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Advanced hybrid and combined small-scale thermal energy conversion systems for efficient use of locally available resources

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Introduction

Sustainable development and security of energy supply require rational use of available resources

Decentralized and on-site power production in small-scale cogeneration plants optimized for locally available primary energy resources is an interesting option for savings of fossil fuels and emission reduction

It is nowadays technically possible to configure complex technological structures that can significantly boost energy and environmental performance of energy conversion systems.

Supporting use of natural gas and cooperation of the plant with a low-temperature district heating network can be also considered as means of performance improvement.

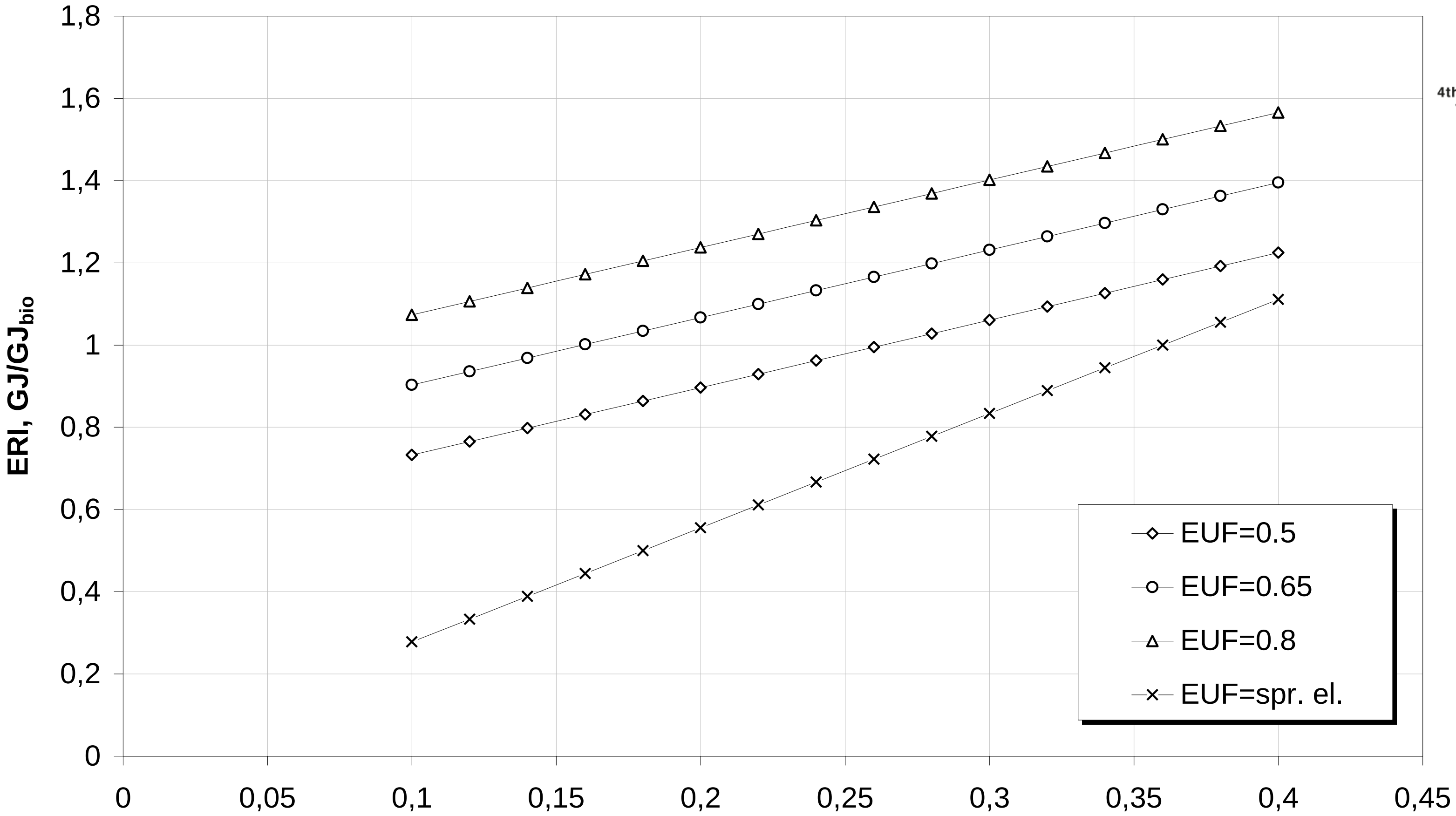
Energy conversion and environmental performance

Performance of small-scale cogeneration plants can be examined using simple indices such as:

$$ERI = \frac{\Delta m_{coal} LHV_{coal} + \dfrac{3.6 E_{el}}{\eta_{ref,system}}}{m_{wood} LHV_{wood}} = \frac{EUF - \eta_{el}}{\eta_b} + \frac{\eta_{el}}{\eta_{ref,system}}$$

