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ShinyEnet: an in-house simulation software for data-driven waste-to-energy gasification and pyrolysis

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ABSTRACT

ShinyEnet is an open-source software tool for modelling waste-to-energy processes, including gasification and pyrolysis. Developed at IT4Innovations, the National Supercomputing Centre of the Czech Republic at VSB - Technical University of Ostrava, it utilizes operational data from experimental facility at the Centre for Energy and Environmental Technologies—Explorer (CEETe), also part of the same university. The software models a modular, mobile, and scalable system that converts waste into gaseous or liquid fuels. ShinyEnet supports dynamic simulation, including component-failure cases, optimization, and scenario analysis. The platform thus facilitates development and assessment of compact and mobile waste-to-energy units and provides tools for addressing municipal waste-management challenges. ShinyEnet is based on real operational datasets, with continuously updated data currently available for the pyrolysis process via real-time monitoring system. The interactive web application is implemented using open-source Python libraries and employs validated historical data and machine-learning models to simulate and optimize system performance.

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Machine learning; hydrogen; pyrolysis; syngas; software; waste-to-energy

1. Introduction

The increasing demand for sustainable municipal waste management has driven the development of waste-to-energy technologies, particularly gasification and pyrolysis (Srivastava et al. 2025; Swami et al. 2025, El Abdellaoui et al. 2025, Brkić et al. 2026). These thermochemical processes enable the conversion of waste into valuable energy resources, contributing to both waste reduction and energy recovery. However, effective design, optimisation, and operation of such systems require reliable and flexible simulation tools capable of capturing complex process behaviour. The system follows a modular data flow architecture consisting of data ingestion, preprocessing, model execution, and interactive visualisation.

The main contribution of this work is the development of an open-source, interactive software tool tailored to municipal waste gasification and pyrolysis. In contrast to previous research, ShinyEnet combines real-time operational data with data-driven modelling and optimisation capabilities within a single platform. A further novel aspect is the use of experimental data acquired from a facility equipped with an advanced pyrolysis data acquisition system, enabling realistic and continuously updated process representation. Despite the availability of various waste-to-energy simulation tools, important limitations remain. Existing solutions are often either general-purpose process simulators that are not specifically tailored to municipal waste gasification and pyrolysis, or specialised models that lack interactivity, optimisation capabilities, and integration with real operational data. In particular, the use of continuously updated experimental datasets in simulation environments is still limited, reducing their applicability for operational decision support and future digital-twin development. To address these challenges, the ShinyEnet software is developed as an interactive virtual modelling tool for municipal waste gasification and pyrolysis processes. The software integrates real operational data obtained from an experimental

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facility operated by the Centre for Energy and Environmental Technologies—Explorer (CEETe) at VSB - Technical University of Ostrava, Czech Republic. It is publicly available as an open-source web application at <https://shinyenet.vsb.cz/> and <https://it4i-energy.github.io/ShinyEnet/>.

At the beginning of the project, it was considered to use standard commercial programmes for processing the required functions and algorithms. After considering the necessary functionality and, above all, the need for further independent scaling and expansion of the programme, it was decided to create our own open product/programme into which it would be possible to enter and implement the necessary data connections and functionality. For this reason, the ShinyEnet platform was created, which meets the required functionality and the possibility of expansion and is primarily focused on the management of technological flows of the circular economy with elements of pyrolysis, hydrogen cells, solar panels and plasma gasification.

The application is implemented in Python as a web-based platform and incorporates machine-learning techniques and optimisation algorithms to represent process behaviour and support decision-making. Additional resources, including a video tutorial and example datasets, are provided in Electronic Annexes A and B.

The system models two key thermochemical processes, gasification and pyrolysis, and enables their optimisation. Gasification converts municipal waste into syngas in the presence of an oxidising agent, typically air, with the product composition depending on temperature and feedstock properties. The modelled gasification system includes a plasma torch, reactor, hydrogen separation and storage, and fuel cells for electricity generation (Gotmare et al. 2026), with syngas components used for power production or co-combustion.

2. Physical model of the observed waste-to-energy facility

The physical model of the observed waste-to-energy facility is described in Brkić et al. (2026). Two key thermochemical processes—gasification and pyrolysis—are included with possibility of their optimisation (Brkić et al. 2026). Gasification and pyrolysis are implemented as separate simulation modules due to their distinct physical models, input parameter sets, and output variables. The optimisation module interacts with both modules based on the user's choice of process to be optimised. In each case, simulation outputs are passed to the corresponding regression models, which are then used to evaluate objective functions during optimisation, with results returned to the user interface in a reactive manner.

Description of the examined waste-to-energy system developed for the Centre for Energy and Environmental Technologies—Explorer (CEETe) which consists of two main physical subsystems: 1) Gasification and 2) Pyrolysis, is given in subsection 2.1 and 2.2. Brkić et al. (2026) give detailed physical descriptions of the both systems.

2.1. Gasification

The gasification module simulates the thermochemical conversion of municipal waste into synthetic gas (syngas) in the presence of an oxidising agent (Júnior et al. 2024; Mikeska et al. 2020; Suyitno et al. 2024), typically ambient air, in contrast to the oxygen-free pyrolysis process. The composition of syngas is influenced by operating conditions, particularly the temperature within the gasification reactor and the characteristics of the waste feedstock. The modelled gasification facility comprises a plasma torch, gasification reactor, hydrogen separation unit, hydrogen storage tanks, and fuel cells for electricity generation, as given in Figure 1.

Produced syngas contains hydrogen (Devarajan et al. 2026; Olugasa et al. 2025), which—after purification can be used for production of electricity in fuel cells (Mahadevan et al. 2026), while the remaining combustible gases, primarily methane and carbon monoxide, are utilised in conventional combustion-based electricity generation when fuel cells are unavailable, with hydrogen optionally co-combusted. In addition to this forward energy pathway, the facility incorporates a reverse operating mode in which electricity from renewable sources, including wind turbines and photovoltaic panels, powers an electrolyser to produce hydrogen from water. These bidirectional and reverse energy pathways (Benmehel et al. 2024; Zeinali et al. 2023) are explicitly represented and simulated within the software model.

