

$$C_nH_m + n\ H_2O \leftrightarrow n\ CO + (n + 0.5m)\ H_2$$

- Endothermic reaction → supply of heat
- Heat is converted into fuel enthalpy
  → high SOFC system efficiencies
- Low probability of carbon formation

Catalytic partial oxidation (CPOX)

$$C_nH_m + 0.5n\ O_2 \rightarrow n\ CO + 0.5m\ H_2$$

- Exothermic reaction → adiabatic operation
- Fuel enthalpy is converted into heat
  → lower SOFC system efficiency
- Higher probability of carbon formation
  and catalyst deactivation

Oxidative steam reforming (OSR)

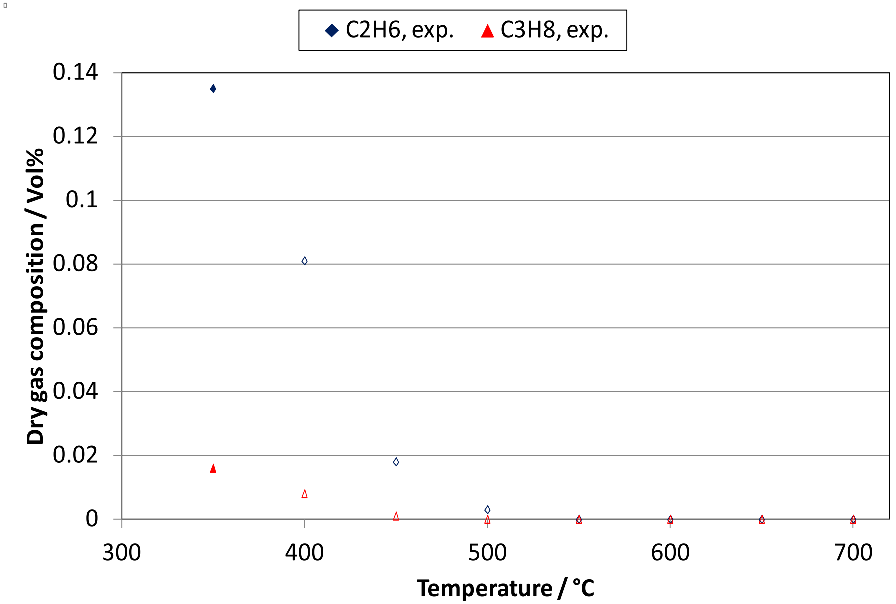
$$C_nH_m + a\ H_2O + b\ O_2 \leftrightarrow c\ CO + d\ H_2$$

- Mixture of SR and CPOX
  → special case autothermal reforming (ATR)
- Decrease of carbon formation likelihood
  (e.g. liquid fuels)

Pre-reforming

Application

- Usage of internal reforming capabilities of SOFC stacks → increase of electrical efficiency due to decreasing air flows
- Conversion of complex hydrocarbons (diesel, gasoline, ethanol) into a light gas mixture
- Hydrogen generation for desulphurization (ZnO)
- Conversion of higher hydrocarbons ($>C_1$) into $CO + H_2$ to avoid carbon deposition at anode)



Conversion of higher hydrocarbons from natural gas

$$C_nH_m + H_2O \leftrightarrow CO + H_2 + CH_4$$

Definitions

- Oxygen-to-carbon ratio
  → *defines mainly soot formation limit*

$$O/C = \frac{2\,\dot{n}_{O_2}\, k\,\dot{n}_{CO_k} + \dot{n}_{H_2O} + o\,\dot{n}_{C_lH_mO_o}}{\dot{n}_{CO} + \dot{n}_{CO_2} + l\,\dot{n}_{C_lH_mO_o}}$$

- O/C ratio for anode off-gas recirculation

$$O/C = \frac{2\dot{n}_{O_2} + 2\dot{n}_{CO_2} + \dot{n}_{CO} + \dot{n}_{H_2O}}{\dot{n}_{CO} + \dot{n}_{CO_2} + \dot{n}_{CH_4} + 2\dot{n}_{C_2H_6} + 3\dot{n}_{C_3H_8} + 4\dot{n}_{C_4H_{10}}}$$

- Steam-to-carbon ratio (ideal gas)

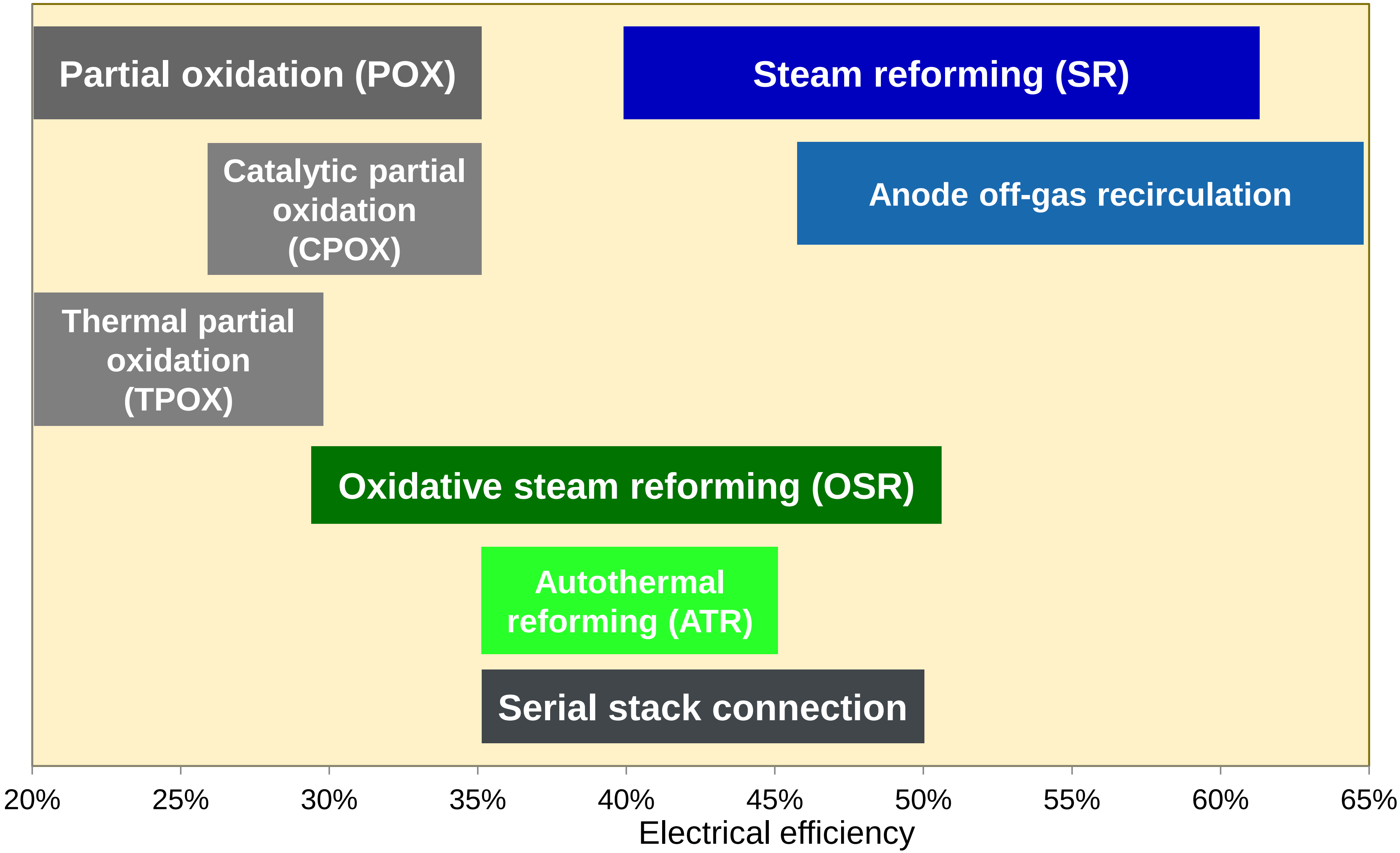
$$S/C = \frac{\dot{n}_{H_2O}}{l\,\dot{n}_{C_lH_mO_o}} \qquad S/C = \frac{\dot{V}^N_{H_2O}}{\dot{V}^N_{NG}\left(x_{CH_4} + 2\cdot x_{C_2H_6} + 3\cdot x_{C_3H_8}\right)}$$

- Air ratio / oxygen-to-carbon ratio for CPOX

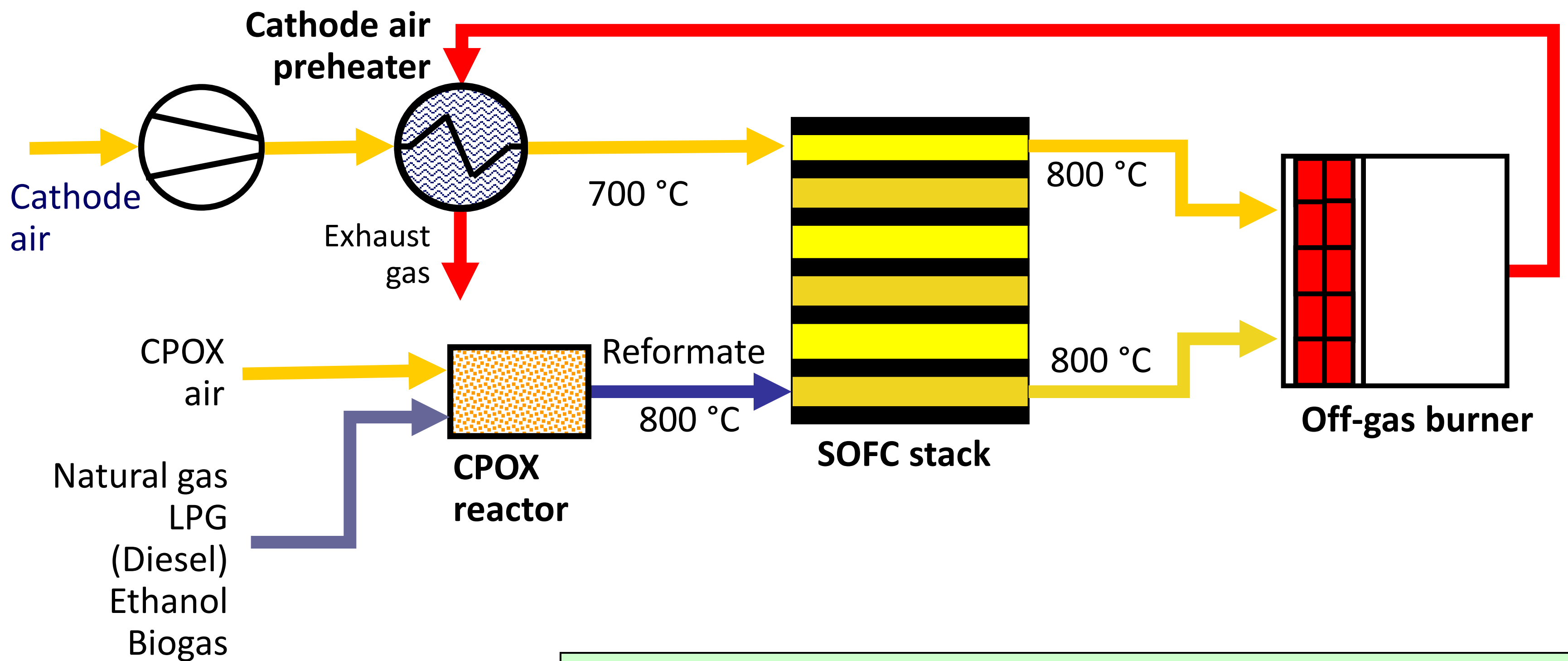
$$\lambda = \frac{\dot{n}_{O_2}}{\dot{n}_{O_2,\min,\lambda=1}} \qquad \lambda = \frac{0.21\cdot\dot{V}^N_{air}}{2\cdot\dot{V}^N_{CH_4}} \qquad O/C = \frac{2\cdot\left(0.21\cdot\dot{V}^N_{air}\right)}{\dot{V}^N_{CH_4}} = 4\cdot\lambda$$

System concepts

Fuel processing options in SOFC systems



CPOX based SOFC systems



Reformer air-to-fuel ratio

$$\lambda = \frac{\dot{V}_{air}}{\dot{V}_{air}^{min}} = \frac{x_{O_2}\,\dot{V}_{air}}{2\,\dot{V}_{CH_4} + 3.5\,\dot{V}_{C_2H_6} + 5\,\dot{V}_{C_3H_8} + 6.5\,\dot{V}_{C_4H_{10}}}$$

CPOX based SOFC systems

Advantages

- No water required
- Reduced number of components
- Compact, adiabatic reactor

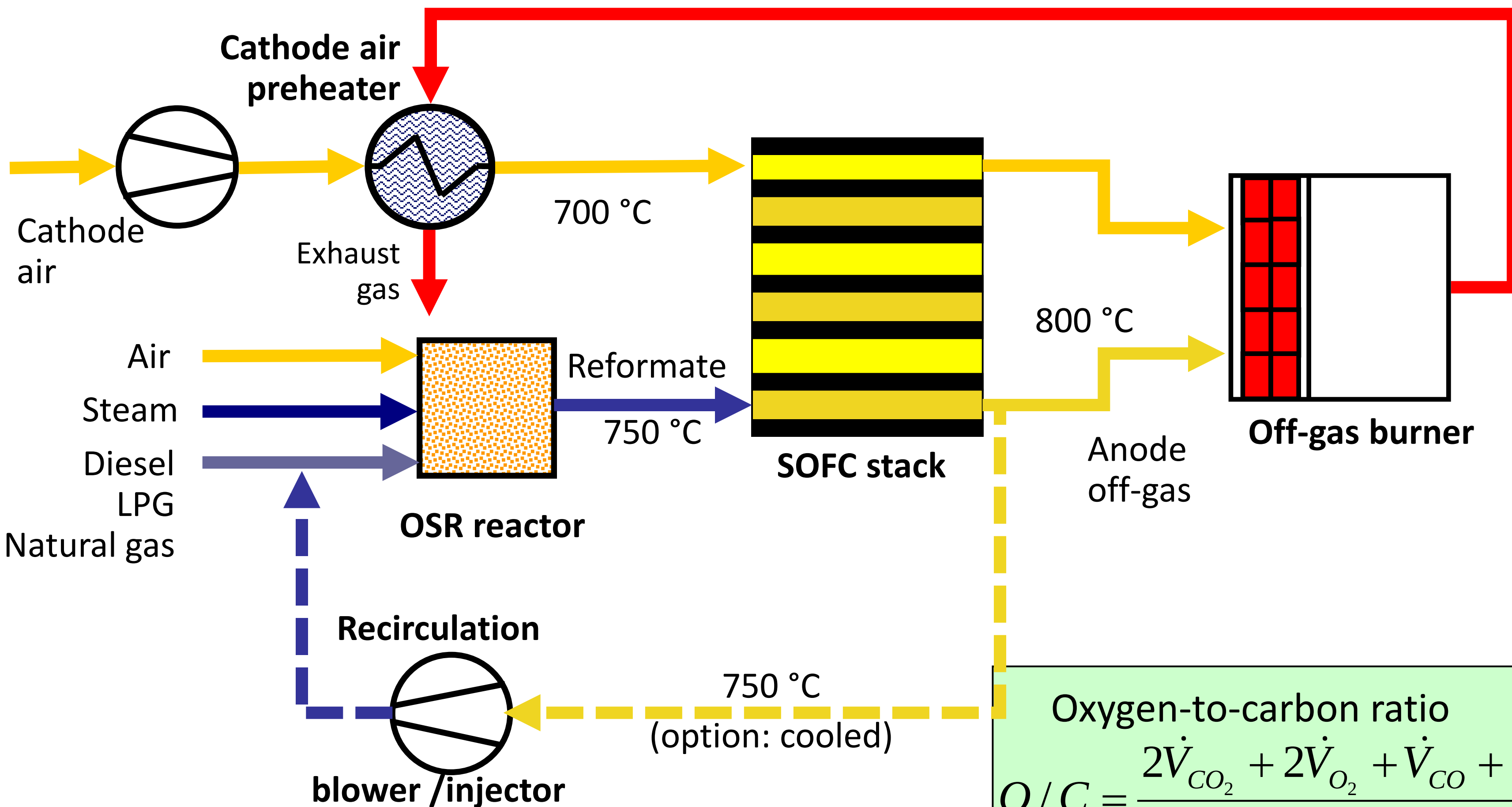
Disadvantages

- Electrical efficiency maximal 35 %
- Narrow operation window:
  $0.27 \ldots 0.3 < \lambda < 0.34 \ldots 0.36$ (soot formation / catalyst deactivation at T_{max} =950 °C)
- High air demand for stack cooling
- Costly precious metal catalyst
- Reformate temperature >700-750 °C needed (soot)
- Likelihood of soot formation if more complex hydrocarbons are used