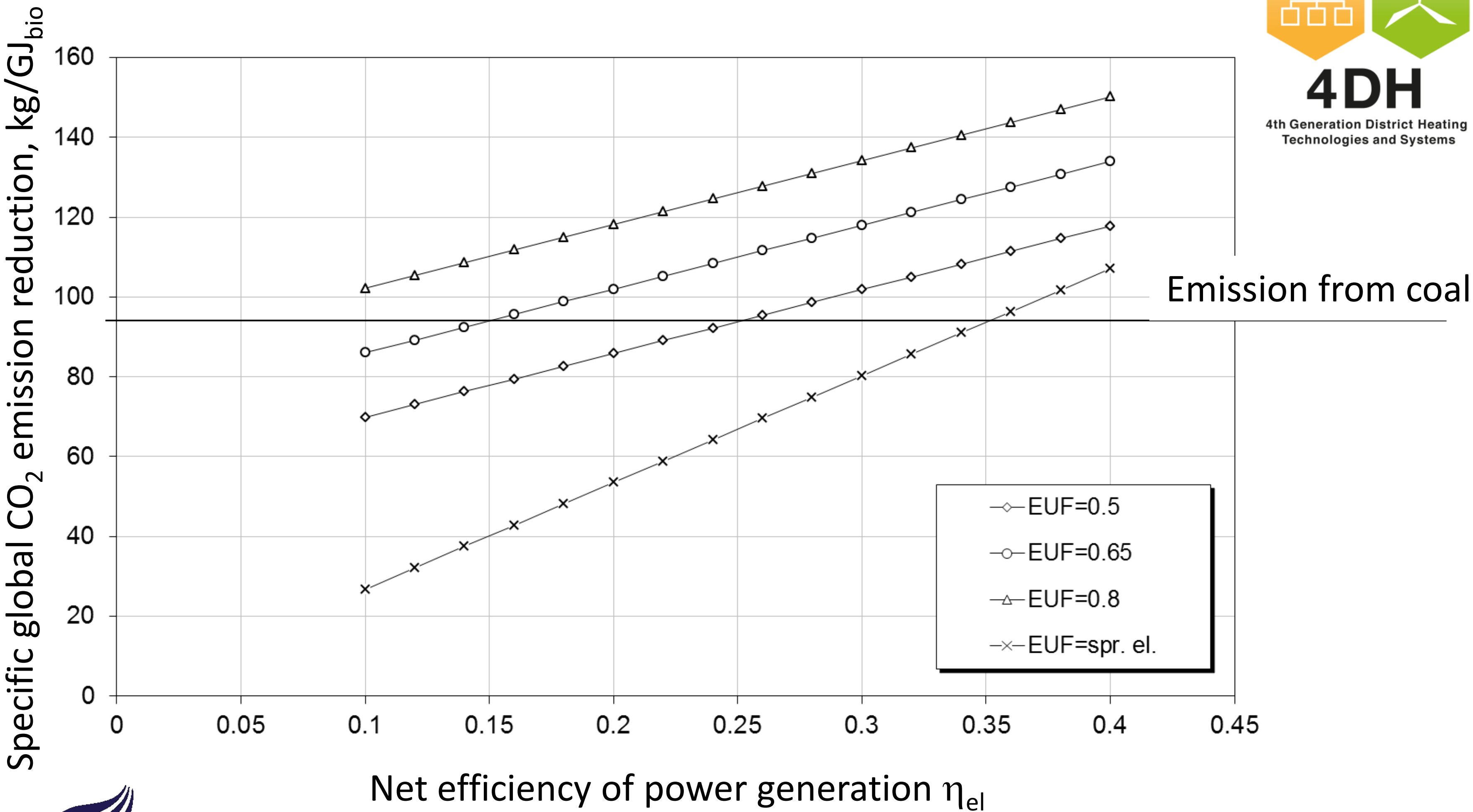
$$\delta_{CO_2} = \frac{\Delta m_{coal} LHV_{coal} WE_{coal} + E_{el} WE_{ref}}{m_{bio} LHV_{bio}}$$