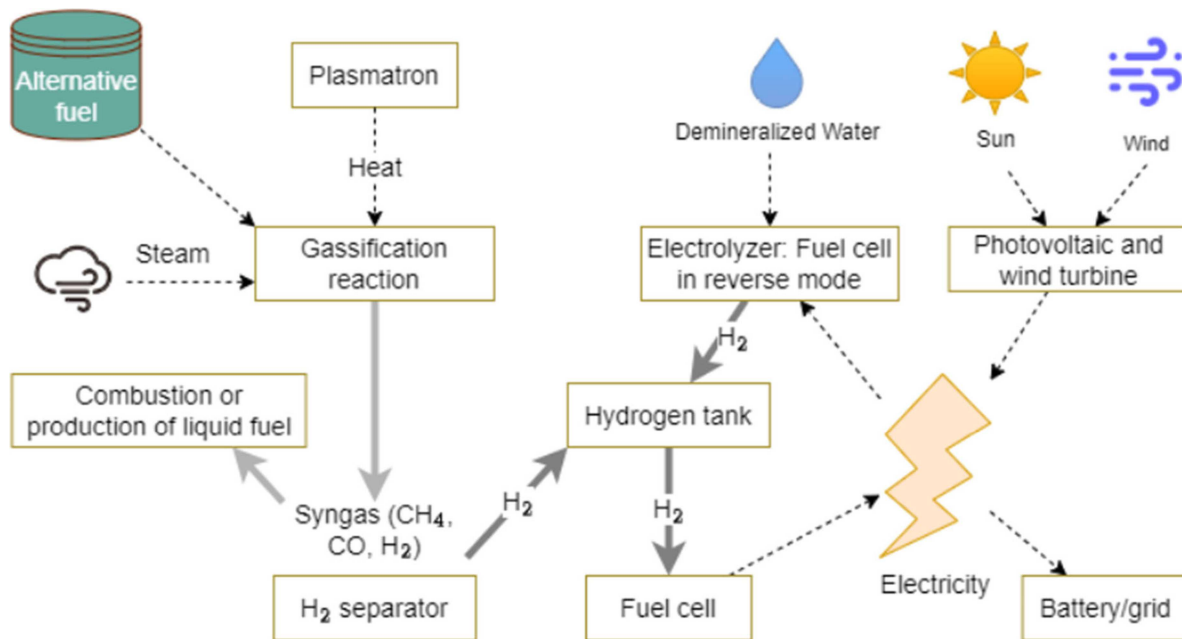


Figure 1. Simplified scheme for gasification process used in the ShinyEnet software.

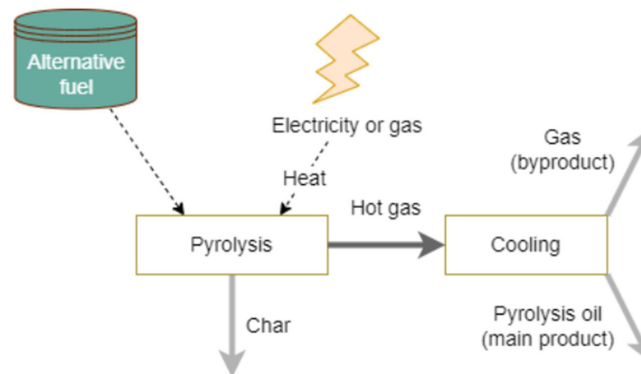


Figure 2. Simplified scheme for pyrolysis process used in the ShinyEnet software.

2.2. Pyrolysis

The pyrolysis module simulates the thermochemical transformation of waste in the absence of ambient air and is primarily optimised for the production of liquid fuel in the form of pyrolysis oil (Chojnacki et al. 2024; Rabet et al. 2026; Shcheklein et al. 2024; Singh, Raizada, and Yadav 2022). In contrast to gasification, pyrolysis involves non-oxidative thermal decomposition, resulting in a syngas byproduct with a distinctly different composition. The pyrolysis facility is equipped with a real-time data acquisition system developed by ABB in Ostrava, Czech Republic, and the collected operational data were used to develop a realistic process model subsequently implemented in the ShinyEnet software. This module focuses on maximising the yield of pyrolysis oil as the principal valuable output [Figure 2](#).

3. Conceptual model architecture for data-driven waste-to-energy application

ShinyEnet is based on real operational datasets derived from historical measurements, combining stoichiometric balances with machine-learning techniques to represent waste-to-energy flows. Process behaviour is modelled using stoichiometric balance equations that comply with the law of conservation of

mass, whereby the total mass of reactants equals the total mass of products. Conversion between mass and volume is performed using molar-mass relationships, enabling accurate modelling of gaseous species in gasification, pyrolysis, and combustion (Athari et al. 2017). Users can configure a variety of parameters, including plasma torch settings and the amount of waste introduced to the system. Outputs are displayed in an interactive graphical interface that integrates dynamical diagrams. The software dynamically recalculates results when parameters are modified, automatically capturing interdependencies across process components.

The software also supports scenario analysis, including simulations of component malfunctions, such as fuel cell failure, that may affect the system interoperability. This capability makes ShinyEnet suitable for both design-stage analysis and operational decision-support. The framework can be readily adapted to support simulations for other waste-to-energy facilities within similar technological configurations. The results obtained using the ShinyEnet software provide value for the planning, development, management, and optimisation of waste-management systems in the Czech Republic as well as internationally.

An integral component of the project involved control and validation studies based on finite element method (FEM) simulations of key components, such as plasma generators and pyrolysis units. These simulations were used to validate functional principles and to identify relevant physical dependencies and governing equations, which were subsequently incorporated in the control and modelling logic of the ShinyEnet application. FEM simulations were conducted using established commercial packages, including COMSOL Multiphysics, ANSYS Maxwell, and ABAQUS/CEA. Existing waste-to-energy simulation tools either lack integration with real operational data or do not support interactive optimisation and scenario analysis in a user-friendly environment. ShinyEnet addresses this gap by combining real-time experimental data, machine-learning-based modelling, and optimisation within an open-source interactive platform tailored to municipal waste gasification and pyrolysis. Several software tools related to this topic have been developed in the Czech Republic, such as GreenMet (www.greenmet.cz), which is commercially available. However, these tools differ substantially in scope and functionality (Kropáč et al. 2011). ShinyEnet is released as open-source software, providing a significant comparative advantage over widely used commercial tools such as Aspen Plus (Ashwini, Resmi, and Reghu 2025; Bhurse et al. 2025; Rekik and El Alimi 2024; Yabandeh et al. 2025, Bouchelkia and Abchiche, 2025).

Based on the physical facilities and the informational/model for waste-to-energy processes, the ShinyEnet software integrates three major functional modules: 1) Gasification, 2) Pyrolysis, and 3) Optimisation. The first two core components of the developed ShinyEnet software correspond directly to the physical modules, whereas the optimisation module is shared by both:

1. **Gasification; subsection 3.1:** Key operational dependencies include the plasma torch temperature which is approximately 1500–2500 °C for the plasma in the combustion reactor and up to 3500–7000 °C for the arc (Marek et al. 2025; Seddik, Shazly, and Eteiba 2024; Sikarwar et al. 2024), determined by the nozzle constant, torch power, and filling pressure, which directly influences syngas composition and hydrogen yield. Electricity generation performance is determined by fuel cell efficiency, lower and higher heating values of the produced gases, and the installed fuel cell capacity. Additional important parameters include hydrogen storage conditions (pressure, volume, temperature) and the extent to which renewable electricity is utilised for electrolytic hydrogen production.
2. **Pyrolysis; subsection 3.2:** Operational inputs are power for heating provided by gas or electricity and amount of waste.
3. **Optimisation; subsection 3.3:** The purpose of optimisation is twofold:
 - to maximise hydrogen production in the gasification subsystem, and
 - to maximise pyrolysis-oil production in the pyrolysis subsystem.

Through these optimisation targets, the software ultimately supports the overarching goal of maximising electricity generation from the combined waste-to-energy system.

The conceptual model architecture for the data-driven waste-to-energy application is given in [Figure 3](#).

