UNIVERSITA' degli STUDI di ROMA
TOR VERGATA

Facoltà di Ingegneria
Corso di laurea in Engineering Sciences
Thesis on applied Thermal Engineering

Energy Conversion Technologies for Biomass fuelled small-systems

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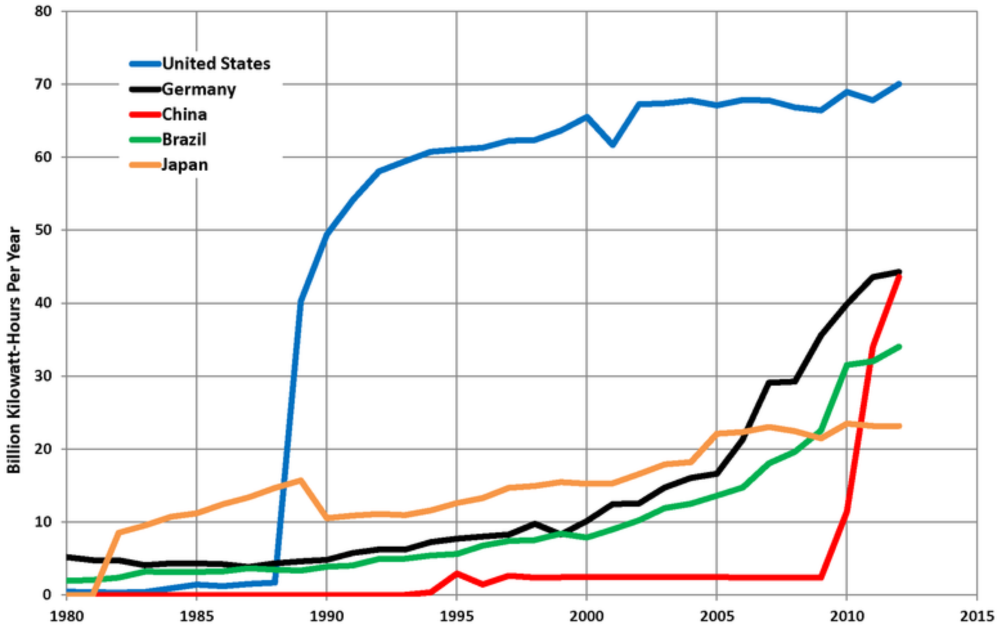
Biomass challenges

Biomass is one of the most significant options to generate electric power from distributed renewable sources.

Drivers to biomass energy solutions:

- CO_2 emissions
- Energy security
- Potentially reduced energy cost
- Fuel independency



How to attain biomass full potential?
size of a power plant up to 100 kW_{th} (small-scale CHP systems)

- fuel logistic chain
- transmission and distribution network

Obstacles in the small-scale CHP systems

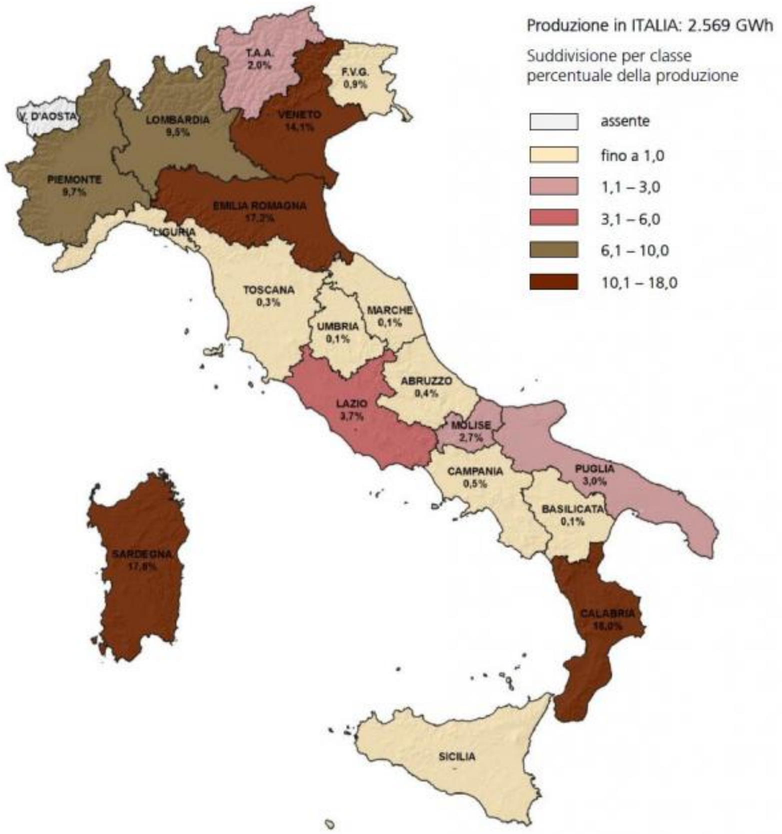
Despite of the successful commercial
operation of large/medium-scale system
The commercialization of the small-scale
systems is not yet reached

obstacles

1. High specific investment cost
2. Limited electrical efficiency
3. Technical data limited

solution

Simple structure



Biomass production by region

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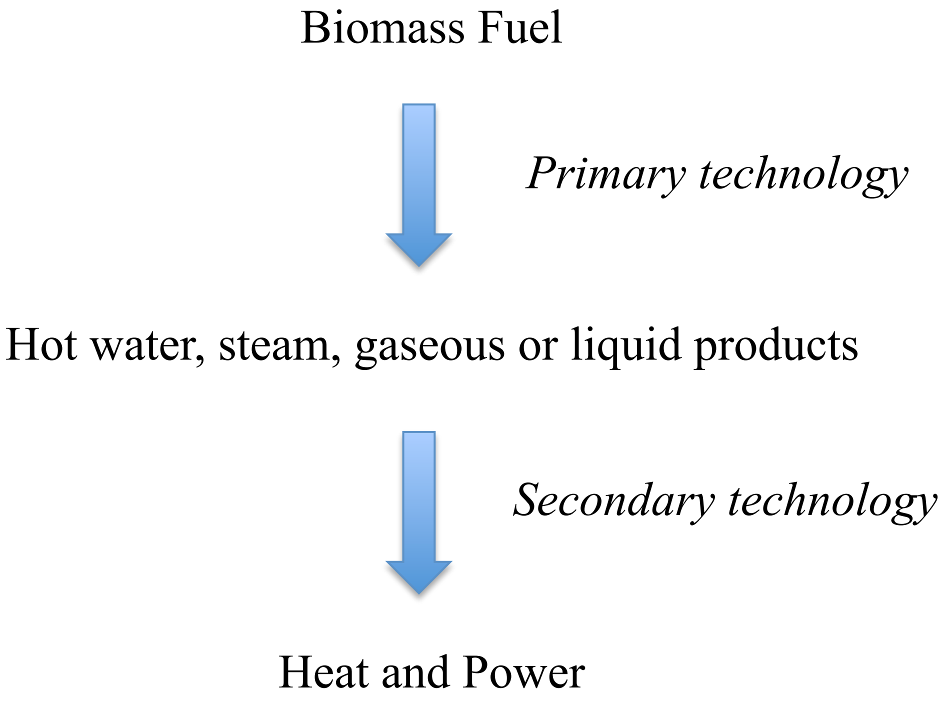
Processes:



Biomass Fuel

Primary technology

Hot water, steam, gaseous or liquid products

Secondary technology

Heat and Power

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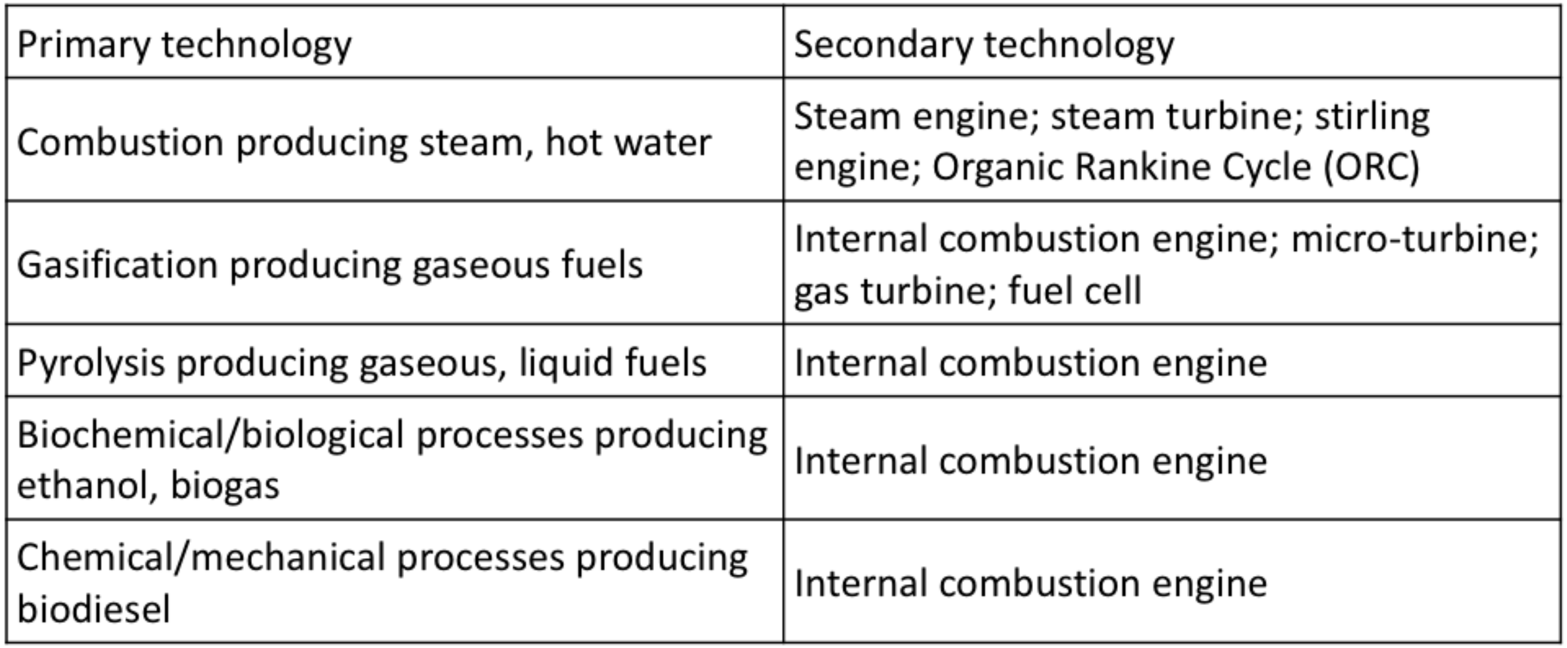
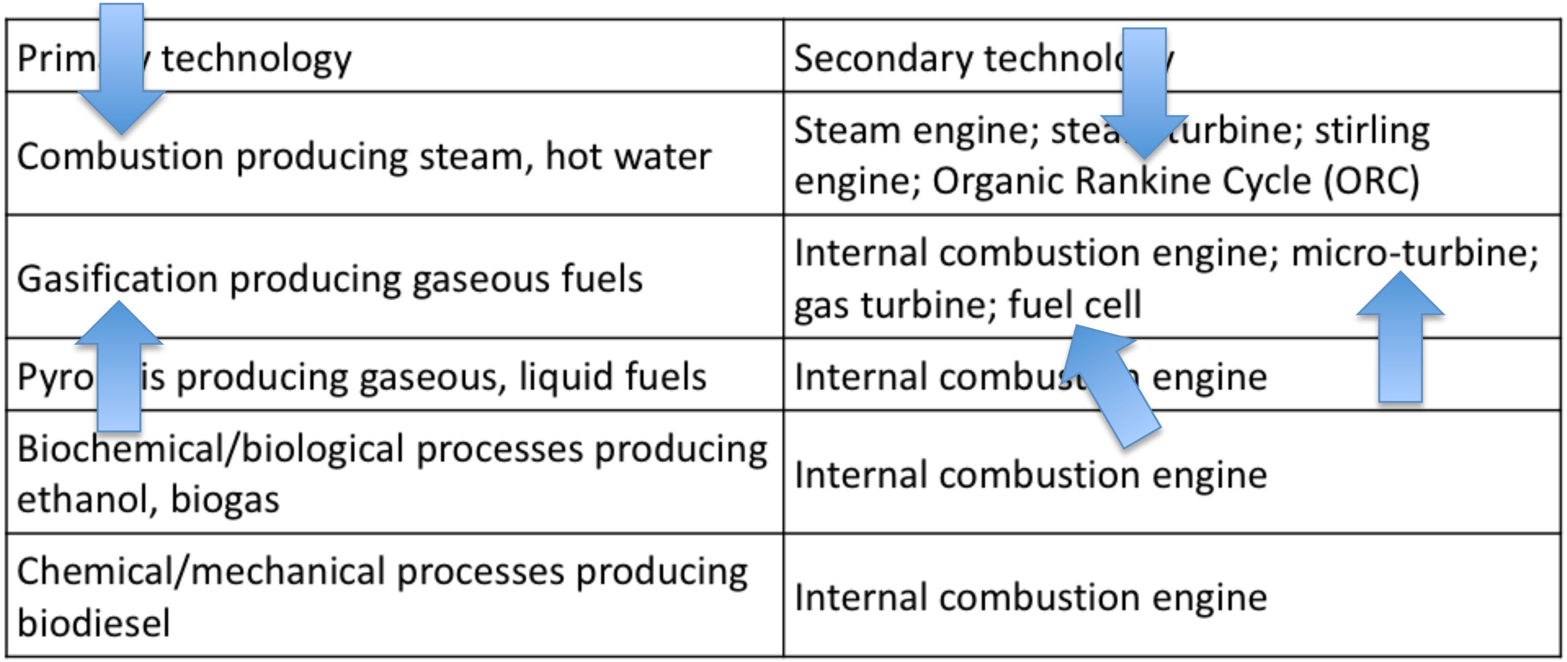
Technologies



