IEA Bioenergy
Technology Collaboration Programme

Direct Thermochemical Liquefaction (DTL) Technology Options for BECCS

IEA Bioenergy: Task 34

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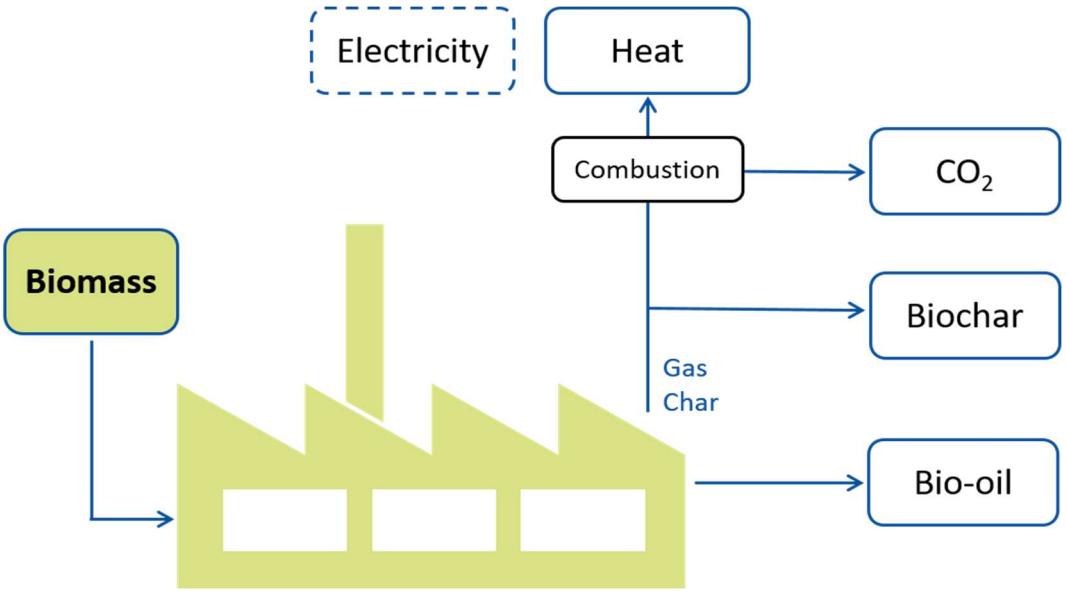

Direct Thermochemical Liquefaction (DTL) Technology Options for BECCS

WP4 Case Study Report

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Contribution of IEA Bioenergy Task 34 to Strategic Inter-Task Project Management of biogenic CO_2: BECCUS Phase 2

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Abbreviations

AC	Aqueous Condensate
BECCS	Bioenergy with Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CHP	Combined Heat and Power
DTL	Direct thermochemical liquefaction
FPBO	Fast Pyrolysis Bio-Oil
HTL	Hydrothermal Liquefaction
HHV	High Heating Value
HVO	Hydrotreated Vegetable Oils

Preface

Bioenergy combined with carbon capture and utilisation or storage, also known as bio-CCUS or BECCUS is a concept that has been discussed in climate change mitigation research for quite some time. However, implementation has only become the subject of serious consideration within governments and private actors within the last 5 years. The reasons for this are largely related to four factors that are somewhat entwined: a) an emerging awareness of the need for BECCS and other negative emissions technologies in order for governments to reach net-zero targets, b) increased interest in buying carbon negative or neutral products and value of biogenic CO_2, c) rising CO_2 prices, and d) the rapidly decreasing costs of electricity generation from solar & wind (and expectations of similar developments for electrolysers) that have made BECCU options based on power-to-X technologies more cost-effective.

In light of this, identifying and implementing approaches for how BECCUS systems can be deployed and integrated in ways that maximise benefits in terms of climate change mitigation - as well as in terms of energy system integration and sustainability ambitions more broadly - is highly important.