In Polish conditions



Net efficiency of power generation η_{el}

In Polish conditions



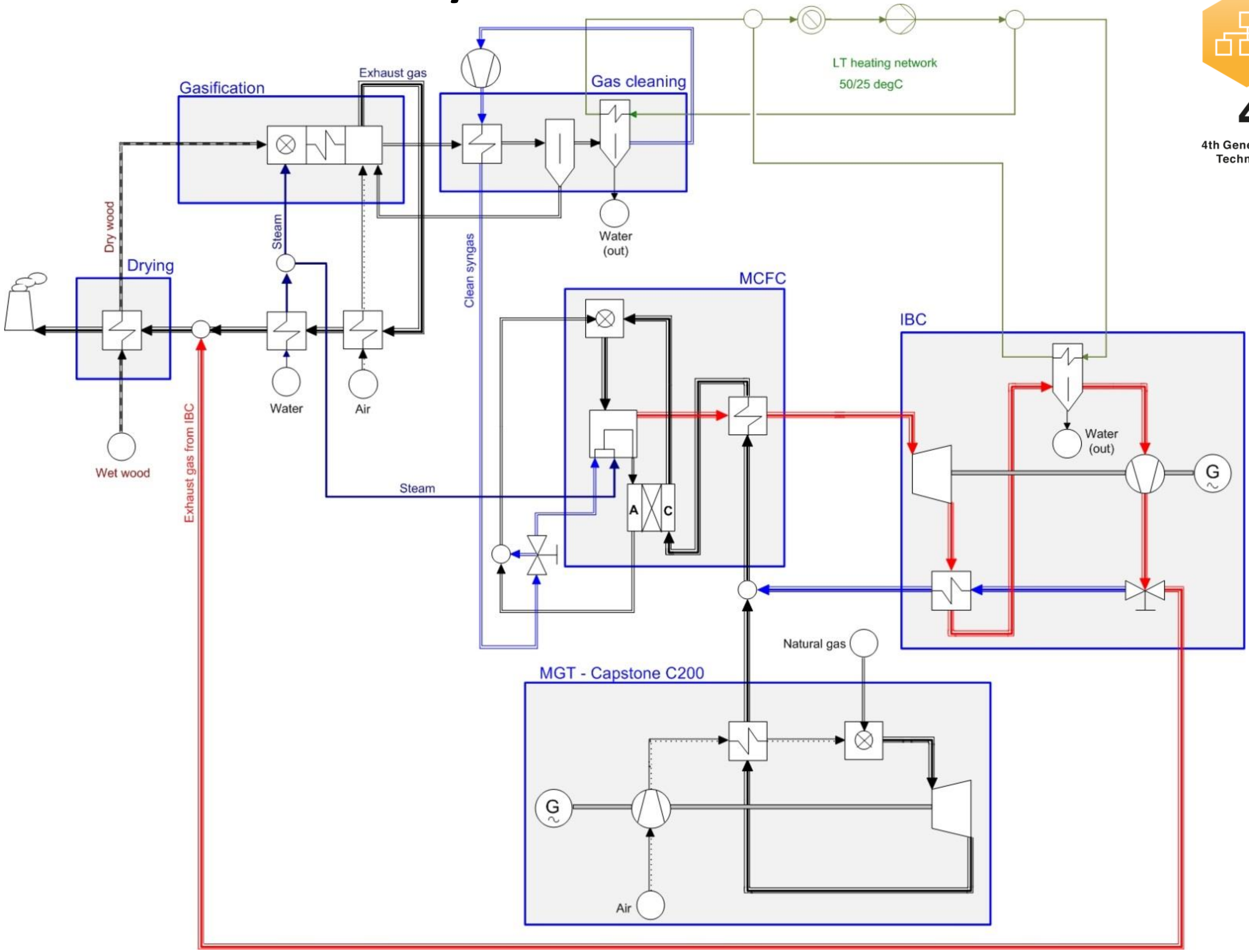
System studied

Concept of modular cogeneration plant composed of:

- ***Allothermal wood gasification***
- ***MCFC – molten carbonate fuel cell***
- ***MGT – conventional natural gas fired microturbine Capstone C200***
- ***IBC – inverted Bryton cycle module.***

The plant delivers heat to a low temperature heating network (LTHN) that allows for condensation of water from syngas as well as within the IBC heat exchanger.

System studied



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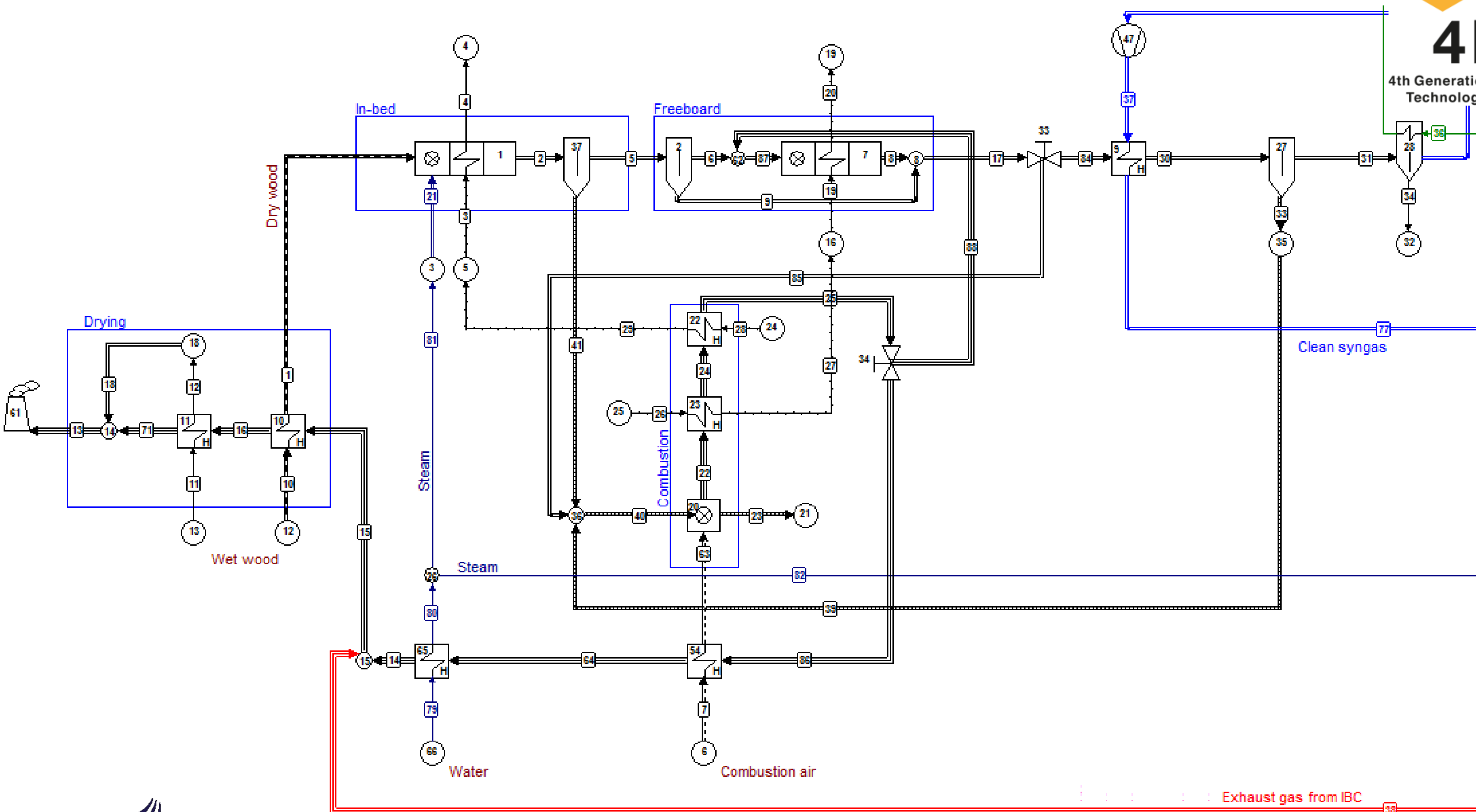
Cycle-Tempo model of gasification