Primary technology	Secondary technology
Combustion producing steam, hot water	Steam engine; steam turbine; stirling engine; Organic Rankine Cycle (ORC)
Gasification producing gaseous fuels	Internal combustion engine; micro-turbine; gas turbine; fuel cell
Pyrolysis producing gaseous, liquid fuels	Internal combustion engine
Biochemical/biological processes producing ethanol, biogas	Internal combustion engine
Chemical/mechanical processes producing biodiesel	Internal combustion engine

Technologies



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Micro-turbine technology can be combined also with direct combustion

Introduction: Combustion + Organic Rankine Cycle

Advanced power generation technology based on a water-vapour process similar method with the difference that instead of water an organic working fluid (silicone oil) is used.

Overview of the whole module of the biomass-fired ORC Plant

Two-stage axial turbine for the biomass-fired ORC process

Advantages and weaknesses

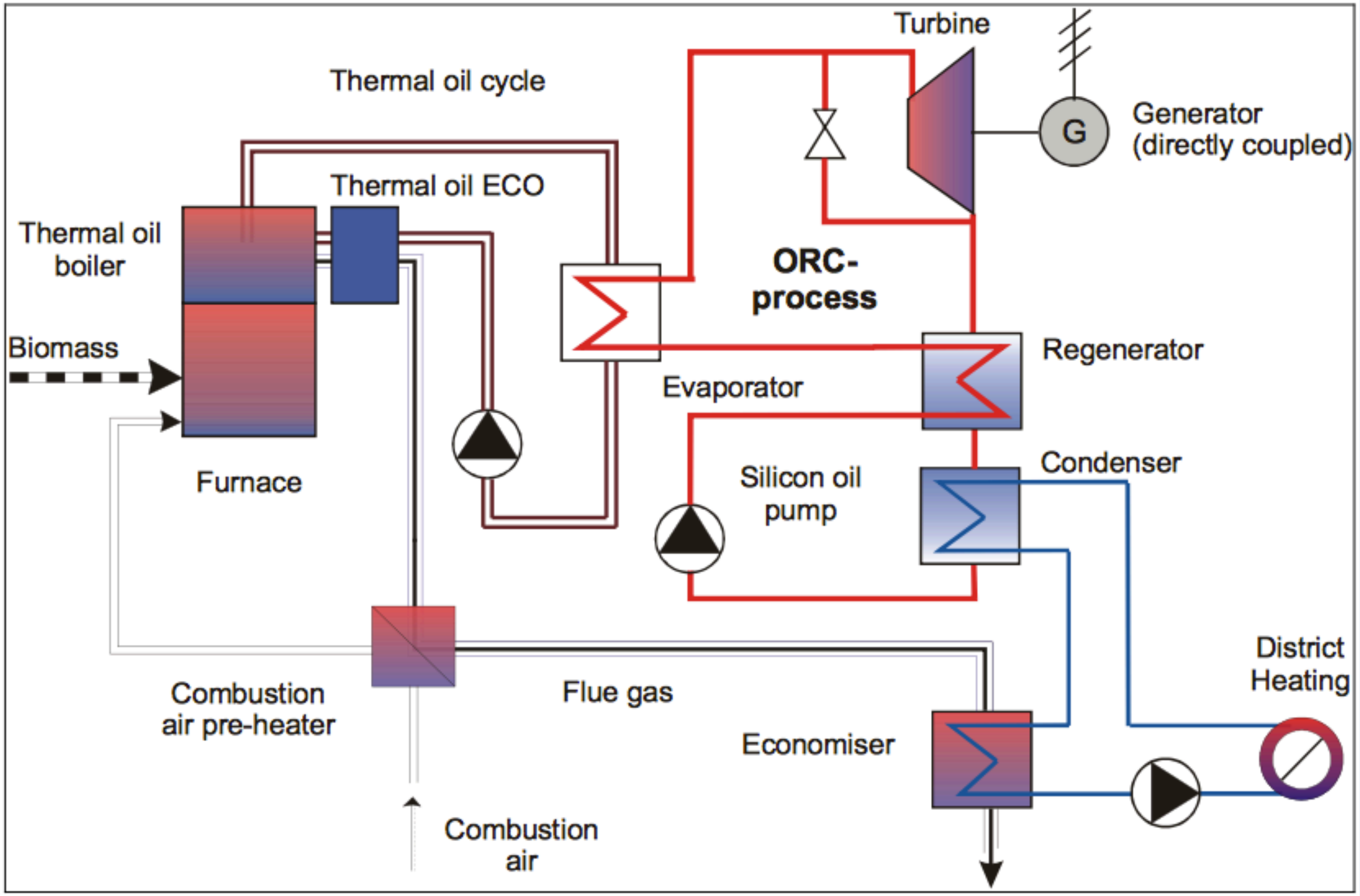
Advantages with respect to Steam Engine:

- Operating cost (controllability, automation, maintenance cost)
- Organic chemicals
  - lower temperatures
  - lower pressures
  - turbine cycle efficiency
  - turbine low mechanical stress
  - no erosion of the blades
- Efficiency
- Long operational life

Weaknesses: (which becomes more relevant decreasing the size of the plant)

- Electricity production
- Power-to-heat ratio
- High investment costs

ORC-based biomass-fuelled CHP systems



Working principle of the biomass-fired ORC process

Demonstration plants in Austria

In Austria were installed two plants for demonstration.
The key innovative components are:

- Silicon oil (400 kW_e Admont)
- Internal heat recovery system with combustion air preheater(1000 kW_e Lienz)

Biomass CHP plant based on an Organic Rankine Cyle process (Lienz, Austria)

Introduction: Externally Fired Gas Turbine (EFGT)

Aim of the study:

- Potential of the biomass fuelled conversion system based on a gas turbine coupled to a furnace
- Experimental results and a complete model of the power-plant with a simple quasi 2D approach
- Individual contribution of each component to the overall performance
- Sensitivity analysis of the output as function of the most significant operating parameters
- Cost Of electric Energy under different power-plant utilization scenarios