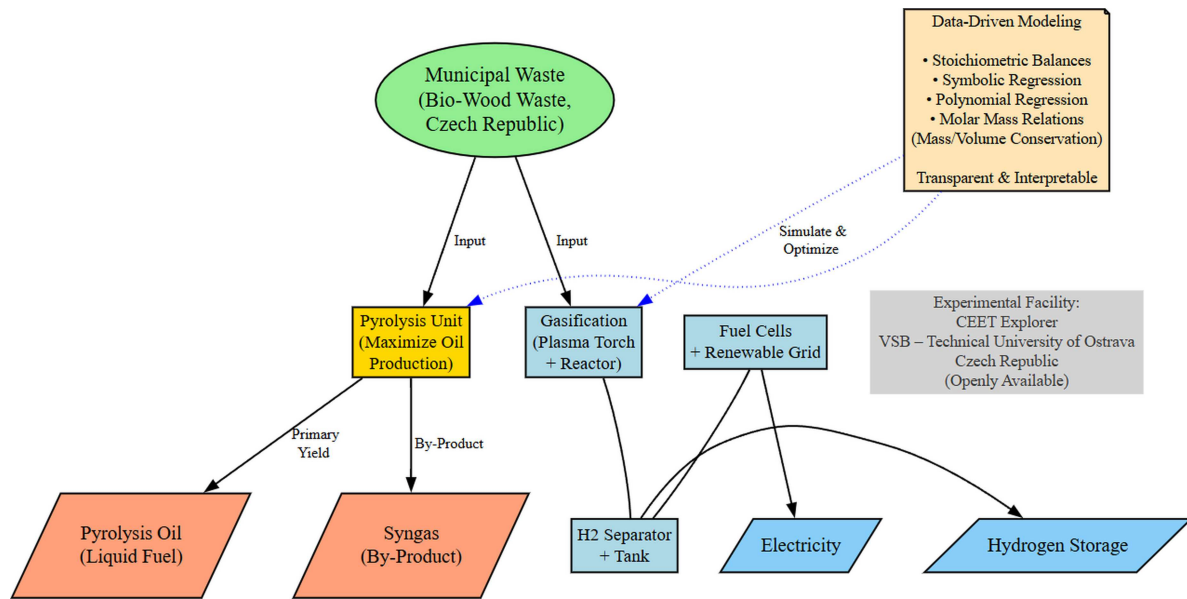


Figure 3. Conceptual architecture of the data-driven waste-to-energy system integrating gasification and pyrolysis at CEETe (VSB - Technical University of Ostrava). Municipal bio-wood waste (green) is processed via a primary gasification subsystem (light blue), optimised for hydrogen generation and electricity production via fuel cells, and a secondary pyrolysis subsystem (gold), optimised for liquid fuel yield. Outputs include clean energy carriers (hydrogen and electricity, sky blue) and carbon-rich products (pyrolysis oil and syngas, orange). A transparent modelling layer (beige) supports simulation and optimisation using stoichiometric balances, symbolic and polynomial regression, and molar mass relations. Dotted blue links indicate informational/model influence rather than material/energy flow.

The ShinyEnet application follows a reactive client–server architecture implemented using Shiny for Python. The system is composed of a user interface (frontend layer) and a server-side computational backend, connected through Shiny’s reactive programming model.

The frontend is defined using Shiny user interface components and is responsible for user interaction. It includes input widgets (parameter selection and configuration controls) and output panels for displaying simulation results, model predictions, and optimisation outcomes.

The backend is implemented in the Shiny server function and contains all computational logic, including the machine learning models implemented as Python functions. User inputs from the frontend trigger reactive server functions. The results of all computations are returned reactively to the frontend, where they are displayed as updated plots, tables, and summary metrics.

Gasification and pyrolysis are implemented as separate simulation modules due to their distinct physical models, input parameter sets, and output variables. The optimisation module interacts with both modules based on the user’s choice of process to be optimised. In each case, simulation outputs are passed to the corresponding regression models, which are then used to evaluate objective functions during optimisation, with results returned to the user interface in a reactive manner.

Input data are specified directly by the user via the interactive web application ShinyEnet. The application enforces data validity for both modelling and optimisation by restricting inputs to predefined, physically meaningful values. Two primary types of input controls are used: option buttons and checkboxes.

An option button allows the user to select a single value from a group of predefined choices. This control is used, for example, when setting gasification parameters, including the nozzle base constant (dimensionless), plasma torch power (kW), filling pressure (bar), and waste input rate (kg/h).

A check box allows the selection of multiple options simultaneously. For example, this control is used in the gasification optimisation procedure, where the user may specify parameters whose values are held fixed during the optimisation process.

The methodological core of ShinyEnet is fully transparent and based on open source resources, integrating regression based and stoichiometric modelling approaches. The interactive web application

enables on demand model training and evaluation, allowing rapid experimentation and comparison of different configurations. The underlying models and validation procedures are described in Brkić et al. (2026).

All developed models, including validation workflows, are provided as open source resources (Brkić et al. 2026), with permanent access via Zenodo (<https://doi.org/10.5281/zenodo.17411891>).

Electronic Appendix A contains an MS Excel tool integrating key thermochemical processes developed at the Centre for Energy and Environmental Technologies—Explorer (CEETe).

Electronic Appendix B provides the file CEET_raw_data_gasification.xlsx, which includes raw datasets from repeated gasification experiments.

Electronic Appendix C ensures full reproducibility of the reported results for bio wood waste from the Czech Republic. The associated Python scripts perform automated regression analysis, five fold cross validation, and generate MS Word reports.

Overall, the architecture of ShinyEnet enables transparent, reproducible, and interactive analysis of complex energy related data, effectively bridging domain specific expertise and machine learning methodologies within a unified web based environment.

Although the ShinyEnet software currently simulates conditions of a specific facility in the Czech Republic, it can be readily adapted to facilities worldwide, thereby supporting municipal heat transition planning (Malacek et al. 2025).

3.1. Software description for gasification module

The simulated gasification facility is versatile, capable of transforming energy from the combustible components of syngas in multiple ways. In the ShinyEnet software, the produced hydrogen is either directed to fuel cells (the main process) or alternative pathways, such as combustion or liquid fuel production, which operate only if the main process is inactive. Currently, use methane and carbon monoxide combustion are modelled as alternative processes (plus alternatively hydrogen).

Structure of the software parts used in gasification is given in Figure 4. Figure 4 presents a schematic of the modelled waste-to-energy system, showing how pyrolysis and gasification units are interconnected. It illustrates the main material flows, including feedstock input and the formation of gas, char, and other products. The diagram also reflects how individual process steps are organised into a unified simulation framework. Overall, it clarifies the structure and interactions within the model used for analysis.

The input parameters for gasification are either 1) Time-independent, and 2) Invariant in time:

- 1) Time-independent gasification parameters are the plasma torch parameters, i.e. the basic nozzle constant, the plasma torch power and the filling pressure (Brkić et al. 2025) which affect the temperature in the gasification reactor, and in final composition of syngas:
 - a) Nozzle base constant [no units]; from 5 to 20,
 - b) Plasma torch power [kW]; from 5 kWh to 15 kWh,
 - c) Filling pressure [bar]; from 3 bar to 8 bar, and
- 2) Time dependent parameter is the amount of waste entering the gasification reactor, which determines the amount and composition of syngas produced; Waste input [kg/hour]; from 1kg/h to 100kg/h.