THE IEA BIOENERGY STRATEGIC PROJECT ON BECCUS

In 2019 the IEA Bioenergy TCP initiated a strategic project on bioenergy carbon capture, utilisation and storage (BECCUS) in order to understand the concept and opportunities for deployment. The project involves several of the IEA Bioenergy Tasks and is led by Task 40 (Deployment of biogenic value chains and carbon management)[1]. The project has evolved to a multi-annual research project, in which the findings of each project phase led to new research question for a next phase. Details on the project focus in the different phases are presented below, and more information on the BECCUS project can be found on Task 40's website.[2]

Phase I (2019-2021)

During the 2019-2021 triennium, IEA Bioenergy Task 40 worked together with Task 36 (Material and Energy valorisation of waste in a Circular Economy), Task 44 (Flexible Bioenergy and System Integration) and Task 45 (Climate and Sustainability Effects of Bioenergy within the Circular Bioeconomy) on a strategic project called *Deployment of BECCUS value chains* that focused on understanding the opportunities for, and obstacles to, deployment of BECCUS in different sectors. Focus was on trying to cut across the full set of factors that determine successful deployment, from technology readiness, to business model viability and design of policy and regulatory frameworks.

Phase I findings

Factors determining successful deployment of BECUSS include technology readiness, business model viability, upstream supply chain set up, and current and expected public policy design. The investigations indicate that while the majority of the required individual BECUSS technology components can largely be considered proven, there is still R&D needed into finding models for on-the-ground deployment. Supply chain set up and possibly alterations of existing supply chain concepts are important. Many concepts are looking for viable business

[1] An overview of all Tasks of IEA Bioenergy TCP is found here: https://www.ieabioenergy.com/our-work-tasks/

[2] https://task40.ieabioenergy.com/inter-task-project-bioenergy-with-carbon-capture-storage/.

models for the captured carbon. Thus far, the focus is on utilising rather storing the carbon. Lack of governance with corresponding support measures and regulations for carbon storage pose a challenge. A synthesis report summarising phase I findings (Olsson, et al., 2022), as well as publications covering case studies topical reports, and system studies can be found on the IEA Bioenergy strategic project on BECCUS phase 1 website.[3]

Phase I suggestions for further work

Research and development are still required to identify models of on-the-ground deployment that make the most sense from techno-economic and climate perspectives. This includes aspects such as specific designs, deployment scales and choice of site locations. In addition, there are many questions remaining when it comes to process and supply chain integration as well as policy design and implementation. Answers to the above questions can assist in addressing key and most complex questions, i.e., *in a given situation should biogenic CO_2 be sequestered, or utilised? Which type of facilities (i.e., bioenergy installations) shall best provide BECCS and/or BECCUS under certain criteria (economics, CO_2 emissions mitigation potential etc.)? What are the main challenges for commercialising BECCUS projects and the lessons learnt thus far? How to monetise the carbon negative products that bioenergy can deliver? How to govern the different energy system services when targeting a high level of CO_2 emissions mitigation? And related to this, what factors and parameters should guide this decision-making process?*

Phase II

Phase II of the BECCUS project is more diverse in its scope, with a stronger emphasis on cross-sector and cross-country learning about implementation of BECCUS projects using different energy conversion processes. A further goal is to shed some light on the effects of the integration of BECCUS facilities and systems within the overall energy system and its interaction with other energy system services. In addition, although we tend to refer to "BECCUS" as a unified concept, we also emphasise and analyse the important differences between BECCS and BECCU, not least from the perspective of potential business models and policy development. An understanding of the impacts of BECCUS on overall climate system in terms of potential for CO_2 mitigation is addressed and all different aspects covered are analysed jointly and policy recommendations provided. This approach allows for a systemic consideration of how to take different BECCUS applications to deployment, thereby building upon, but going beyond, Phase I. In this second phase of the BECCUS project, besides the Tasks already participating in Phase 1, Tasks focused on conversion technologies become involved as well: Task 32 (Biomass Combustion), Task 33 (Biomass Gasification) and Task 34 (Direct Thermal Liquefaction).

Phase III (2025-2027)

While the current report is part of the Phase II work, preparations for Phase III have been initiated. Overall biochar, biorefineries, first-of-its-kind projects, permanence of storage and the BECCS/BECCU potential and financing are foreseen as central themes. Further examples for case studies look to potentially include: BECCUS for biogas installations, BECCUS with novel capture technologies e.g. oxyfuel, H_2 from biomass with CCS, BECCS with decentralised storage solutions, BECCUS with mixed feedstocks, CCU from the chemical industry, and further small- to medium scale BECCS installations.

