Modelling a biomass gasification installation for use in hybrid renewable energy sources

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Plan

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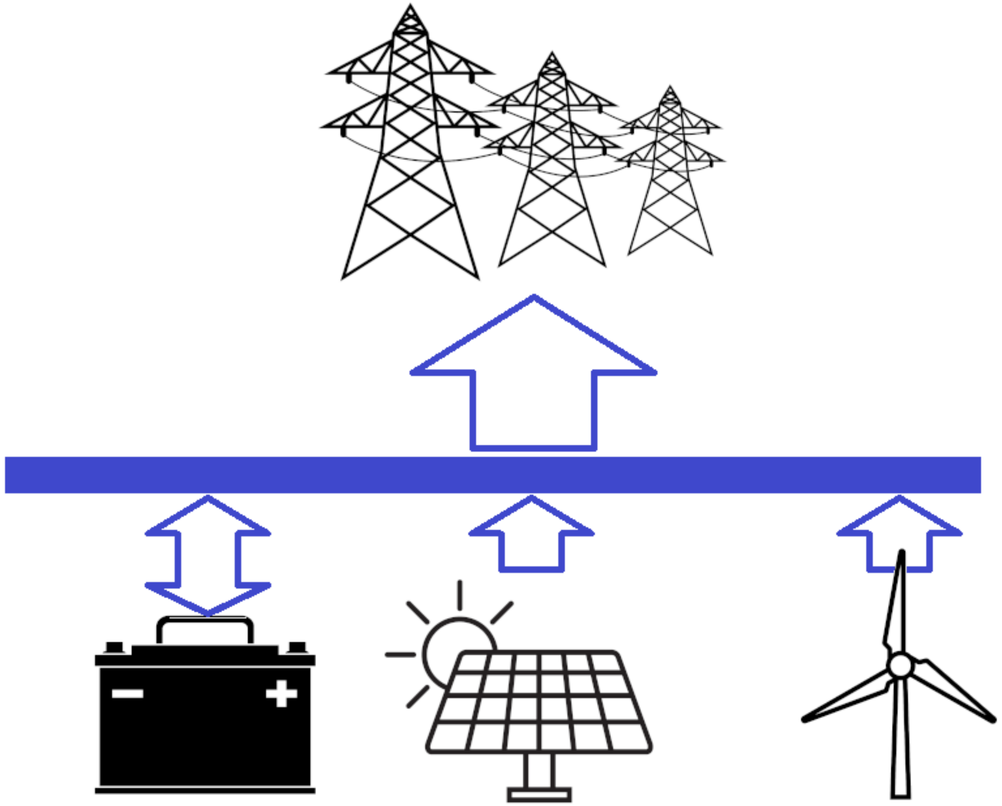


Introduction – hybrid renewable energy sources (HRES)

- Connecting several types of electricity sources to a single connection, with installed capacity being oversized to the connection capacity.
- Goal: increase generation and reliability of energy supply
- Connection capacity may be exceeded, resulting in generation limitations.
- Relying on weather-dependent sources and energy storage, ensuring high and stable generation may be difficult to achieve.

The use of controllable and weather-independent sources is advantageous.

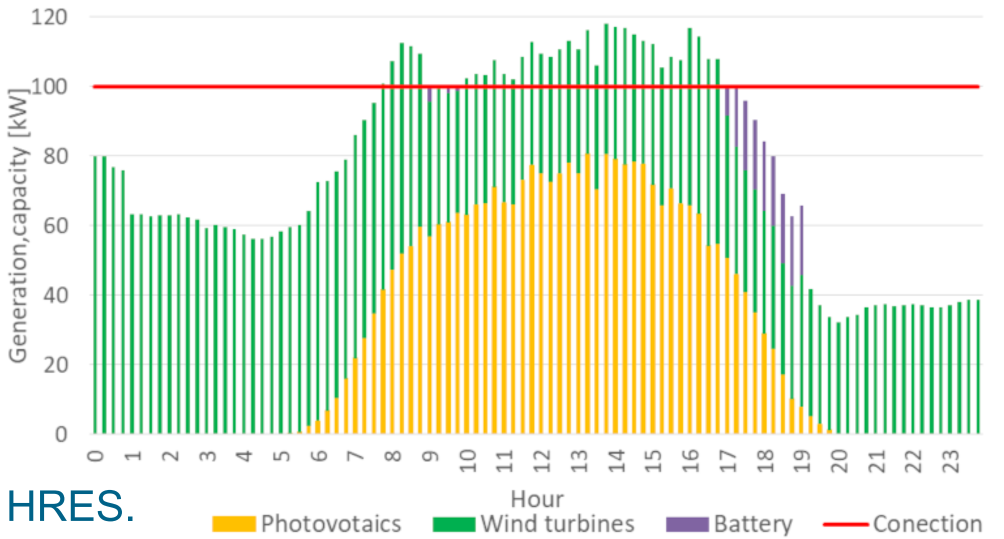


Fig. 1. Operating principle of HRES.

Introduction – controllable sources in HRES

The use of controllable and weather-independent sources is advantageous.