Applications

- Simple, low-cost systems
  → µCHP, off-grid systems
  (NG, LPG, propane, *diesel*)
- Small-scale systems

Oxidative steam reforming based systems



Oxygen-to-carbon ratio

$$O/C = \frac{2\dot{V}_{CO_2} + 2\dot{V}_{O_2} + \dot{V}_{CO} + \dot{V}_{H_2O}}{\dot{V}_{CH_4} + \dot{V}_{CO_2} + \dot{V}_{CO}}$$

Oxidative steam reforming

Advantages

- Increase of electrical efficiency compared to CPOX systems
- Reduction of carbon formation likelihood
- Reduction of reforming temperature
- Adiabatic reformer

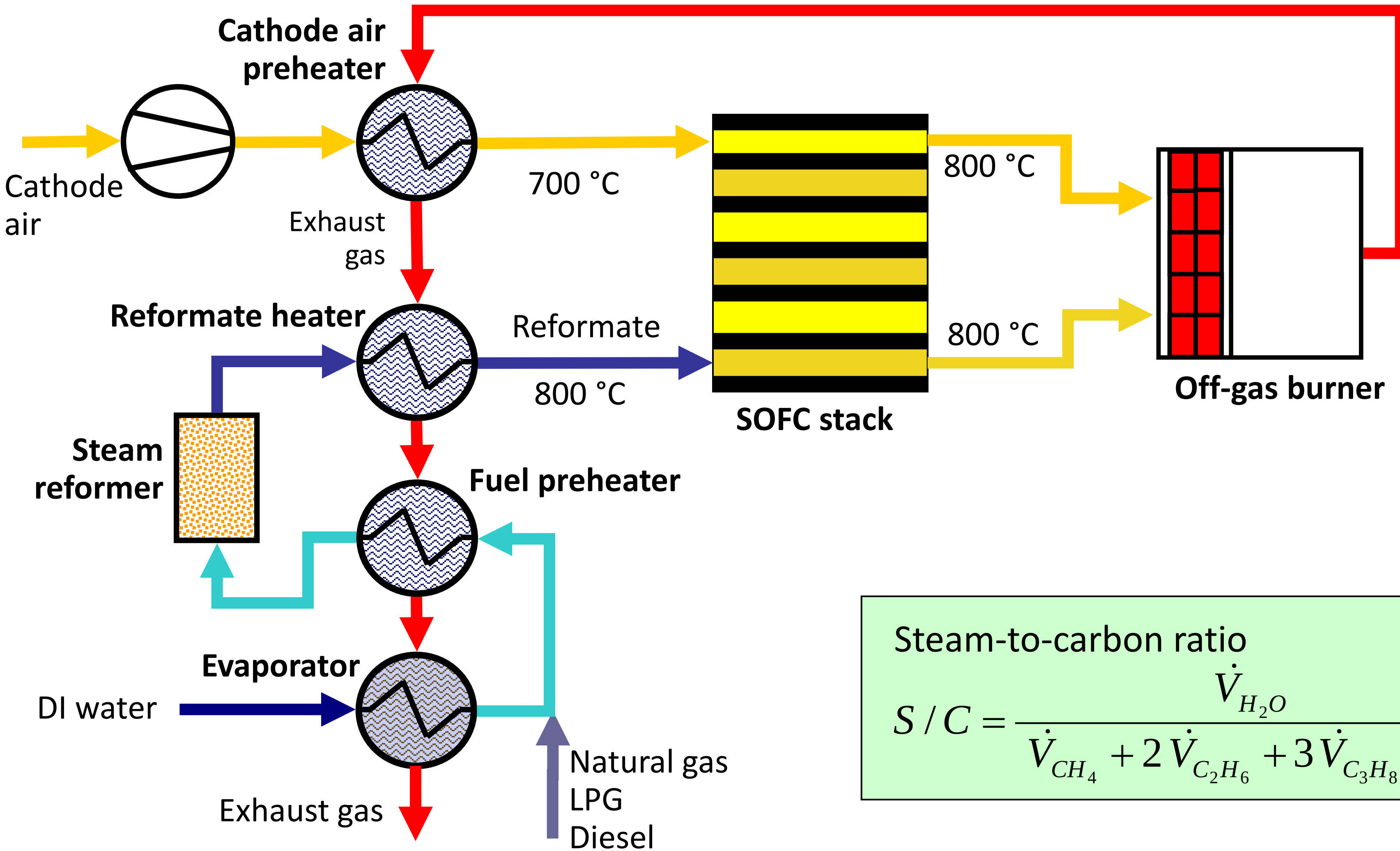
Disadvantages

- External steam supply or anode off-gas recirculation
- Measurement and control of recirculation loop (blower, injector)
- Long-term stable recirculation blower

Applications

- Mostly off-grid systems that use higher hydrocarbons (LPG, diesel, gasoline)
- Dependent or independent of external water supply

Steam reforming based SOFC systems



Steam-to-carbon ratio

$$S/C = \frac{\dot{V}_{H_2O}}{\dot{V}_{CH_4} + 2\,\dot{V}_{C_2H_6} + 3\,\dot{V}_{C_3H_8} + \ldots}$$

Steam reforming based SOFC systems

Advantages

- Electrical efficiency 45-60 %
- Wide operation window (S/C, T)
- Internal reforming possible
  → reduced air demand

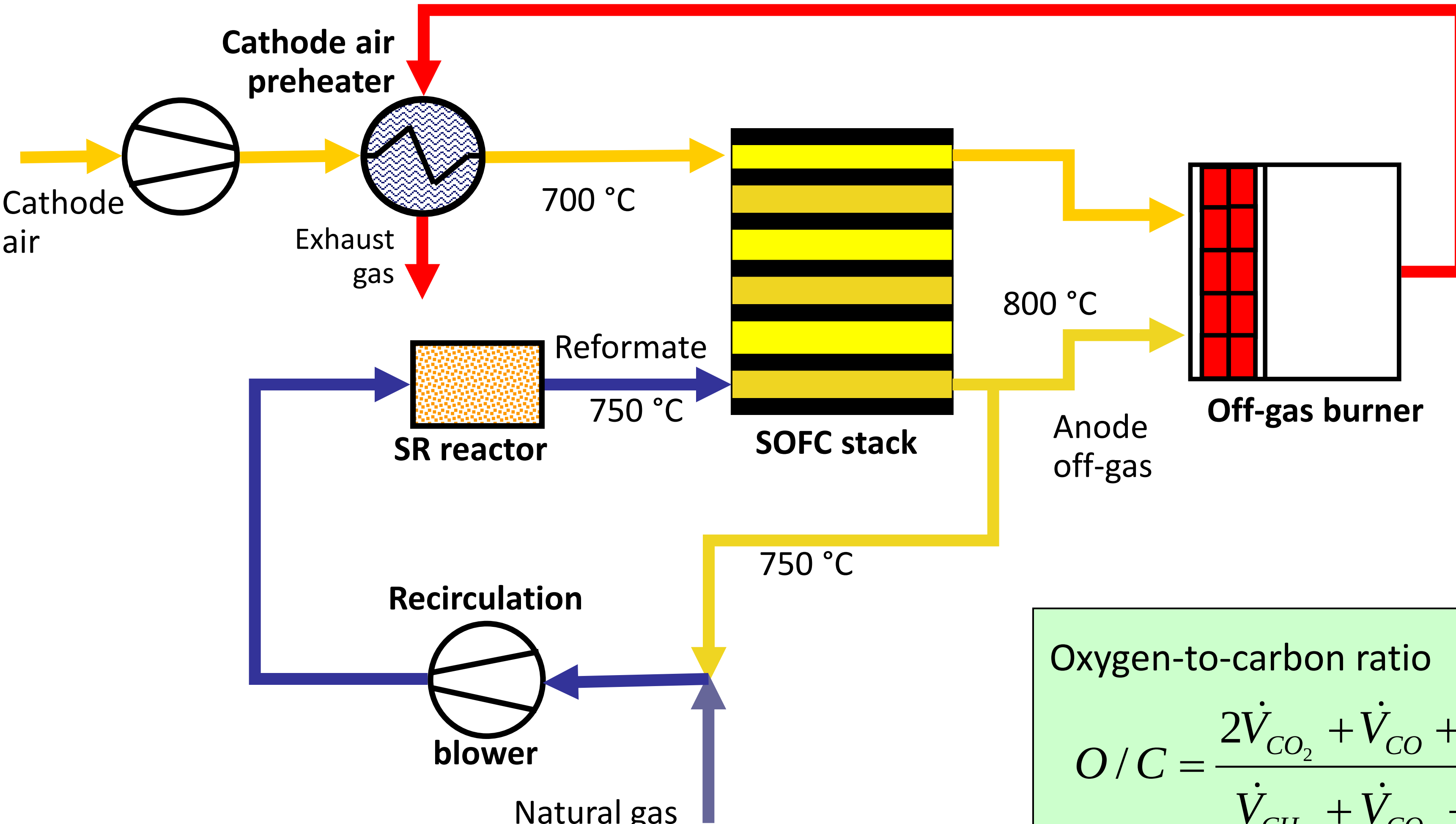
Disadvantages

- Large number of components
- Costs for water processing
- Reliability of water supply
- Bad dynamic system behaviour
- Large catalyst volume

Applications

- Systems with high electrical efficiency
  → µCHP, large-scale systems
- Reforming of complex hydrocarbons

Anode off-gas recirculation



Oxygen-to-carbon ratio

$$O/C = \frac{2\dot{V}_{CO_2} + \dot{V}_{CO} + \dot{V}_{H_2O}}{\dot{V}_{CH_4} + \dot{V}_{CO_2} + \dot{V}_{CO}}$$

Anode off-gas recirculation

Advantages

- Electrical efficiency > 50 %
- Closed water loop
- Internal reforming possible
  → reduced air demand
- Low number of components

Disadvantages

- Recirculation blower required
- Measurement and control of recirculation loop is challenging (soot formation)

Applications

- Systems with maximal electrical efficiency or ATR based systems
- Mainly larger systems → costs of recirculation blower

Anode off-gas recirculation: Recirculation rate

Definition of recirculation rate

$$A_R = \frac{\dot{V}_{RC}}{\dot{V}_{EX}}$$

V_{RC} … Recirculation flow rate

V_{EX} … Exhaust gas flow rate

- Increases with O/C ratio of steam reformer
- O/C of steam reforming normally 2 … 2.5, successful experiments down to 1.5 (VTT)

Calculation of O/C from recirculation rate

- General equation:

$$O/C = \frac{2\dot{V}_{CO_2}^{in} \cdot \left[1 + A_R \cdot \left(u_f - 1\right)\right] + A_R \cdot u_f \cdot \left(4\dot{V}_{CH_4}^{in} + 7\dot{V}_{C_2H_6}^{in} + 10\dot{V}_{C_3H_8}^{in} + 13\dot{V}_{C_4H_{10}}^{in}\right)}{\left(\dot{V}_{CO_2}^{in} + \dot{V}_{CH_4}^{in} + 2\dot{V}_{C_2H_6}^{in} + 3\dot{V}_{C_3H_8}^{in} + 4\dot{V}_{C_4H_{10}}^{in}\right) \cdot \left[1 + A_R \cdot \left(u_f - 1\right)\right]}$$

100 % methane

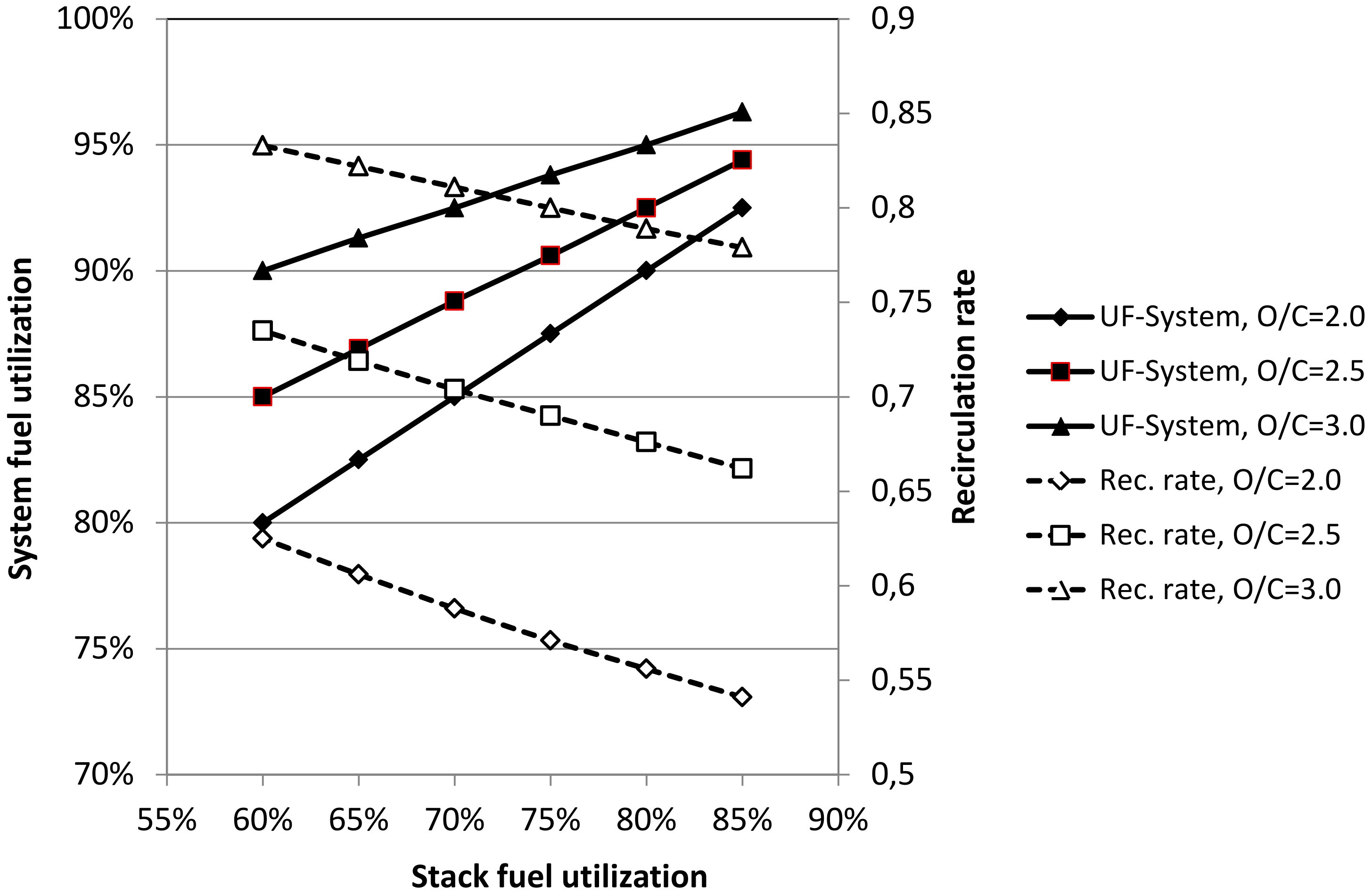
$$O/C = \frac{4A_R \cdot u_f}{1 + A_R \cdot \left(u_f - 1\right)}$$

Biogas (CH_4, CO_2)