View of the EFGT power-plant installed at the University of Rome Tor Vergata

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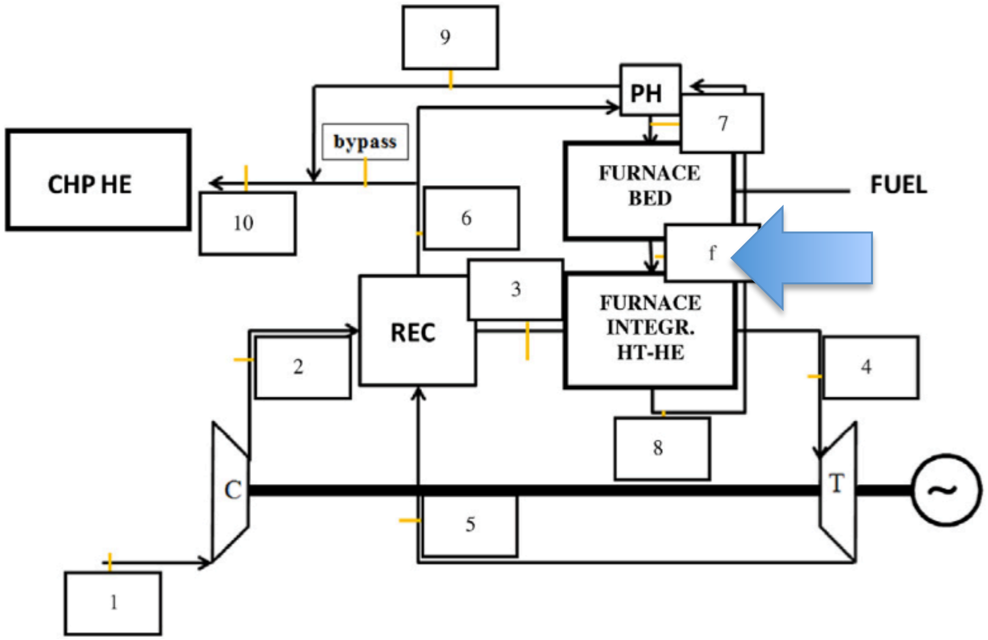
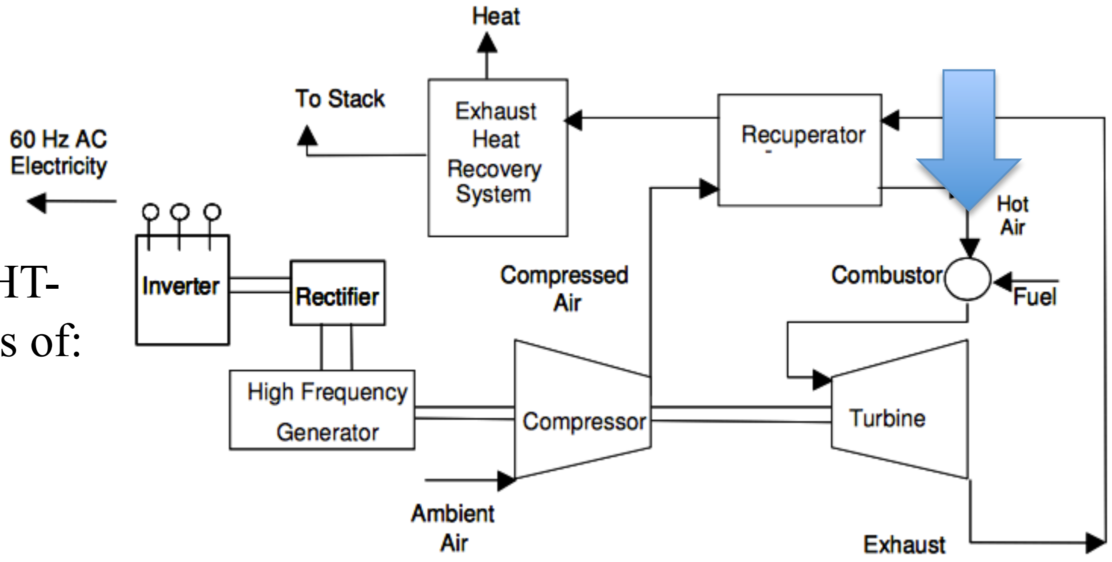
IFGT-EFGT



EFGT prototype is a modification of the baseline micro-turbine in its internal combustion configuration by REPLACING the natural gas combustor with an external heat exchanger integrated within the biomass furnace



Biomass furnace and HT-HE are critical in terms of:

- Performance
- Reliability
- Cost

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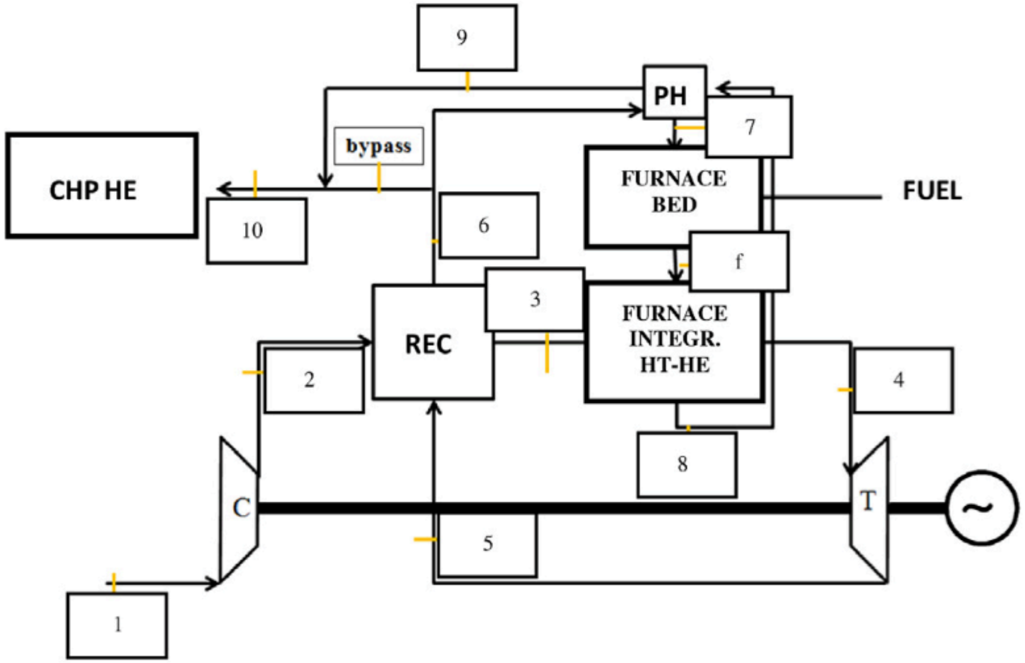
Power plant layout and experimental setup



1. Advantages and disadvantages of coupling the furnace with the HT-HE

2. Components:
    - Recuperator (REC)
    - Turbine
    - Pre-Heater (PH)
    - By pass
    - Combined Heat and Power Heat Exchanger (CHP-HE)

Modelling details: Simulation model

- Simulation model to compute both power output and thermal efficiency at full load:

Conservation equations

$$\frac{m_{ex}}{\dot{m}_{ex}}\frac{c_{pex}}{L}\frac{\Delta T_{ex}}{\Delta t} + c_{pex}\frac{\Delta T_{ex}}{\Delta t} = -\frac{\alpha_{\mathrm{ex}}}{\dot{m}_{\mathrm{ex}}L}\left(T_{\mathrm{ex,b}} - T_{\mathrm{w}}\right) - \frac{\dot{Q}_{\mathrm{rad}}}{\Delta x\,\dot{m}_{\mathrm{ex}}} + \frac{\mathrm{LHV}}{1+\alpha}\frac{\Delta A}{A_{\mathrm{tot}}}\frac{1}{\Delta x}$$

$$m_w c_{pw}\frac{\Delta T_{\mathrm{w}}}{\Delta t} = \alpha_{\mathrm{ex}}A_{\mathrm{ex}}\left(T_{\mathrm{ex,b}} - T_{\mathrm{w}}\right) - \alpha_{\mathrm{a}}A_{\mathrm{a}}\left(T_{\mathrm{w}} - T_{\mathrm{a}}\right) + \dot{Q}_{\mathrm{rad}}\frac{L}{\Delta x}$$

$$m_a c_{pa}\frac{\Delta T_a}{\Delta t} + \dot{m}_a c_{pa} L\frac{\Delta T_a}{\Delta x} = \alpha_a A_a\left(T_w - T_a\right)$$

Mass and energy balances

$$\dot{m}_{\mathrm{ex,b}} = \dot{m}_{\mathrm{ex}}\frac{\Delta A}{A_{\mathrm{tot}}}$$

$$\dot{m}_{\mathrm{ex,b}}c_{\mathrm{pex}}T_{\mathrm{ex}} = \dot{m}_{\mathrm{b}}c_{\mathrm{pb}}T_{\mathrm{b}} + \dot{m}_{\mathrm{u}}c_{\mathrm{pu}}T_{\mathrm{u}}$$

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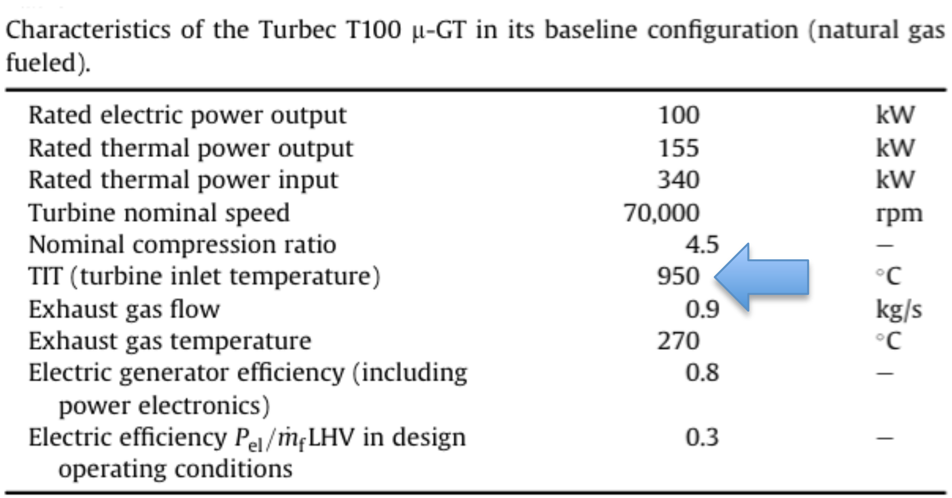
Discussion of results: Performance analysis



Characteristics of the Turbec T100 μ-GT in its baseline configuration (natural gas fueled).

Rated electric power output	100	kW
Rated thermal power output	155	kW
Rated thermal power input	340	kW
Turbine nominal speed	70,000	rpm
Nominal compression ratio	4.5	–
TIT (turbine inlet temperature)	950	°C
Exhaust gas flow	0.9	kg/s
Exhaust gas temperature	270	°C
Electric generator efficiency (including power electronics)	0.8	–
Electric efficiency $P_{el}/\dot{m}_f\mathrm{LHV}$ in design operating conditions	0.3	–

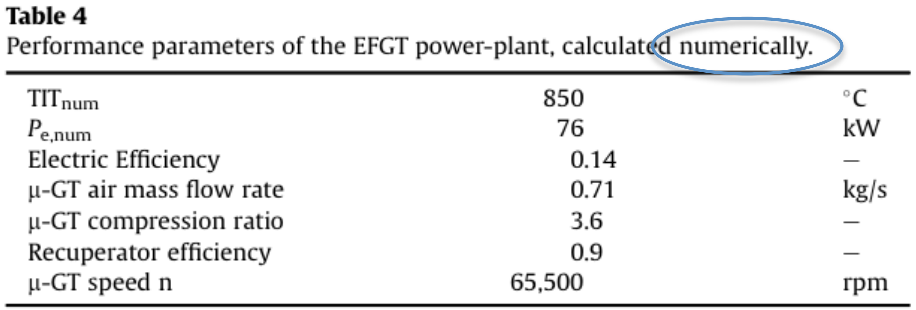


Table 4
Performance parameters of the EFGT power-plant, calculated numerically.

TIT_{num}	850	°C
$P_{e,num}$	76	kW
Electric Efficiency	0.14	–
μ-GT air mass flow rate	0.71	kg/s
μ-GT compression ratio	3.6	–
Recuperator efficiency	0.9	–
μ-GT speed n	65,500	rpm

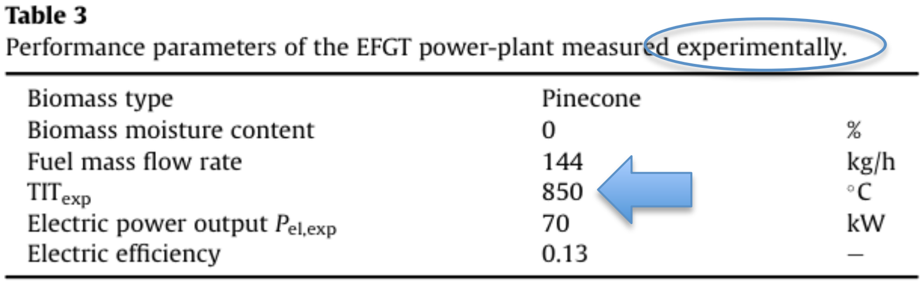


Table 3
Performance parameters of the EFGT power-plant measured experimentally.