- Engine generators – high efficiency and flexibility across a wide operating range, ease of power regulation, and short start-up times:
  - Non-renewable fuels: oil, gasoline, or natural gas.
  - Biodiesel, green hydrogen, or **wood gas produced by biomass gasification**.

Introduction – gasification

- Thermochemical process that converts solid fuels into a gaseous form.
- The amount of oxygen is less than the stoichiometric amount required for complete combustion.
- The resulting gas contains, combustible components (mainly CO, H_2, CH_4), noncombustible components (N_2, H_2O, CO_2), and impurities and tars. The gas has a low calorific value – in biomass gasification, it ranges from 4 to 12 MJ/m^3.
- Fixed-bed or fluidised-bed reactors are most commonly used for biomass gasification. In the low-power sector, fixed-bed reactors dominate, as they are the simplest designs.

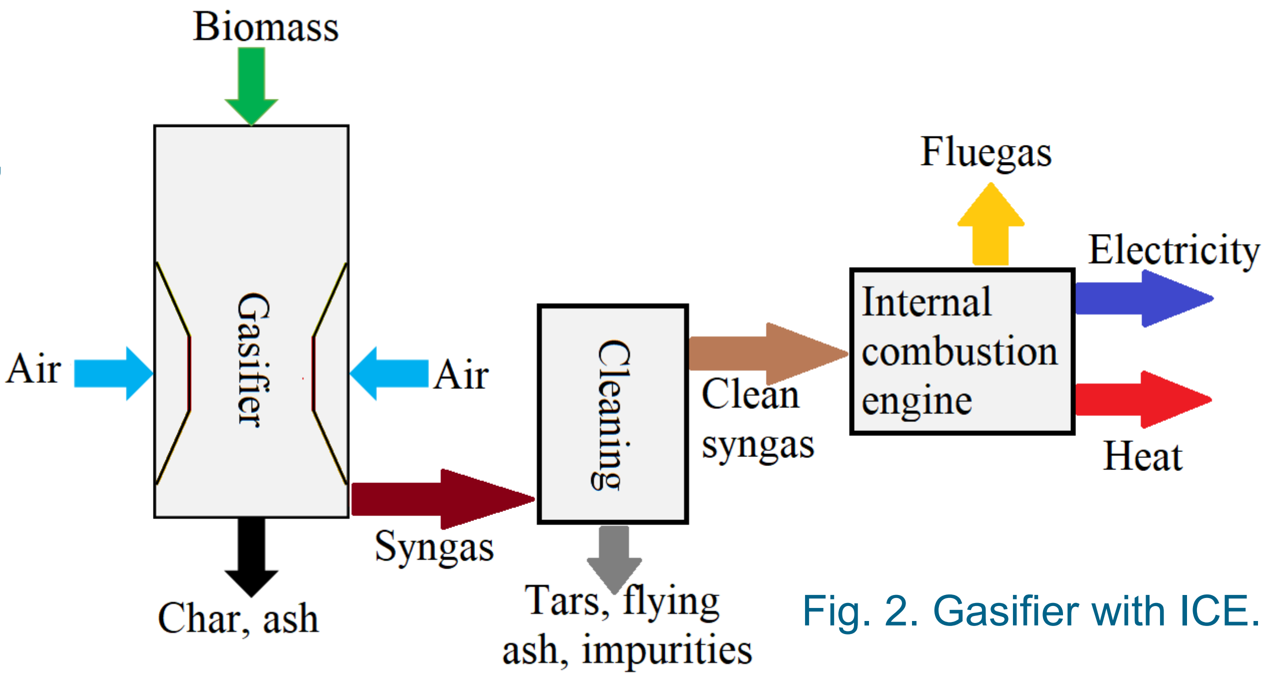


Fig. 2. Gasifier with ICE.

Aim of the research

The research aims to present the modelling capabilities of downdraft biomass gasification installations (using air as the gasifying agent) designed to cooperate with other renewable energy sources in hybrid renewable energy sources.