[3] https://www.ieabioenergy.com/blog/task/deployment-of-beccus-value-chains/

Introduction

The traditional concept of bioenergy with carbon capture and storage (BECCS) is based on biomass combustion for the provision of heat and power and an integrated capture of CO_2 from the emitted flue gases. Significant carbon containing waste streams/ byproducts also emerge during conversion of biomass to biofuels, be it directly as CO_2 or as solids that represent the biomass fraction unsuitable for biofuel production (e.g. distillers dried grains with solubles from ethanol production, seed expeller from oil extraction for the production of HVO (Hydrotreated Vegetable Oils), lignin from lignocellulosic fractionation etc). Some of these carbonaceous byproducts represent high value products e.g. as animal feed while others, e.g. CO_2, can be readily used to enable carbon dioxide removal (CDR) from the atmosphere. For the case of direct thermochemical liquefaction as relatively new established commercial process[4], there are varying possibilities on how to achieve CDR with its products.

Table 1 summarizes the carbon content of the products from fast pyrolysis and also exemplary uses. Fast pyrolysis bio-oil (FPBO) as main product can be directly used as boiler fuel or biobased commodity to further produce advanced fuels and chemicals. It has been proposed to sequester the bio-oil in geological deposits[5], which might be beneficial since it exhibits a similar carbon content as the original biomass and is thus higher than that of e.g. CO_2. While this gives the impression of replenishing natural oil resources, it is highly likely that the FPBO will further react in the deposits to form solids once thermodynamic equilibrium is achieved over time.

[4] https://task34.ieabioenergy.com/commercial-status-of-dtl-technologies/
[5] Schmidt, H.-P. et al. Pyrogenic carbon capture and storage. *Global Change Biology Bioenergy* 2019, 11: 573-591; https://charmindustrial.com/

Table 1: Carbon content of products from fast pyrolysis and a selection of potential uses.

	Carbon content (w/w)	Use
FPBO	~50%	Fuel, chemicals
Char	~75%	E.g. soil amendment, construction material, activated carbon
Gas (CO_2)	27%	Power-to-X

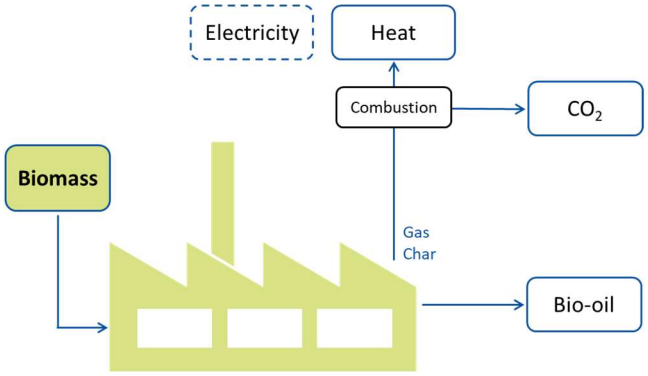

Figure 1: Scheme of a common concept for a commercial fast pyrolysis unit

Char produced from fast pyrolysis can be utilized in several ways. It has the potential to combine use and carbon sequestration, which directly reduces the cost for the achieved carbon dioxide removal e.g. when the char is used for soil amendment[6]. Char could theoretically also be sequestered in geological deposits. Finally, pyrolysis gas is typically combusted on site and the resulting CO_2 available to be captured from the resulting flue gas. The technical challenge to do so is comparable to biomass combustion, i.e. primarily related to flue gas impurities and scale of the flue gas volume flow.

This report aims at discussing these different alternatives for DTL technologies and how they relate to the process, namely fast pyrolysis and hydrothermal liquefaction (HTL). For the case of fast pyrolysis, quantitative data is provided to better assess the underlying potential.

[6] https://www.news.iastate.edu/news/2022/04/22/xprizemilestone

Fast Pyrolysis

Any pyrolysis process produces solid, liquid, and gaseous product fractions, whose distribution vary depending on process conditions and type of feedstock. Fast pyrolysis aims at maximizing liquid yields to recover a product termed 'fast pyrolysis bio-oil' (FPBO), which is a registered and standardized fuel for industrial scale boilers[7]. The solid by-product char and the remaining pyrolysis gas are typically combusted within the process to provide both the required heat to run the fast pyrolysis process and external heat (which is sometimes used in an integrated combined heat & power unit). This reduces the products to FPBO, heat (and electricity) while emitting CO_2 (and ash) from internal combustion.