Biomass type	Pinecone	
Biomass moisture content	0	%
Fuel mass flow rate	144	kg/h
TIT_{exp}	850	°C
Electric power output $P_{el,exp}$	70	kW
Electric efficiency	0.13	–

Power plant performance (dry pinecone):

$$P_{el,\ out} = 70\ \mathrm{kW}$$

$$\eta_{el} = P_{el}/\dot{m}_f\mathrm{LHV} = 13\%$$

Loss of performance due to TIT

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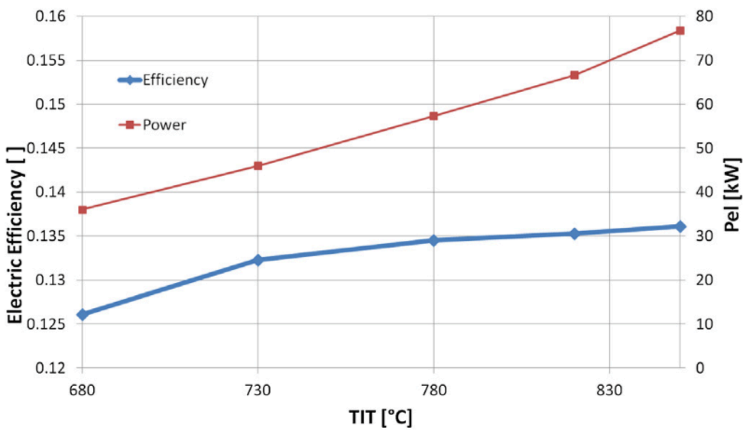
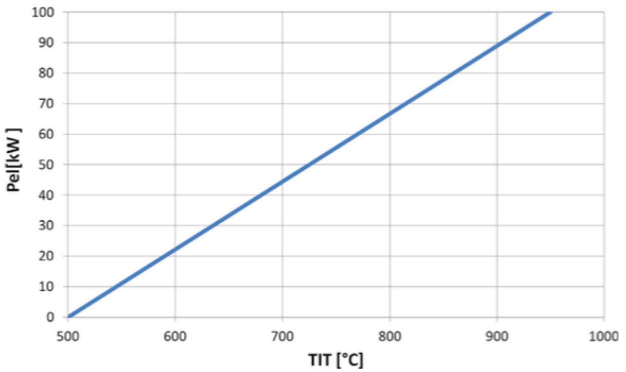
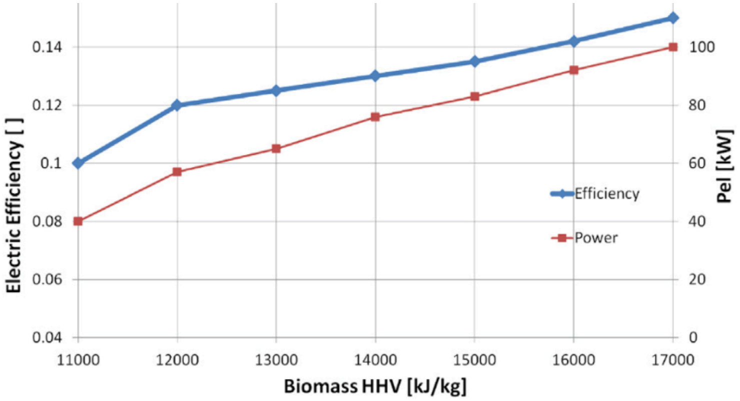
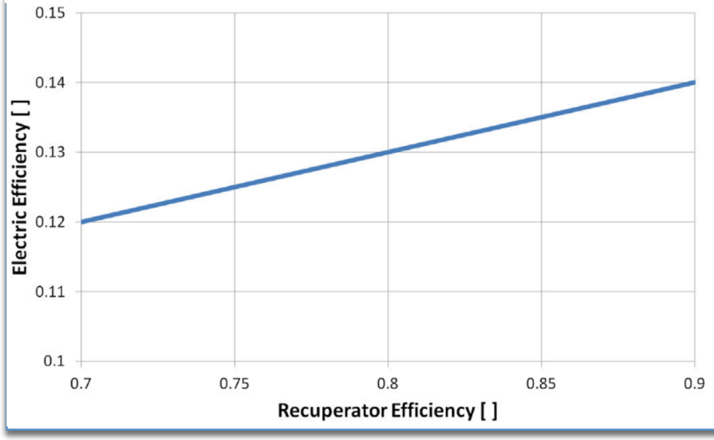
Discussion of results: Sensitivity analysis





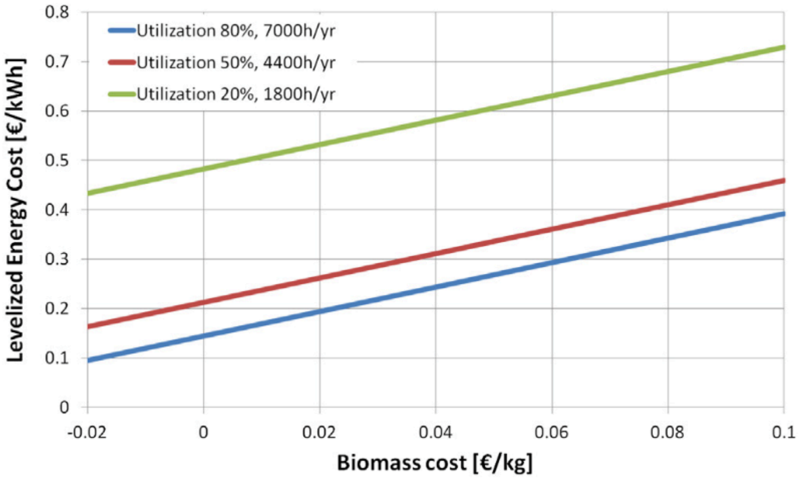




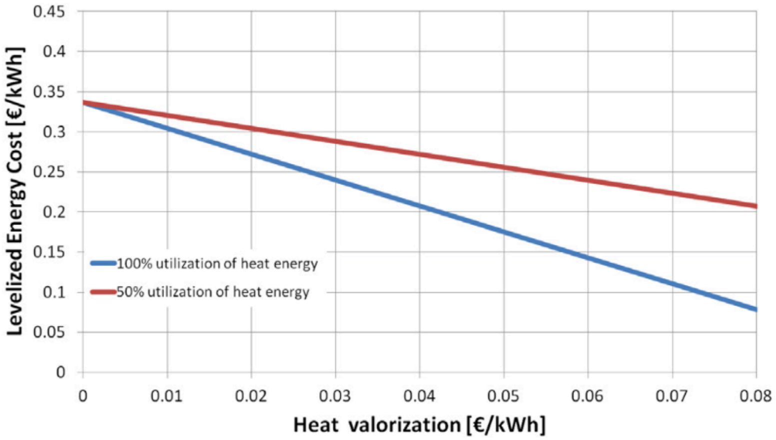
Influence of:
- Fuel Moisture Content
-Turbine Inlet Temperature
- Recuperator size
on electrical efficiency and output power

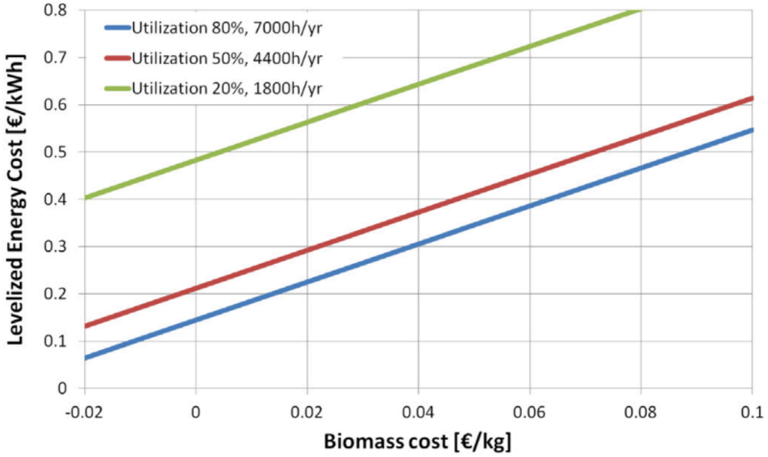
⇨ Behaviour at partial load: P_{out} and η_{el} as function of biomass HHV, TIT and REC

Discussion of results: Economic analysis



The analysis of the COE (levelised Cost Of Energy) demonstrates that both biomass costs and utilization (in terms of operating hours per year) have a high impact on feasibility.

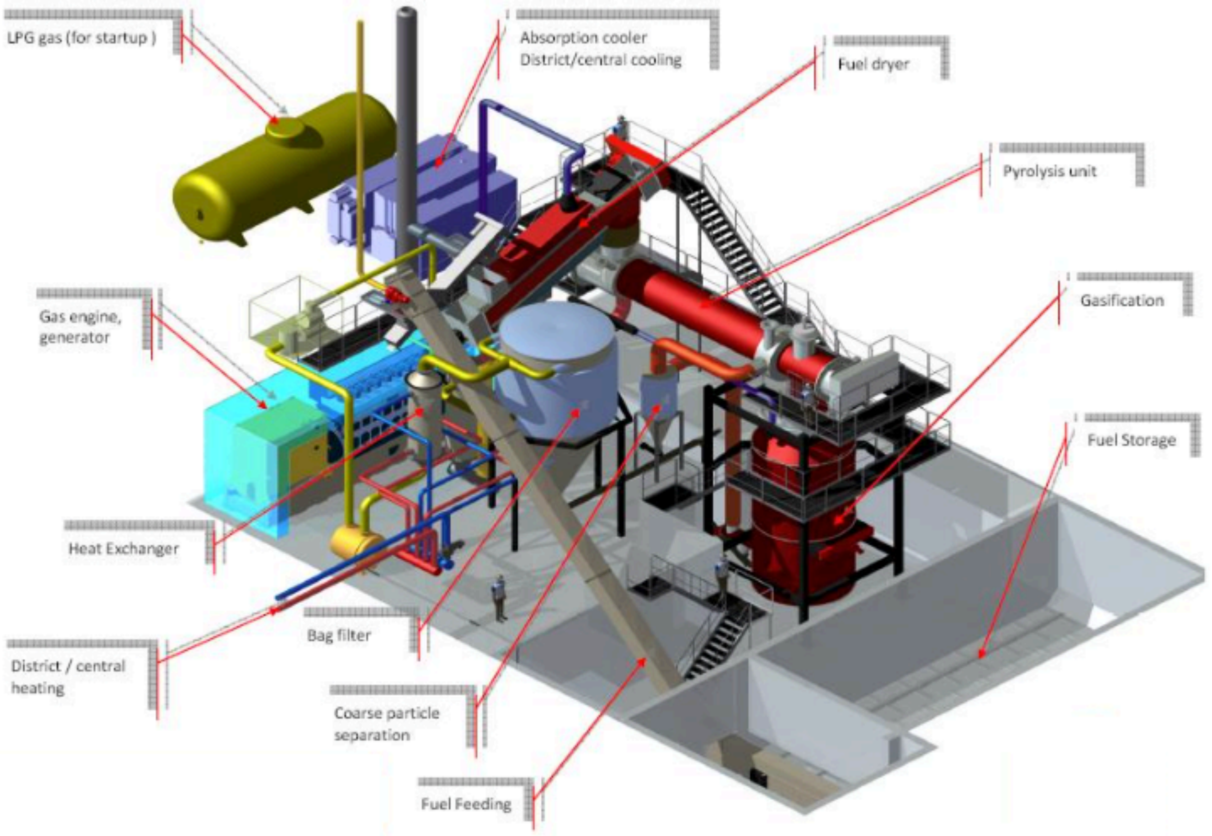




⇨ Valorisation of thermal energy for COE.

