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PROJECT NEWSLETTER

Fuel-Up

Powering a Greener Future for Aviation and Marine Transport

We are pleased to share the third issue of FUEL-UP newsletter, keeping you up to date with the latest updates and activities implemented by the project. FUEL-UP – *Production of advanced biofuels via pyrolysis and upgrading of 100% biogenic residues for aviation and marine sector, including full valorisation of side streams* – is a Horizon Europe Innovation Action aimed at transforming biogenic waste into advanced biofuels to enable the green transition and the decarbonisation of the aviation and the marine transport sectors.

CONTENT

1. Production of Stabilized Deoxygenated Pyrolysis Oils

Over the first 18 months of the project, BTG, with the support of SINTEF and RANIDO, has made significant strides in its multi-step process to convert pyrolysis oil into a refinery-like product, largely targeted to be a fully **Hydrotreated Pyrolysis Oil** (HPO). This process, a crucial step toward producing sustainable transportation fuels like gasoline, kerosene, and diesel, involves two main stages: stabilization and deoxygenation.

Stabilization & Deoxygenation
The research established a two-step process to transform raw pyrolysis oil into a more stable and usable fuel.

To stabilize pyrolysis oil, a process called **hydrogenation** is used to reduce its reactivity. This involves adding hydrogen to "carbohydrate-like" compounds in the oil, which is similar to how sugar is converted. This process uses a nickelbased catalyst, called "Picula" at moderate temperatures (200–250 °C) and high hydrogen pressure (200 bar). The resulting stabilized pyrolysis oil (SPO) has improved characteristics compared to the original pyrolysis oil (PO):

- **Aldehydes are converted to alcohols**, which reduces the oil's tendency to char.
- **Water content is reduced** to less than 10% through vacuum evaporation.
- **The average molecular weight is lowered**, and the range of molecular weights is narrowed, indicating a limited amount of cracking has occurred.

The stabilized oil (SPO) then undergoes **deoxygenation**, where a commercial molybdenum-based catalyst removes over 90% of the oxygen, resulting in a product called **stabilized deoxygenated pyrolysis oil** (SDPO). The resulted SDPO has now lower water content, reduced viscosity and it has a very low charring tendency, which makes it suitable for almost full distillation.

Pilot-Scale Production and Catalyst Innovation

A **Process Development Unit** (PDU) at BTG was used to produce stabilized deoxygenated pyrolysis oil (SDPO – 25 L/d) from stabilized pyrolysis oil (SPO – 50 L/d), both in continuous runs.

In order improve the process, a recycle was introduced, where part of the freshly produced SDPO is mixed with the fresh SPO feed.
This not only added thermal stability to the system, eliminated the temperature spikes, and made the process much more predictable and constant, but also improved process performances.

Hydrogen is delivered to the units through a **water electrolyser**, now operating reliably over the 12 months. In addition, a hydrogen cleaning system on **Pressure Swin Adsorption** (PSA) to allow recycling of unconverted hydrogen based is in commissioning phase.

SINTEF also performed a key study on **catalyst performance**, finding that optimized catalysts can reduce oxygen content to less than 1%, a notable improvement over standard commercial catalyst.

Future Work

Building on this research, BTG is now in the process of preparing to scale up production to **1,200 liters of SDPO**. This will contribute to further upgrade the oil into a **fully oxygen-free product**. To support this, BTG has selected best available catalysts for both SDPO and SPO production based on their ability to maximize oxygen removal while minimizing hydrogen consumption and unwanted cracking.