When considering a different use of the solid and gaseous by-products other than an energetic use, one needs to be aware of the fact that typical measurements of pyrolysis gas (H_2/ CO_2/ CO/ CH_4) do not identify light volatiles (primarily water, but also C2 to C6 oxygenated compounds), that are also significantly present in the gas flow (see *Figure 2*). Knowledge of these volatiles is frequently determined by adding a low temperature condensation step and analysing the recovered condensate.

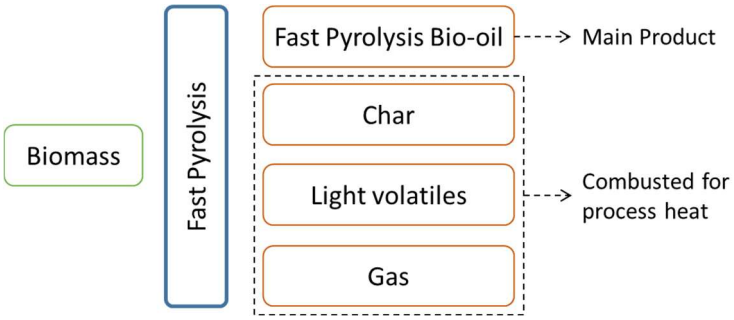

Figure 2: Products from fast pyrolysis of biomass

To differentiate between the different products, the term 'fast pyrolysis bio-oil' (FPBO) will be used for the fraction that is recovered in the first condensation step (typically between 60-110°C) and that is traded under the same name, and 'aqueous condensate' (AC) for the light volatiles, which remain uncondensed in most commercial installations so that they can be efficiently burnt together with char and other combustible gases.

FAST PYROLYSIS PROCESS CALCULATIONS

Basis for the mass balances presented in this report is a set of comparative fast pyrolysis experiments using fractional condensation at 90°C and 20°C with beech wood, poplar wood, a wood blend, and wheat straw with very high ash content (12.9%) as feedstocks[1]. The advantage of this data for the present study lies in the fact that a) all product fractions are identified in the yields, including char and the vapours that are typically burnt internally in commercial installations and b) it provides a consistent set for both a reference wood material and a feedstock with high ash content (i.e. wheat straw). The mass yield of FPBO for

[7] https://task34.ieabioenergy.com/dtl-brochure/

wood is at the lower end of the typically reported 50-75% in this field (see *Table 5*); however, this can be explained with the applied condensation temperature of the first stage (90°C) which is higher than the ones more frequently used (60-70°C). A more important measure in this context is the energy contained in the FPBO, and those results are fully in line with the Empyro industrial fast pyrolysis unit used as base for this case study, i.e. approx. 60% of the feedstocks energy is recovered with the FPBO[8]. It is also noted that the reported yields of wheat straw are largely in line with data reported from a similar demonstration facility with a feedstock capacity of around 2 MW. This opens the opportunity to rely on product characteristics (e.g. HHV, composition) observed from long term continuous operation, that are different from shorter runs due to replacing initial start-up material. The experimental mass yield data has been proportionally adjusted to meet 100 %, i.e. full mass balance closure (see *Table 5*).

Focus of this study is placed on the combustion of the by-products namely gas, char, and AC together with the use of the released heat from combustion. Heat for pyrolysis process demand was subtracted from the heat supplied by combusting by-products and the remaining heat is used to run a Rankine cycle. Live steam parameters of the Rankine cycle integrated into the fast pyrolysis process were assumed to be 400°C/ 40 bar due to its comparably small capacity. Backpressure operation of the steam turbine was assumed with steam outlet of 113°C/ 1.5 bar so that process steam for external use can be generated. Details of the process simulations are available in a separate publication; however, in this case for a different feedstock/ mass balance distribution[9]. Additional process model data/ assumptions are summarized in the Appendix to this report.

The reference simulation case resulting from this study is presented in *Table 2*. The energy recovered with the main product is 54.4% and thus slightly lower than figures presented for the commercial installation (60%)[8]. In the simulated case, also less heat is available for external use (6.5 MW as opposed to 7.7 MW) despite the fact that the energy balance is slightly overestimated. These observed differences might be easily explained with assumptions for the heating values of the products, heat demand for the pyrolysis process and heat losses with the flue gases. They are considered acceptable based on the limited data available to align process parameters/ assumptions.