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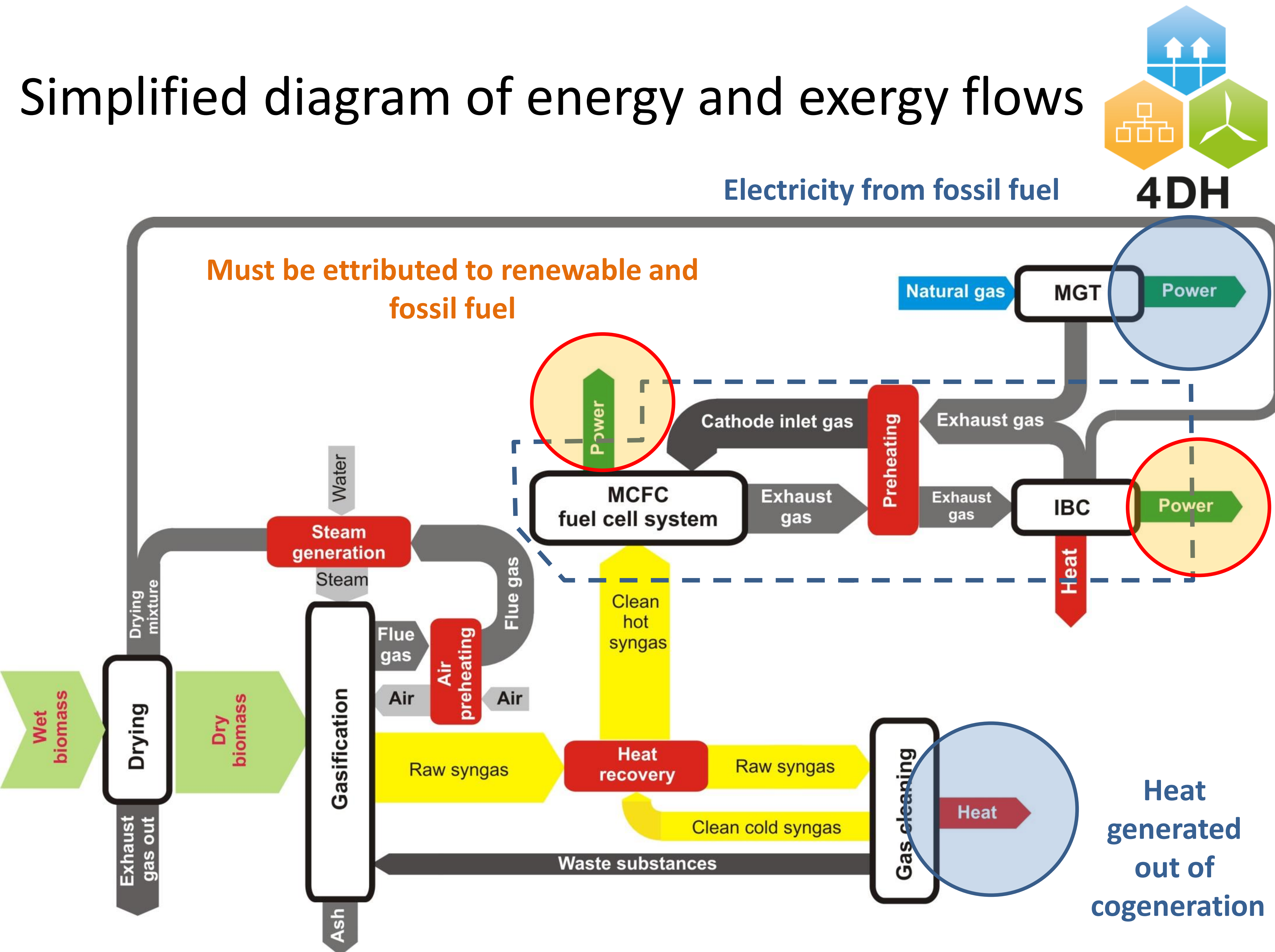
Simplified diagram of energy and exergy flows