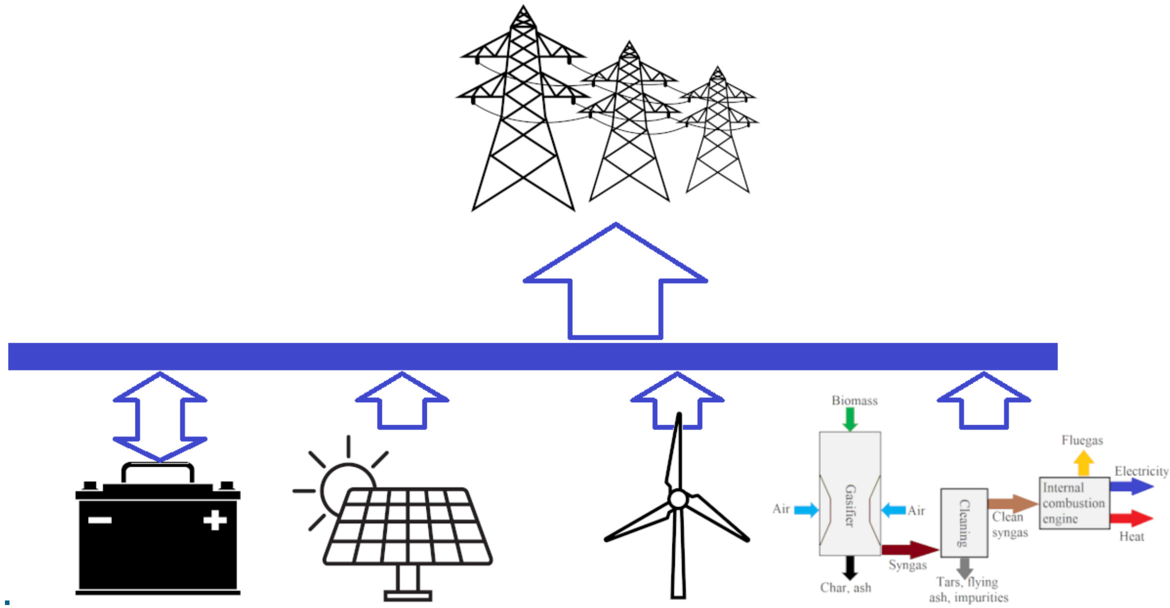


Fig. 3. HRES with gasification installation.

Methodology – key aspects of modelling a gasification in HRES

- Before the modeling, key aspects of proper modeling fo a gasification installation being a part of HRES were identified.

- Syngas:
  - **Composition;**
  - **Calorific value;**
  - **Mass/volume flow;**
  - **Temperature;**
  - Stability.

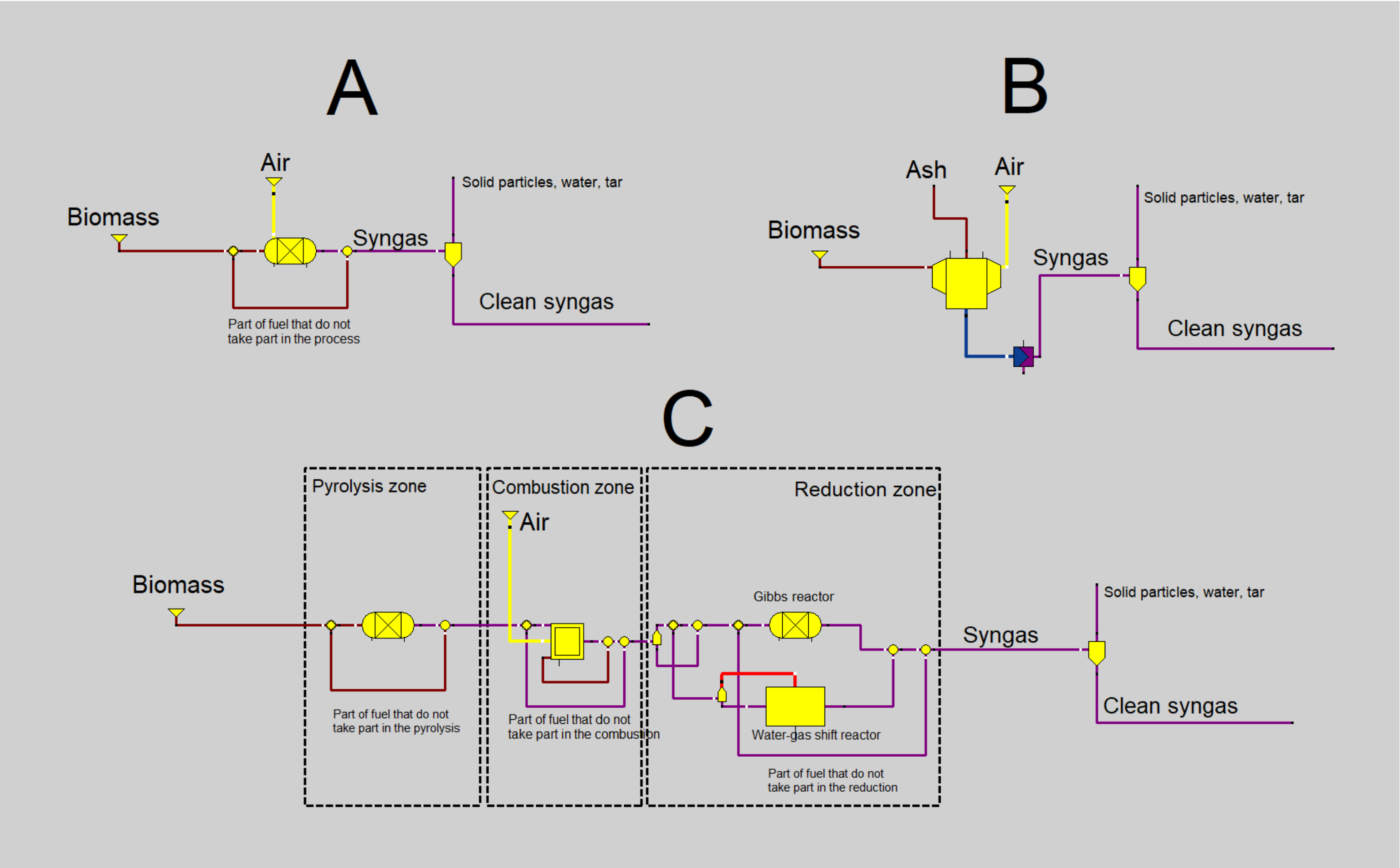
- Gasifier:
  - **Efficiency;**
  - **Fuel consumption;**
  - Start-up time;
  - Continuous operation time;
  - Power variation gradient;