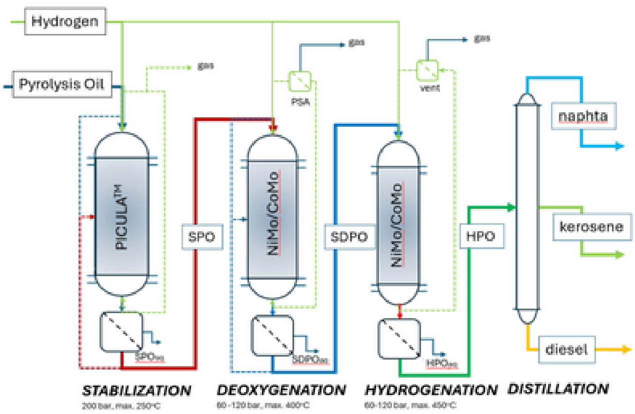

Figure 1: Schematic representation of the hydrotreatment process. Source: BTG.

Figure 2: Photograph of the bench-scale (left) and PDU (right) hydrotreatment setups. Source: BTG.

2. Process Alternatives to Valorize Side-Streams

Advanced biofuels are crucial to meet Europe's climate goals, with the potential to provide **14% of global transport fuel** and **45% of aviation fuel by 2050**, **cutting CO_2 emissions by 2.1 gigatons annually** when produced sustainably.

However, scaling up these fuels faces several challenges. Unlike fossil fuels, converting solid biomass is complex due to its variability in feedstock and the presence of oxygen-rich compounds. To overcome this, innovative technologies are needed to turn lignocellulosic biomass into high-performance fuels.

FUEL-UP project aims to address these issues by turning **fast pyrolysis bio-oils** into advanced biofuels through **stabilization**, **deoxygenation**, and **refining at scale**. The project's key objectives include **creating stable fuel intermediates**, **demonstrating full-scale production**, and **qualifying the final product** for use in planes and ships. The project also focuses on **environmental sustainability**, making use of **byproducts**, and **scaling up technologies** through engineering and economic analysis, all while working to **establish EU certification pathways** to help these biofuels get to market.

In FUEL-UP project, the activities on **Carbon Management and Side-Stream Valorization** aim to design processes that maximize the utilization of biomass carbon content and identify the most environmentally friendly and economically viable side-streams valorization process alternatives.
In the first 18 months of project's activities, AristEng, with the contribution of project's partners BTG, BTG-Next, Avecom, LIST and SINTEF, has designed alternative processes on a conceptual basis for the valorization of the side streams produced in the FUEL-UP value chain. These side-streams include: i) **pyrolysis off gases** and ii) **aqueous phase streams** produced in the hydrotreatment process seps. The process alternatives are then optimized, with the goal to minimize heat, electricity and raw material consumption, while maximizing overall reactor yields. All processes are assessed to maximize biomass carbon content recovery and minimize GHG emissions compared to the existing, state-of-the-art processes. Each process is simulated using a specialized software (COCO® simulator), along with in-house models developed by AristEng.

On the basis of mass and energy balances produced from the simulations, three KPIs are estimated for each process: **elemental carbon recovery**, **carbon footprint** (considering a "basket of products" methodology) and **economic potential**. The research investigates two main categories of waste streams, each with its own set of potential solutions.

1. Pyrolysis Off-Gases
The study examines four scenarios, with one serving as a baseline scenario (i.e., state-of-the-art). The baseline scenario (hereafter named as Scenario 0) involves the combustion of off-gases with air to produce heat and electricity, while cold flue gas is purged.
The other three scenarios explore different approaches for the valorization of the off-gases:

- **Scenario 1**: Off-gases and biochar combustion to maximize electricity production.
- **Scenario 2**: Off-gases combustion with pure oxygen to produce CO_2 and electricity. CO_2 is then electrochemically converted into valuable formic acid and oxygen, which is then recycled to the combustor. Biochar is combusted separately to produce electricity.
- **Scenario 3**: Reforming the off-gases into syngas, which is downstream converted to methanol with the addition of a make-up stream of H_2. Biochar is combusted to produce electricity.

To perform a consistent analysis and facilitate a fair benchmarking, all the above-mentioned alternative scenarios are designed so as not to further affect the overall pyrolysis process (i.e. taking into account recycling streams, dryer and pyrolizer operation).