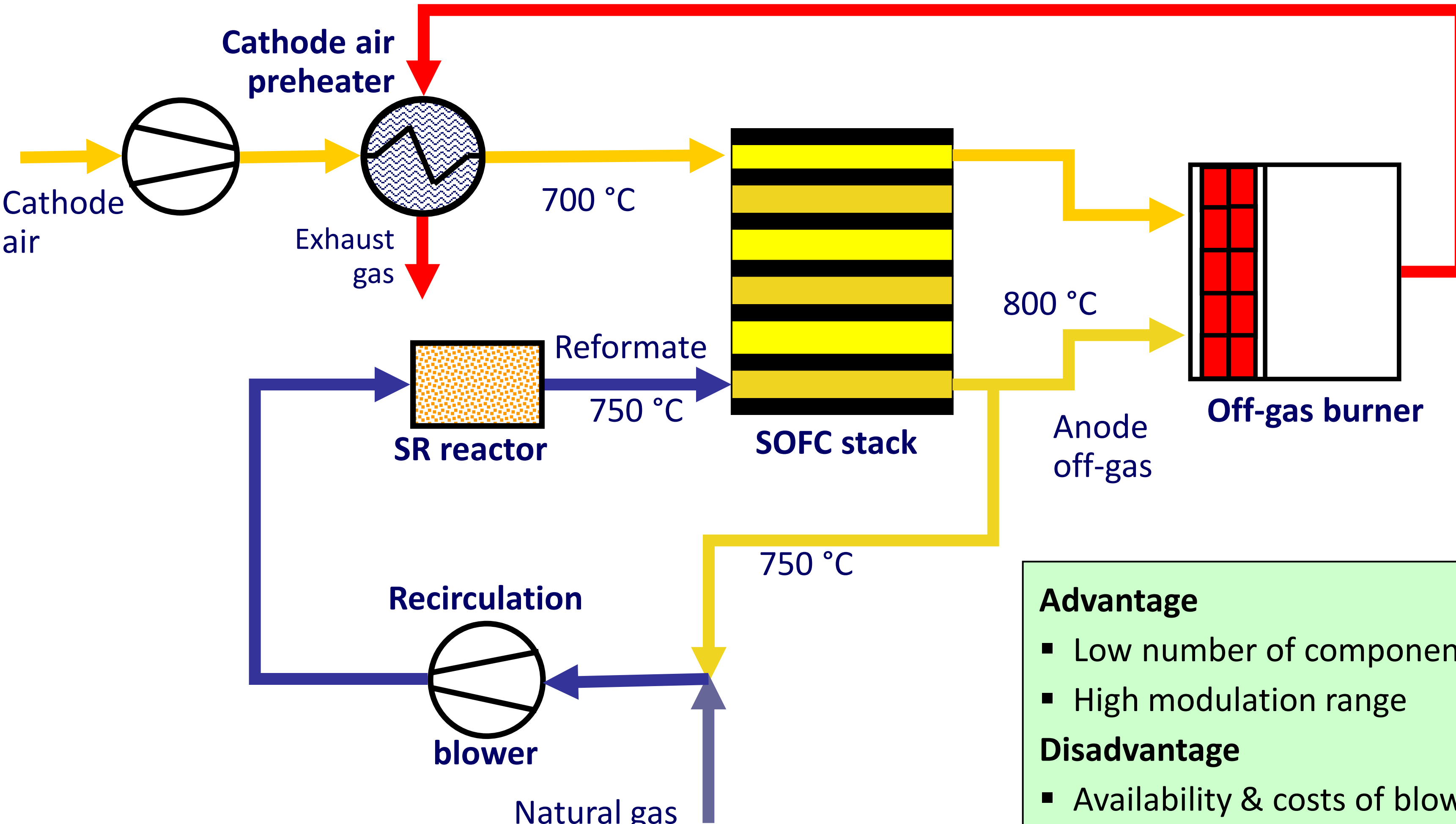
$$O/C = \frac{2\dot{V}_{CO_2}^{in} \cdot \left[1 + A_R \cdot \left(u_f - 1\right)\right] + 4A_R \cdot u_f \cdot \dot{V}_{CH_4}^{in}}{\left(\dot{V}_{CO_2}^{in} + \dot{V}_{CH_4}^{in}\right) \cdot \left[1 + A_R \cdot \left(u_f - 1\right)\right]}$$

Anode off-gas recirculation: Fuel utilization

The overall system fuel utilization is higher than the stack fuel utilization resulting in higher electrical efficiencies.



Anode off-gas recirculation: Hot anode off-gas blower



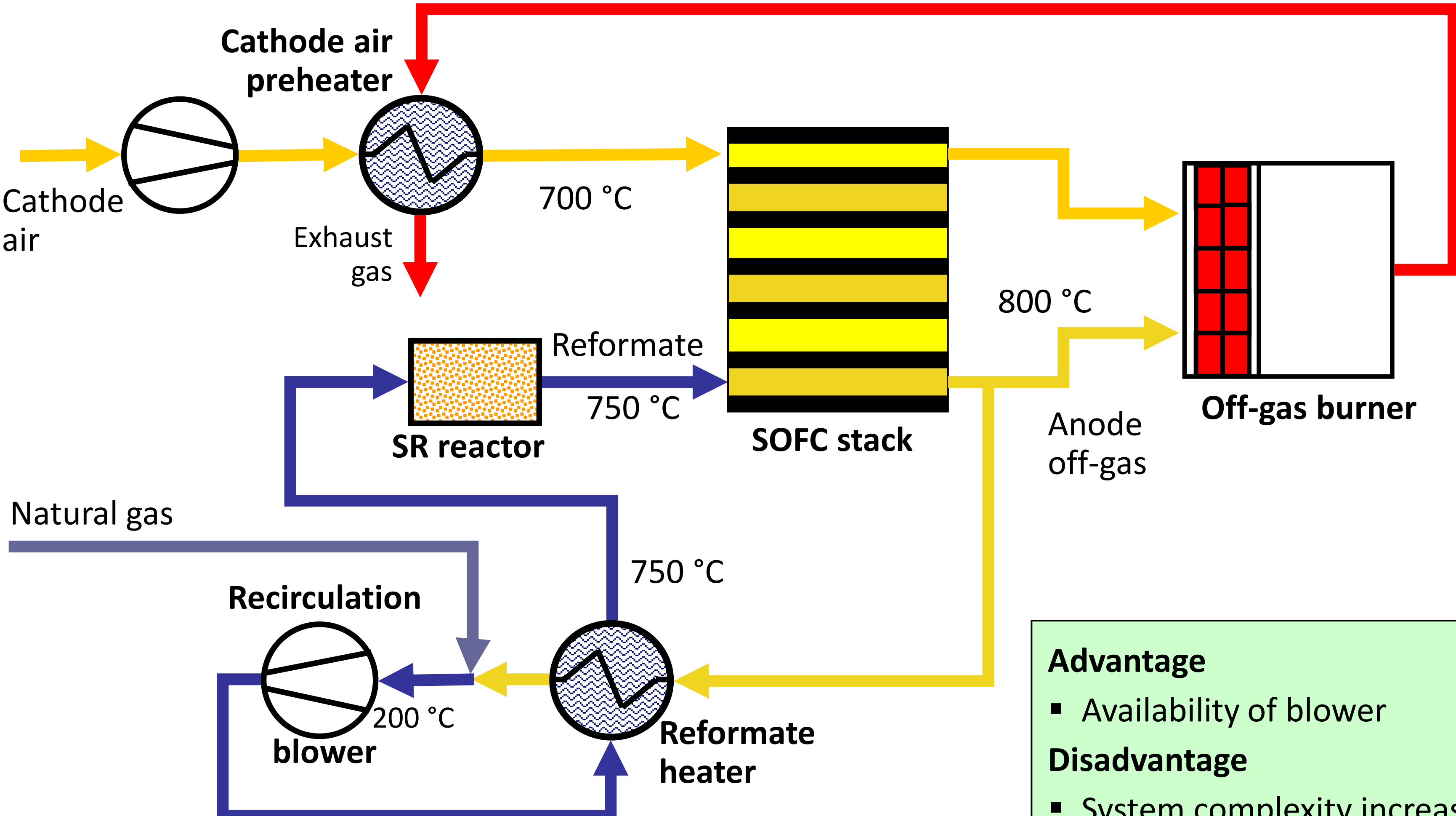
Advantage

- Low number of components
- High modulation range

Disadvantage

- Availability & costs of blower

Anode off-gas recirculation: 'Cold' anode off-gas blower



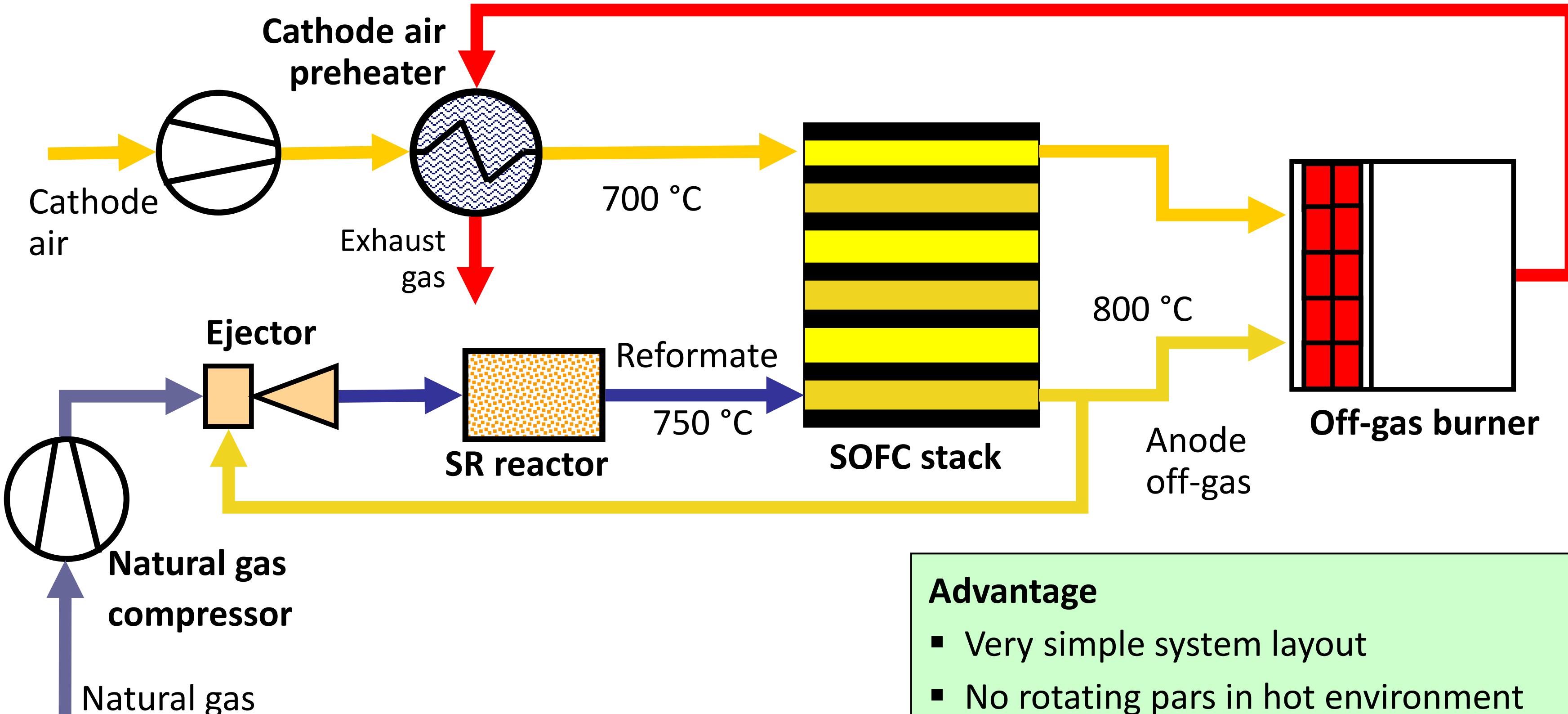
Advantage

- Availability of blower

Disadvantage

- System complexity increases

Anode off-gas recirculation: Ejector based recirculation



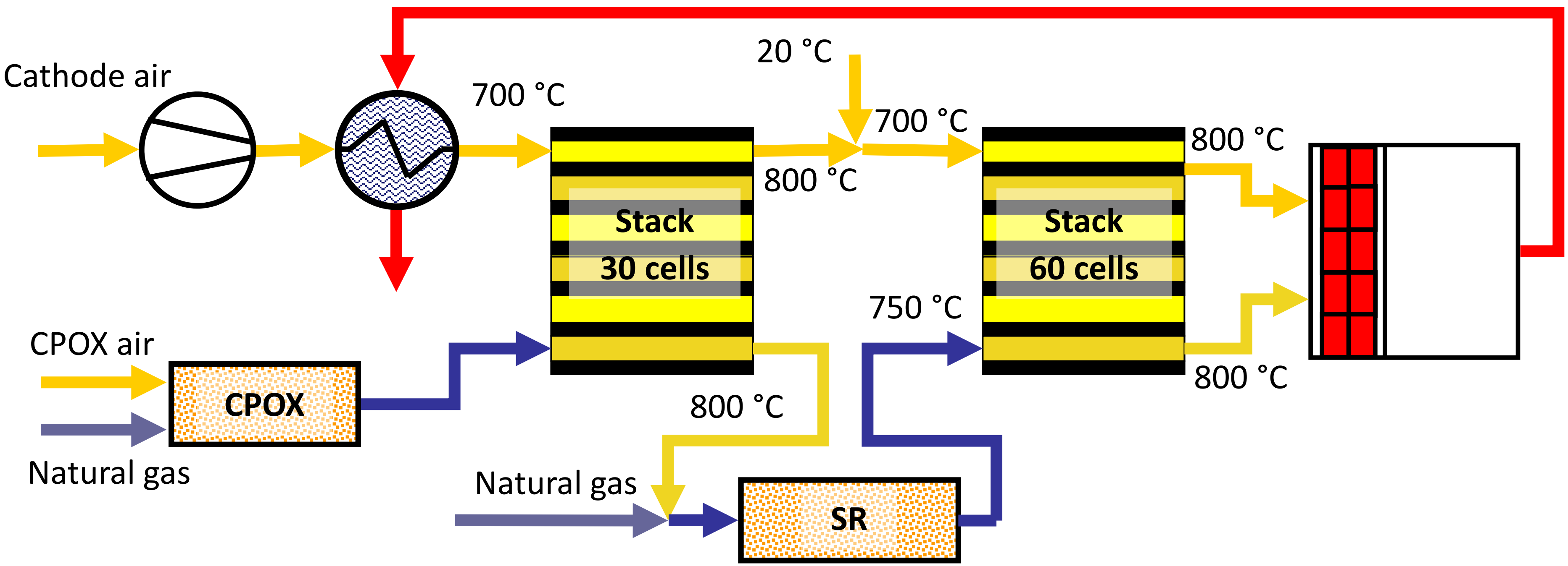
Advantage

- Very simple system layout
- No rotating pars in hot environment

Disadvantage

- Limited modulation range
- High gas inlet pressure required

Serial connection of SOFC stacks



Two-staged system with serial connection of stacks with CPOX and steam reformer as gas processor

Serial stack connection

Applications

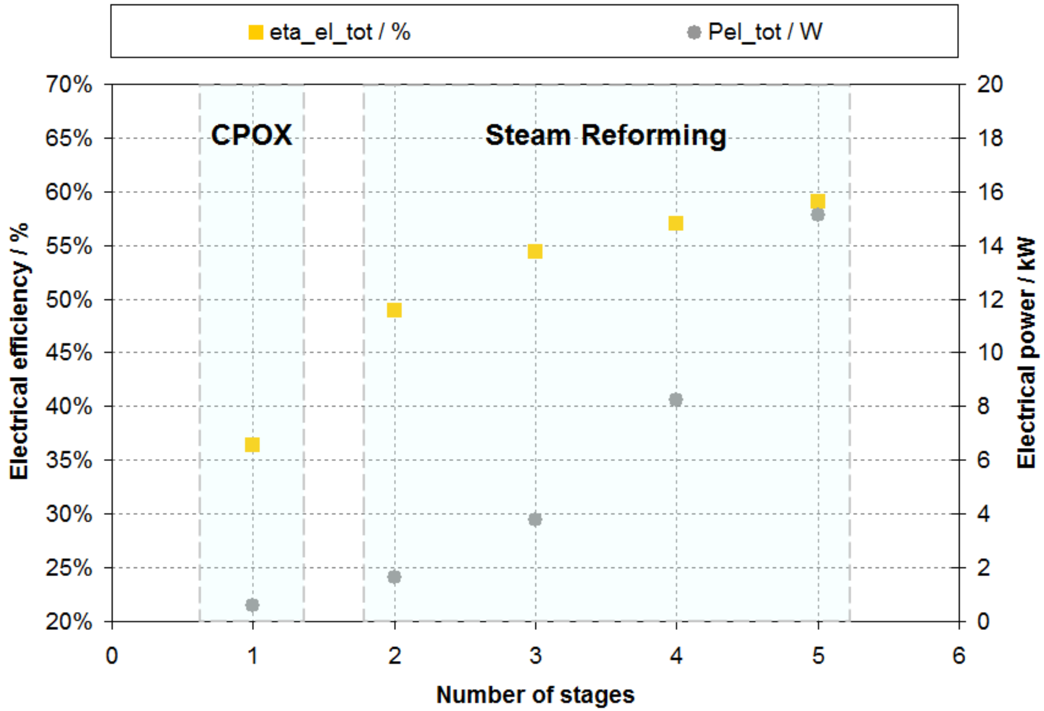
- Systems with higher electrical efficiencies (µCHP, smallCHP)