Plasma torch generates plasma arc which directly provides temperature in gas reactor¹. Software part with gasification reactor provides as an output syngas produced [m³/hour] while its composition can be estimated using symbolic regression and polynomial regression (Brkić et al. 2026; Praks et al. 2022). Composition of syngas is given in Figure 5 (Symbolic regression creates an artificial peak for hydrogen production so use of polynomial regression curves is recommended in this case). The monitored variable is the time it takes to fill the container.

Figure 5 presents the model outputs and their comparison with experimental or reference data, highlighting how well the simulation reproduces real process behaviour. It typically shows key variables (such as gas composition, temperature, or product yields) across operating conditions. It illustrates trends

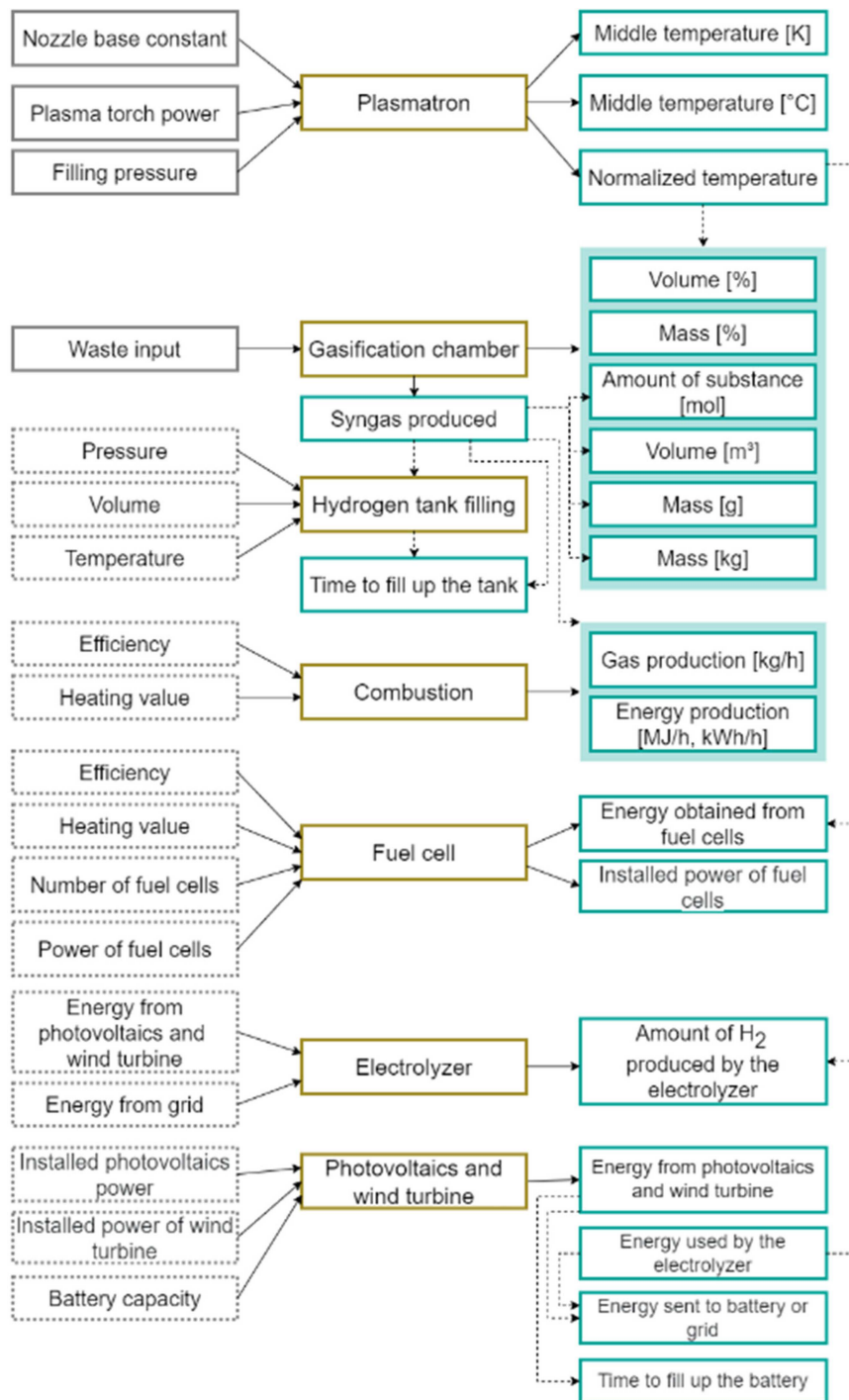


Figure 4. Structure of the software parts used in gasification.

and deviations, allowing assessment of model accuracy and reliability. Overall, it demonstrates the validation and predictive capability of the developed model.

Based on the volume of tank, pressure and temperature inside it, and based on already provided parameters above gives as an output: Time to fill up the tank [hours].

An alternative process of gasification is combustion, for which the efficiency and heat value can be adjusted. These parameters affect the amount of gas produced per hour and consequently the energy production. Combustion as an alternative process operates only when production of electricity in fuel cells is closed. Efficiency of combustion can be from 20% to 100%. Its part in the software is given in Figure 6.



Figure 5. Composition of syngas; Select an option can be in Volume [%], Volume [m³], mol, Mass [%], Mass [g], and Mass [kg].

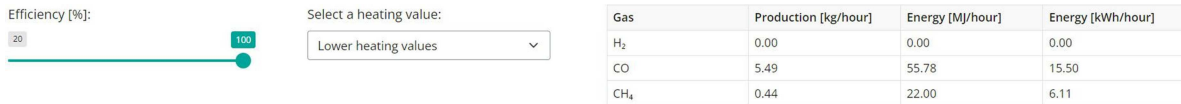


Figure 6. Combustion; Lower or Higher Heating Value can be chosen.

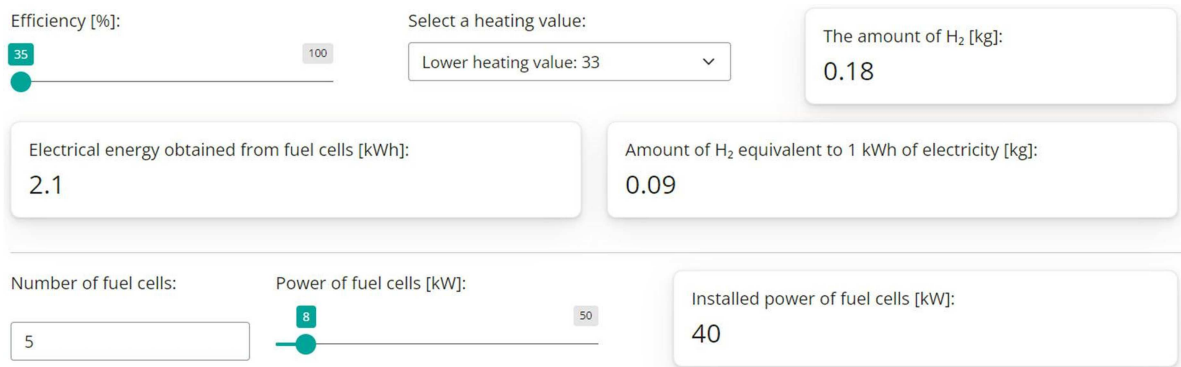


Figure 7. Fuel cell part of the software.