These are the results from the process stimulation and evaluation:

- **Scenario 0** (Baseline): This scenario produces electricity and heat. It serves as the benchmark for the other processes.
- **Scenario 1**: This process is designed to maximize profit by generating as much electricity as possible. It is a simple and direct approach. It demonstrates a positive economic potential and a 22% reduction in fossil GHG emissions in comparison to Scenario 0.
- **Scenario 2** (**Formic Acid Production**): This is the only scenario that requires a significant external electricity input, mainly to power the electrolyzer and gas compression units. It also has the highest heating and cooling demands due to downstream separation to reclaim formic acid at a commercial purity. Despite these energy costs, it has the highest carbon recovery, reclaiming about 91% of the carbon from the off-gases (or 8% of initial carbon in biomass) and converting it into tradable formic acid. However, this scenario demonstrates a 19% increase in GHG emissions compared to Scenario 0, while it is not economically viable considering the current maturity of CO_2 electrolyzers.
- **Scenario 3** (**Methanol Production**): This scenario also produces a net amount of electricity and completely eliminates the need for an external heat supply. It reclaims about 90% of the carbon from the off-gases (or 8% of initial carbon in biomass) by converting them into methanol, a tradable product. Finally, it demonstrates a 19% reduction in fossil GHG emissions compared to Scenario 0, while economic potential ranges from negative to positive values, depending on the cost of hydrogen.

2. Aqueous Phase Streams

The report also examines four different scenarios for treating aqueous waste streams from hydrotreatment, benchmarked against a conventional wastewater treatment plant (Scenario 0).

These alternatives include:

- **Scenario 1**: Anaerobic treatment and energy production from biogas.
- **Scenario 2**: Anaerobic treatment to produce biogas which is then converted into hydrogen via reforming for recycling in the hydrotreatment process.
- **Scenario 3**: Reclaiming valuable chemicals like methanol and ethanol from the aqueous streams using distillation columns.
- **Scenario 4**: A combination of scenarios 2 and 3: i) methanol and ethanol reclaim (similar to scenario 3), ii) anaerobic treatment of the residual compounds (i.e., from the distillation columns) to produce biogas and iii) H_2 production from biogas reforming.

2.1 Assessment of Different Scenarios for Aqueous Phase Streams Valorisation

The results from the aqueous stream valorization scenarios can be summarized as follows:

Energy and Utility Demands:

- Scenario 1 is the most energy-efficient, as it produces both electricity and heat, requiring no external energy input.
- All other scenarios have a lower electricity demand than the baseline (Scenario 0) but a higher demand for heating and cooling.

Raw Material Consumption and Carbon Recovery:

- All new scenarios (1-4) require **fewer nutrients** (urea, phosphoric acid, sodium hydroxide) than the baseline scenario.
- Scenarios 3 and 4 are the only ones that **recover carbon**. They reclaim 239 kg/h of carbon in the form of methanol and ethanol, which accounts for 72.1% of the carbon from the aqueous stream or 3.63% of the total carbon from the original biomass.

Carbon Footprint and Economic Potential:

- **Fossil GHG emissions are lower** in all investigated scenarios compared to the baseline: 42-58% reduction.
- **Economic potential** is positive for both scenarios that yield H_2 (Scenario 2 and 4).

All of these processes were designed and simulated to match the scale of the proposed FUEL-UP demo-plant, which processes 14 tons of dry biomass per hour.

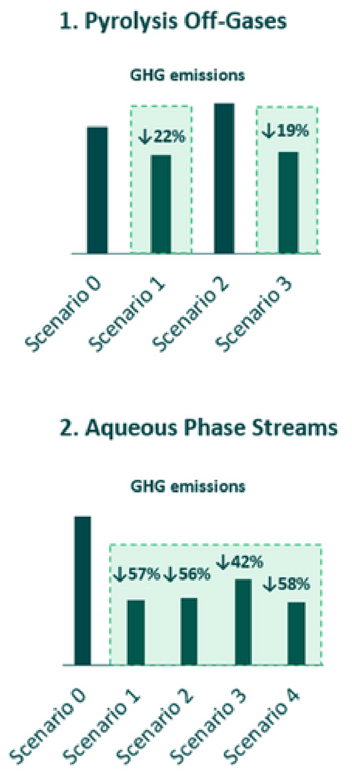

Figure 3: GHG emissions reduction results. Source: Aristeng.