- **All parameters are required in wide range of load.**

Methodology – models

- MODEL 1 – a **single-zone** model that **minimise the Gibbs free energy** for given reaction temperatures and substrate compositions.
- MODEL 2 – a model that uses the **constants** of thermochemical equations**, Gibbs free energy minimisation**, and the **water-gas shift reaction**
- MODEL 3 – a **three-zone** (pyrolysis, combustion, and reduction) model. Zones were modelled using components that **minimise Gibbs free energy**. The reduction zone was modelled using also **water-gas shift reaction** component.

Fig. 4. Models in the Ebsilon Professional program: A) MODEL 1, B) MODEL 2, C) MODEL 3.



Methodology – models

Table 1. Input data for each model

MODEL 1	**MODEL 2**	**MODEL 3**
Reduction temperature	CH_4 to C ratio	Pyrolysis temperature
The part of the fuel that does not undergo the gasification process	H_2S to S ratio	Combustion temperature
Air ratio	NH_3 to N ratio	Reduction temperature
	Tar to C - ratio	The part of the fuel that does not undergo the pyrolysis process
	Degree of coal gasification	The part of the fuel that does not undergo the combustion process
	Reaction constant for the shift reaction	The part of the fuel that does not undergo the reduction process
	Molar ratio of the whole oxygen to the whole carbon	The ratio between the fuel mass flow undergoing water-gas shift reactions and the total fuel in the reduction zone
	Freezing temperature for the shift reaction	Air ratio
	Air ratio	

Methodology – data sources

[1] Soares J et al. Experimental assessment of pine wood chips gasification at steady and part-load performance. Biomass Bioenergy 2020;139:105625.
[2] Guo F, et al. Effect of design and operating parameters on the gasification process of biomass in a downdraft fixed bed: An experimental study. Int. J. Hydrogen Energy 2014;39:5625–33.
[3] Li CY et al. Experimental and modeling investigation of an integrated biomass gasifier–engine–generator system for power generation and waste heat recovery. Energy Convers. Manag. 2019;199:112023.
[4] Martínez JD, et al. Experimental study on biomass gasification in a double air stage downdraft reactor. Biomass Bioenergy 2011;35:3465–80.
[5] Canabal AI, et al. Elemental composition of raw and torrefied pellets made from pine and pine-eucalyptus blends. Biomass Bioenergy 2023;177:106951.

Table 2. Chosen literature sources

Source	P1 [1]	P2 [2]	P3 [3]	P4 [4]
Load	17.2%-100%	62.4%-100%	36.5%-100%	73.4%-100%
Fuel	Pine wood chips. Lack of fuel composition. Estimated based on [5]	Corn stalk. The composition given in the paper.	Redwood pellets. The composition given in the paper.	Eucalyptus wood. The composition given in the paper.
LHV	In the full range	In the full range	In the full range	In the full range
Efficiency	In the full range	Only with one load	In the full range	In the full range
ER	In the full range	In the full range	In the full range	In the full range
Gas composition	Only at rated load. Raw gas and purified gas.	In the full range. Raw gas	In the full range. Purified gas	In the full range. Only flammables. Purified gas.
Temperatures	Combustion, reduction	Combustion, reduction, pyrolysis	Reduction	Combustion, reduction, pyrolysis

Methodology – data sources

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Table 3. Chosen literature sources

Source	P1 [1]	P2 [2]	P3 [3]	P4 [4]
LHV	5.3-5.8 MJ/kg	5,3-5,5 MJ/m^3	4,7-5,3 MJ/m^3	3,9-4,6 MJ/m^3
Efficiency	58.9-71,5%	65%	65.8-73.4%	61.2-66.7%
ER	0.25-0.37	0.27	0.30-0.43	0.4-0.41
Gas composition	CO: 25.8% H_2: 19.5% CH_4: 2.2%	CO: 17.9-20.6% H_2: 11.8-14.6% CH_4: 1.8-2.2%	CO: 17.2-18.8% H_2: 13.8-15.9% CH_4: 2.3-2.6%	CO: 14.8-17.1% H_2: 14.1-16.2% CH_4: 1.6-2.0%
Temperatures	Combustion: 870-920°C Reduction: 630-710°C	Pyrolysis: 310-350°C Combustion: 920-1060°C Reduction: 650-760°C	Reduction: 630-840°C	Pyrolysis: 470-640°C Combustion: 670-830°C Reduction: 600-760°C