Calcullation of biomass energy conversion efficiency and allocation of financial support

$$\eta_{el,bio} = \frac{P_{el,bio}}{\dot{m}_{bio} LHV_{bio}}$$

$$P_{el,bio} = \left(P_{el,MCFC} + P_{el,MGT} + P_{el,IBC}\right) \frac{\dot{m}_{gf}\left(LHV_{gf} + h_{ph,gf}\right)}{\dot{m}_{gf}\left(LHV_{gf} + h_{ph,gf}\right) + \dot{m}_{ex,MGT} h_{ph,ex}}$$

An alternative way to calculate the amount of electric energy from biomass is according to exergy key

$$P_{el,bio} = \left(P_{el,MCFC} + P_{el,MGT} + P_{el,IBC}\right) \frac{\dot{B}_{gf}}{\dot{B}_{gf} + \dot{B}_{ex,MGT}}$$

Calculated Capstone C200 turbine model data at ISO conditions

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Parameter	Unit	Value
Net electric power	kW	200.8
Power generation efficiency	%	33.6
Naural gas energy input	kW	598.3
Compressor pressure ratio	-	4.27:1
Exhaust gas temperature	°C	275.1
Exhaust gas flow rate	kg/s	1.33
Turbine inlet temperature	°C	954
Expander isentropic efficiency	%	83
Compressor isentropic efficiency	%	81
Mechanical efficiency	%	99
Power generator efficiency	%	95
Exhaust gas composition:		
N_2	% mol	76.06
O_2		17.20
H_2O		4.19
Ar		0.90
CO_2		1.65

Good efficiency

Unfavorable exhaust gas temperature

Unfavorable CO_2 content

MCFC modelling results

Parameter	Unit	Value	
Fuel utilisation factor U_f	-	0.70	0.80
Operating temperature	°C	650	650
Current density	A/m^2	1300	1300
Cell voltage	V	0.81	0.79
IBC exhaust gas recirculation ratio	-	0.80	0.80
Cathode inlet gas O_2 content	%mol	6.8	8.28
Cathode inlet gas CO_2 content	%mol	11.6	10.0
O_2 utilisation factor	-	0.24	0.19
CO_2 utilisation factor	-	0.28	0.31
Syngas consumption	kg/s	0.210	0.176
Syngas inlet temperature	°C	721	721
Cathode gas inlet temperature	°C	550	550
AC electric power	kW	1208	1133
MCFC power generation efficiency*	%	43.8	49.1

* efficiency calculated as electric power divided by fuel chemical energy input.

IBC modelling results

Parameter	Unit	Value	
U_f at MCFC	-	0.70	0.80
Expander inlet temperature	°C	630	500
Expander inlet pressure	kPa	89	89
Expander outlet pressure	kPa	43.0	42.5
Expander inlet flow	kg/s	7.522	7.425
Compressor inlet pressure	kPa	40.5	40.0
Compressor inlet flow	kg/s	7.424	7.354
Inlet enthalpy flow	kW	5635	4278
Net electric power	kW	192	39
Power generation efficiency	%	3.4	0.9
LTHN heat output	kW	1947	1634

System performance

Parameter	Unit	Value	
U_f at MCFC	-	0.70	0.80
Wet biomass flow (w = 0.40)	kg/s	0.328	0.275
Wet biomass energy input	kW	3299	2760
Natural gas energy input	kW	598	598
Gross electric power output	kW	1602	1373
Net electric power output	kW	1518	1302
IBC heating output	kW	1947	1634
Gasification system heating output	kW	267	224
Total $\eta_{el,net}$	%	38.9	38.8
Total EUF_{net}	%	95.9	100.9
Syngas energy input into MCFC	kW	3021	2532
MGT exhaust enthalpy flux	kW	369	369
Syngas exergy input into MCFC	kW	2866	2402
MGT exhaust exergy flux	kW	100	100
Energy utilization in cogeneration EUF_{CHP}	%	104.7	103.8
Electric power from biomass $P_{el,bio}$ (energy key)	kW	1249	1024
Electric power from biomass $P_{el,bio}$ (exergy key)	kW	1355	1126
Efficiency of electricity generation from biomass (energy key)	%	37.8	37.1
Efficiency of electricity generation from biomass (exergy key)	%	41.1	40.8