Introduction: Gasification + Solid Oxide Fuel Cells

Combination of two stage thermal biomass gasification and solid oxide fuel cells



The whole CHP plant combining two stage gasification and SOFCs modelled here is a modification of the 0.6 MW$_{th}$ demonstration plant where the power producing gas engine set up is REPLACED by a power producing SOFC setup.

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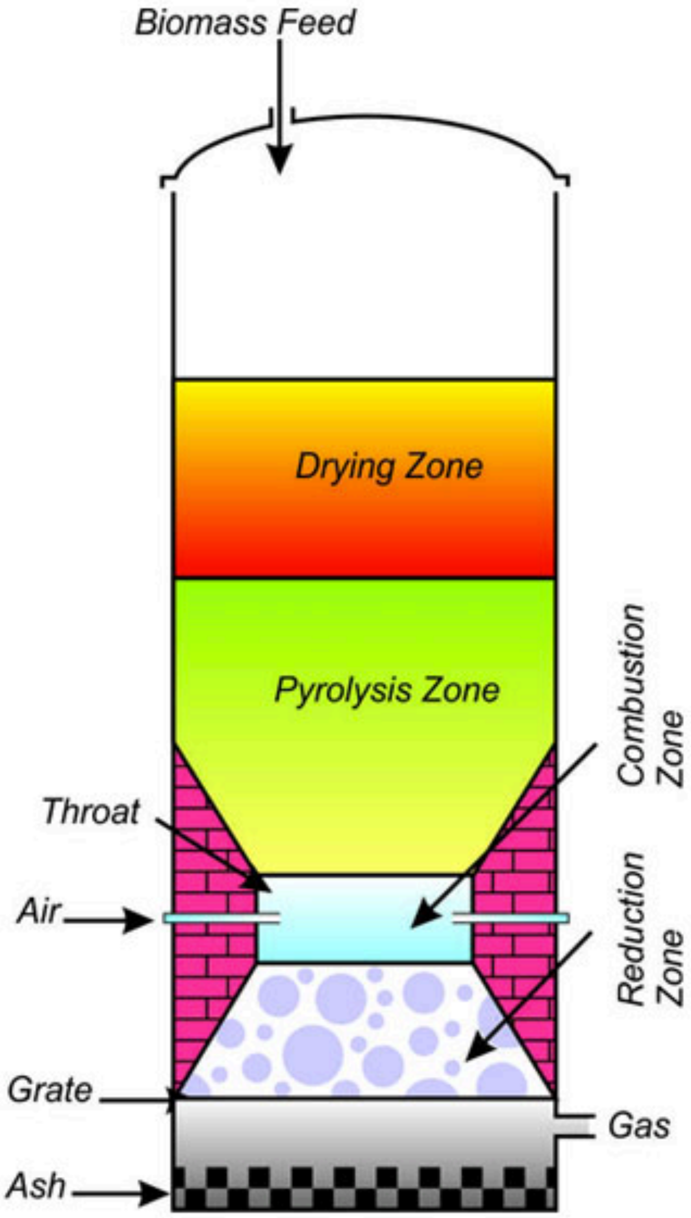
Gasification

Gasification is a thermal conversion technology where a solid fuel is converted into a combustible gas

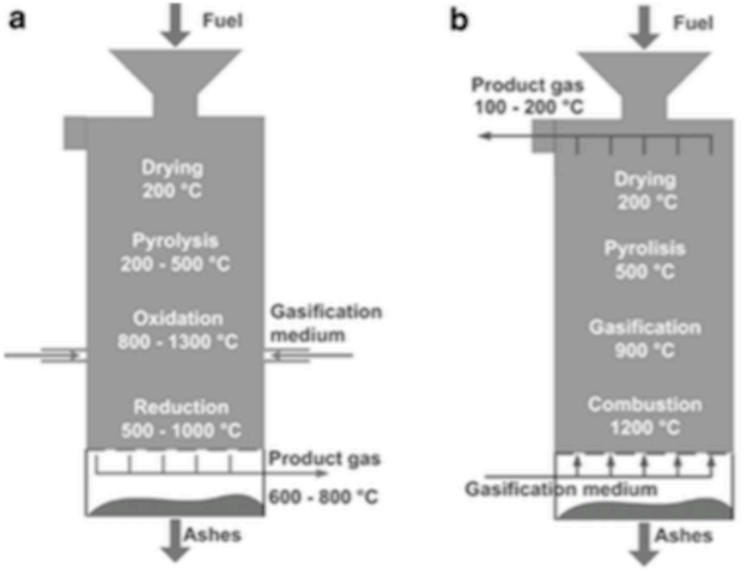
(CO, CO_2, H_2, CH_4, H_2O, N_2, ash, tars)

after proper cleaning and conditioning this gas can be used by boilers, internal combustion engine, fuel cell to produce heat and power.

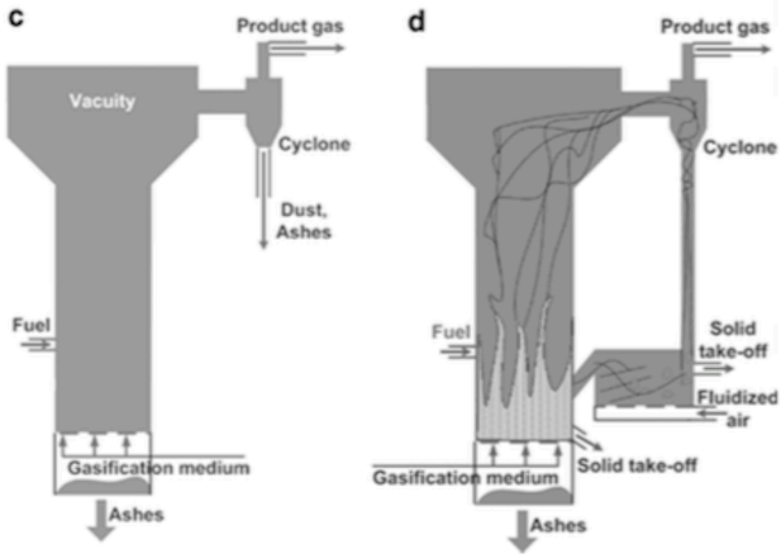


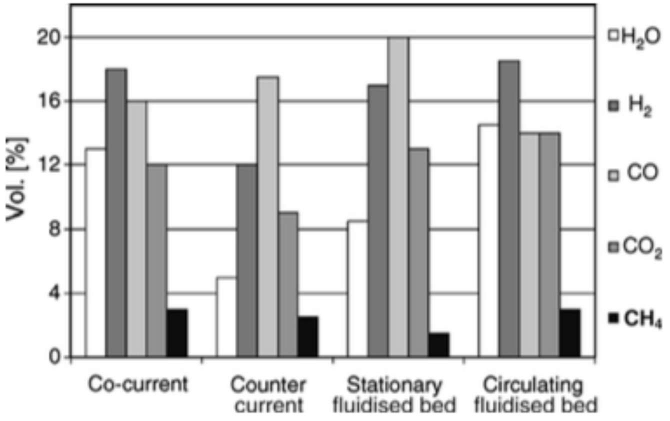
Types of gasifiers

Downdraft/co-current and Counter current/updraft



Fluidized bed





Composition of product gas
in selected gasifiers

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Advantages and weaknesses

Advantages with respect to direct combustion systems:

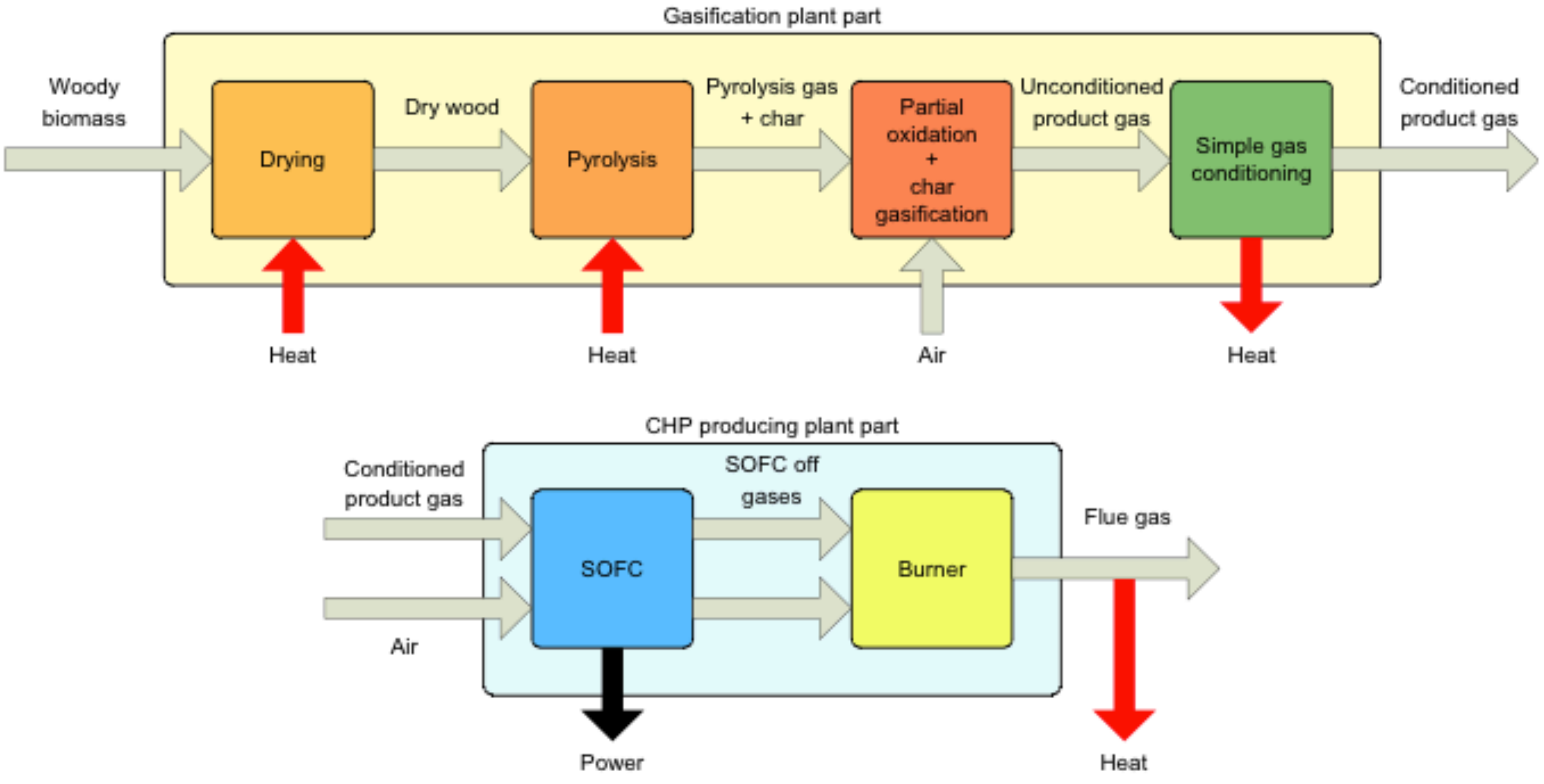
- Efficiency
- Automatic operations and controls (fully)
- No harmful emissions and liquid effluents