Advantages

- High electrical efficiencies without water processing or anode off-gas blower
- Electrical efficiency > 45 %

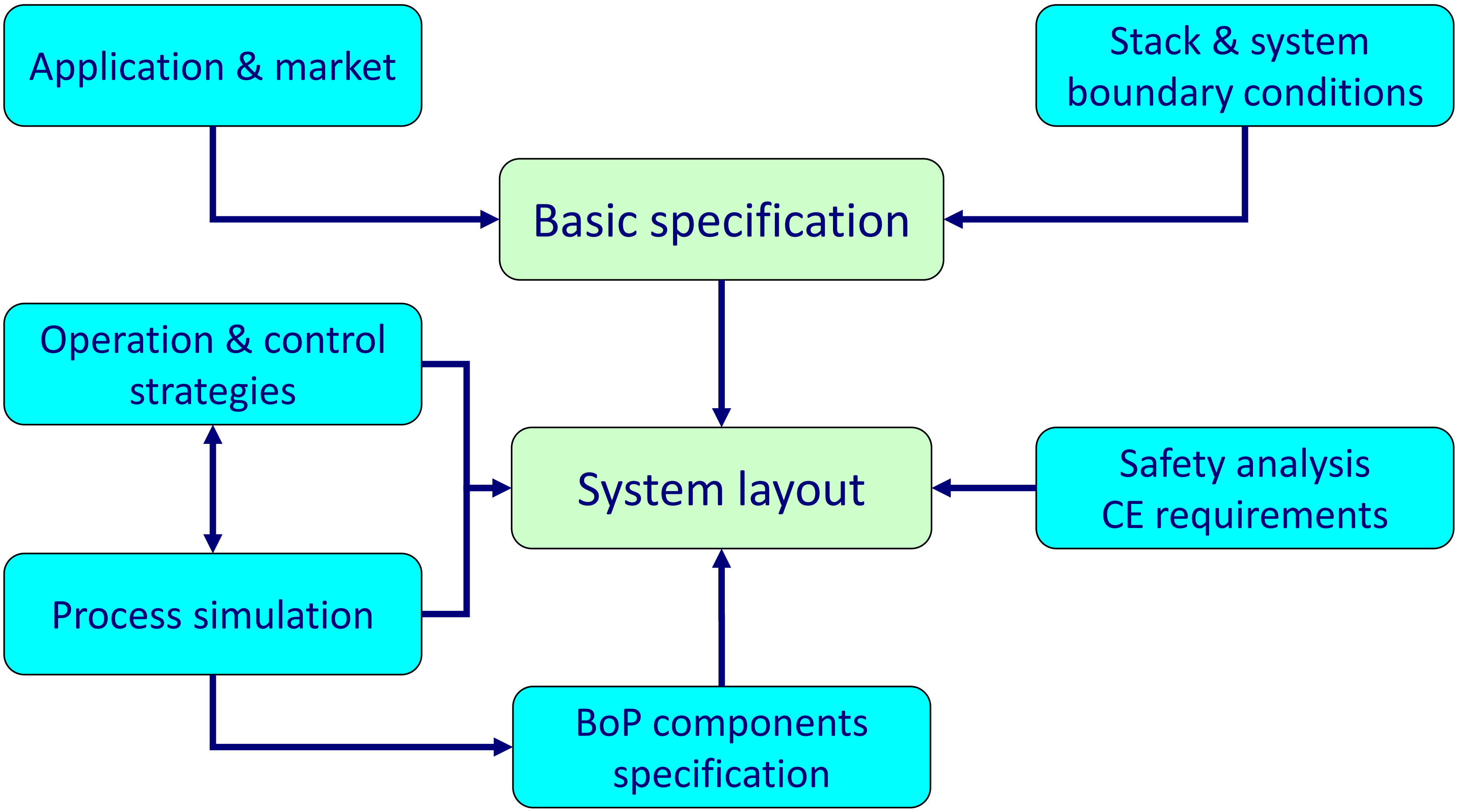
Disadvantages

- Power electronics more complex
- Additional fluid streams
- Complex stack



SOFC system design

Design process



System specification

Application

Requirements

- Electrical & thermal power output
- Electrical and total efficiencies
- Required start-up time
- Operation time / cycling
- Cost targets and payback periods
- Safety and certification requirements

Design options

- Fuel processing
- System size
- Stack type
- Start-up strategy
- Components choice and costs

Stack and system

Stack

- Fuel utilization
- Air and fuel inlet temperatures
- Reformate composition
- Thermal and redox cycling capabilities

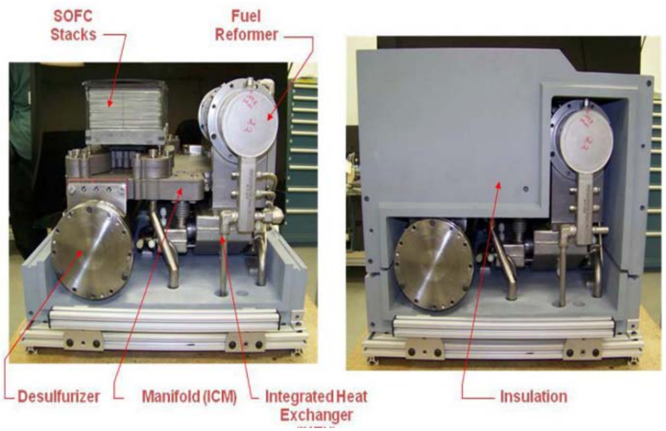
System

- Fuel quality
- Soot formation limits
- Available heat flows
- Start/stop procedure
- Control strategies
- Thermal losses

System design practice

Designing a compact system

- Minimize heat exchanger areas
  → “Pinch point” analysis
- Functional combination of components
- No piping between components
- Optimize components arrangements
- Stack integration in hot box



Source: Delphi

“Pinch point” analysis

The pinch point is the minimal temperature difference between hot stream and cold stream in a heat exchanger. It defines the heat transfer rate and required heat exchanger area. The analysis of a system reveals critical minimal temperature differences between different streams.

Safety and CE certification

1. Off-gas burner has to guarantee that no explosive or toxic (CO) gas leaves the system

- Reliable start-up procedure / ignition detection
- Flame detection important, but difficult in SOFC systems
- Burner control according to standards (air ratio)

2. Components and connections in hot environments can leak

- Avoid mixing of air and gas (e.g. in heat exchangers)
- Operate gas stream in under-pressure mode → exhaust gas suction blower
- Ventilate housing

3. Stack leakages

- Supply gas only if stack is above ignition temperature
- Purge stack environment

Safety and CE certification

Fuel Cell Standards

- EN 50465 Gas appliances - Fuel cell gas heating appliances - Fuel cell gas heating appliance of nominal heat input inferior or equal to 70 kW *(Classification, Construction, Operation, EMC)*
- EN 62282 Fuel cell technologies *(Safety, Test methods, Safety checks)*
- ISO 23273 Fuel cell road vehicles including all APU *(hazards inside and outside of the vehicles caused by the fuel cell system)*

Gas Appliances / Burner Standards

- EC Gas Appliances Directive (90/396/EEC)
- EN 483 Gas-fired central heating boilers *(requirements, construction, rational use of energy, test methods)*
- EN 161 Automatic shut-off valves for gas burners
- EN 298 Automatic gas burner control systems
- EN 125 Flame supervision devices
- EN 1854 Pressure sensing devices for gas burners

System efficiencies

Definitions

Electrical efficiency: $\eta_{el} = \frac{P_{el}}{P_{fuel}}$

DC stack power (LHV=Lower Heating value):

$$\eta_{DC,Stack} = \frac{P_{DC,Stack}}{P_{fuel}} = \frac{N \times U_{cell} \times I}{\dot{V}_{fuel}^{N} \times LHV}$$

LHV is used in Europe, HHV (Higher Heating value) is normally applied in USA or Asia

DC system power:

$$\eta_{DC,System} = \frac{P_{DC,Stack} - P_{AUX}}{P_{fuel}}$$

P_{AUX} = power consumption of auxiliaries → **blowers**, pumps, control system, valves, …

AC system power:

$$\eta_{AC,System} = \eta_{DC,System} \times \eta_{Inverter}$$

Thermal efficiency:

$$\eta_{th} = \frac{\dot{Q}_{heat}}{P_{fuel}} = \frac{\dot{m} \times c_p \times (T_H - T_K)}{\dot{V}_{fuel}^{N} \times LHV}$$

Overall efficiency: $\eta_{tot} = \eta_{el} + \eta_{th}$

CHP coefficient: $\sigma = \frac{P_{el}}{\dot{Q}_{heat}}$

LHV and HHV of typical gaseous fuels

Fuel	HHV in MJ/m³	LHV in MJ/m³
Hydrogen	12,745	10,783
Carbon monoxide	12,633	12,633
Natural gas	35…46	31…41
Methane	39,819	35,883
Ethane	70,293	64,345
Propane	101,242	93,215
n-Butane	134,061	123,810

Why high efficiencies?

CHP systems

- High overall efficiency increases profitability
- High electrical efficiency makes power feed-in attractive
- High electrical efficiency increases number of operation hours (due to limitations in heat usage)

Off-grid systems

- Mostly high electrical efficiencies required
- Decrease of fuel consumption:
  - Reduction of fuel costs
  - Range extension / operation time extension

Electrical efficiency

Maximization of electrical efficiency

- Steam reforming for fuel processing (resp. anode off-gas recirculation)
- Operation at high fuel utilization
- Reduction of power consumption of auxiliaries:
    - Decrease of system pressure losses (< 30-50…100 mbar)
    - Usage of internal reforming capabilities for stack cooling
    - Operation of blowers at maximal efficiency
    - Reduction of power consumption of pumps, valves, controls
- Operation of stack at high voltage (oversizing)

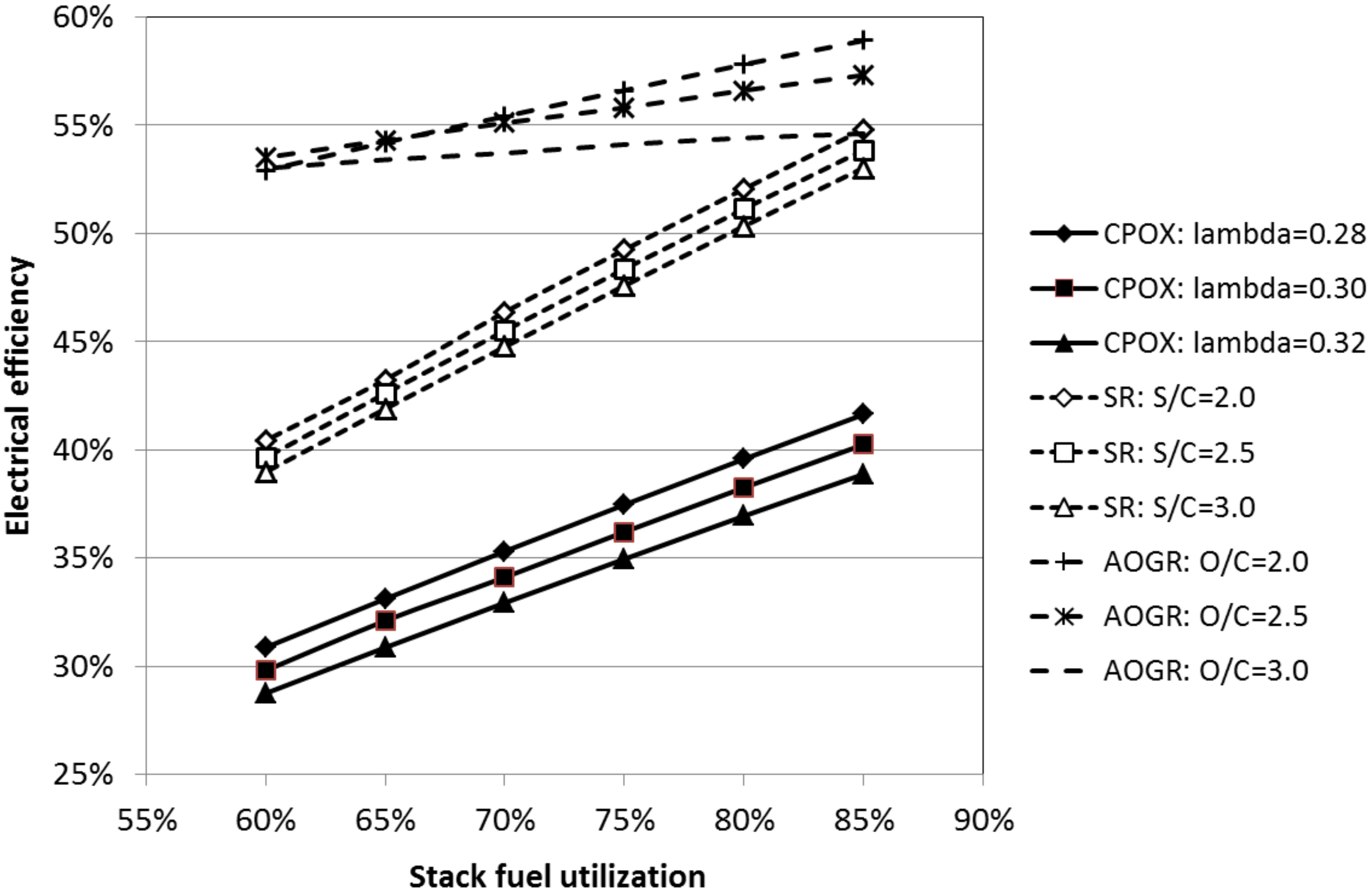
Ceramic Fuel Cells (CFCL)

… has demonstrated electrical efficiencies of 60 % at 1.5 kW power output. This is similar to the latest generation of Combined Cycle Power Plants.

The exhaust heat usage additionally allows a high overall efficiency.