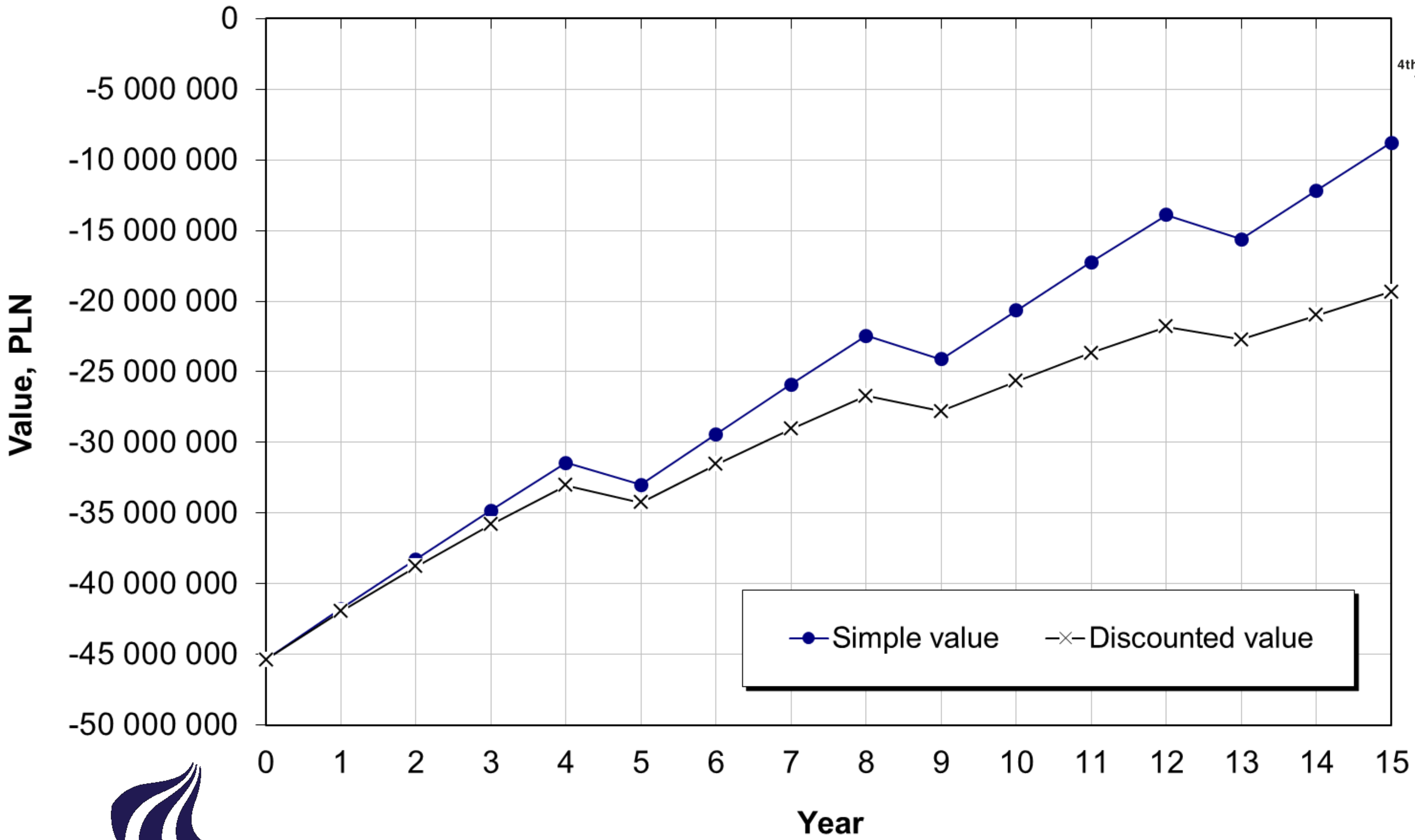
Main assumptions for financial profitability calculation

❑ **Lifetime:**	**15 years**
❑ **Annual plant operation hours:**	**8000**
❑ **Discounted cash flow rate:**	**5.0%**
❑ **Electricity selling price:**	**200 PLN/MWh**
❑ **Cost of wet biomass :**	**130 PLN/ton**
❑ **Fixed annual operating and maintenance costs:**	**3% of TIC**
❑ **Variable operating and maintenance costs:**	**3 EUR/MWh**
❑ **Renewable energy certificate:**	**113 PLN/MWh**
❑ **Cogeneration certificte (natural gas):**	**116 PLN/MWh**
❑ **Cogeneration certificate (biomass):**	**11 PLN/MWh**
❑ **Value of heat:**	**30 PLN/GJ**

Estimation of investment cost

Cost item	Value, PLN	
U_f at MCFC	0.70	0.80
Gasifier system (including peripheral equipment and gas cleaning)	13,531,827	11,751,078
Rotary drum drier	807,633	807,633
MCFC system	10,400,880	9,755,130
MGT system	757,752	757,752
IBC module	727,897	149,622
Total Equipment Cost (TEC)	26,225,989	23,221,215
Installation of equipment and piping (0.40 TEC)	10,490,396	9,288,486
Instrumentation, control and interconnections (0.20 TEC)	5,245,198	4,644,243
Design and commissioning (0.10 TEC)	1,049,040	928,849
Startup (0.05 TEC)	1,311,299	1,161,061
Contingencies (0.10 TEC)	1,049,040	928,849
Total indirect costs	19,144,972	16,951,487
Total Investment Cost (TIC)	45,370,961	40,172,702
Unit investment cost EUR/kW of installed electric power	6908	7136