Methodology – optimisation function

- The values compared between the model and the literature data were cold gas efficiency, LHV, and gas composition.
- Mean absolute percentage error (MAPE) was modified to avoid a situation where the gas composition (typically 5 components, compared to only two other parameters) becomes overly important.

$$min \quad 100\frac{1}{n}\sum_{i=1}^{n}\frac{\left|\frac{LHV_{A\_i}-LHV_{M\_i}}{LHV_{A\_i}}\right|+\left|\frac{\eta_{cg\_A\_i}-\eta_{cg\_M\_i}}{\eta_{cg\_A\_i}}\right|+\frac{1}{m}\sum_{j=1}^{m}\left|\frac{C_{A\_j}-C_{M\_j}}{C_{A\_j}}\right|}{N}$$

Methodology – optimisation function

- Minimisation was performed using a **genetic optimisation algorithm**.
- Assumption: the variability of each parameter could be described using second-degree equations.

$$y = Ax^2 - Bx - C$$

- The curves for the parameters were determined using regression (while minimising the R2 value).
- It was necessary to select parameters A, B, and C. Sets of parameters were selected for three load points (two extreme ones and the middle one). Then, the values of coefficients A, B, and C were determined according to equations on the right. The next step was to determine the parameter values at the remaining load points and calculate the error value.

Table 4. Parameters characterising the genetic algorithm

Parameter	Unit	Value
Population size	-	30
Probability of crossover	-	0.6
Probability of mutation	-	0.5
The fraction of the population in which each gene is replaced	-	0.75
Maximum number of generations	-	30
Simulation-Ending Convergence	-	0.99

$$A = \frac{y_3 + \frac{y_2 - y_1}{x_2 - x_1}(x_1 - x_3)}{(x_3^2 - x_1^2) - (x_2 + x_1)(x_3 - x_1)}$$