Weaknesses:

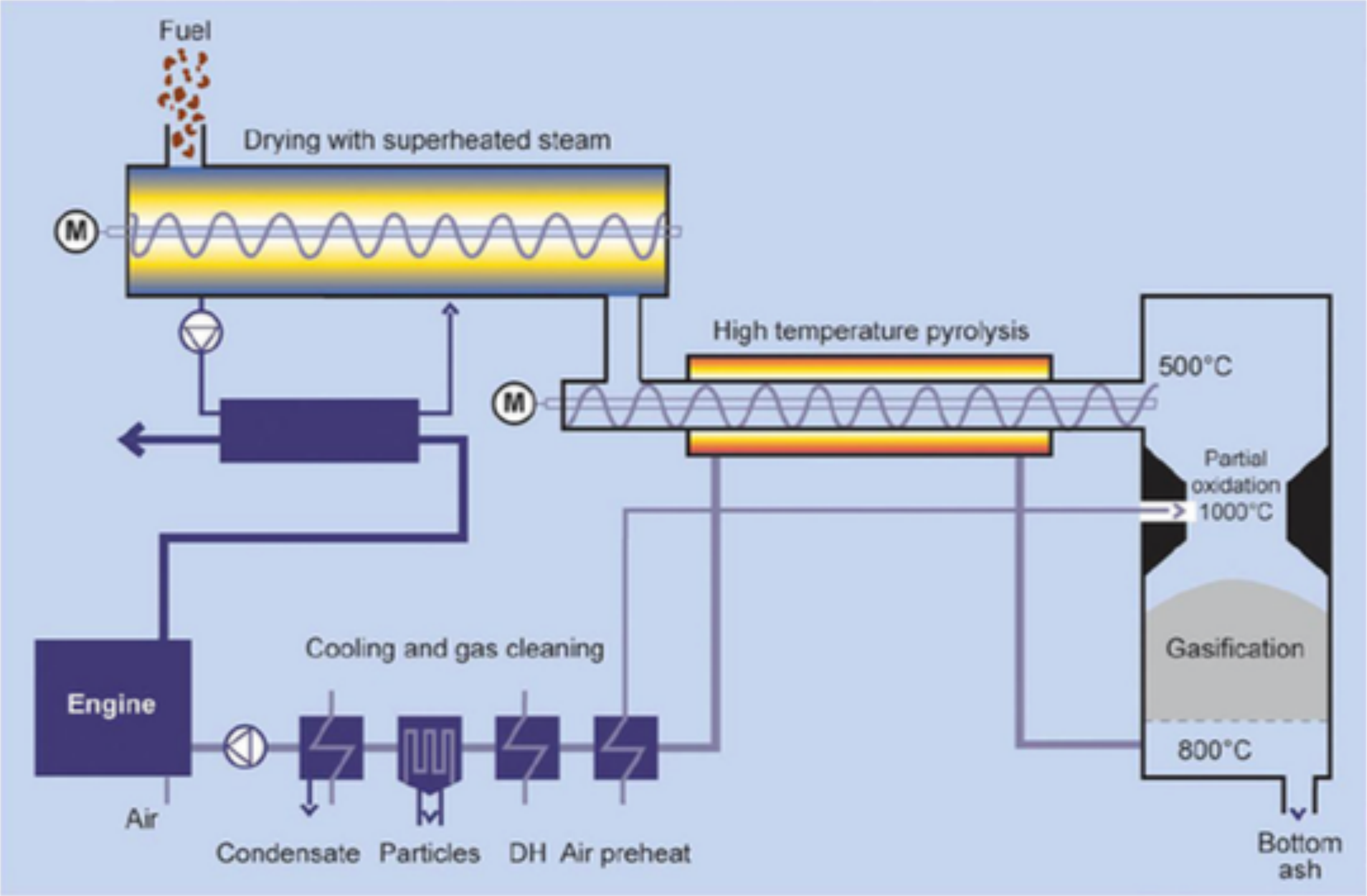
- Variation of parameters
- Tar contamination and unstable operation
- Automatic measurement and controls (rarely used)

Plant concept

The conditioning includes:
a cyclone, gas cooling, bag filter,
condensing gas cooler and a demister



The demonstrated 0.6 MW_{th} two-stage gasifier



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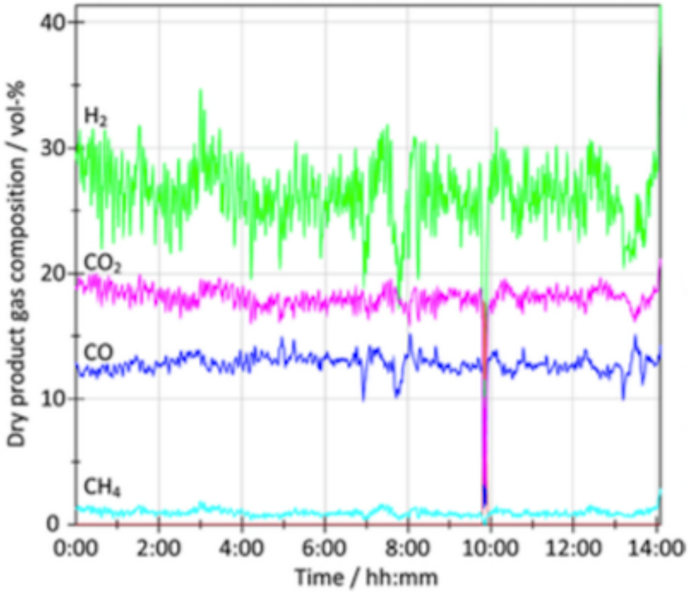
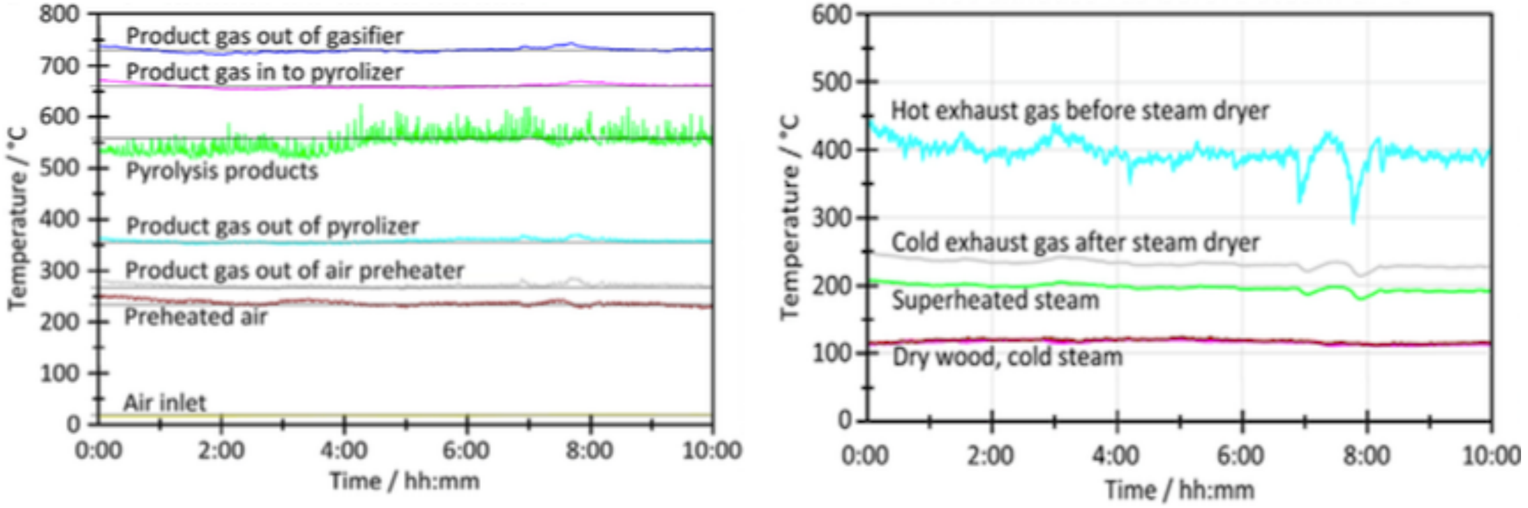
0.6 MW_{th} two-stage gasifier: Gas and Temperature