Combustion is treated as a supporting process that complements pyrolysis and gasification by providing the necessary heat for endothermic reactions. A portion of the produced gases, char, or auxiliary fuel is oxidised with a controlled air supply, generating high-temperature flue gases. This heat is transferred to the reactor, sustaining stable operation of the overall waste-to-energy system. The combustion stage is therefore not the main objective, but a thermal driver ensuring energy balance and process efficiency.

The parameters of a fuel cell are the efficiency and the heat value, which affect the amount of energy obtained. The number and power of the fuel cell indicate the installed power. Fuel cell part of the software is given in Figure 7. Fuel cells are used as the main technology for converting hydrogen-rich syngas into electricity. Hydrogen produced during gasification is separated and fed into fuel cells, where it is electrochemically converted into electrical energy. This pathway is preferred over direct combustion due to its higher efficiency and lower emissions. Thus, fuel cells represent the core element of the primary energy conversion process in the modelled system.

The electrolyser receives electricity from photovoltaic panels and wind turbines or from the grid. This energy is converted into hydrogen. The electrolyser works in reverse compared to fuel cells—it produces hydrogen from water and electricity. Its part is given in Figure 8. Electrolysers serve as a complementary source of hydrogen by converting electricity into hydrogen through water electrolysis. The produced hydrogen can be stored and later used in fuel cells for electricity generation. This improves system flexibility and energy storage. However, electrolysis plays a secondary role compared to hydrogen produced via gasification.

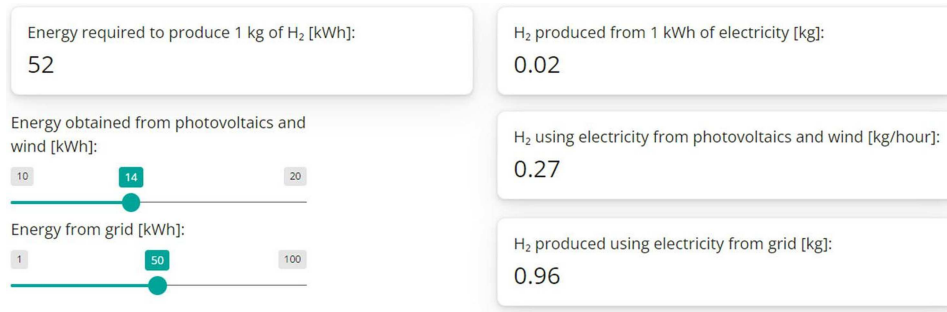


Figure 8. Electrolyser part of the software.

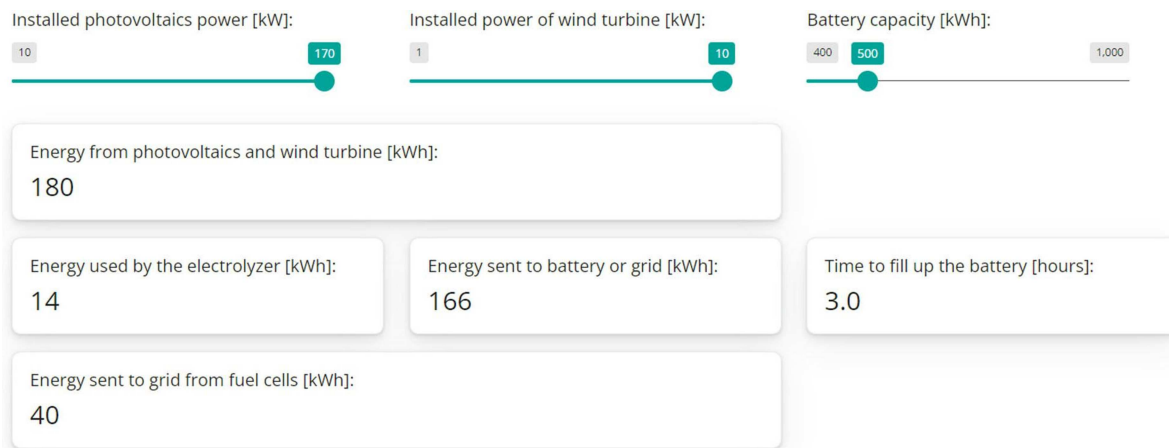


Figure 9. Electricity from photovoltaic panels and wind turbines.

The energy from solar panels and wind turbines is determined by the installed capacity of the photovoltaic system and the installed capacity of the wind turbine (Arashrad et al. 2025). Part of the energy is used by the electrolyser, part is sent to batteries or the grid. The time needed to recharge a battery depends on its capacity. Photovoltaic panels and wind turbines provide electricity to the battery and electrolyser. This part in the software is given in Figure 9. Photovoltaic panels and wind turbines are used as renewable electricity sources supporting the waste-to-energy system. They supply electrical energy to operate key components such as the electrolyser and other auxiliary systems. This reduces dependence on external grid electricity and improves the overall sustainability of the facility. In addition, their intermittent surplus energy is stored in batteries to balance system operation.

3.2 Software description - pyrolysis

The proposed pyrolysis system has input variables: 1. Time-independent and 2. Invariant in time;

1. Energy to maintain pyrolysis process [kWh]; from 3.3kWh to 9kWh, and
2. Waste input [kg/hour]; from 2kg/h to 5kg/h.

Outputs are given in Figure 10, and are amount of produced gas, liquid (pyrolysis oil as the main product) and tar, while composition of gas is also given (gas is here byproduct). The proportions depend on operating conditions such as temperature and heating rate. These products are then used in other parts of the system for further energy recovery.

To support future digital twin implementation, the ABB Pyrolysis Data Pipeline application has been developed to assist pyrolysis operators and researchers with comprehensive management of data

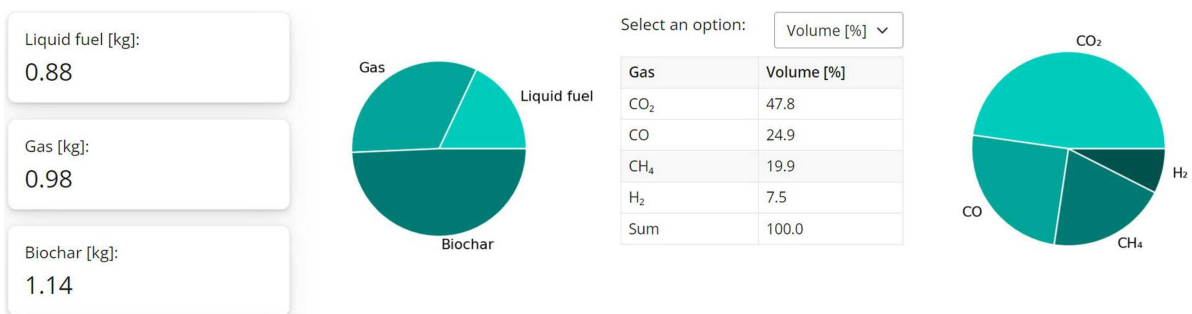


Figure 10. Output of pyrolysis.