2.2: High Potential for Aqueous Phase Streams Conversion Into Biogas

To assess biogas (methane) production and Chemical Oxygen Demand (COD) removal from an aqueous phase mixture, Avecom conducted a **100-day laboratory study**.

The study demonstrated that by using aerobic effluent as a diluent for anaerobic influent (Picture 1), 80% of COD could be converted into biogas. Moreover, aerobic post-treatment allowed for additional purification and an overall **COD removal of 95%**.

These findings highlight the significant potential for biogas (methane) production from aqueous phase streams and the successful reusability of treated water.

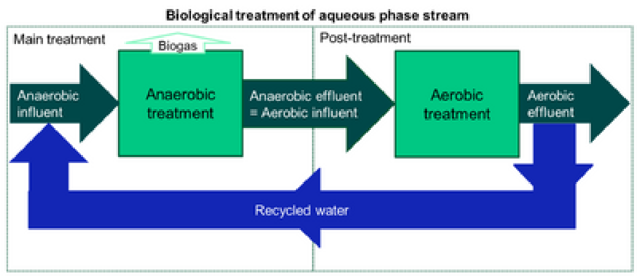

Figure 4: Treatment of aqueous phase streams. Source: Avecom.

Hence, a novel **Aqueous Phase Treatment Plant** (ATPT) pilot unit is being installed at Avecom to further test and confirm the conversion efficiency of newly produced aqueous phase streams within the FUEL-UP project into biogas.

3. Project Activities Updates

FUEL-UP is approaching month 24, marking the beginning of the third year of all project's activities as well as the beginning of several new work packages and tasks.

Production of Stabilized Intermediates

Work package 3, managed by BTG with the contribution of Ranido, Avecom and Sintef, has the goal of optimizing and scaling up the first stages of the oil production process and effectively managing the resulting water waste. The activities related to this task are all about the production and refinement of **stabilized pyrolysis oil** (SPO) and partially **deoxygenated stabilized pyrolysis oil** (SDPO), along with supporting activities like catalyst development and **water waste treatment.**

Pre-tests for Hydrotreatment / Hydroisomerisation Catalyst Screening
The activities of work package 4, managed by Tüpraș, DLR, Ketjen and BTG, will be mainly focused on research and testing the best catalyst and conditions to turn the kerosene fraction of **Hydro-processed Pyrolysis Oil** (HPO) into **Sustainable Aviation Fuel** (SAF) optimized process conditions. Once optimized, this biofuel production will be demonstrated at a larger, more realistic scale (TRL6).

Aviation Fuel Prescreening
The main purpose of this task, managed by DLR, is to prescreen the intermediate products and final fuels from the production teams (BTG and Tüpraș) to ensure they are on track to meet **aviation fuel standards** and to provide rapid feedback for process adjustments. A key focus is to evaluate how different raw materials (feedstock variability) influence the final fuel quality. The results will provide critical input for the larger-scale production and the final approval strategy.

Fuel Approval with EU Clearinghouse
A regulatory and strategy task focused on gaining certification for the pyrolysis-based SAF will begin from January 2026 .The main output of this activity, managed by DLR with the support of Tüpraș and BTG, is the development of a clear and final **approval strategy** in full cooperation with the EU Clearinghouse and all project partners. This strategy will allow the consortium to make the crucial decision on how to proceed with the final approval of the new SAF production pathway.