Simple and discounted value over years



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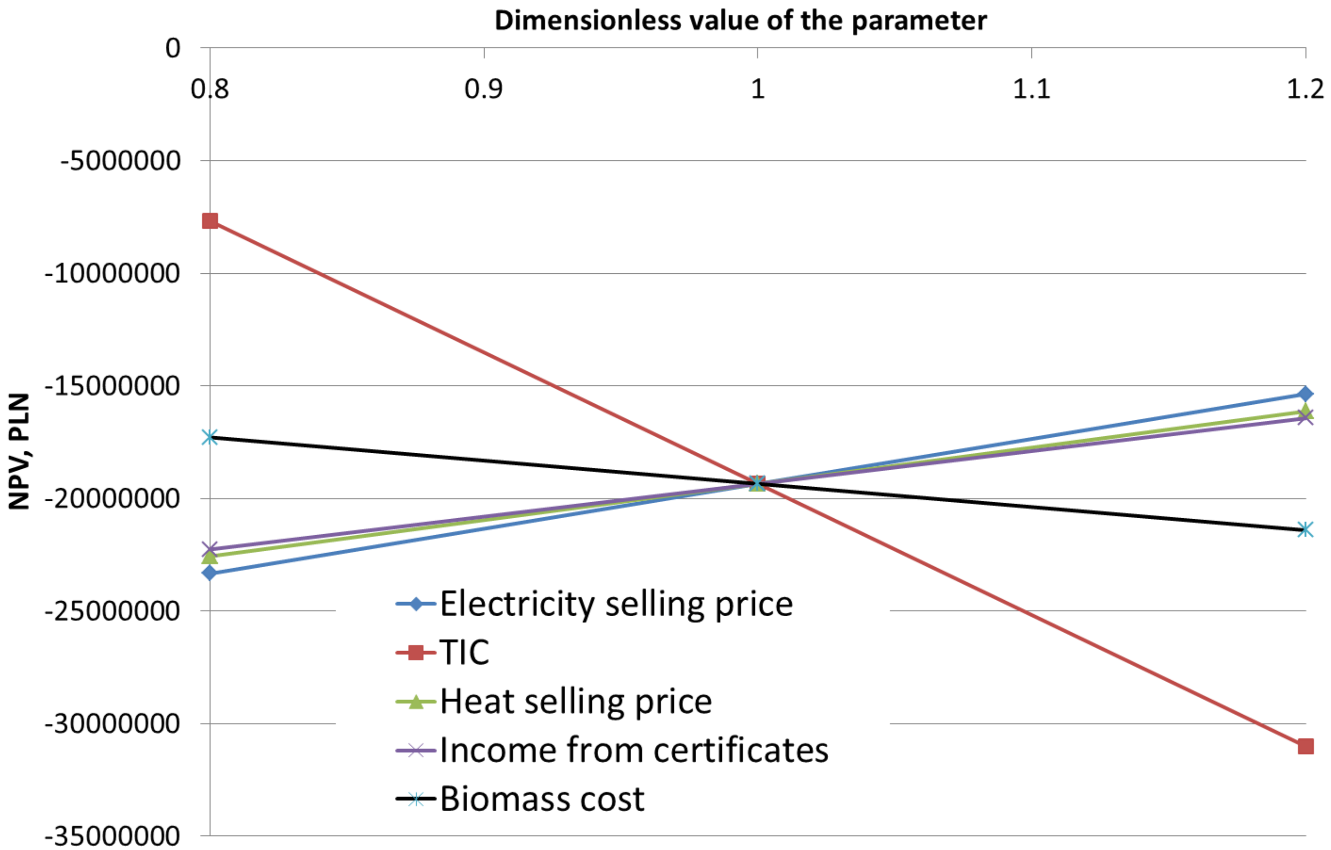
Sensitivity test