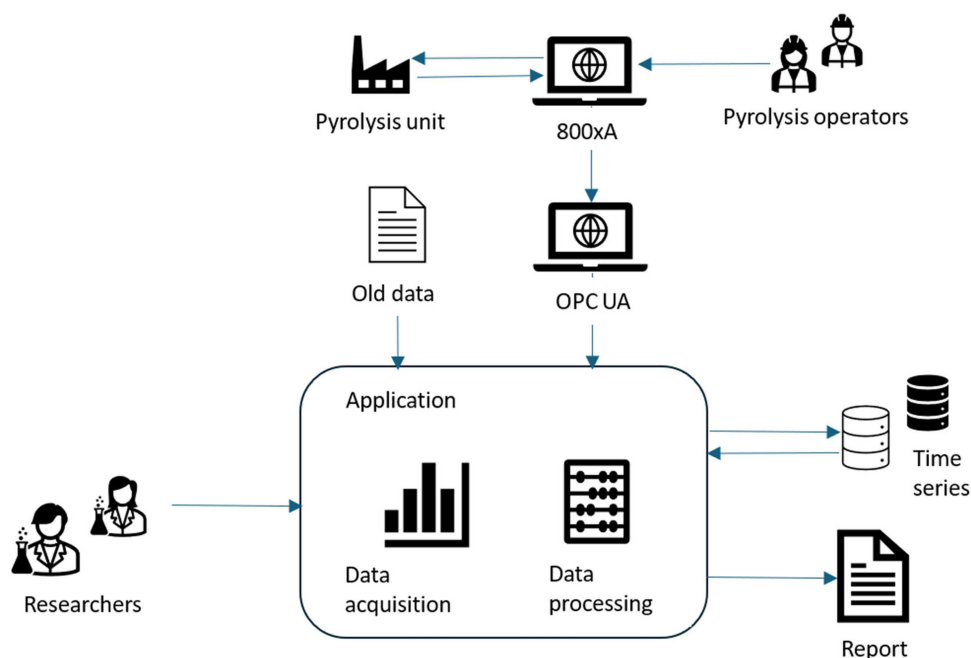


Figure 11. Automated collection of data from pyrolysis facility provided by ABB.

acquisition, interpretation, and reporting. The term ‘digital twin’ refers to a virtual representation of a thermochemical process that leverages real-time sensor data, such as process temperature and power input, to simulate, predict, and analyse key output parameters, including product composition, weight percentages, and calorific value. Machine learning will be integrated into the system to continuously improve the digital twin’s predictive capability. As a result, the model outputs will closely approximate the data obtained from the actual technology. Key functionalities include initiating and halting data acquisition, describing and visualising measured signals, selecting subsets of signals, comparing experimental datasets, generating structured reports, and importing/exporting data in CSV format. The application interfaces with a pyrolysis facility controlled by the ABB 800xA system, which exposes real-time data via an OPC UA interface as given in Figure 11. All acquired data is stored in a PostgreSQL database enhanced with the TimescaleDB extension, enabling efficient time-series data handling and historical data retrieval (Electronic Annex B).

The software architecture of ABB comprises a Flask-based backend API and a Grafana-powered frontend, offering interactive dashboards for acquisition control, data annotation, and comparative analysis. Users can annotate measurements with metadata such as fuel type, weight, and experiment timestamps, facilitating reproducibility and cross-experiment comparisons, Figure 12. Reports are



Figure 12. Data acquisition dashboard during active measurement of pyrolysis provided by ABB, green curve represents Pressure, yellow represents Temperature and blue represents Water Level.

automatically generated in DOCX format and stored on a shared network drive, supporting collaborative workflows.

An example of the pyrolysis datasets is given in Electronic Annex B. Sheets, named according to the experimental temperature in degrees Celsius, store data recorded by the programmable logic controller (PLC) and the gas-analysis system:

- TemperatureT—PLC temperature and operational records
- TemperatureG—gas-composition curves

The meaning of the individual columns in PLC data file (TemperatureT) is described in Table 1. The columns in the gas-composition sheet (TemperatureG) represent the volume concentrations of individual gas species, each determined using the corresponding analytical detector.

3.3. Software description: optimisation

The optimisation tasks addressed in ShinyEnet are formulated as box-constrained numerical optimisation problems defined over physically meaningful parameter ranges (Topolanek et al. 2023). Accordingly, two independent optimisation problems are considered in ShinyEnet. Gasification optimisation is defined over three design variables: the nozzle base constant, plasma torch power, and filling pressure, whereas pyrolysis optimisation is defined as a one-dimensional problem governed by the energy input parameter. In both cases, objective function values are evaluated using validated regression models representing the respective thermochemical processes.

For pyrolysis, the main goal is to maximise liquid fuel (pyrolysis oil) yield, which is the most valuable condensable product. Operating conditions are therefore tuned to enhance volatilisation and condensation

Table 1. The meaning of the individual columns in PLC data file (TemperatureT.xlsx).

Column on file	Id	Time	Description	Identifier	Time
_121A_EH01_AVG_IO_SignalValue			Average temperature of the EH01 element		
_121A_EH03_AVG_IO_SignalValue			Average temperature of the EH03 element		
_121A_EH02_AVG_IO_SignalValue			Average temperature of the EH02 element		
_121A_PT01_PV_IO_SignalValue			Pressure (kPa) on PT01 sensor		
_121A_PT03_PV_IO_SignalValue			Pressure (kPa) on PT03 sensor		
_121A_PT04_PV_IO_SignalValue			Pressure (kPa) on PT04 sensor		
_121A_TT01_PV_IO_SignalValue			Temperature (°C) on thermocouple TT01		
_121A_TT02_PV_IO_SignalValue			Temperature (°C) on thermocouple TT02		
_121A_TT03_PV_IO_SignalValue			Temperature (°C) on thermocouple TT03		
_121A_TT04_PV_IO_SignalValue			Temperature (°C) on thermocouple TT04		
_121A_TT05_PV_IO_SignalValue			Temperature (°C) on thermocouple TT05		
_121A_TT07_PV_IO_SignalValue			Temperature (°C) on thermocouple TT07		
_121A_TT06_PV_IO_SignalValue			Temperature (°C) on thermocouple TT06		
_121A_LT01_PV_IO_SignalValue			Amount of raw fuel in hopper (%vol.)		
_121A_TT08_PV_IO_SignalValue			Temperature (°C) on thermocouple TT08		

of hydrocarbons while controlling char and gas formation. Together, these complementary objectives support an integrated system optimised for both hydrogen and liquid fuel production.

Optimisation in ShinyEnet software can have two goals:

1. Maximisation of amount of hydrogen as a goal in gasification - [Figure 13](#), and
2. Maximisation of amount of pyrolysis oil (liquid fuel) in pyrolysis - [Figure 14](#).