Life Cycle Assessment
Work Package 9, managed by Aristeng with the contribution of BTG-Next, Sintef, BTG, Tüpraș, Sintef Ocean, Avecom, LIST and DLR, is focused on assessing the full environmental and social sustainability of the FUEL-UP process. The goals of the activities related to this work package are:

- Collect process data and identify early "**polluting drivers**" and provide feedback for immediate process improvement.
- Conduct a detailed **cradle-to-gate study** to measure all environmental impacts (GHG, water use, land use, etc.). The final result is benchmarked against fossil fuels.
- Evaluate the **social impacts** (jobs, safety) and combine the social, environmental, and economic results into one **Life Cycle Sustainability Assessment** (LCSA).
- Assess the **indirect environmental impacts** caused by market changes, specifically looking at Indirect Land Use Change (iLUC).

Full Feasibility Study and Process Design, Business Cases and Market Analysis
Work Package 11, managed by BTG-Next with the support of Tüpraș, focuses on the full **commercial feasibility** of the FUEL-UP process. Its main objectives are the design of a **commercial plant** with an accurate cost estimate, the conduction of a **fuel market analysis** to estimate market competitiveness, added value, regulatory constraints, and risks as well as the conduction of **Techno-Economic Assessment** (TEA) and the evaluation of specific business cases for production.

Communication, Dissemination & Exploitation
Work package 13, managed by ETA-Florence, is the logical continuation of the first 18 month work package and it is focused on all dissemination, communication and exploitation activities to promote the project’s activities and results.

4. Past and Future Events

On 9-12 June 2025 FUEL-UP participated in the **33rd European Biomass Conference and Exhibition (EUBCE 2025)** in Valencia, Spain with a poster presentation as well as with a parallel event presentation.

The poster presentation was given on June 10, 2025, by Bernd Wittgens, Senior Business Developer at SINTEF Industry, and focused on key findings from a **feasibility assessment study** conducted as part of FUEL-UP project, aimed at recovering high-value chemicals from the complex aqueous streams produced during advanced biofuel processing. The study, ***Recovery of Alcohols in Aqueous Stream from Stabilized Pyrolysis Oil Process***, leveraged COCO-COFE process simulations to design and optimize distillation systems for separating components like ethanol, methanol, and acetic acid, despite their high water content, optimizing both energy use and economic potential. This foundational work considered various case studies to balance economic potential with energy requirements. This work is vital for boosting the **sustainability of aviation** and **maritime fuels**, helping Europe achieve its climate objectives.

Figure 5: Poster presentation at EUBCE 2025. Source: ETA-Florence.

FUEL-UP objectives and first results were also presented during the EUBCE 2025 Parallel Event ***"Innovation and Sustainability for Maritime Biofuels"*** on 10 June 2025, by Duncan Akporiaye, Vice President Research at SINTEF Industry. This event, organised by M²ARE Project, brought together a great lineup of Horizon Europe projects including POSEIDON project, SEAFAIRER project and COCPIT project. The event represented an opportunity to better explore the wide range of applications of **maritime biofuels** and several approaches that different European projects are using to build a more **sustainable biofuel market** for the shipping sector.

Figure 6 :Parallel event at EUBCE 2025. Source: ETA-Florence.

On 17-18 June 2025 FUEL-UP project partners had a productive **third consortium meeting** at German Aerospace Center (DLR)'s facilities in Stuttgart. We dove deep into the progress of each work package, shared the latest updates, and mapped out the project's future activities.

A major highlight was our visit to **DLR Institute of Combustion Technology**. We explored their cutting-edge **SAF Prescreening and SimFuel Lab** and the **HiPOT high-pressure combustion chamber test bench**, where real gas turbine conditions are simulated for in-depth combustion analysis. We also toured their **mobile measuring laboratory**, a versatile truck crucial for analyzing emissions from various sources, including aircraft engines, car traffic, and industrial operations, as well as studying air quality and alternative fuels. It was an inspiring two-day meeting of collaboration as we continue to advance FUEL-UP project's activities.

Figure 7: Third consortium meeting in Stuttgart. Source: ETA-Florence.