$$B = \frac{y_2 - y_1}{x_2 - x_1} - A(x_2 + x_1)$$

$$C = y_1 - Ax_1^2 - Bx_1$$

Results – P1

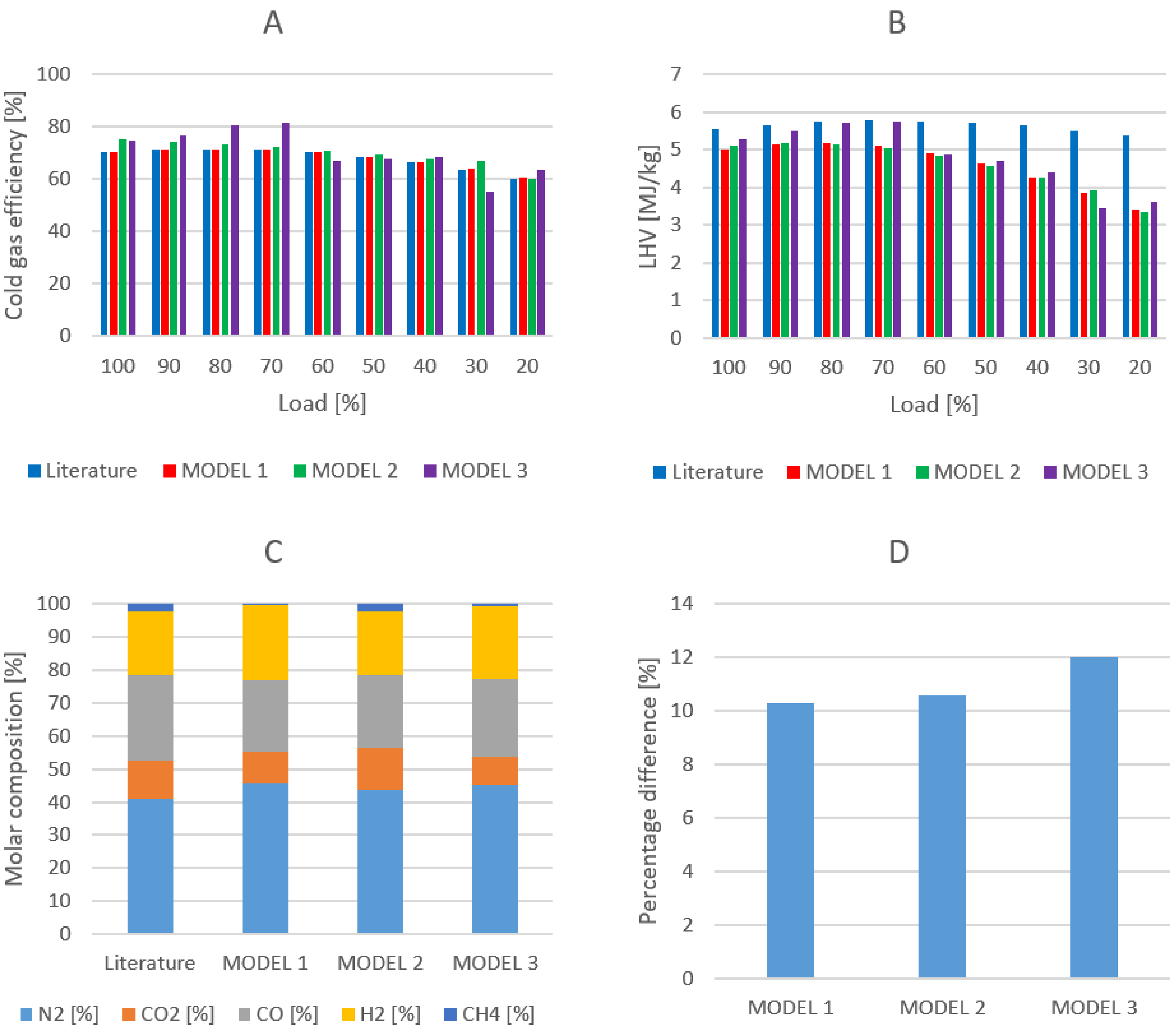

Fig. 5. Comparison of modelling results with literature data P1:
A) gasification process efficiency,
B) calorific value of purified syngas,
C) syngas composition at rated load,
D) comparison of error values in individual models.

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Results – P2

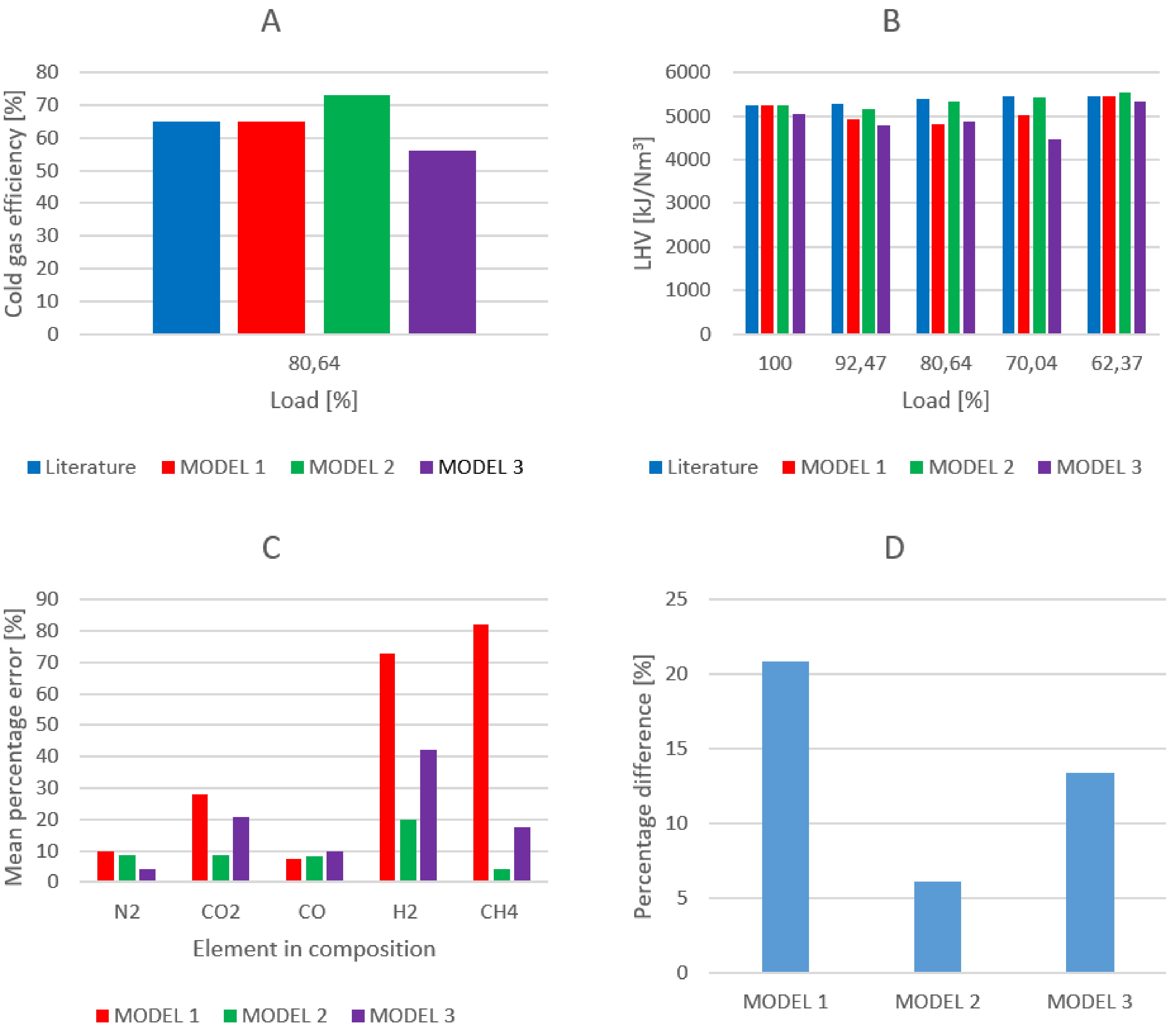

Fig. 6. Comparison of modelling results with literature data P2:
A) gasification process efficiency,
B) calorific value of purified syngas,
C) syngas composition at rated load,
D) comparison of error values in individual models.