[8] https://itp-hightemperatureheat.ieabioenergy.com/wp-content/uploads/sites/14/2020/10/CS3_T34_-High-temperature-heat-from-pyrolysis-oil-final.pdf, last accessed August 24th, 2023

[9] Sen, U. et al. Fast Pyrolysis of the Waste Lignocellulosic Phloem Fraction of Quercus Cerris Bark in a Twin-Screw Reactor. *Biomass Conversion Bioref*, 2024, 15: 10251-10260;

Table 2: Simulation results for fast pyrolysis of wood. FPBO is the fraction condensed at 90°C, aqueous condensate (AC) is condensed at 20°C.

	Mass (kg/h)	Energy (MW)	Carbon (kg/h)
Biomass	4812.8	25.0	2387.2
FPBO	2454.5	13.6	1227.3
AC	673.8	0.7	29.2
Gas	1010.7	5.6	391.5
Char	673.8	5.4	519.5
Sum Out	4812.8	25.4	2167.5

ASSESSMENT OF CARBON SEQUESTRATION POTENTIAL

Since the carbon content of the co-produced char is much higher than for the main product FPBO, in sum almost 50% of the carbon contained in the original feedstock ends up in the by-products (see *Table 2*). This represents a significant potential for creating carbon dioxide removal from biomass that translates into -70 $g_{CO2}/MJ_{Product}$. The proportion of char in relation to the main product FPBO is increasing with ash content of the feedstock, which is a well-known relationship based on catalytic activity of primarily alkali metals during pyrolysis. For the case of ash-rich feedstocks the carbon yield in the byproducts increases to around 60%, which translates into a carbon dioxide removal potential of -150 $g_{CO2}/MJ_{Product}$. Consequently, a highly carbon negative biofuel can be achieved from fast pyrolysis of biomass.

One straightforward solution to achieve this carbon dioxide removal is the capture of CO_2 from the flue gases of process internal combustion of these by-products[10]. Combustion of these by-products is state-of-the-art in commercial fast pyrolysis units to sustain the process and deliver external heat. Capturing CO_2 from the flue gases is comparable to BECCS concepts based on biomass combustion to generate combined heat and power in lower MW scale. It

[10] The non-condensed gases already contain up to 50% CO_2 before process internal combustion and could potentially directly be tapped for carbon capture. Currently, this represents more of a theoretic potential since all commercial facilities combust the non-condensed gas.

would not even require substantial changes to the design of the fast pyrolysis process itself.

Table 3: Results for fast pyrolysis of wheat straw. FPBO is the fraction condensed at 90°C, aqueous condensate (AC) is condensed at 20°C.

	Mass (kg/h)	Energy (MW)	Carbon (kg/h)
Biomass	5421.7	25.0	2320.5
FPBO	1664.1	9.2	832.0
AC	751.5	0.8	32.6
Gas	1342.0	6.1	508.2
Char	1664.1	8.3	832.0
Sum Out	5421.7	24.4	2204.9

Another option would be to separately recover char from the fast pyrolysis. Recovering char from fast pyrolysis is not an established commercial process as of today but has been demonstrated at TRL 6-8[11]. It contains 22% of the original feedstock carbon (36% for the case of wheat straw) which translates into a carbon dioxide removal potential of -40 $g_{CO2}/MJ_{Product}$ (for the case of wheat straw -90 $g_{CO2}/MJ_{Product}$). Consequently, the heat from process internal combustion is reduced due to the missing mass flow of char into the combustion chamber. While the available heat from gas/ light volatiles combustion appears to be sufficient to even provide some additional heat for external offtake, the low amount of generated power most likely renders the integration of a Rankine cycle economically unfeasible (see *Table 4*). Thus, separate recovery of char seems only reasonable if an added value can be created together with a permanent carbon storage (such as e.g. the use for soil amendment).

In summary, the results from these calculations indicate that it appears most promising to keep process internal combustion in case there is a local offtake for the heat because this

[11]Niebel, A. et al. Fast Pyrolysis of Wheat Straw—Improvements of Operational Stability in 10 Years of Bioliq Pilot Plant Operation. *Energy & Fuels* 2021, 35: 11333-11345; https://groupeonym.com/; https://biogas-energy.com/

way the maximum carbon dioxide removal potential is achieved most easily. At the same time, separately recovering the char allows for fast pyrolysis units to be placed in locations with little to no local heat offtake while still enabling carbon dioxide removal through permanent char uses. While capturing CO_2 from the combustion of the remaining by-products is technically still possible and will allow for approaching the maximum carbon dioxide removal potential, whether or not this can be realized is a question of local infrastructure and available CO_2 capturing technology at the required, comparably low scale of around 1-1.5 MW.

