OPTIMISING FLEXIBLE PYROLYSIS PATHWAYS FOR CLIMATE NEUTRALITY

Meritxell Domènech Monfort[i1], Taco Niet[2], Niklas Hartmann[1]

meritxell.domenech@hs-offenburg.de, taco_niet@sfu.ca, niklas.hartmann@hs-offenburg.de

[1] *Institute of Sustainable Energy Systems, Offenburg University of Applied Sciences, Offenburg, Germany*

[2] *Simon Fraser University, Surrey, British Columbia, Canada*

Introduction

The integration of biomass conversion technologies is gaining increasing relevance in the transition towards a climate-neutral energy system [1]. Among these technologies, pyrolysis represents a promising and flexible option, as it enables the simultaneous production of energy carriers and biochar. Depending on the configuration and processing steps, biomass pyrolysis can deliver heat, electricity, bio-oil, and hydrogen, while also providing negative emissions through the stable carbon stored in biochar [2, 3]. From an energy system perspective, this combination of **multi-output production and carbon sequestration** makes pyrolysis especially attractive for sector coupling and cross-sectoral decarbonisation. A new modelling approach has been developed that represents the **flexibilization of pyrolysis outputs**, enabling dynamic switching between heat, electricity, oil, hydrogen, and biochar production depending on system demands and cost-optimal operation.

Methodology

The modelling framework has been developed to represent the flexibility of pyrolysis outputs within a sector-coupled energy system. This approach was implemented by extending PyPSA-Eur, which enables pyrolysis to dynamically select different output pathways depending on the conditions of the system and the optimal cost.

The pyrolysis process is modelled as a sequence of interconnected conversion steps that together form a **multi-output technology**. Each step is represented by a set of PyPSA links, which convert one energy carrier into another while respecting mass and energy balances. In Figure 1, a sketch of the proposed pyrolysis is showed. Biomass enters the pyrolysis unit, where it undergoes thermal decomposition under low-oxygen conditions. This process produces **biochar**, which provides negative emissions, and **hot syngas** containing condensable vapours. The syngas can either be combusted directly to supply heat or routed through a **condenser**, where bio-oil and other liquids are separated, and the remaining gas is sent to cleaning and storage. The resulting **bio-oil** is stored and can be used in three ways: upgraded into synthetic fuels using Fischer-Tropsch, sent to a cogeneration unit to produce heat and electricity, or combusted directly to provide heat. The **clean syngas** stored after condensation can be dispatched flexibly. It may be used in direct combustion for heat, sent to a syngas-fired cogeneration unit for combined heat and electricity production, or processed in a pressure swing adsorption unit to separate hydrogen. The extracted **hydrogen** is supplied to the H_2 sector, while the pressure swing adsorption left over gas is stored and can again be used for combustion or cogeneration.

This modular representation allows pyrolysis to flexibly shift between producing heat, electricity, hydrogen, upgraded fuels, and biochar. All pathways operate in parallel, enabling the energy system optimisation to determine the most valuable output mix in each hour.

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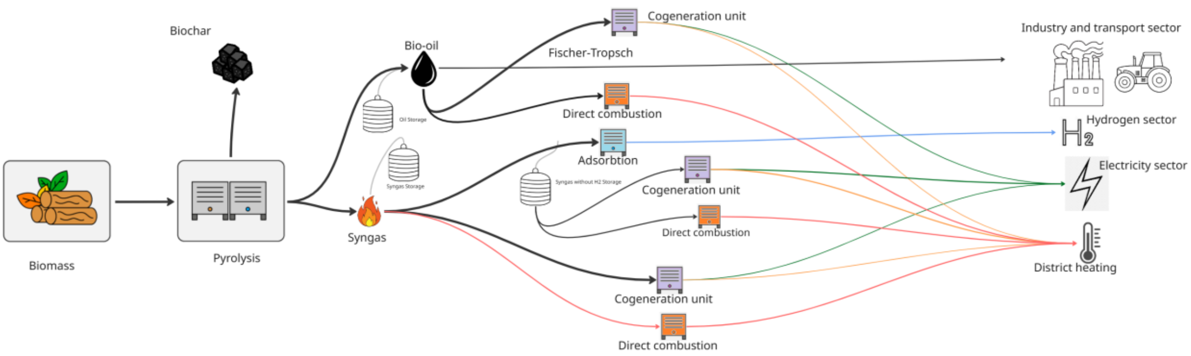

Figure 1: Sketch of the flexible pyrolysis.

Results

The integration of flexible pyrolysis leads to a **reduction in total system costs**. This cost decrease results from two factors: (i) pyrolysis provides an additional heat source with negative emissions, which reduces the need for more expensive decarbonisation options, and (ii) the flexible output allocation allows the system optimiser to use biomass more efficiently across sectors. The system adopts pyrolysis primarily as a **heat-driven technology**, with the majority of syngas flows directed towards direct combustion or cogeneration, as observed in Figure 2. As a result, pyrolysis contributes around **3% of total heat production**. As pyrolysis is producing heat for district heating, it reduces the need for centralised thermal infrastructure in urban areas; specifically, the system deploys **fewer large hot-water storage tanks** and **fewer central air-source heat pumps**. Both technologies become less critical once pyrolysis provides a stable and dispatchable heat supply. In the hydrogen sector, flexible pyrolysis decreases the reliance on steam methane reforming with carbon capture (SMR-CC), as hydrogen can be co-produced through the pressure swing adsorption route. Finally, the presence of flexible pyrolysis eliminates the need for BioSNG-CC (biomass-derived synthetic natural gas with carbon capture). In scenarios without pyrolysis, part of the available biomass is routed to BioSNG-CC for synthetic natural gas production. However, once flexible pyrolysis is included in the system, this biomass is instead redirected to the pyrolysis pathways, where it can be used more efficiently and with higher system value. This demonstrates that flexible, multi-output conversion systems provide a more cost-effective use of limited biomass resources than single-output gasification technologies.

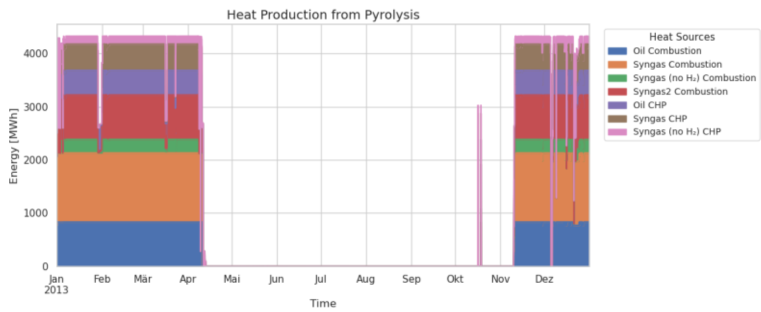

Figure 2: Heat production from pyrolysis.

References

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