From August 31 to September 5, 2025, FUEL-UP was represented at **EuropaCat 2025** in Trondheim, Norway , thanks to the participation of SINTEF and RANIDO in the event. EuropaCat 2025 gathered scientists and students from academia and industry to discuss successful **catalyst development** and innovative solutions to tackle future resource and environmental challenges.

One of the aims of FUEL-UP project is to develop cost-effective, **non-precious metal catalysts** for **stabilizing biomass-derived pyrolysis oil (FPBO)**. The goal is to improve the fuel properties of the

Figure 9: DLR Mobile measuring laboratory. Source: ETA-Florence

oil, which is naturally unstable and corrosive due to a high content of oxygenated compounds. On Tuesday 2 September, Tomáš Ružovič, R&D Scientist, Ranido, with his poster presentation "***Catalytic Upgrading of Biomass Pyrolysis Oil to Sustainable Biofuels Applied in Transportation***" discussed the potential of **specific non-precious**

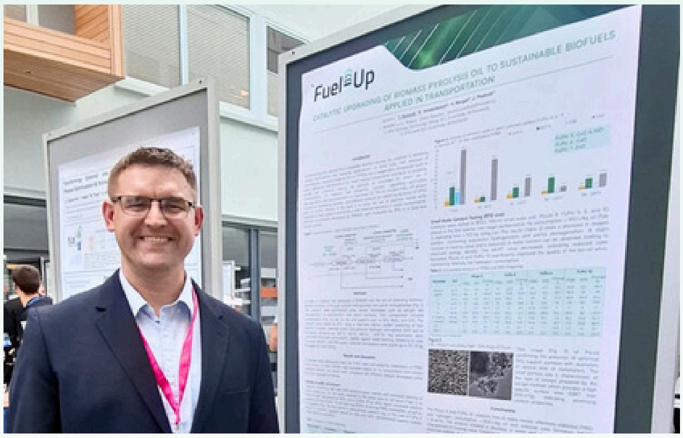

Figure 8: Poster presentation at EuropaCat 2025. Source: Ranido.

metal catalysts, particularly those using SiO2 and ZrO2 as supports, for the production of sustainable biofuels. The results highlight the importance of **catalyst stability** in acidic environments.

FUEL-UP will be also participating in the **2025 AIChE® Annual Meeting** in Boston, USA in November 2025 with the presentation "***Re-parametrization of NRTL model for C_{1+} organics and alcohols recovery from aqueous phase in biofuel production***" by Sintef.

Figure 10: FUEL-UP at EuropaCar 2025. Source: SINTEF.

AIChE Annual Meeting is the premier educational forum for chemical engineers seeking innovation and professional development.

Green methods like hydrothermal liquefaction (HTL), pyrolysis, and fermentation can turn renewable sources and waste into valuable chemicals and clean fuels instead of using fossil fuels.

At AIChE 2025 Sintef will describe in detail FUEL-UP's **aqueous phase valorization process** resulted from liquid-liquid separation with pyrolysis oil withdrawn to recover alcohols and other relevant chemicals such as acetic and formic acid. A key step in these processes is separating and purifying valuable chemicals like alcohols, carboxylic acids, and ketones from the water they are mixed in to sell them as side products on the market and therefore increase the economic sustainability of biofuels production.

The main advantage introduced by this technology is the opportunity to replace fossil fuels with renewable carbon sources and wastes, leading to reduced emissions and improved circularity.

To make this process efficient and profitable, it's crucial to have accurate thermodynamic models.

However, a current challenge, highlighted by the FUEL-UP project, is that existing models, specifically the NRTL model are not reliable enough to correctly predict how these complex mixtures behave.

The work that will be presented by SINTEF at AICHE 2025 aims at improving the NRTL model by using a large database of experimental data to recalibrate the model.

All partners will meet again in **January 2026** in **Prague**, Czech Republic, for the **project's fifth consortium meeting**.

Figure 11: 2025 AIChE annual meeting. Source: AIChE.

Figure 12: Prague., Czech Republic. Source: Canva

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