The optimisation module in [Figures 13](#) and [14](#) is used to find the best operating conditions of the simulated waste-to-energy system. It systematically varies key process parameters (such as feed composition, operating temperatures, or conversion efficiencies) to maximise or minimise a chosen objective function, typically energy output or efficiency. The module is based on an iterative search approach, evaluating multiple simulation runs and comparing their results. It helps identify optimal configurations for gasification and pyrolysis. In this way, it supports decision-making by improving overall system performance and resource utilisation.

For gasification in [Figure 13](#), the main goal is to maximise hydrogen-rich syngas production, since hydrogen is the primary energy carrier used downstream (e.g. in fuel cells). This involves adjusting conditions such as temperature and oxidant supply to favour hydrogen formation.

For pyrolysis in [Figure 14](#), the main goal is to maximise liquid fuel (pyrolysis oil) yield, which is the most valuable condensable product. Operating conditions are therefore tuned to enhance volatilisation and condensation of hydrocarbons while controlling char and gas formation.

Together, complementary objectives of optimisation in gasification and pyrolysis support an integrated system optimised for both hydrogen and liquid fuel production.

PySR package ([Cranmer 2023](#)) was used for symbolic regression models, and scikit-learn ([Hao and Ho 2019](#)) for polynomial regression models.

4. Deployment of the ShinyEnet web application

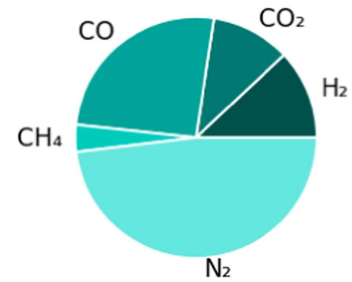
ShinyEnet is provided through two complementary deployment approaches to ensure accessibility and flexibility for users. [Subsection 4.1](#) describes the server-based deployment on dedicated Linux infrastructure using Shiny Server, while [subsection 4.2](#) presents a server-less alternative enabled by Shinylive, in which the application runs entirely within the user's web browser. Together, these approaches support both traditional hosting and browser-native execution. The performance evaluation is summarised in [subsection 4.3](#).

4.1. Server-based deployment architecture of the ShinyEnet application

This section describes the deployment of ShinyEnet software, which is available online at <https://shinyenet.vsb.cz/>.

The current choice of parameters:

Parameter	Value
Nozzle base constant	8.9
Plasma torch power [kW]	10.0
Filling pressure [bar]	5.0
Volume of H ₂ [%]	11.99



Optionally, choose a parameter and its value to be fixed during the optimization process:

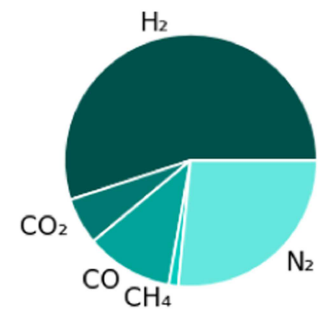
- Base constant of the nozzle
- Power of the plasma torch
- Filling pressure

(a) Inputs

Start optimization

The optimization results:

Parameter	Value
Nozzle base constant	5.6
Plasma torch power [kW]	12.9
Filling pressure [bar]	4.5
Volume of H ₂ [%]	55.04



Use the optimized values

Reset the optimization

(b) After optimization

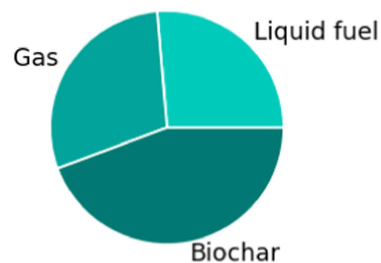
Figure 13. Maximisation of amount of hydrogen as a goal in gasification.

The application is served via Shiny server (<https://posit.co/download/shiny-server/>) on a Linux Virtual Machine (VM) running Rocky Linux 9.5. Shiny server is configured as a system process that is launched automatically whenever the VM boots and is dedicated to serving the ShinyEnet application.

The Linux VM is protected by a firewall and it is not directly accessible from the public Internet. To make it accessible, it runs reverse proxy providing running on another machine and taking care of communication encryption through HTTPS protocol. In addition to Shiny server, the VM also runs Shiny Proxy (<https://www.shinyproxy.io/>), which hosts several Shiny applications written in R.

The current choice of parameters:

Parameter	Value
Energy [kW]	5.0
Liquid fuel [kg]	0.88

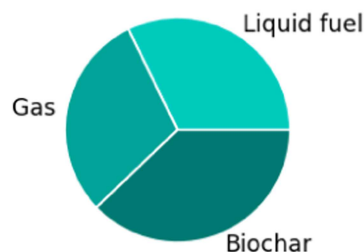


(a) Inputs

Start optimization

The optimization results:

Parameter	Value
Energy [kW]	3.3
Liquid fuel [kg]	0.97



Use the optimized values

Reset the optimization

(b) After optimization

Figure 14. Maximisation of amount of pyrolysis oil (liquid fuel) as a goal in pyrolysis.

The Python-based Shiny application (Brun, Janée, and Curty 2025) is served via Shiny server rather than Shin Shiny Proxy due to compatibility issues between ShinyProxy and the reverse proxy configuration. While ShinyProxy reliably serves R-based Shiny applications, certain HTTP headers and resources required by Python-based Shiny applications were not consistently forwarded to web clients, resulting in incomplete page rendering. Deploying the application via Shiny Server resolved these issues.

The computational workload of the server-based deployment remains moderate, as no large datasets are processed during application runtime. All computations are executed on the server side, thereby minimising client-side resource requirements. The deployment operates behind an HAProxy instance that enables load balancing across multiple server processes, allowing the system to scale dynamically with increasing user demand while maintaining stable performance.

4.2. Server-less deployment of shiny applications using shinylive

Traditionally, Shiny applications require a active Python process running on a backend server, as described in Section 4.1. To enable a fully serverless deployment in which the application executes locally in the web browser, Shinylive is used. With Shinylive, no backend server is required, and the application can be deployed as static web content. The ShinyEnet application is hosted via GitHub Pages at <https://it4i-energy.github.io/ShinyEnet/>.

In this deployment model, all computations are performed locally within the user's browser environment. Although the range of Python libraries supported by Shinylive is expanding, at the time of writing this manuscript Shinylive does not support the Pymoo optimisation algorithms (Blank and Deb 2020). Consequently, optimisation tasks are implemented using a ShinyEnet-specific Python library within the Shinylive environment.

A limitation of the serverless approach is the initial loading overhead: during the first visit, several megabytes of the Python runtime must be downloaded to the browser. Although this payload is cached for subsequent visits, the initial startup introduces a noticeable delay, as discussed in Section 4.3.

Due to the constraints of the Shinylive execution environment, a lightweight genetic algorithm was additionally implemented entirely in pure Python to perform optimisation tasks directly within the browser. The algorithm initialises a population of 200 candidate solutions uniformly within predefined variable bounds. Each generation applies tournament selection (size three), blend crossover with probability 0.5, and Gaussian mutation with probability 0.2 per individual and per decision variable, with mutation variance scaled to 10% of the parameter range. Elitism implicitly preserves the globally best solution, and the algorithm terminates after a fixed number of generations (100 for gasification and 200 for pyrolysis). The H₂ objective additionally uses large penalty values (1×10^{12}) to avoid numerical instabilities such as division by zero or invalid logarithms.