Measured dry product gas composition:
26% H_2
18% CO_2
13% CO
0.85% CH_4
42% N_2

Temperature level relevant to the pyrolysis and gasification and to the dryer



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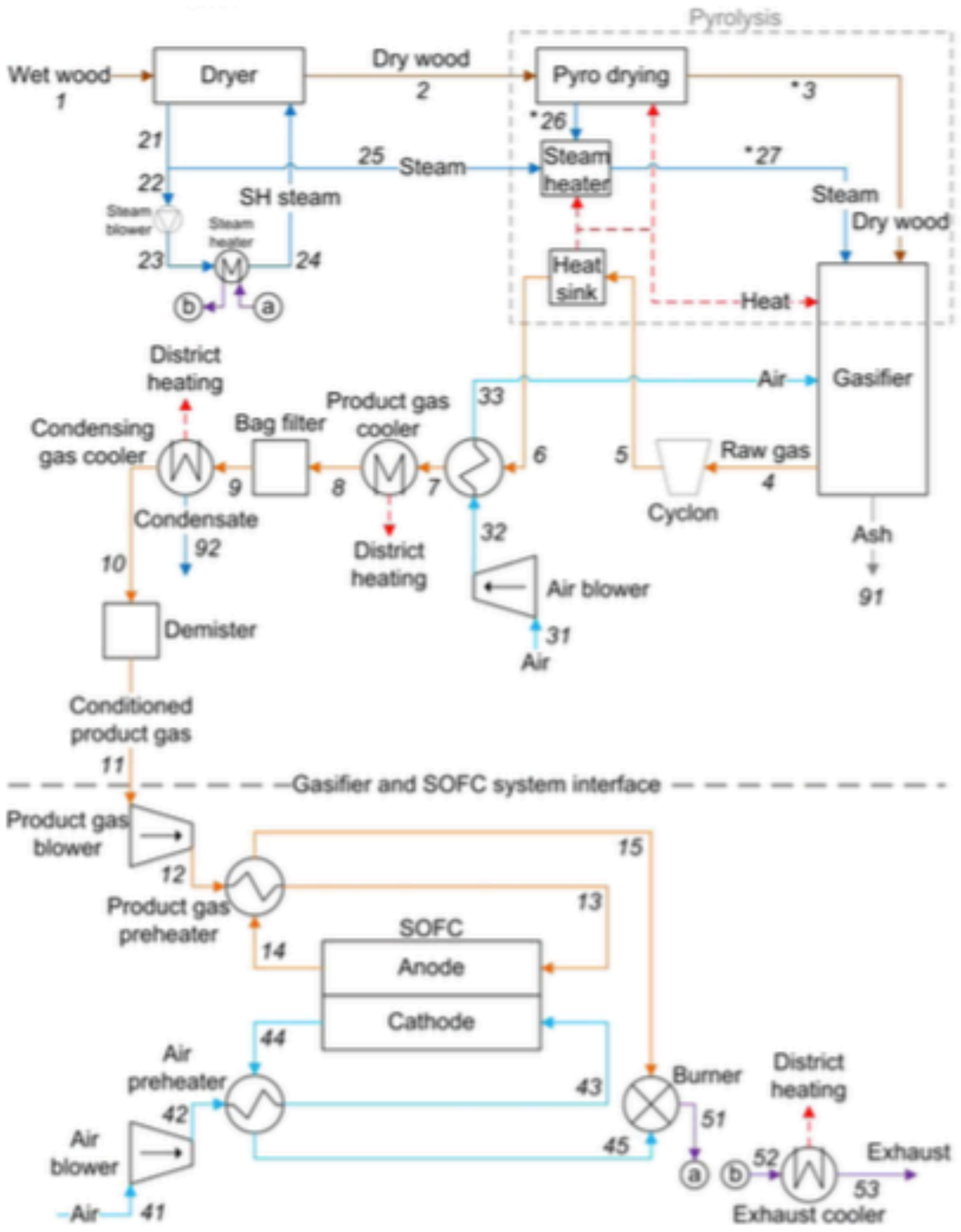
Plant model (3-10 MW_{th})



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Plant model: SOFC model

$$\eta_{\mathrm{SOFC}} = \eta_{\mathrm{rev}}\eta_{\mathrm{v}}U_{\mathrm{F}}$$

Fuel utilization factor is estimated

Reversible efficiency $\eta_{\mathrm{rev}} = \dfrac{\left(\Delta\bar{g}_{\mathrm{f}}\right)_{\mathrm{FO}}}{\left(\Delta\bar{h}_{\mathrm{f}}\right)_{\mathrm{FO}}}$

Voltage efficiency $\eta_{\mathrm{v}} = \dfrac{V_{\mathrm{cell}}}{E},$

$$V_{\mathrm{cell}} = E - V_{\mathrm{act}} - V_{\mathrm{ohm}} - V_{\mathrm{conc}}$$

Nernst potential $E = \dfrac{-\Delta\bar{g}_{\mathrm{f}}^{0}}{2F} + \dfrac{RT_{\mathrm{SOFC}}}{2F}\ln\left(\dfrac{\bar{p}_{\mathrm{H_2}}\sqrt{\bar{p}_{\mathrm{O_2}}}}{\bar{p}_{\mathrm{H_2O}}}\right)$

Activation overpotential $V_{\mathrm{act}} = \dfrac{2RT_{\mathrm{SOFC}}}{F}\left[\sinh^{-1}\left(\dfrac{i+i_{\mathrm{n}}}{2i_{0,\mathrm{a}}}\right) + \sinh^{-1}\left(\dfrac{i+i_{\mathrm{n}}}{2i_{0,\mathrm{c}}}\right)\right],$

$$i_{0,\mathrm{a}} = \gamma_{\mathrm{a}}\left(\frac{\bar{p}_{\mathrm{H_2}}}{\bar{p}_{\mathrm{a}}}\right)\left(\frac{\bar{p}_{\mathrm{H_2O}}}{\bar{p}_{\mathrm{a}}}\right)\exp\left(\frac{-E_{\mathrm{act,a}}}{RT_{\mathrm{SOFC}}}\right),$$

$$i_{0,\mathrm{c}} = \gamma_{\mathrm{c}}\left(\frac{\bar{p}_{\mathrm{O_2}}}{\bar{p}_{\mathrm{c}}}\right)^{0.25}\exp\left(\frac{-E_{\mathrm{act,c}}}{RT_{\mathrm{SOFC}}}\right)$$

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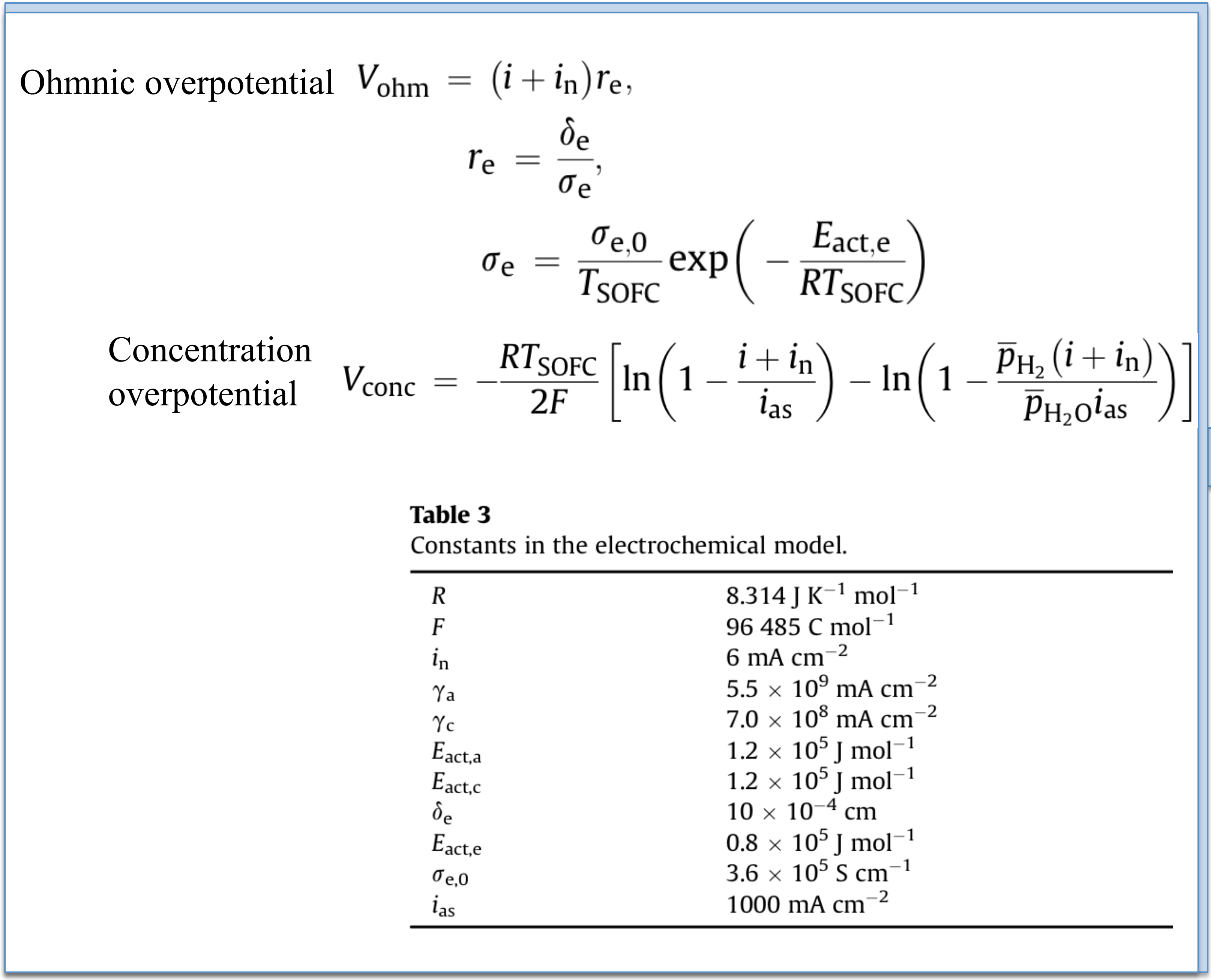
Plant model: SOFC model



Ohmnic overpotential $$V_{\text{ohm}} = (i + i_{\text{n}}) r_{\text{e}},$$

$$r_{\text{e}} = \frac{\delta_{\text{e}}}{\sigma_{\text{e}}},$$

$$\sigma_{\text{e}} = \frac{\sigma_{\text{e},0}}{T_{\text{SOFC}}} \exp\left(-\frac{E_{\text{act,e}}}{R T_{\text{SOFC}}} \right)$$

Concentration overpotential $$V_{\text{conc}} = -\frac{R T_{\text{SOFC}}}{2F} \left[\ln\left(1 - \frac{i + i_{\text{n}}}{i_{\text{as}}} \right) - \ln\left(1 - \frac{\bar{p}_{\text{H}_2} (i + i_{\text{n}})}{\bar{p}_{\text{H}_2\text{O}} i_{\text{as}}} \right) \right]$$

Table 3
Constants in the electrochemical model.