Electrical efficiency

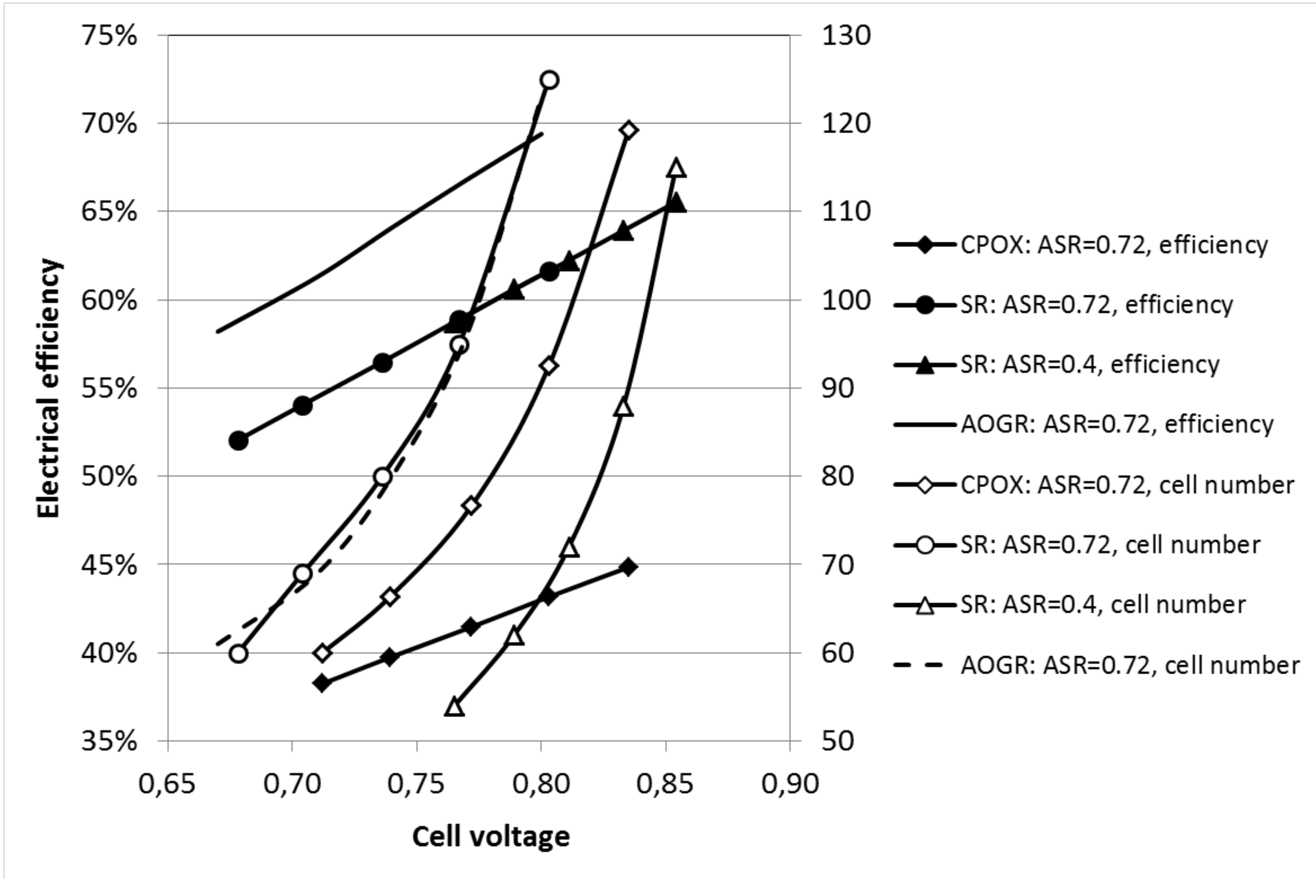
Influence of fuel processing, fuel utilization and fuel composition



staxera:

Electrical efficiency

Influence of cell voltage – number of cells to generate 1500 W: ASR=0.72 Ohm/cm² (ESC technology) and 0.4 Ohm/cm² (ASC technology)

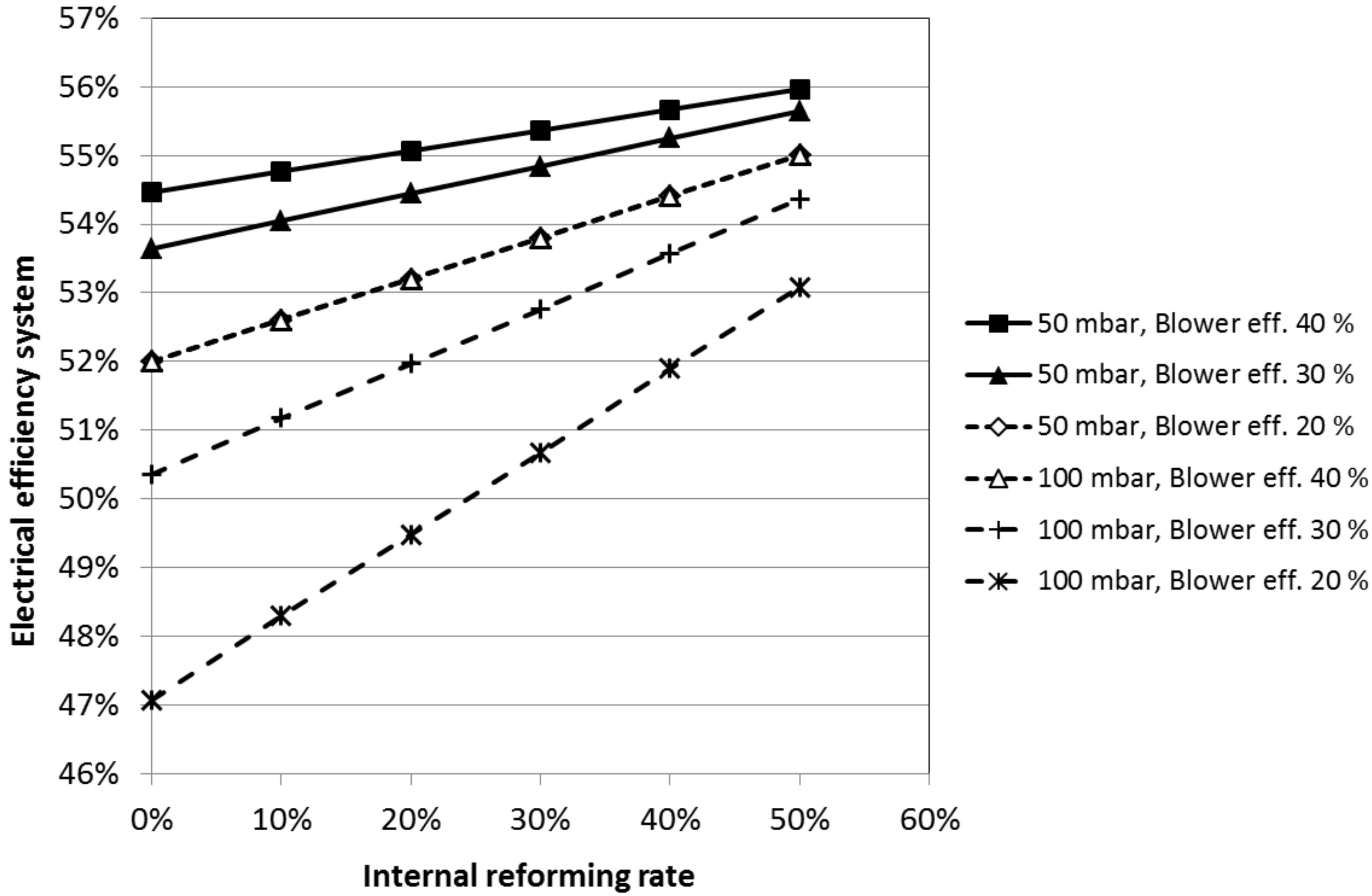


Does oversizing of stacks make sense for higher electrical efficiencies?

The required number of cells increases more steeply than the electrical efficiency: Amortization time of a system would increase!

Electrical efficiency

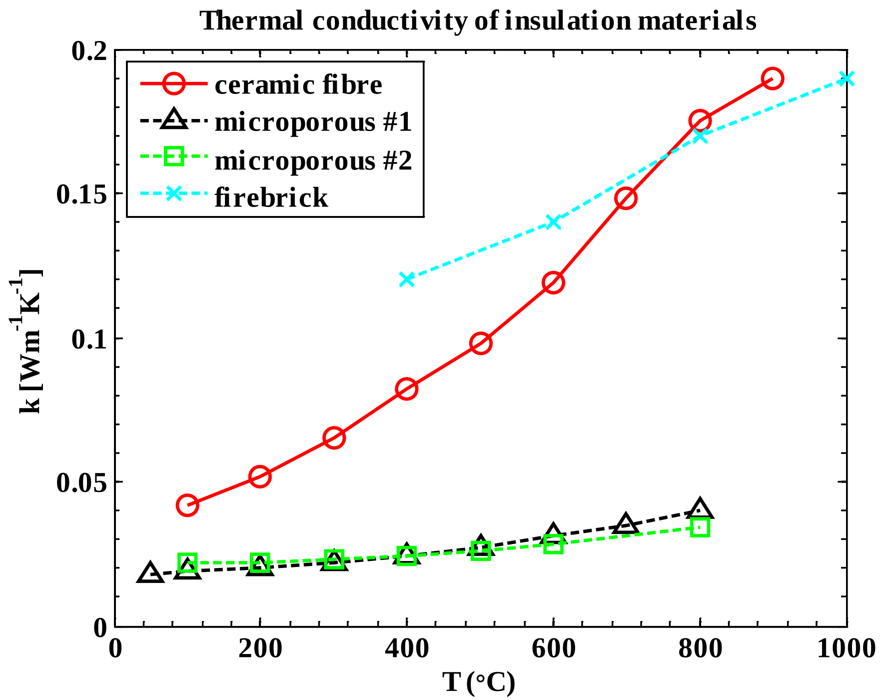
Influence of internal reforming rate, system pressure loss and blower efficiency



Thermal efficiency

Maximization of thermal efficiency

- Compact system for reduction of thermal losses
- High-grade insulation in hot parts
- Hotbox design with highest temperatures in the core
- Stack integration within hotbox
- Avoidance of thermal bridges → low number of sensors in hot parts
- Condensation of exhaust gas
  - Low temperature water cycle in application
  - Exhaust gas with min. air ratio (high dew point)

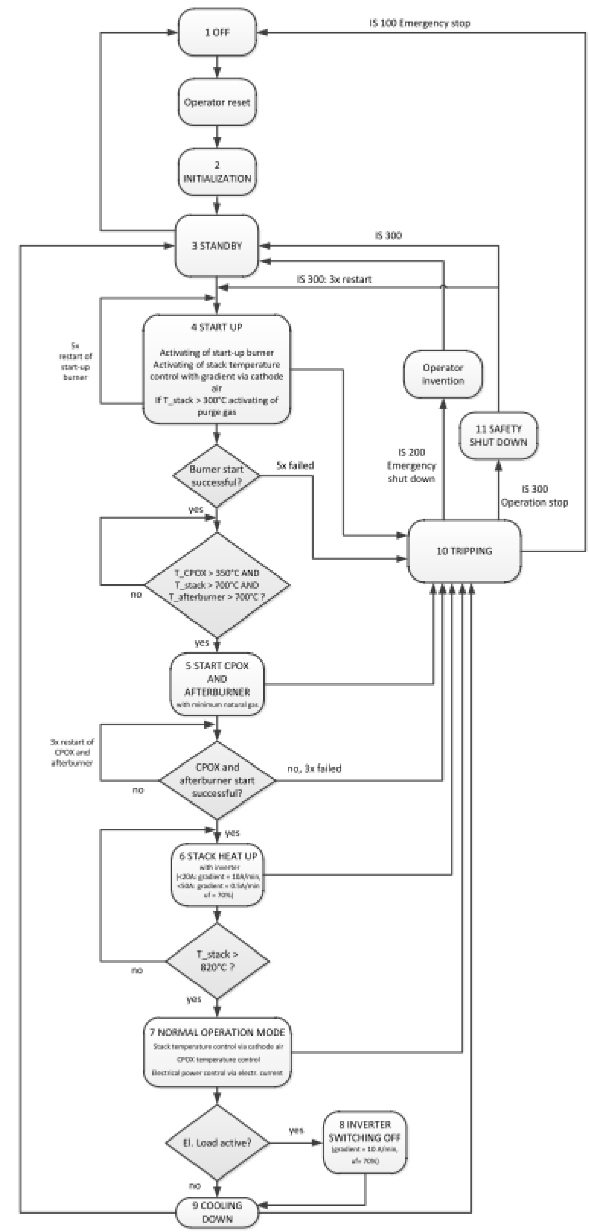


Source: VTT

Control & operation procedures

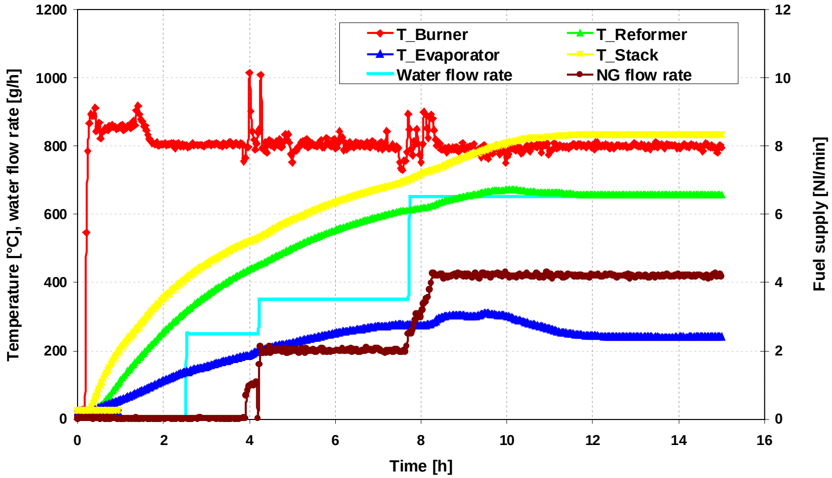
Operational states

- Represented in state diagrams
- Main states:
  - System heat up
  - Normal operation (load following)
  - Cool down procedure
  - Emergency situations
- Operational procedures depend on:
  - System design
  - Gas processing type
  - Stack type
  - Application (stationary, off-grid, …)



Hints on operation & control

- Investigate temperature control of reactors (reformer, off-gas burner, stack)
- Simulate heat-up and cool-down process
- Avoid start-stop cycles and fast transients
- Set useful limits for system parameters (safety checks)
- Check load following capability of stack and system
- Minimize number of actuators
- Operate blowers at optimal design conditions → efficiency



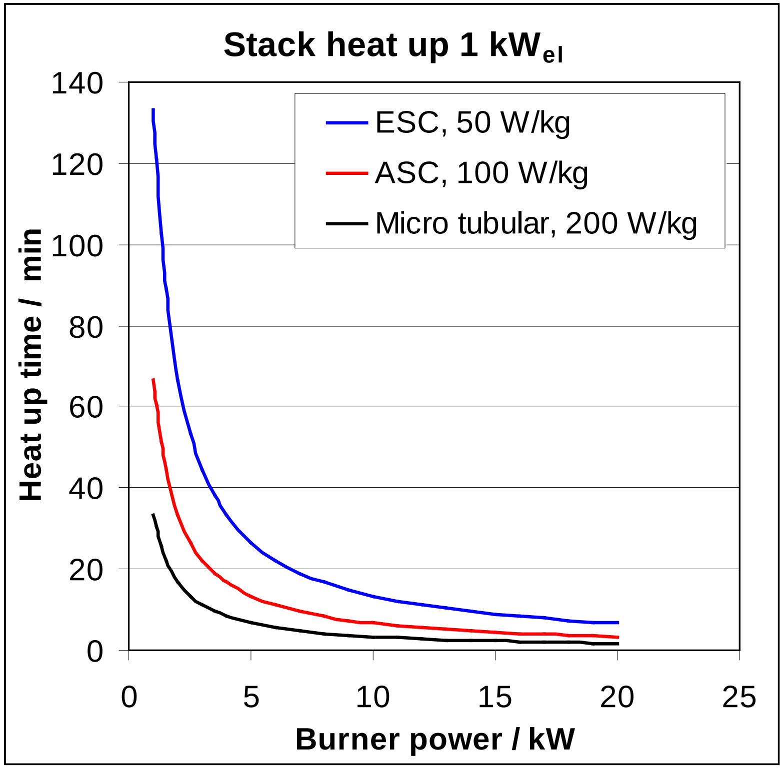
System heat up

Can be largely simplified by using electrical devices (start-up burner not required). A reasonable option for continuously running systems.

Systems with fast start-up

System design for fast start-ups

- CPOX systems faster in heat up and load following than SR based
- Over-dimensioning of start-up burner required
- Minimize components weight
- Stacks based on tubular cells favorable (lower weight)
- Use of stacks with high power density
- Close connection of start-up burner and stack (radiative heat transfer)



Portable SOFC systems and APUs require very fast start-up times. This is a challenge for SOFC technology. An underestimated fact is very often the required start-up burner capacity.

