<u>Supplementary File S1</u>

Theoretical Economic Model

For the current scenario, a monetary value is allocated to each material and energy stream available in the thermochemical system. The total cost flow rate related to the total exergy flow rate of nth material is represented by $\dot{C}_n^T$, which can be divided into the relevant cost rate components associated with physical ($\dot{C}_{PH}$) and chemical ($\dot{C}_{CH}$) exergies.

$$\dot{C}_n^T = \dot{C^n}_{PH} + \dot{C^n}_{CH} \tag{S1}$$

Eq. A 1 can be rewritten as

$$\dot{C}_n^T = c_n^T \dot{\psi}_n^T = c_n^{PH} \dot{\psi}_{PH}^n + c_n^{CH} \dot{\psi}_{CH}^n \tag{S2}$$

Here, c represents the average cost per exergy unit, whereas the superscripts *T, PH*, and *CH* denote the total, physical, and chemical.

The average cost of fuel (pellets) ($c_{F,l}$) and product ($c_{P,l}$) for the lth component are represented by the cost rate required to provide each exergy flow rate unit of fuel ($\dot{\psi}_{F,l}$) to the lth component or the rate of generated exergy of the product ($\dot{\psi}_{P,l}$).

$$c_{F,l} \equiv \frac{\dot{C}_{F,l}}{\dot{\psi}_{F,l}} \tag{S3}$$

Likewise, for the product stream:

$$c_{P,l} \equiv \frac{\dot{C}_{P,l}}{\dot{\psi}_{P,l}} \tag{S4}$$

The total cost of the product/output stream is estimated by equating it with the total cost imposed on the input stream along with the investment and operating and maintenance charges. Since, for the given system, the unit received electric power (W) through the variable transformer and heat transfer by the joule heating system (Q), then it can be represented by Eq. (A 5):

$$\sum_{j=1}^N \dot{C}_j^T = \dot{C}_W + \dot{C}_Q + \sum_{i=1}^n \dot{C}_i^T + \zeta - \sum_{l=1}^{l=k} \dot{C}_{L,l}^T \tag{S5}$$

Here, $\dot{C}_{L,l}^T$ is the cost rate associated with the exergy loss stream at the lth component.

The additional parameters that can help to understand the exergoeconomics of the system are the relative change in the average cost of fuel and product (I) and the exergoeconomic factor (O_l), which is the ratio of the cost involved in the operation and maintenance to the total cost incurred due to the exergy destruction and exergy loss in the lth component.

$$I \equiv \frac{c_{P_l} - c_{F_l}}{c_{F_l}} \quad \text{or} = \frac{\zeta_l}{c_{F_l}\dot{\psi}_{P,l}} + \frac{1 - \eta_{II,l}}{\eta_{II,l}} \tag{S6}$$

The reciprocal of the second term ($\frac{\eta_{II,l}}{1 - \eta_{II,l}}$) exhibits the impact of the exergetic efficiency on the capital investment in a particular component.

$$O_l = \frac{\zeta_l}{\zeta_l + c_{F_l}\left(\varepsilon_{D_l} + \varepsilon_{L_l}\right)} \tag{S7}$$

Here**,** the total annual cost related to the lth is denoted by ζ_l, which can be related to the sum of costs associated with the capital investment ($\zeta_{C,l}$) and operation and maintenance (O&M), $\zeta_{OM,l}$ [1].

$$\zeta_l = \zeta_{C,l} + \zeta_{OM,l} = (\rho_l + \phi_l)\mu_l + \delta_l \tau \dot{\psi}_{P,l} + \chi_l \tag{S8}$$

Here, ρ_l, ϕ_l, μ_l, δ_l, τ, and χ are the capital recovery factor, the fraction of O&M that can be affected by $\zeta_{C,l}$, the constant related to the variable levelized cost of O&M, the annual operation time of the unit at its nominal capacity, and the miscellaneous cost that is independent of $(\rho_l + \phi_l)\mu_l$ and $\delta_l \tau \dot{\psi}_{P,l}$, respectively.

Metrological information

Tar measurement

As a solvent, isopropanol was used to collect the pyrolysis oil, which was distilled through a rotary evaporator (RVO 400, Boeco). The sampling technique used in the measurement is non-isokinetic, which is usually considered when the temperature of the gas is higher than 350 °C and the tar is in a gaseous stage. To distil the isopropanol, the vacuum pressure and temperature of the water bath are, respectively, kept at 0.137 bar and 60 °C in a rotary evaporator. The decanter was allowed to undergo 70 revolutions per minute till no further condensation of isopropanol was observed. The vacuum pressure and revolution are subjected to change, and it relies on the viscosity of oil and the quantity of the substrate being distilled. The vacuum pressure must not be low to avoid any accidents with RB flasks.

Processing of pine waste

Around 4 kg of pine waste underwent milling in a 1.5 kW rotor milling machine (six-disc rotor) (Retsch SM 2000). The material was allowed to pass through the hopper of size 80 × 80 mm. The feed rate and the selection of the hopper depend on the moisture content and the size of the processing material. For pine waste, it was kept between 200 and 300 g/h. The material was ground up to 1.5 mm; however, the relative fineness required to densify the feedstock might change the category of the pellet machine used for the compacting purpose. The multifunction analyzer was used to determine the power consumption with an accuracy of ± 0.5% during densification, crushing, and heating of the raw feedstock in the pellet machine, grinder, and muffle furnace, respectively. The insulation voltage of the equipment was noticed to be 3.70 kVAC for 1 min. After milling the pine waste, the moisture content was measured to estimate the binding ability for pelletization. Once moisture content was measured, around 110 mL/kg of water was added to the fine powder of feedstock. The moisture content should be around 10 – 15 % so that it can be heated up to 70 °C in the pellet machine. During the process, the temperature of the pellet die was kept between 49 °C and 60 °C. The densification was performed using a machine with a ring die (CL3, California Pellet Mill).

After the densification process, the pine pellets were thermally pretreated in the modified furnace for 10 minutes at 250 °C. The power consumption of a single-phase furnace was measured by the Energy Logger 400 (Volt craft). The digitally programmed furnace was provided with a modified lid, which provided two ports to allow for the inert carrier gas to drive away the volatile products from the furnace. After reaching the desired temperature, the nitrogen gas is simultaneously allowed to flow from the ports. Once the heated air is expelled from the chamber, the processed pellets are slowly injected into the vessel available at the other end of the cylinder. To measure the mass variation during torrefaction, the vessel is connected to the strain gauge through a mechanical link.

References

[1]   Tsatsaronis, G. (1993). Thermoeconomic analysis and optimization of energy systems. Progress in Energy and Combustion Science, 19(3), 227–257. https://doi.org/10.1016/0360-1285(93)90016-8