Table 4: Energy from fast pyrolysis integrated CHP unit. Heat for the CHP is provided by combustion of all fast pyrolysis by-products (char, gas, and aqueous condensate). At 0%, only gas and aqueous condensate are combusted.

Amount of char burnt	100%	80%	50%	0%
Wood				
Power (kW)	1181.8	997.9	701.1	205.1
Heat (kW)	5335.8	4505.3	3165.5	925.8
Wheat Straw				
Power (kW)	2582.6	2134.1	1458.0	274.9
Heat (kW)	11660.0	9635.0	6582.7	1240.9

Hydrothermal liquefaction

Due to very low solids production, HTL transforms most of the initial feedstock mass to biocrude while 15-45% is vented with the gas phase with high concentration of CO_2[12]. The importance to capture the CO_2 contained in the gas phase is comparable to the case of fast pyrolysis and has been recognized by recent scientific activities. The decisive difference to the flue gas emitted by commercial fast pyrolysis installations is the high concentration of

[12] Lozano Sanchez, E. et al. Techno-economic evaluation of carbon capture via physical absorption from HTL gas phase derived from woody biomass and sewage sludge. *Energy Conversion and Management: X* 2021, 11: 1000897708-7726

CO_2 (>60 %[13]) in the gas phase leaving the HTL reactor while H_2 and CH_4 make up most of the remaining composition. Direct absorption of CO_2 from this gas phase appears interesting prior to other uses of the remaining gas compounds (e.g. combustion). Some concepts evolve around capturing the remaining H_2 to integrate hydrotreatment of the produced biocrude and additionally produce methanol from the captured CO_2[13,14].

The use of the solid by-product from HTL, sometimes referred to as hydrochar, is still subject to research[14].

Conclusions

In contrast to biomass combustion for the provision of combined heat and power together with carbon capture and storage, biomass conversion to liquid (or gaseous) products inevitably leads to the fundamental conflict whether to maximize carbon use or carbon storage because only carbon losses during conversion can be captured for storage. The case of direct thermochemical liquefaction is a perfect example to showcase the decision between carbon use and storage because there are applications where the main liquid product itself is used to store carbon.

Even though it is technically possible to store the liquid product from fast pyrolysis and that some advantages could be associated with doing so (pumpability, high carbon content, replenishing geologic carbon sources), it ultimately appears to be an inefficient process for achieving CDR. Bio-oil from fast pyrolysis contains only around 50% of the carbon contained in the original feedstock or even less for ash rich material (in contrast to almost 100% for the case of BECCS based on biomass combustion). At the same time, it represents a biobased commodity suitable to replace fossil resources for the provision of fuels and carbon materials. Unless the priority to replace fossil fuels has been addressed adequately[15], bio-oils should be used in this manner and the focus on carbon storage should be set on by-products, which in sum also contain around 50% of the carbon contained in the original feedstock.

Capturing the CO_2 from the flue gases of pyrolysis internal combustion is a readily available option to realize CDR from fast pyrolysis for all by-products generated because they are already combusted internally in existing installations to provide heat. It can be expected that adding carbon capture technology to such a unit has comparable challenges to a ~10 MW biomass combustion unit (in terms of scale and handling flue gas impurities). This option is expected to have lowest impact on design and operation of the fast pyrolysis process.

Alternatively – or additionally – char can be separately recovered to enable uses that also realize carbon sequestration, such as e.g. soil amendment. While this improves economic viability of the CDR method, it also represents process changes and additional investment to

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[13] Lozano Sanchez, E. et al. Integrated e-Methanol and Drop-in Fuels Hydrothermal Liquefaction Platform - Techno-Economic and GHG Emissions Assessment for Grid-Connected Plants under Flexible BECCU(S) Operation. *Industrial & Engineering Chemistry Research* 2024, 63: 7708-7726

[14] https://project-circulair.eu/

[15] Baldwin-Cantello, W. et al. The Triple Challenge: Synergies, Trade-Offs and Integrated Responses for Climate, Biodiversity, and Human Wellbeing Goals. *Climate Policy* 2023, 23: 782-99.

realize them. This might prove an interesting option especially in cases where onsite heat offtake from internal combustion is not possible.