Avoidance of stack failures

How to keep the stack alive

- Low number of thermal cycles
- Avoidance of anode oxidation
- Minimization of thermal gradients
- Minimization of pressure differences between anode and cathode and environment
- Reliable desulphurization / fuel cleaning
- Prevention of carbon formation
- Usage of materials with low chromium evaporation
- Don’t draw electricity if there is no fuel

Cell fracture due to production failure

Source: Staxera

Soot formation due to wrong operation conditions

Source: Staxera

Costs & profitability

Profitability of µCHP systems

Factors that must be taken into account for profitability calculations

Capital expenditure (CAPEX)

- Fuel cell system costs
- Costs of peak burner, water storage, control
- Installation costs
- Capital service
- Depreciation period → total costs of ownership
- Investment supports (subsidies)

Operational expenditure (OPEX)

Customer

- Load profile of heat and electricity consumption
- Average and maximum loads

System

- Electrical and total efficiencies (CHP coefficient) → load depending!
- Maximal electricity and heat generation
- Modulation (turn down ratio)
- Maintenance costs

Utility

- Electricity price
- Fuel price
- Feed-in tariffs

Simple cost modelling

Target

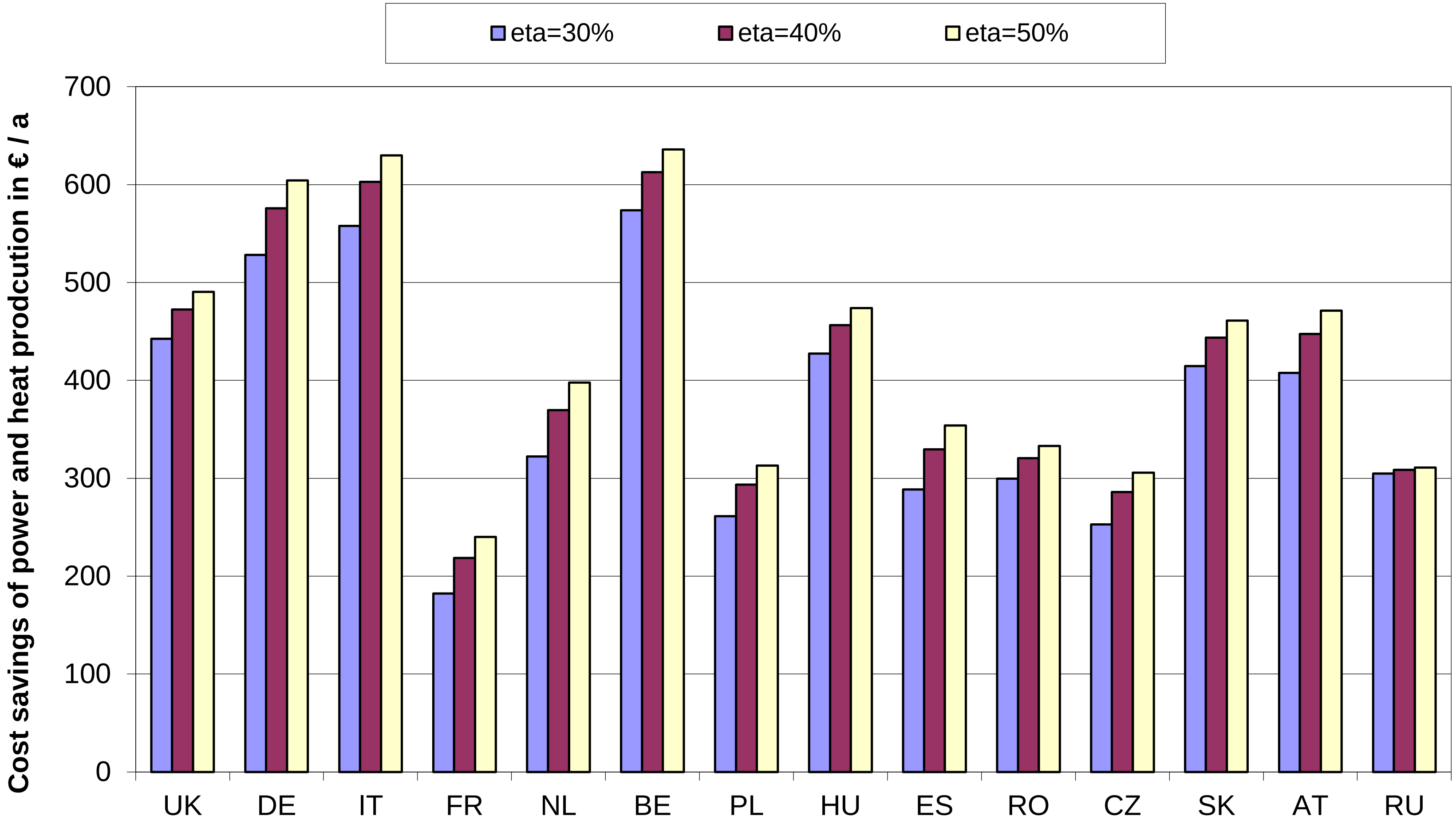
- Initial calculation of yearly cost savings by CHP installation

Assumptions

- 5000 h yearly full-load operation hours
- 85 % total efficiency, variation of electrical efficiency
- No maintenance costs
- Full usage of heat and electricity, no feed-in of electricity
- Local gas and electricity prices
- No funding

	Natural gas price	Electricity price
France	40.2 €/MWh	125.6 €/MWh
Germany	43.6 €/MWh	237.5 €/MWh
Italy	47.6 €/MWh	196.7 €/MWh
Spain	41.2 €/MWh	172.8 €/MWh
United Kingdom	31.3 €/MWh	138.6 €/MWh

Simple cost modelling



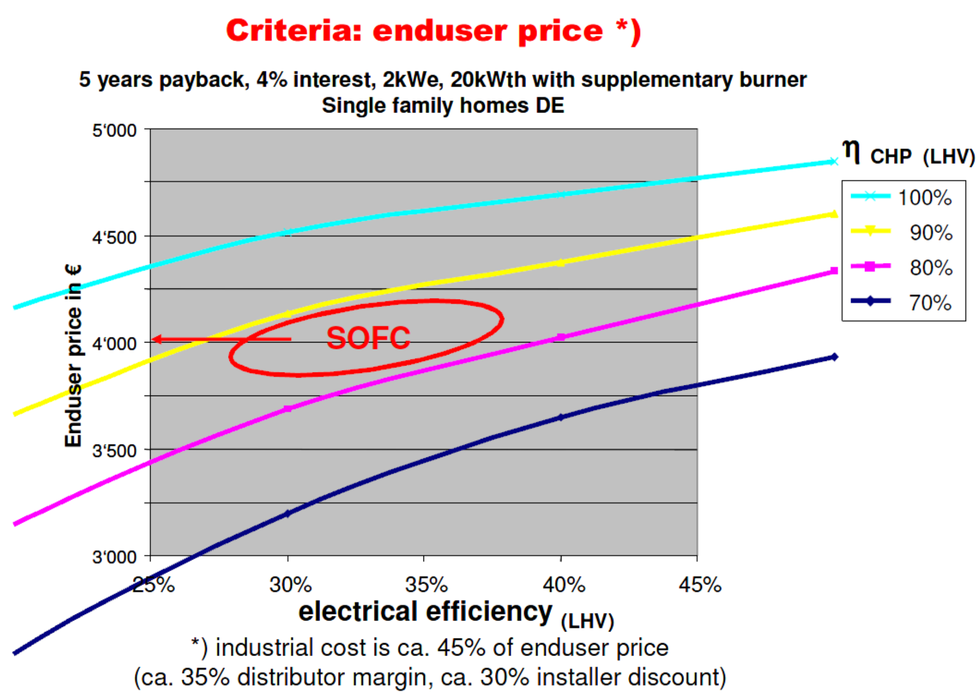
Identification of potential markets for µCHP applications. Market size (Belgium) and heat/electricity demands (Italy) to be considered.

Simple modelling of µCHP systems

General

→ *High total efficiencies required for cost effective CHP systems*

- High electrical and thermal efficiencies
- High modulation range to increase yearly operation hours and avoid start-stop-cycles
- System size and CHP coefficient must fit to heat and electricity demands



Source: Ariston/Elco (Flame-SOFC)

Detailed cost modelling

- Requires load profiles for heating system, domestic water supply and electricity consumption → in Germany VDI guideline 4655
- Requires data of the µCHP unit like turn down ratio and efficiencies changes versus load, speed of load changes
- To be considered:
  - Thermal insulation of building
  - Size and load of thermal storage
  - Feed-in tariffs including funding
- Comparison of CFCL “BlueGen” and Hexis “Galileo 1000 N”

Business cases should work without funding (only in market penetration period). Changes in funding politics are likely.

Basic assumptions for cost

- Single-family home (2005) → new house, low heat demand
- Peak boiler: $\eta_{th} = 0.85$
- Electricity price (Dresden): 0.231 €/kWh
- Natural gas price (Dresden): 0.086 €/kWh_{LHV}
- Thermal Storage System:

heat conductivity	λ [W/m²K]	0,03
isolation	d [m]	0,1
thermal storage system size	V [m³]	0,5
leakage heat per day	Qleakage [kWh]	1,28
storable heat	Qstorage [kWh]	11,64
difference in temperature (storage and installation location)	ΔT [K]	35

Cases to be compared

1) Including German CHP-funding
   a) Powered in the summer period
   b) Disabled in the summer period

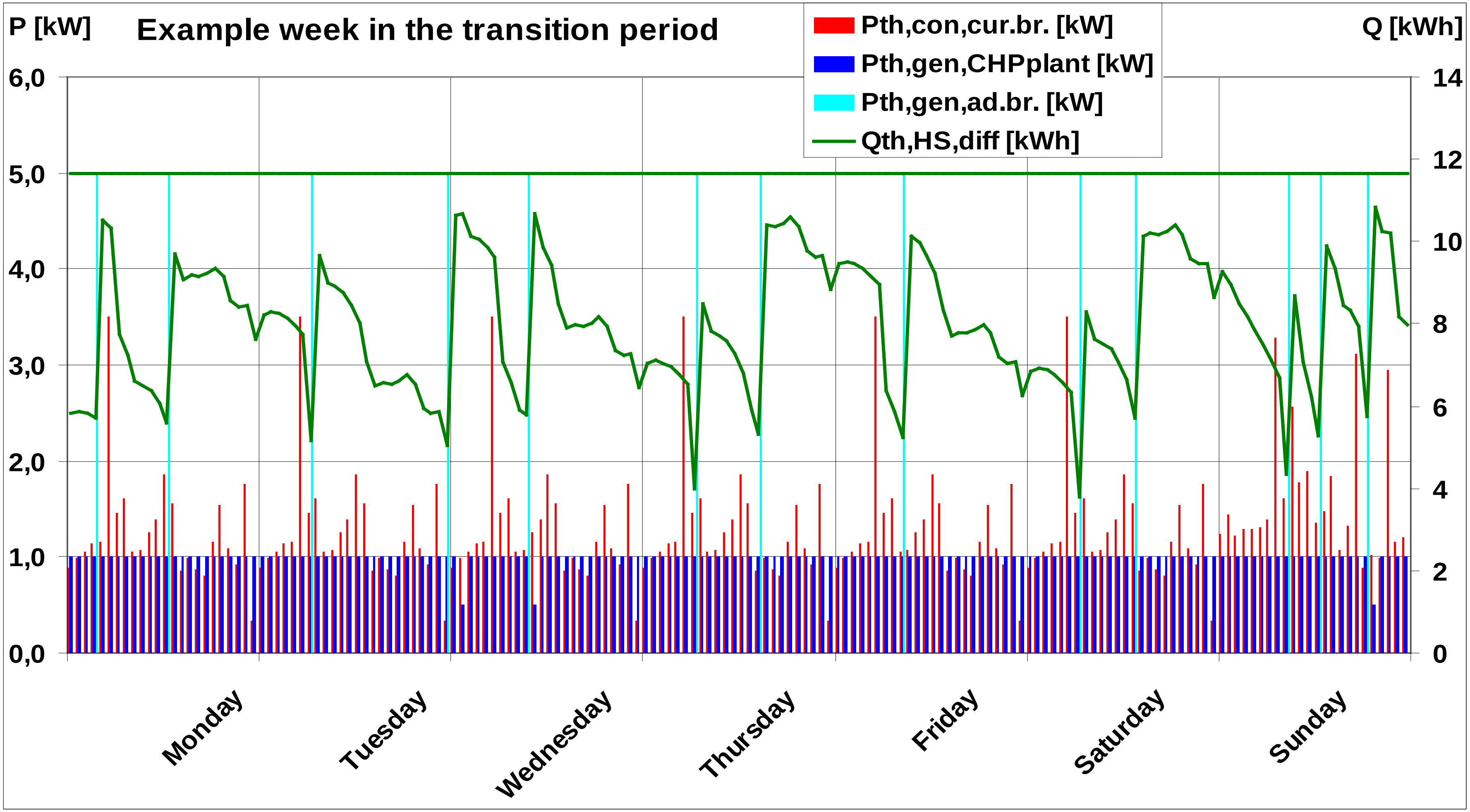
2) Excluding German CHP-funding
   a) Powered in the summer period
   b) Disabled in the summer period

3) Operation regimes of BlueGen:
   a) Heat driven (HD)
   b) Electricity driven (ED)

CFCL - BlueGen µCHP unit	
Max. electrical load	2.0 kW
Electricity to heat ratio σ	2
Max. thermal load	1.0 kW
Peak burner power	5.0 kW
Electrical efficiency	60 % @ 1500 W
Overall efficiency	85 %
Modulation range	20 … 100 %

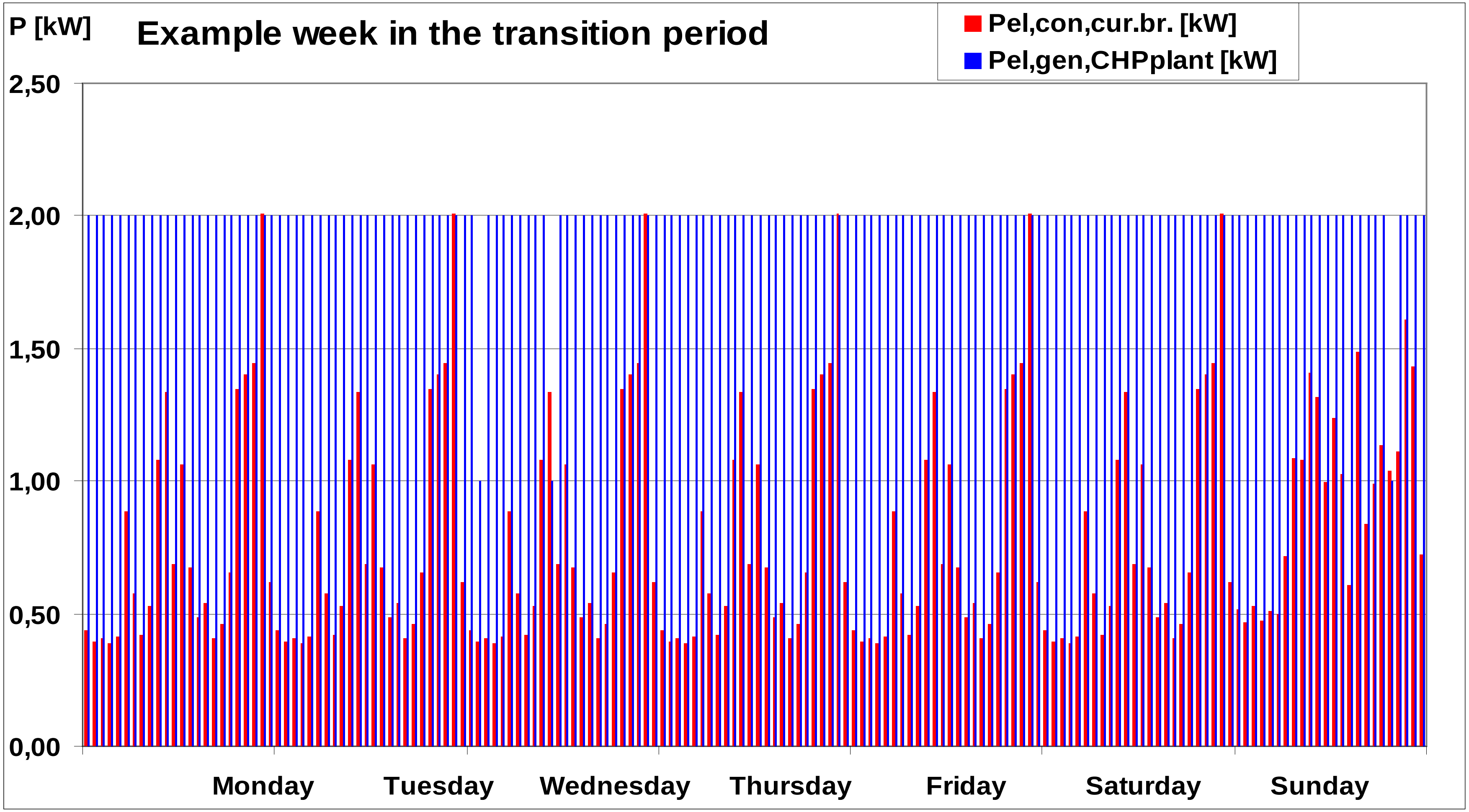
Hexis - Galileo 1000 N µCHP unit	
Max. electrical load	1.0 kW
Electricity to heat ratio σ	0.4
Max. thermal load	2.5 kW
Peak burner power	5.0 kW
Electrical efficiency	35 %
Overall efficiency	90 %
Modulation range	33 … 100 %

BlueGen: Thermal Demand and Generation (heat driven)