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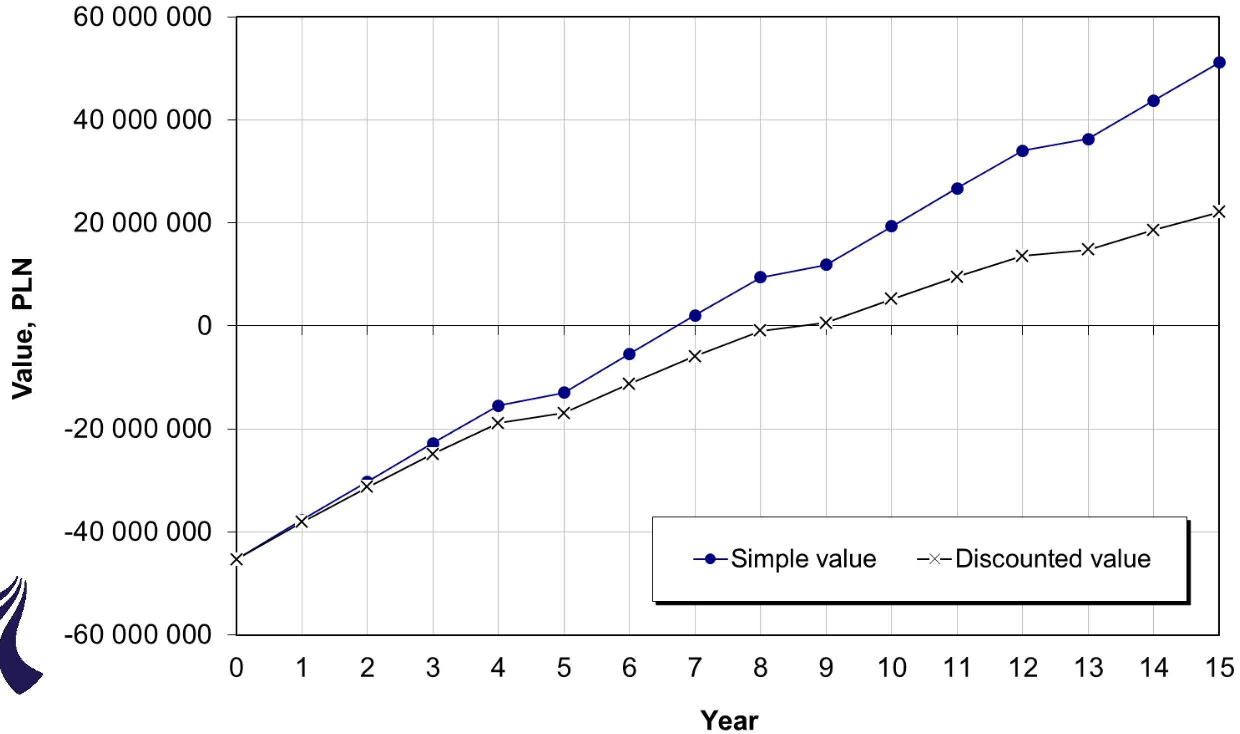
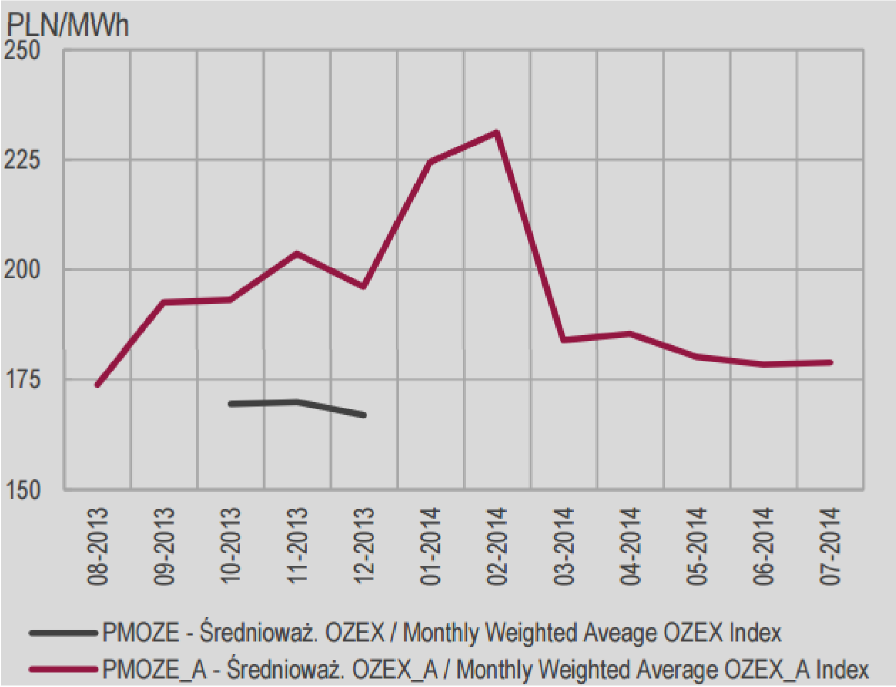
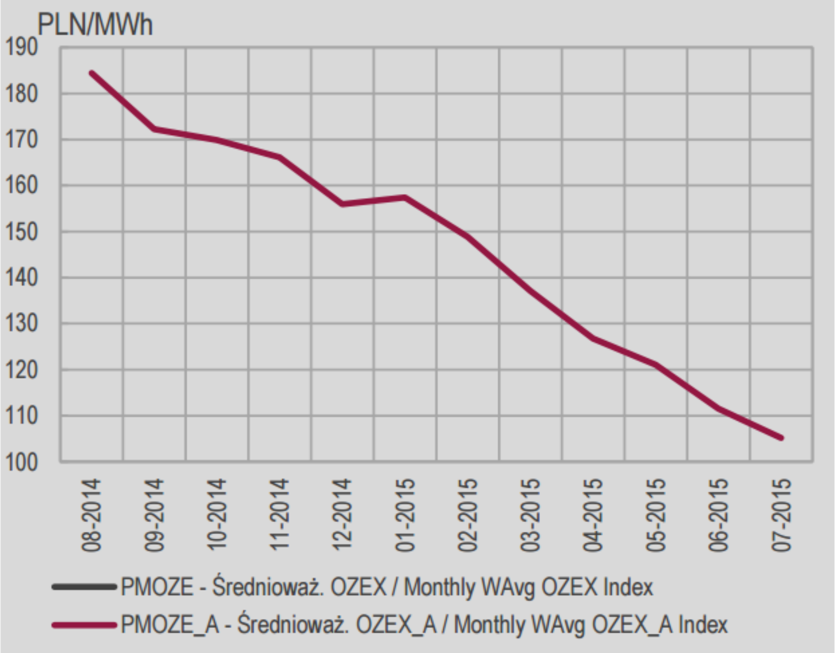
Assumptions for financial profitability calculation – positive scenario

- **Electricty attributed to biomass according to exergy key**
- **Electricity selling price: 550 PLN/MWh**
- **Renewable energy certificate: 186 PLN/MWh**



Support mechanism = market risk





Conclusions

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The proposed integrated system is an attractive technological alternative for reduction of consumption of fossil fuels and global CO_2 emission.

Biomass energy to electricity conversion efficiency depends on operating parameters and the way that power is attributed to biomass.

Financial performance of investment projects is poor. Without an intensive and stable financial support such projects would not be profitable in the near future.

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