Results – P3

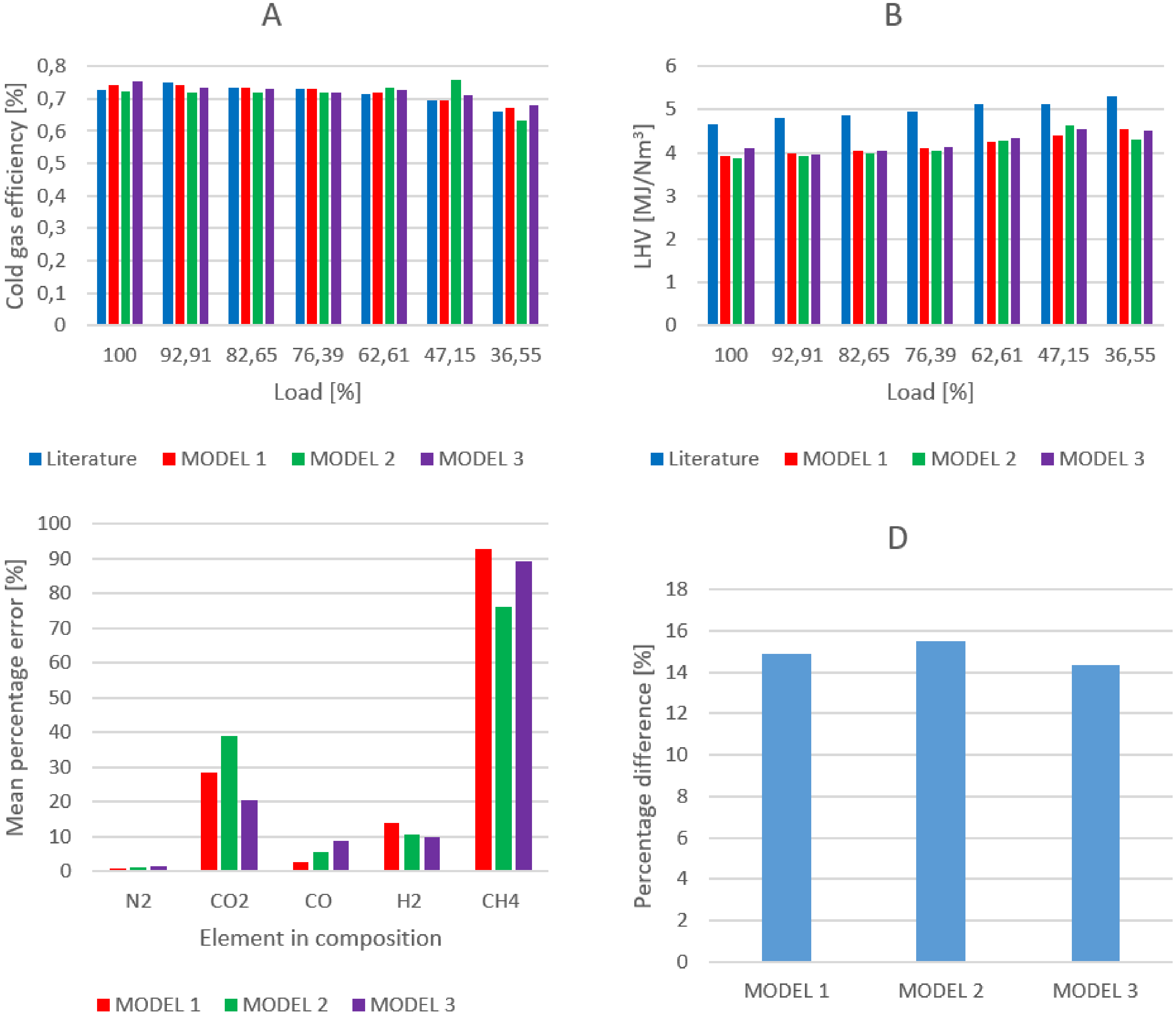

Fig. 7. Comparison of modelling results with literature data P3:
A) gasification process efficiency,
B) calorific value of purified syngas,
C) syngas composition at rated load,
D) comparison of error values in individual models.