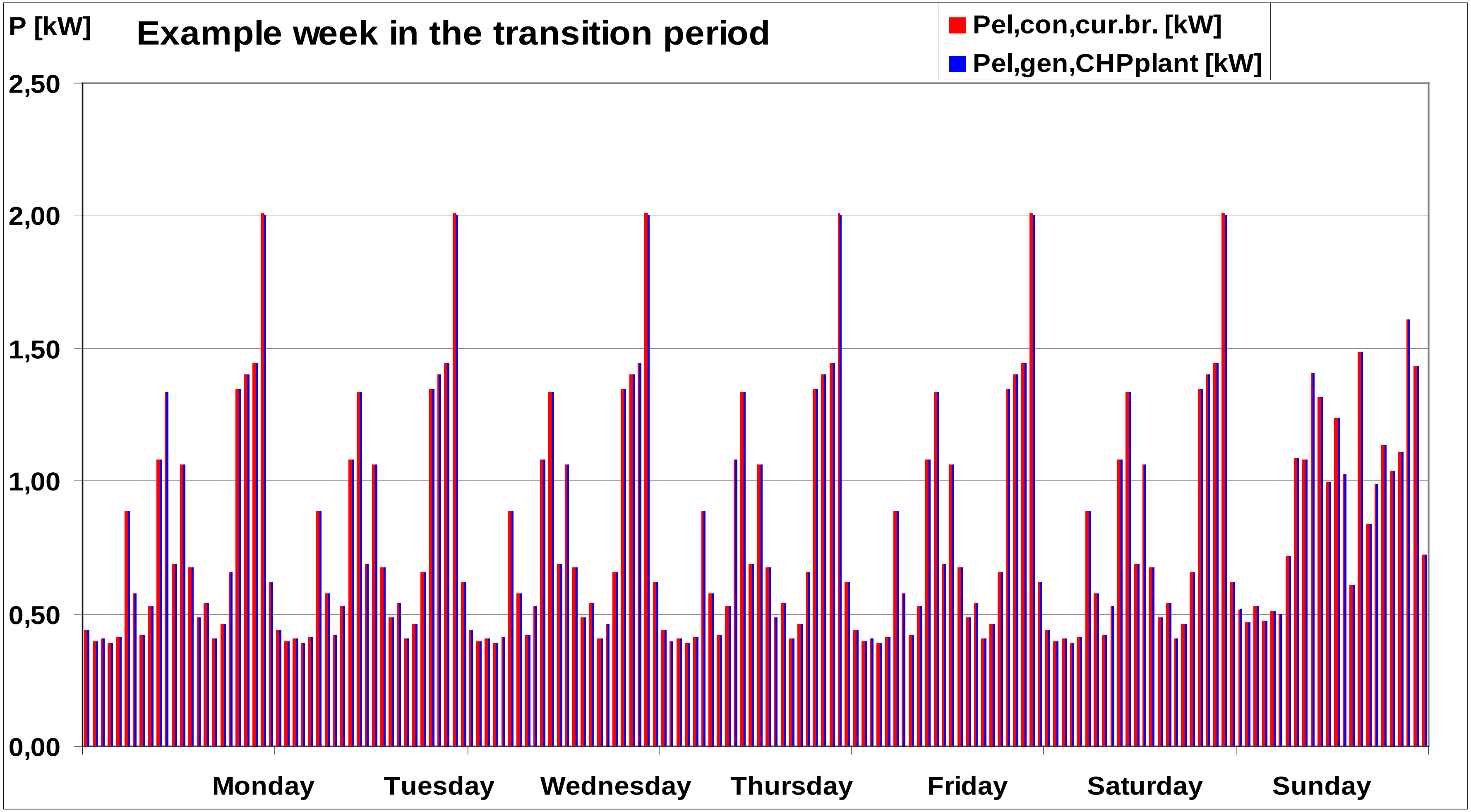


staxera:

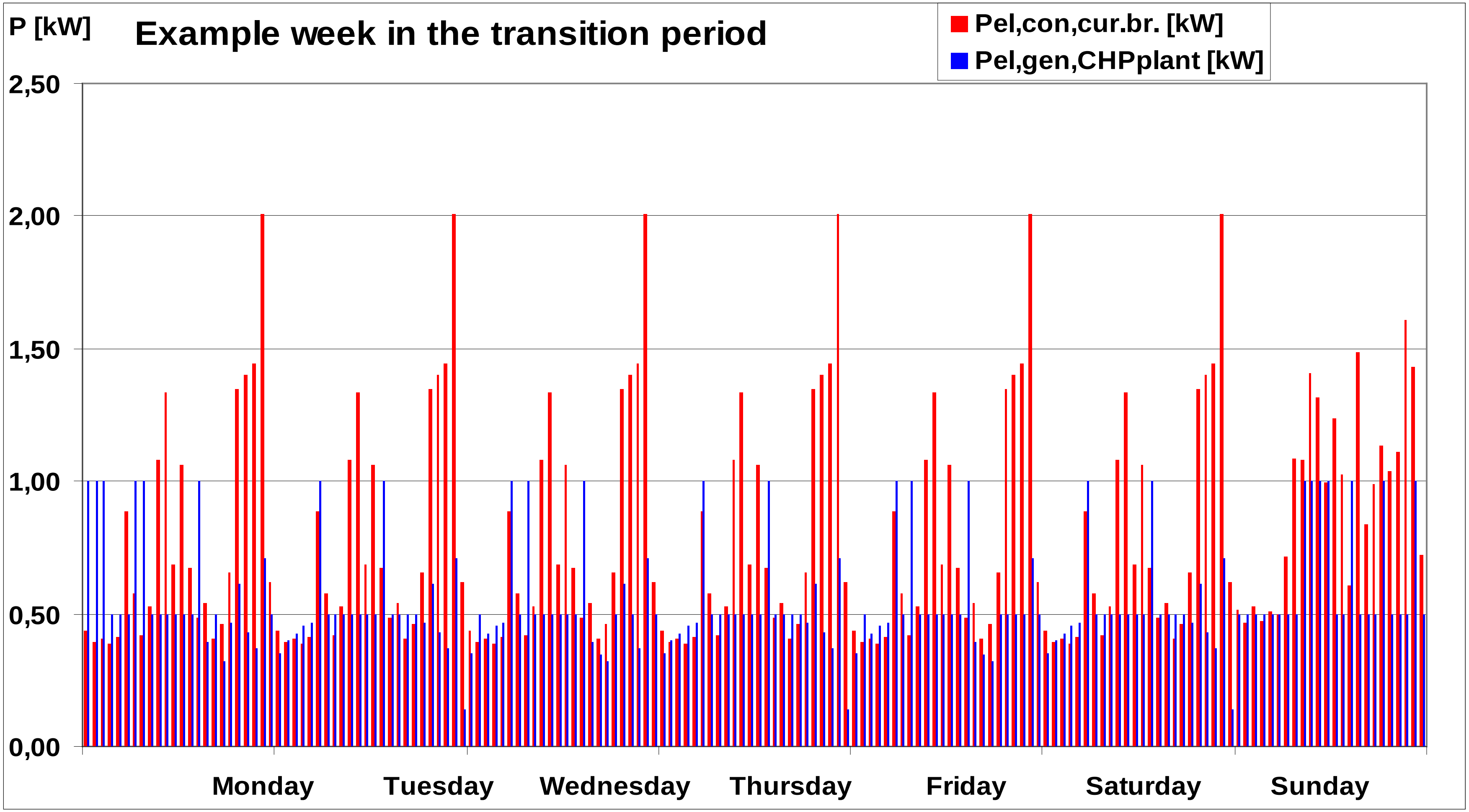
BlueGen: Electrical Demand and Generation (heat driven)



BlueGen: Electrical Demand and Generation (electricity driven)



Galileo 1000 N: Electrical Demand and Generation (heat driven)



Overall yearly savings

Operation mode	Opera-tion in summer period	German CHP funding	Annual saving potential in €
Heat driven	Enabled	Enabled	1267
		Disabled	501
	Disabled	Enabled	1072
		Disabled	403
Electricity driven	Enabled	Enabled	1202
		Disabled	866
	Disabled	Enabled	1009
		Disabled	729

CFCL - BlueGen

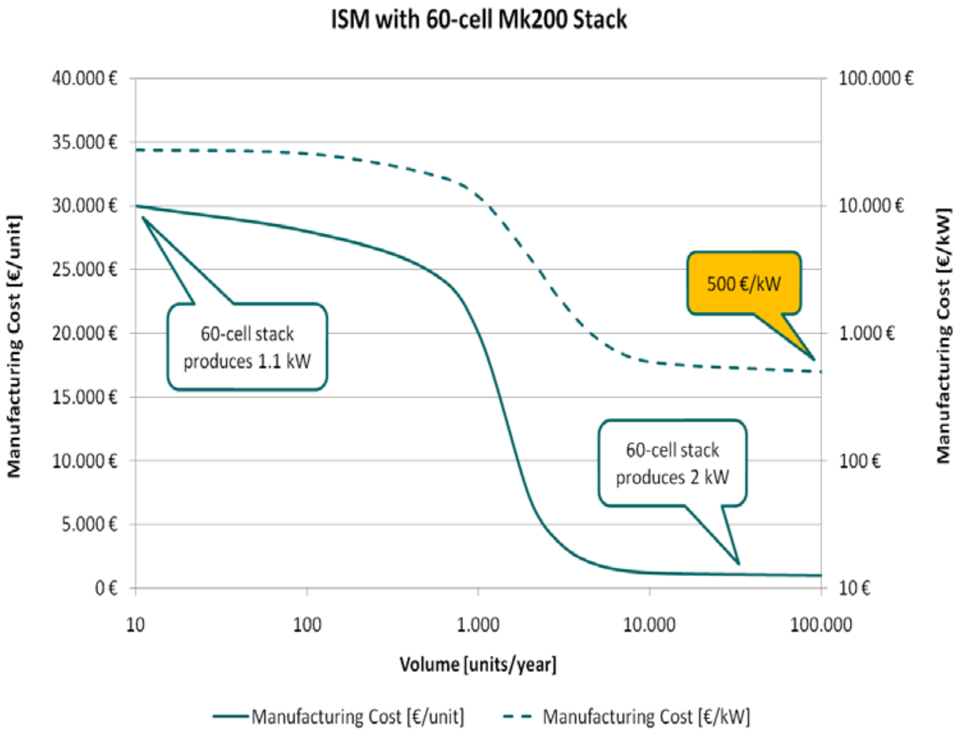
Operation mode	Opera-tion in summer period	German CHP funding	Annual saving potential in €
Heat driven	Enabled	Enabled	830
		Disabled	569
	Disabled	Enabled	788
		Disabled	539

Hexis – Galileo 1000 N

Cost reduction options of SOFC systems

Option for cost reductions

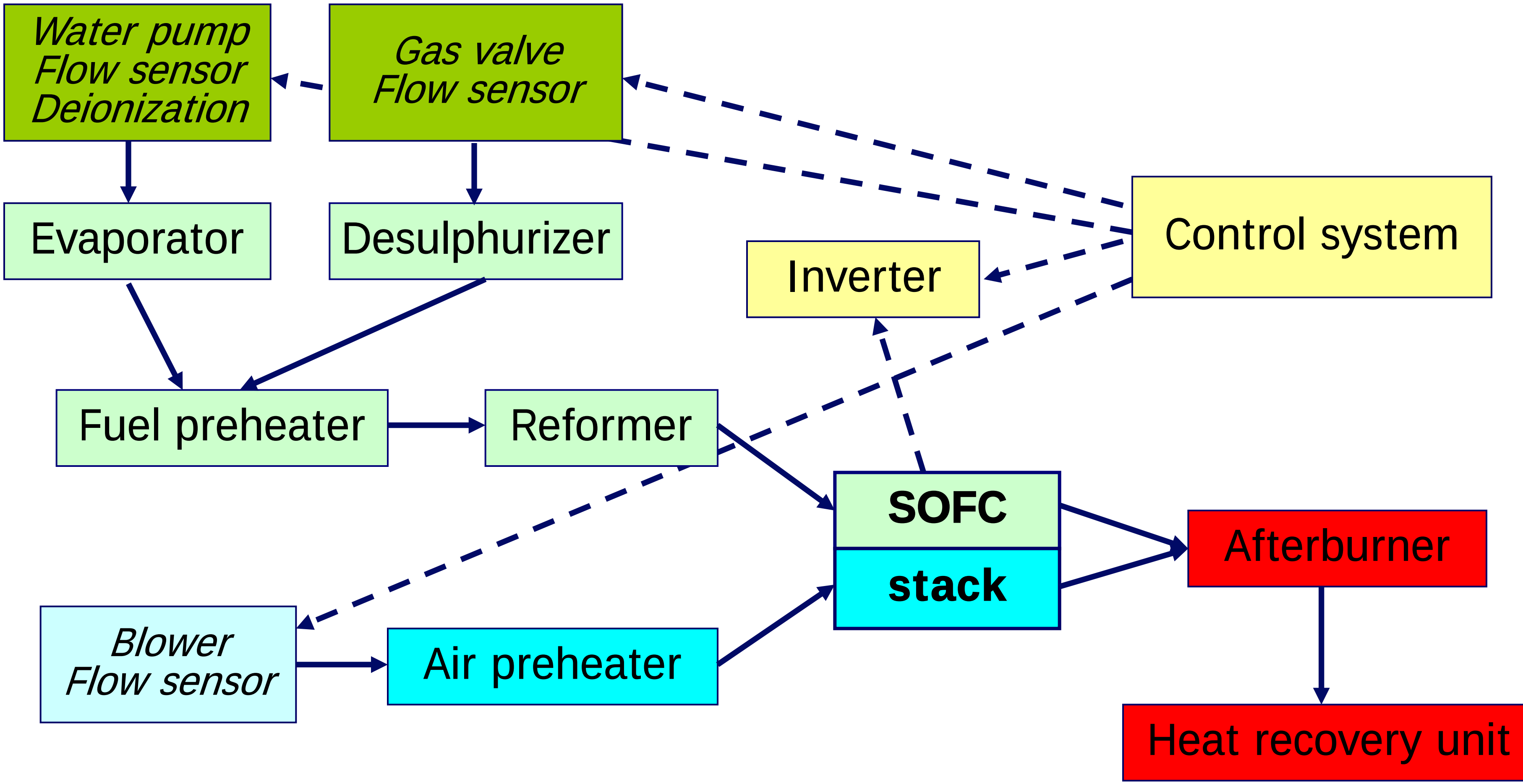
- Low number of components
- Minimize components sizes, apply cheaper materials
- Simple control algorithms
- Mass manufacturing of components
- Integration of standard components from heating or automotive industry



Cost reduction curve for Staxera's stacks and stack & stack modules (data 2009)

Balance of Plant components

Typical SOFC system



BoP requirements

- Safe operation
- High stability, low drift
- Certification where applicable
- Long life-time (> 40,000-60,000 h)
- No harming of downstream components
  - Anode poisoning with sulfur
  - Anode coking
  - Cathode poisoning with chromium

Hot BoP

- Reforming unit
- Heat exchangers / evaporator
- Start-up and afterburner

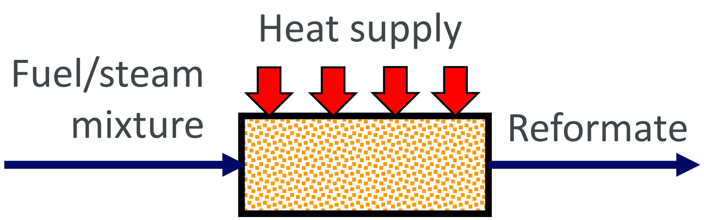
Cold BoP

- Blowers, pumps
- Sensors (temperature, pressure, flame detection, gas concentration, flow)
- Gas and water valves
- Desulphurization
- Control & safety electronics
- Power electronics

Reformer

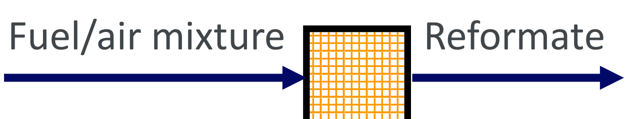
Steam reforming (SR)

- Endothermic reaction → heat supply
- GHSV = 5,000…10,000 h^{-1}
- Catalyst volume mostly larger due to heat transfer requirement
- Catalyst used as pellets, coated heat exchanger plates or coated meshes



Catalytic partial oxidation (CPOX)

- Exothermic reaction
- GHSV = 50,000…100,000 h^{-1}
- Mostly monoliths used



Reactor dimensioning – "gas hourly space velocity (GHSV)"