R	$8.314\ \text{J K}^{-1}\ \text{mol}^{-1}$
F	$96\,485\ \text{C mol}^{-1}$
i_{n}	$6\ \text{mA cm}^{-2}$
γ_{a}	$5.5 \times 10^{9}\ \text{mA cm}^{-2}$
γ_{c}	$7.0 \times 10^{8}\ \text{mA cm}^{-2}$
$E_{\text{act,a}}$	$1.2 \times 10^{5}\ \text{J mol}^{-1}$
$E_{\text{act,c}}$	$1.2 \times 10^{5}\ \text{J mol}^{-1}$
δ_{e}	$10 \times 10^{-4}\ \text{cm}$
$E_{\text{act,e}}$	$0.8 \times 10^{5}\ \text{J mol}^{-1}$
$\sigma_{\text{e},0}$	$3.6 \times 10^{5}\ \text{S cm}^{-1}$
i_{as}	$1000\ \text{mA cm}^{-2}$

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Sensitivity analysis

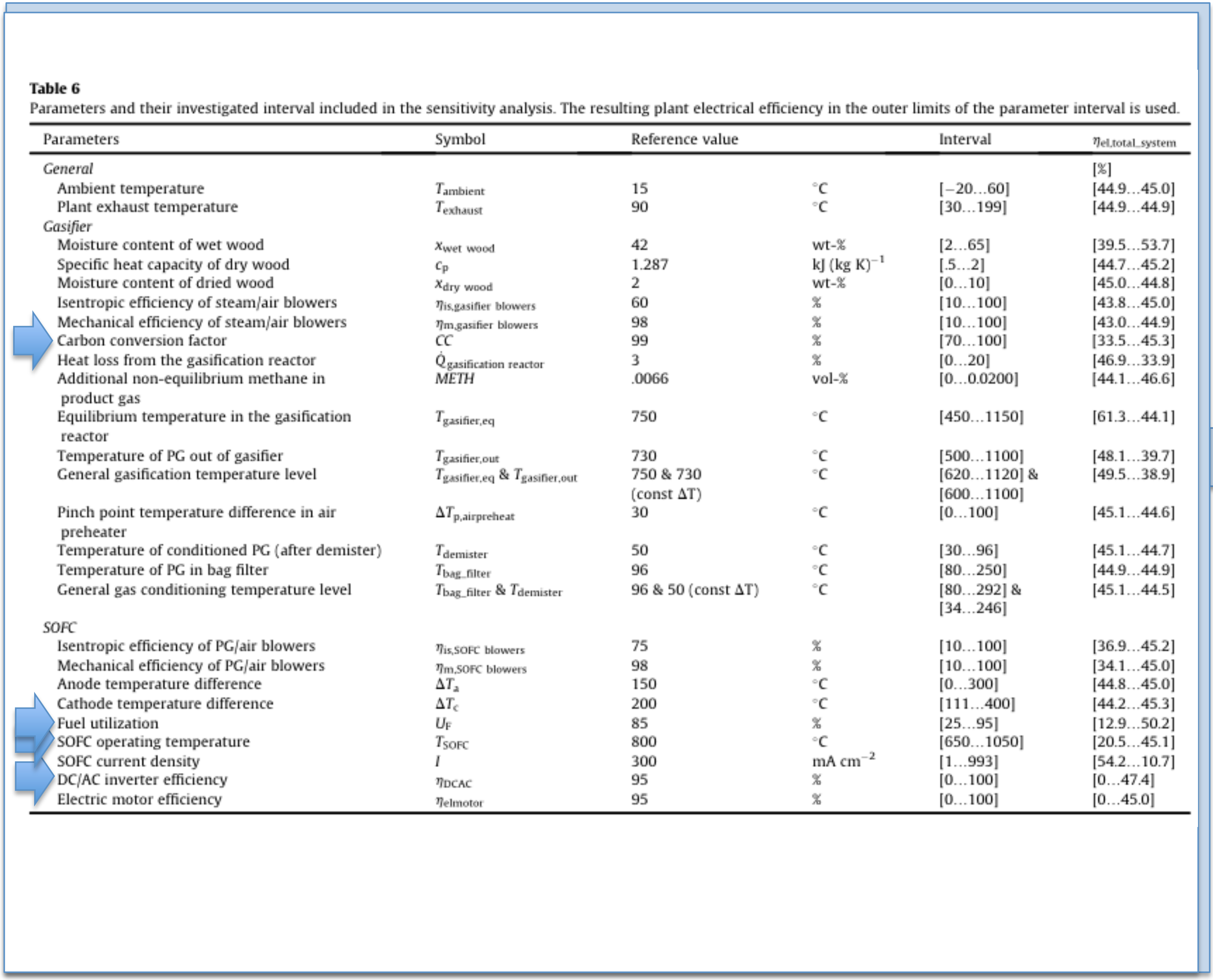

Table 6

Parameters and their investigated interval included in the sensitivity analysis. The resulting plant electrical efficiency in the outer limits of the parameter interval is used.

Parameters	Symbol	Reference value		Interval	$\eta_{el,total\_system}$
General					[%]
Ambient temperature	$T_{ambient}$	15	°C	[−20…60]	[44.9…45.0]
Plant exhaust temperature	$T_{exhaust}$	90	°C	[30…199]	[44.9…44.9]
Gasifier					
Moisture content of wet wood	$x_{wet\ wood}$	42	wt-%	[2…65]	[39.5…53.7]
Specific heat capacity of dry wood	c_p	1.287	kJ (kg K)$^{-1}$	[.5…2]	[44.7…45.2]
Moisture content of dried wood	$x_{dry\ wood}$	2	wt-%	[0…10]	[45.0…44.8]
Isentropic efficiency of steam/air blowers	$\eta_{is,gasifier\ blowers}$	60	%	[10…100]	[43.8…45.0]
Mechanical efficiency of steam/air blowers	$\eta_{m,gasifier\ blowers}$	98	%	[10…100]	[43.0…44.9]
Carbon conversion factor	CC	99	%	[70…100]	[33.5…45.3]
Heat loss from the gasification reactor	$\dot{Q}_{gasification\ reactor}$	3	%	[0…20]	[46.9…33.9]
Additional non-equilibrium methane in product gas	$METH$	.0066	vol-%	[0…0.0200]	[44.1…46.6]
Equilibrium temperature in the gasification reactor	$T_{gasifier,eq}$	750	°C	[450…1150]	[61.3…44.1]
Temperature of PG out of gasifier	$T_{gasifier,out}$	730	°C	[500…1100]	[48.1…39.7]
General gasification temperature level	$T_{gasifier,eq}$ & $T_{gasifier,out}$	750 & 730 (const ΔT)	°C	[620…1120] & [600…1100]	[49.5…38.9]
Pinch point temperature difference in air preheater	$\Delta T_{p,airpreheat}$	30	°C	[0…100]	[45.1…44.6]
Temperature of conditioned PG (after demister)	$T_{demister}$	50	°C	[30…96]	[45.1…44.7]
Temperature of PG in bag filter	T_{bag_filter}	96	°C	[80…250]	[44.9…44.9]
General gas conditioning temperature level	T_{bag_filter} & $T_{demister}$	96 & 50 (const ΔT)	°C	[80…292] & [34…246]	[45.1…44.5]
SOFC					
Isentropic efficiency of PG/air blowers	$\eta_{is,SOFC\ blowers}$	75	%	[10…100]	[36.9…45.2]
Mechanical efficiency of PG/air blowers	$\eta_{m,SOFC\ blowers}$	98	%	[10…100]	[34.1…45.0]
Anode temperature difference	ΔT_a	150	°C	[0…300]	[44.8…45.0]
Cathode temperature difference	ΔT_c	200	°C	[111…400]	[44.2…45.3]
Fuel utilization	U_F	85	%	[25…95]	[12.9…50.2]
SOFC operating temperature	T_{SOFC}	800	°C	[650…1050]	[20.5…45.1]
SOFC current density	I	300	mA cm^{-2}	[1…993]	[54.2…10.7]
DC/AC inverter efficiency	η_{DCAC}	95	%	[0…100]	[0…47.4]
Electric motor efficiency	$\eta_{elmotor}$	95	%	[0…100]	[0…45.0]

Introduction
Technologies
ORC
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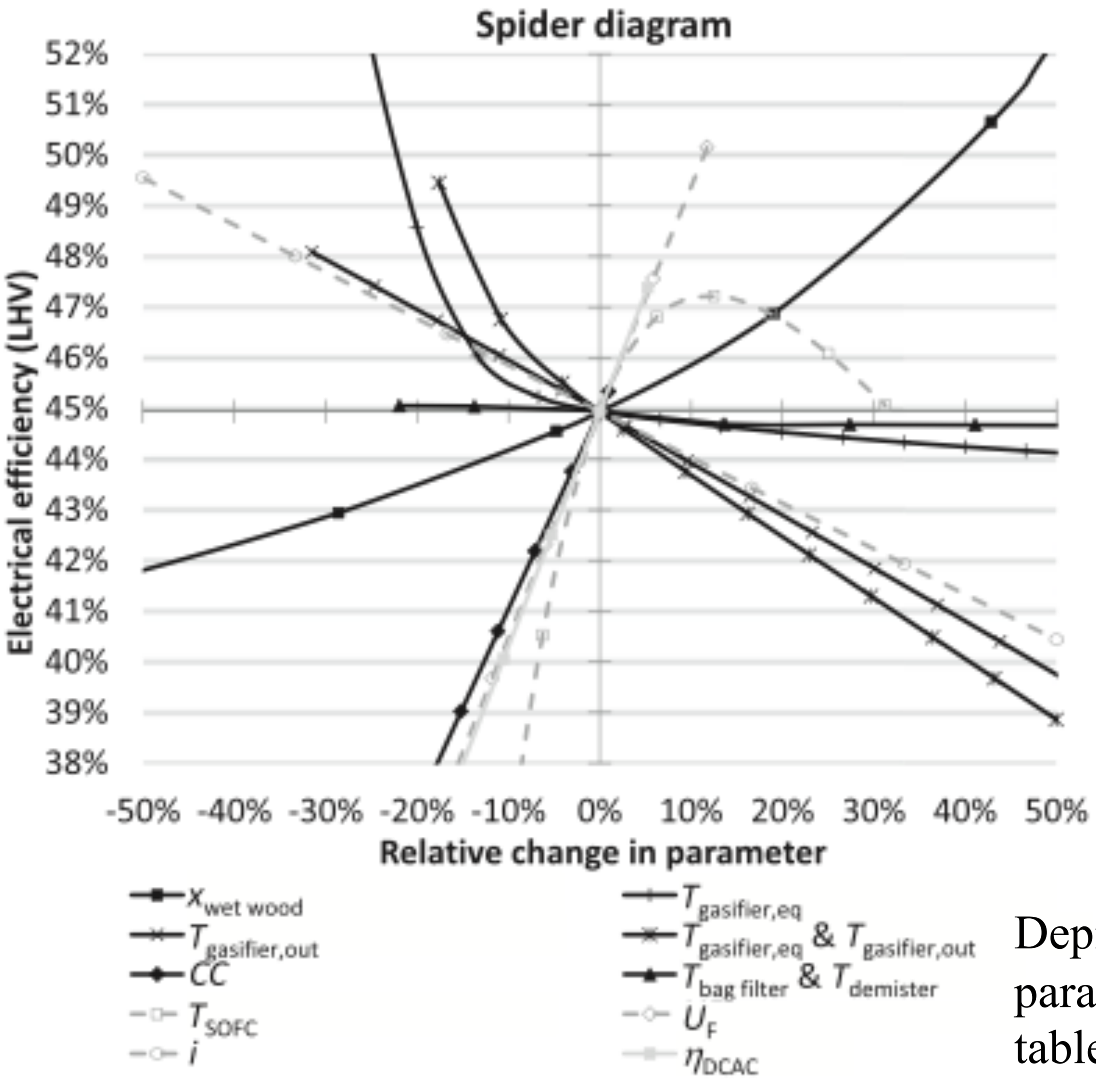
Conclusions

Discussion and conclusions



Depicts all of the parameter of the previous table that with a 10% affect the electrical efficiency of the plant by more than 0.5%

Overall conclusions

Small-scale biomass-fuelled CHP has a great market potential

Urge of environmental protection, economical development and climate change control

Address important issues in the energetic, environmental and economical fields

Research and development are in infant stage

Thank you
for your attention