Results – P4

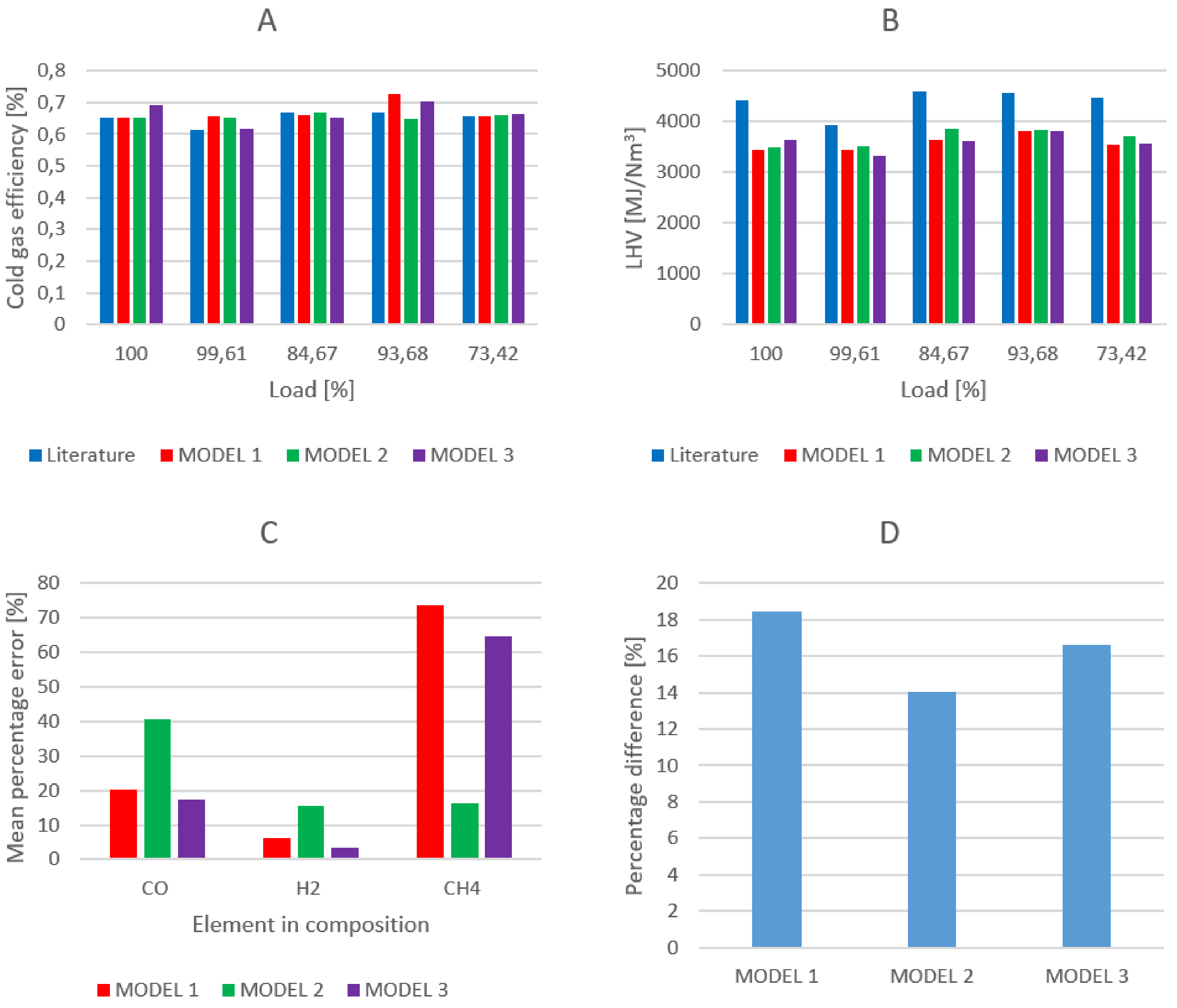

Fig. 8. Comparison of modelling results with literature data P4:
A) gasification process efficiency,
B) calorific value of purified syngas,
C) syngas composition at rated load,
D) comparison of error values in individual models.

Results

Table 5. Models accuracy.

Dataset	Percentage difference [%]		
	MODEL 1	MODEL 2	MODEL 3
P1	10.27	10.59	12.02
P2	20.88	6.11	13.42
P3	14.89	15.49	14.343
P4	18.48	14.05	16.59

Conclusions

- The simplest model (MODEL 1) is based on Gibbs free-energy minimisation. Model preparation and calculations are the fastest. At the same time, they allow for a fairly good representation of the process (data sets P1 and P3). However, using a single temperature value when modelling a fixed-bed gasifier leads to inaccuracies in representing the gas composition (especially CH_4 but also CO and CO_2 concentrations). Omitting the zones with the highest temperatures can lead to an overestimation of the CO_2 fraction relative to CO.
- MODEL 2 is be the most accurate of all models. However, this model relies on constant thermodynamic equations, which must be entered first. This significantly complicates the system and increases the time required for model preparation. At the same time, it provides the best representation of syngas composition due to appropriate reaction coefficients. Hoverer, it can be difficult to transfer values between models of different gasifiers.

Conclusions

- A three-zone model, was slightly less complex and required mainly reaction temperatures which can be measured easily and are reported in the literature. By separately modelling the three reaction zones, it was possible to determine the gas components more accurately, but it was still less accurate than MODEL 2.
- All proposed methods can yield relatively accurate results for energy analyses of gasification systems operating within broader, integrated systems.

Conclusions – limitations

- Models are based on experimental data from literature. Therefore, the modelling considered only the data ranges provided there. The data usually lacks imporant informations such as tars and char production, part of temperatures or syngas compositions.
- To improve the quality and reliability of the study, it is needed to conduct own experimental research, specifically aimed at model validation.