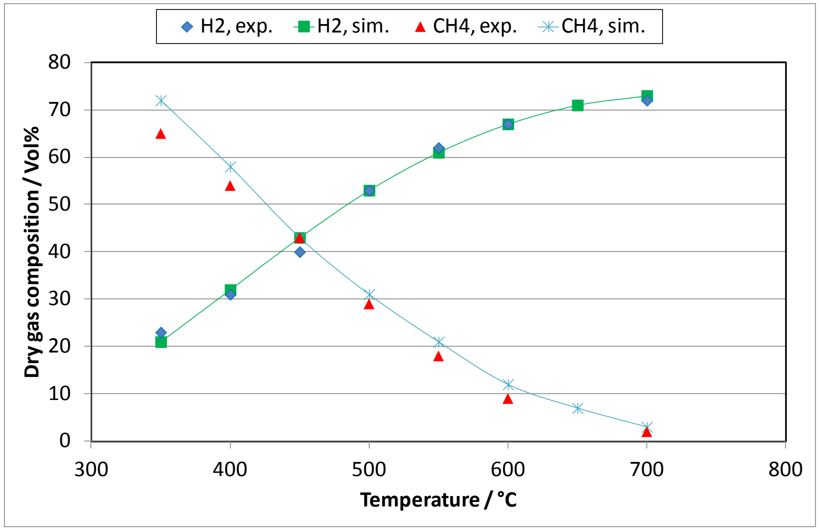
$$GHSV = \frac{\dot{V}^{N}_{total}}{V_{catalyst}}$$

Source: Behr

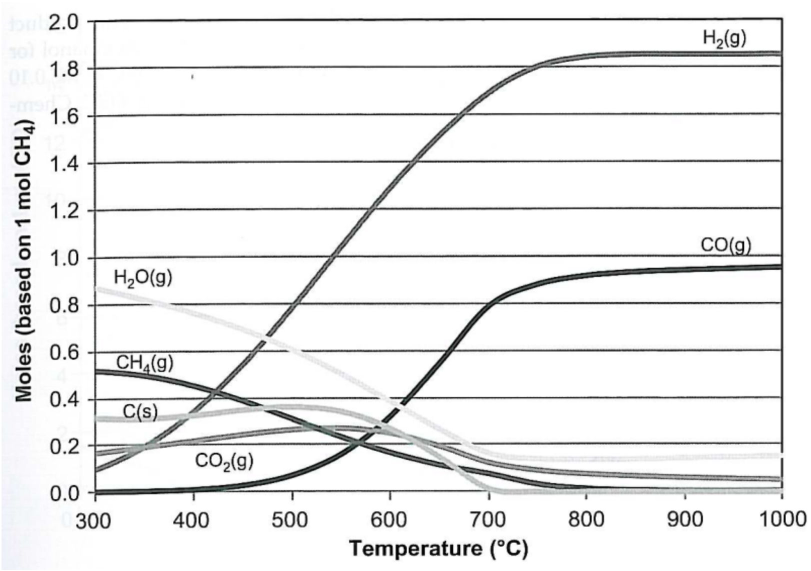
Catalysts

- Nickel/copper (low costs) or noble metal Pt, Pl, Rh (stability, oxidizing atmosphere)
- Sulphur tolerance only useful if stack does not degrade due to sulphur
- Operation at low S/C or O/C ratios increases system efficiency
- Selective cracking of higher hydrocarbons preferred for steam (pre-) reforming

Typical reformate compositions



Hydrogen and methane content versus temperature for stream reforming reaction of methane (S/C=2.0)



Reformate composition versus temperature after CPOX reaction of methane (O/C=1.2)

Heat exchanger applications

- Preheating of gases for fuel processing:
  - Gas preheater / CPOx air preheater
  - Reformer heat exchanger
  - Cathode air heater
- Evaporator for steam supply
- Cooling down of exhaust (off-) gases
- Condensator for water recovery

Gas cooler

Gas/gas heat exchanger

Requirements

Challenges

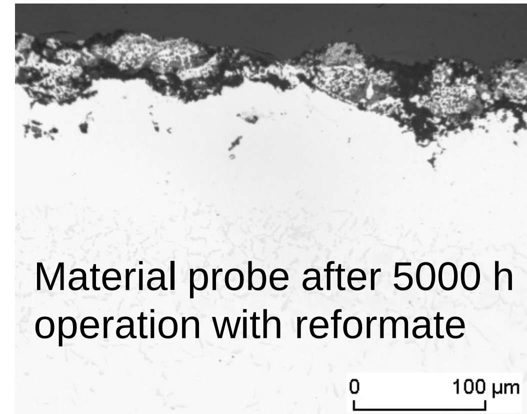
- High thermal stresses due to temperature differences
- Compact heat exchangers with low thermal losses
- Integration in hot areas of system

Pressure losses to be minimized

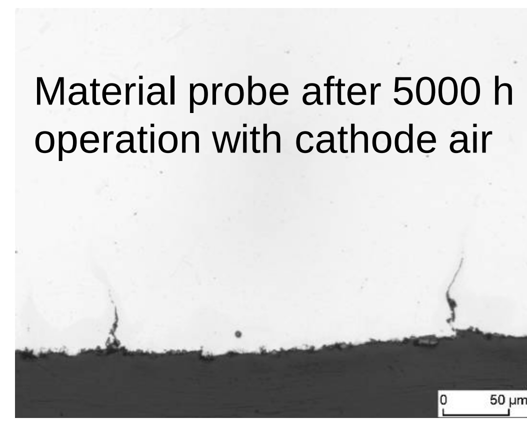
- Power demand of blowers decreases, system efficiency increases
- SOFC stacks not gas tight → reduce differential pressure

Materials

- Materials have to withstand up to 850°C (anode off-gas) / 1000°C (afterburner)
- Usage of high-grade alloys/stainless steels or ceramics
- Corrosion and chromium evaporation needs attention



Material probe after 5000 h operation with reformate



Material probe after 5000 h operation with cathode air

Burners in SOFC systems

Application

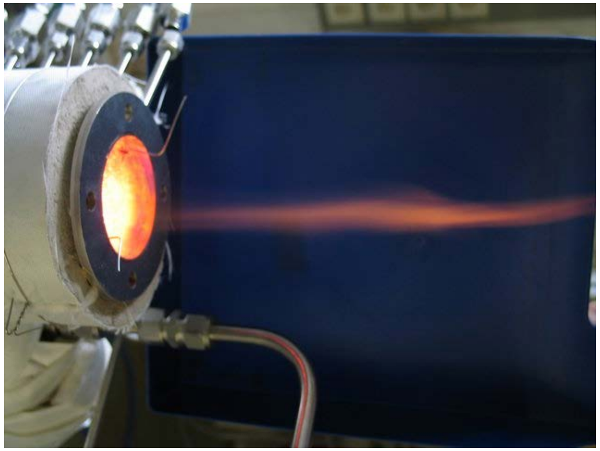
- Provision of heat for the system start-up
- Afterburning of anode off-gases
- Auxiliary or peak load burner

Demands

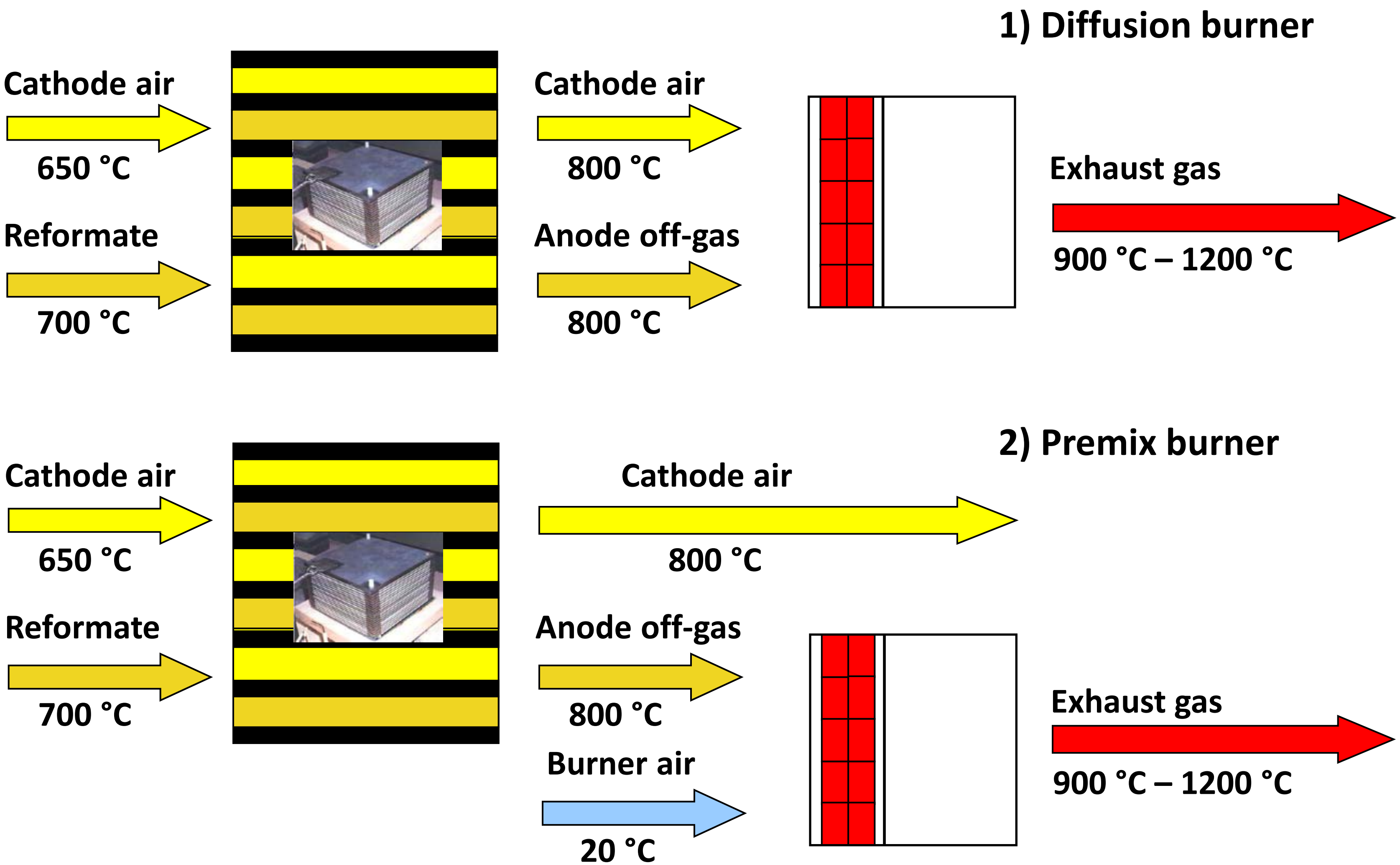
- High modulation range (flow rates, amount of combustibles)
- Afterburning of low and high calorific gases
- Long lifetime
- Safe operation (flame detection!)

Burner types

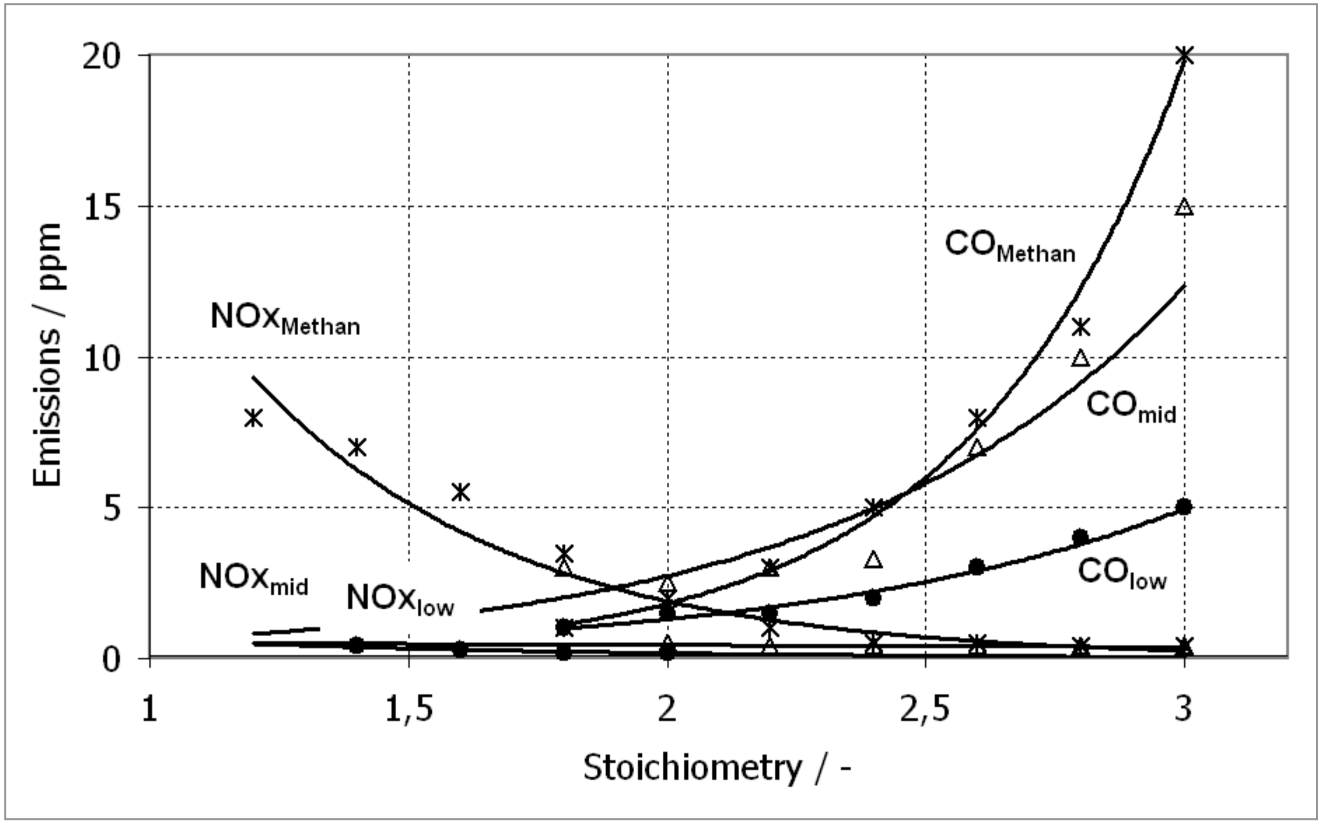
- Catalytic or volumetric (porous media, FLOX burner, …)



Anode off-gas afterburner



Emissions porous media burner



- EN 62282: CO < 615 mg/kWh (300 ppm) in case of malfunction
- ‘Blue Angel’ (German emissions label): 50 mg/kWh CO / 60 mg/kWh NO_x

Blowers

Blower applications

- Supply of air to the cathode, gas/air to the anode, suction of exhaust gas and anode off-gas recirculation
- Side channel blowers or centrifugal blowers used

Requirements

- Air blower is the main consumer of electricity
  → Considerable impact on overall electrical efficiency
- Several 10,000 hours of continuous operation
- Pressure losses and design point have to be known for blower specification

Typical efficiencies

- 60 … 80 %	large blowers
- 50 … 60 %	middle sized blowers
- 30 … 50 %	small blowers
- 25 … 30 %	side channel blowers

Anode off-gas recirculation

Objectives

- Water supply (recovery) for steam reforming process → reduction of operation costs
- Increase of system efficiency due to higher overall fuel utilization

Challenges

- Temperatures up to 800 °C
- Hydrogen leakages
- Reliable measurement of recirculation rates → soot formation
- Safety (certification) and reliability

Variants

- T_{Blower} = 600 ... 800 °C
- Gas/gas heat exchanger → T_{Blower} < 200 °C

Source: R&D Dynamics Cooperation

Suppliers

- R&D Dynamics (USA)
- Cap Co (Japan)

→ Prototypes ca. US-$ 50 T

→ Long-term stability open

Desulphurizer

- TBM / H_2S / COS easy to remove
- THT causes higher costs
- DMS (Japan/UK) difficult
- DBT in liquid fuels very challenging
- Co-adsorption of benzene needs attention → toxic waste
- ZnO with highest sorption capacity, but integration more difficult

Active component	***Operation temperature***
Active carbon	Ambient
Impregnated active carbon	Ambient
Zinc oxide	350-400 °C
Copper oxide	100-170 °C
Nickel, nickel oxide	Ambient
Molecular sieves	Ambient
Zeolite	Ambient

staxera:

Your Heart of Energy

Thank you for your attention