Despite these limitations, Shinylive represents an attractive deployment alternative. The application executes securely within the browser's sandboxed environment, and because all processing occurs locally, sensitive user data remain on the client device and are never transmitted to a remote server.

4.3. Performance evaluation

The performance of ShinyEnet was evaluated for both deployment variants. The two approaches differ primarily in their execution environments and optimisation frameworks.

In the server-based deployment, optimisation is implemented using the evolutionary optimisation framework pymoo. Although pymoo is primarily designed for multi-objective optimisation, the current implementation treats each maximisation task independently by minimising the negated objective function subject to the corresponding constraints. This formulation reflects the independent treatment of pyrolysis and gasification within the ShinyEnet framework while preserving a unified optimisation architecture and enabling straightforward future extension toward simultaneous multi-objective optimisation.

In contrast, the serverless deployment executes the ShinyEnet application in the web browser using Shinylive and Pyodide, a Python interpreter compiled to WebAssembly. Because pymoo depends on compiled C++/Cython extensions and additional heavy dependencies that are incompatible with the Pyodide execution environment, it cannot be used in this context. As a result, the serverless deployment employs the custom, pure-Python genetic algorithm described in Section 4.2.

From a performance perspective, the server-based version becomes available almost immediately upon user access, as the execution environment is persistently available. The serverless Shinylive deployment requires approximately 13 seconds for initialisation due to browser-side environment startup overhead. Once initialised, interactive operations proceed without perceptible latency. For both deployment strategies, optimisation procedures complete in approximately four seconds on average. Comparable behaviour was also observed when accessing the application via a mobile Android web browser, indicating adequate performance across both desktop and mobile platforms.

5. Conclusions

The presented open-source ShinyEnet software combines stoichiometric mass-balance modelling with regression techniques to support data-driven waste-to-energy analysis. By integrating process modelling, optimisation, and renewable-energy coupling, ShinyEnet provides a transparent and scalable approach for evaluating waste-to-energy systems. Model correctness is validated through predefined regression workflows and cross-validation procedures (Brkić et al. 2026). The open-source nature of the platform enables full replicability and reproducibility, supporting independent validation within the Czech Republic, across Europe, and internationally.

The developed software enables user-friendly simulation of compact, mobile, and robust waste-to-energy facilities suitable for a wide range of energy-community stakeholders, including industrial operators and local municipalities. Its modular architecture and reliance on widely used technologies, such as Python, Pandas, NumPy, and Shiny for Python, support extensibility, transparency, and long-term maintainability.

The deployment strategy adopted for ShinyEnet further enhances both its scientific relevance and practical usability by providing a readily accessible, web-based environment for modelling and simulation of key waste-to-energy processes. From a scientific perspective, the ShinyEnet web application enables researchers to efficiently explore gasification and pyrolysis scenarios without requiring complex local software installations or dedicated experimental infrastructure, thereby facilitating transparent and reproducible computational studies. From a practical perspective, the deployment significantly lowers technical barriers for end users such as municipalities and process operators. Municipal decision-makers can rapidly evaluate alternative waste-to-energy configurations for planning purposes, while gasification and pyrolysis operators can simulate different operational conditions to support informed decision-making and process assessment. Overall, the here presented deployment approach bridges advanced data-driven modelling with real-world applicability and use and easy access for diverse stakeholders.

Future research will focus on enhancing the acquisition, management, and interpretation of operational data, which is essential for the digitalisation of waste-to-energy processes. Planned developments include deeper integration with the online pyrolysis database to support real-time data sharing, cross-experiment analysis, and broader accessibility for researchers and practitioners. These efforts are closely aligned with the digital-twin paradigm in smart energy systems, which emphasises data-driven design (Brkić et al. 2026), continuous system monitoring (Arashrad et al. 2025; Devarajan et al. 2026), and dynamic optimisation of operational processes (Devarajan et al. 2026; Swami et al. 2025).

At present, validation is limited to a single experimental facility at the VSB - Technical University of Ostrava. Future studies should therefore evaluate the proposed approach across multiple installations to assess its scalability and transferability. In addition, the current results are based on experimental data derived from wood-based pallets typical of Central Europe, which may limit the direct generalisation to other waste types or regional compositions. To address these limitations, future work will expand the experimental database by incorporating additional fuel categories and operating conditions. Because ShinyEnet is provided as open-source software, its underlying machine-learning models can be retrained and recalibrated using new datasets, enabling adaptation to diverse waste-to-energy applications and improving model robustness and generalisability.

Endnote

1. The arc temperature is expressed in [K], only because this unit is standard in technical documentation, whereas the reactor temperature is typically reported in [°C]

Author contributions

CRedit: **Dejan Brkić**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing; **Judita Buchlovská Nagyová**: Conceptualization, Data curation, Software, Validation, Visualization, Writing – original draft, Writing – review & editing; **Tomáš Martinovič**: Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing; **Renáta Praksová**: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing; **Lukáš Vojáček**: Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing; **Jan Najser**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing – original draft, Writing – review & editing; **Jan Kielar**: Conceptualization, Data curation, Formal analysis, Methodology, Software, Supervision, Validation; **Václav Bolom**: Data curation, Methodology, Software; **Martin Marek**: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing; **Michal Běloch**: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing; **Pavel Praks**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Disclosure statement

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Data availability statement

Data is available within the Zenodo repository under the CC BY 4.0 license at <https://doi.org/10.5281/zenodo.18989200>:

1. The software presented in this study simulates real facilities installed at the Centre for Energy and Environmental Technologies – Explorer (CEETe) of VSB - Technical University of Ostrava (<https://ceet.vsb.cz/en/CEETe/>). The developed software is accessible at: <https://shinyenet.vsb.cz/>. To support transparency, reproducibility, and open science, the complete open-source codebase is released under the CC BY 4.0 license: The code repository is publicly accessible at https://github.com/IT4I-Energy/ShinyEnet/tree/main/app_python.
2. The open pyrolysis datasets used in this work are available in Electronic Annex B. These datasets originate from the CEETe pyrolysis facility and include temperature-resolved Programmable Logic Controller (PLC) logs and gas-composition measurements, enabling detailed analysis and replication of the experiments.

Use of AI tools declaration

During the preparation of this work, the authors used Microsoft Copilot to revise sentences and Grammarly for grammar and spelling check. After using these tools, the authors reviewed and edited the content as needed. The authors assume full responsibility for the content of the publication.

Supplementary

Available in <https://doi.org/10.5281/zenodo.18989200>:

Electronic Annex A: Video tutorial for use of this software (without sound).

Electronic Annex B: Datasets from the CEETe pyrolysis facility: Programmable Logic Controller (PLC) logs with temperature and composition measurements.

A preprint version of this work is available on Research Square (DOI: [10.21203/rs.3.rs-9622800/v1](https://doi.org/10.21203/rs.3.rs-9622800/v1)).

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