Consequently, combining the potential of FPBO to replace fossil resources with carbon capture of by-products represents a highly efficient approach. Depending on the type of feedstock, there is the potential to reduce the CO_2 intensity of the produced bio-oil by -70 $g_{CO2}/MJ_{Product}$ for relatively clean wood and -150 $g_{CO2}/MJ_{Product}$ for ash rich residues without affecting its application to also replace fossil fuels and achieving CO_2 emission savings from doing so.

Appendix: Process model assumptions

The capacity of the considered case was set to match the well described case of Empyro, i.e. 25 MW_{th} biomass input. The mass flow of each feedstock under consideration was adjusted as to meet this capacity using experimental HHV values from the associated pyrolysis runs.

Fast pyrolysis in an endothermic reaction and the heat required to run the process is typically supplied by combusting byproducts. The heat for pyrolysis requirements could be potentially estimated by the process simulation tool (by enthalpy difference of product and feed). In the approach used here, values derived from experiments are used that have been transparently documented in literature[16]. They agree well for the case of beech wood as feedstock (10% deviation); but only one of them reported a value for wheat straw. Preference was given over using values from the consistent approach within one study so that changes are reflected better.

To evaluate the energy and carbon flows associated with the byproducts, several distinct product characteristics were used. The char was characterized by ash, carbon, and hydrogen content in conjunction with pyrolysis experiments used for this study[17]; however, these values remained unpublished until now and are presented in *Table 5*. On a dry, ash-free basis, carbon content of beech wood and wheat straw derived chars are comparable (around 88%). The oxygen content of the chars was determined by difference Ash+C+H+O=100%. The gas composition of the uncondensed pyrolysis gas was used as reported in the previous publication[17]. Composition of the aqueous condensate is unknown for the experiments that are used as basis for this case study. From experience in a demonstration scale facility, it is known that water content of this product fraction is around 81% for wheat straw as feedstock[18]. This value is also used for the present calculations and it is assumed that the remaining 19% can be reasonably well represented by acetic acid, one of the major compounds found in this condensate. These are relatively coarse assumptions, which are still reasonable for the purpose of this study due to the little influence on the energy/ carbon balance of this product fraction.

All calculations have been conducted for water free feedstock, i.e. integrated drying prior to reactor is assumed.

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[16] Kornmayer, C. Verfahrenstechnische Untersuchungen zur Schnellpyrolyse von Lignocellulose im Doppelschnecken-Mischreaktor. PhD-Thesis, Universität Fridericiana, Karlsruhe, 2009; Daugaard, D. E.; Brown, R. C., Enthalpy for pyrolysis for several types of biomass. Energy Fuels 2003, 17, 934-939.
[17] Funke, A.; Tomasi Morgano, M.; Leibold, H.; Dahmen, N., Experimental Comparison of Fast and Intermediate Pyrolysis. J Anal Appl Pyr 2017, 124, 504-514.
[18] Niebel, A.; Funke, A.; Pfitzer, C.; Dahmen, N.; Weih, N.; Richter, D.; Zimmerlin, B., Fast Pyrolysis of Wheat Straw—Improvements of Operational Stability in 10 Years of Bioliq Pilot Plant Operation. Energy & Fuels 2021, 35 (14), 11333-11345.

Table 5: Input data for process simulation

	Wood	Straw
Yield FPBO[17]	51%	31%
Yield AC[17]	14%	14%
Yield Gas[17]	21%	25%
Yield Char[17]	14%	31%
Heat for pyrolysis[16]	1.32 MJ/kg	1.25 MJ/kg
Carbon content FPBO (as received)	50.0%	50.0%
FPBO HHV	20.0 MJ/kg	20.0 MJ/kg
%Water in AC[18]	81%	81%
Char characteristics (dry)		
%Ash	11.7	43.5
%C	77.1	50.0
%H	2.8	1.7
Gas composition[17]		

	Wood	Straw
CO_2	41	55
CO	39	26
H_2	6	4
CH_4	9	8
C2+	5	7
Carbon content biomass[17]	49.6%	42.8%
Feedstock HHV[17]	18.7 MJ/kg	16.6 MJ/kg
Steam in turbine	400°C/ 40 bar	
Steam out turbine	113°C/ 1.5 bar	
Condenser out	101°C	

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