




## **FUEL FOR THE FUTURE**

The vision of CESTAP is to transform the aviation and power generation sectors to run continuous combustion engines on 100% sustainable turbine fuels by 2045.



# **ANNUAL REPORT 2025**

# **CESTAP**

## **Competence cEnter in Sustainable Turbine fuels for Aviation and Power**

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## Preface

After completing its fourth year, the CESTAP initiative continues to accelerate the transformation of the aviation and power generation sectors by advancing technologies that enable jet engines and gas turbines to operate on sustainable fuels. The program's PhD students are now three to four years into their research and have already achieved several key milestones. Ongoing progress is further strengthened through close collaboration with partner projects.

This report summarizes the principal activities and outcomes across the technical Work Packages (WPs) during 2025. Detailed accounts are provided in the main "Progress and Results" section and in the referenced reports and publications listed at the end. Overall, 2025 was a highly productive year for CESTAP, with several major milestones achieved and multiple key publications published, accepted, or submitted.

By the end of Year four, the combined virtual-and-physical pre-certification combustion test bed developed in WP1 had reached production maturity and is fully operational. All combustion rigs are in service except the DESS rig, which is expected to be commissioned in 2026. The platform has been used to evaluate a wide

variety of fuels under diverse operating conditions, generating experimental datasets that have supported multiple publications. The numerical combustion modelling capability is fully operational, with fuels characterised by their liquid properties and chemical composition. Chemical-kinetics modelling has matured to reliably handle most large liquid hydrocarbon fuels using surrogate compositions and a multi-component reaction mechanism developed by Niklas Zettervall at FOI.

WP2 made strong progress in 2025 on turbine fuels from lignocellulosic residues. Liter-scale fuel made entirely from wood residues was produced via pyrolysis followed by slurry hydrotreatment, and organosolv lignin (from renewable GVL) is now available to partners for liter-scale fuel production in 2026. The first SAF from slurry hydroprocessing of pyrolysis oil and lignin is ready for testing, with 3 to 5 additional samples planned for 2026. One of these samples have already resulted in a Pyrolysis-to-Jet (PTJ) biofuel that closely matches drop-in jet-fuel specification. A novel alcohol-to-jet route is advancing, with redesigned zeolite catalysts targeting full jet-range composition; catalyst design and characterization (hydrotreatment and zeolite) continue to ensure robustness and clarify mechanisms.

WP3's work on the mutual adaptation of turbine fuels and engine technology progressed substantially, yielding new insights into combustion in both stationary and aviation gas turbines. High-fidelity numerical studies of fuels and combustors are informing targeted modifications to combustor components to enhance fuel flexibility. In addition, a cluster- and network-based analysis tool has been developed to identify key physical processes and map their interdependencies.

WP4 advances materials science across fuel lubrication, fuel-soft-material interactions, and deposits/corrosion linked to combustion and storage. All tasks are up and running. The soft-material interaction task is continuously delivering results, with several important findings reported in during late 2024 and 2025; a rapid, cost-effective screening method for engine-system soft materials (e.g., gaskets) is in place and is being used routinely to evaluate candidate fuels from within and beyond CESTAP. The lubrication task is progressing very well on a revised 2025 to 2026 schedule, and the deposits/corrosion task is active with a partner-agreed emphasis on long-term storage property characterisation.

WP5's integrated techno-economic and sustainability work remains on track. In 2024, the team delivered a review manuscript benchmarking the techno-economic performance of multiple SAF pathways across diverse feedstocks. Ongoing TEA efforts are aligned with WP2 case studies, lignin, lignocellulosic pyrolysis oil, and methano, while sustainability assessments of production and use progress using data from WP1 tests. The holistic system analysis is also advancing, supported by partner inputs on infrastructure and logistics for fuel manufacture, distribution, and deployment at airports.

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## Introduction and background

The need for Sustainable Turbine Fuels (STF) is apparent: to meet European Union (EU) and Swedish climate goals it is necessary to move away from fossil-sourced fuels for aviation and power generation. Using domestic feedstocks like forestry residues, agricultural waste, municipal solid waste, and algae strengthens energy security. The possibilities for Sweden include affordable surplus electricity for H<sub>2</sub> production<sup>1</sup>. A fully decarbonized energy system is essential to reach climate goals, but of importance also to resilience by providing backup and peak-load power<sup>2</sup>.

Sweden entered 2025 with clear momentum in STF for both aviation and power, driven by large industrial investments, visible research progress, and tighter European policy signals that now begin to operate. The opening of new domestic capacity, upgrades at existing refineries, and the maturation of Sweden-relevant value chains such as lignin, pyrolysis oils, and Power-to-Liquid (PtL) point toward a more resilient national supply base. These developments align with the EU's ReFuelEU Aviation mandate (2% SAF from 2025, rising to 6% by 2030 and 70% by 2050)<sup>3</sup> and Sweden's long-term climate ambitions.

Looking back at the recent progress in Sweden; in 2024, St1 and SCA inaugurated the Gothenburg Biorefinery, designed to produce around 200,000 tonnes per year of SAF via Hydroprocessed Esters and Fatty Acids (HEFA) using feedstocks such as used cooking oil, animal fats, and fatty acids. This is an important domestic anchor for drop-in SAF fuel compatible with current fleets and infrastructure. In addition, VAROPreem AB's ongoing modernization of the Lysekil refinery adds approximately 900,000 tonnes per year of Hydrogenated Vegetable Oil (HVO) and/or HEFA capacity through a new feedstock pretreatment unit and an upgraded IsoC-racker<sup>4</sup>, reinforcing Sweden's ability to process a wider range of biogenic inputs at scale. Beyond Sweden's borders but directly relevant to Nordic supply chains, Neste commissioned its expanded Rotterdam facility in 2025 with a stated capability of approximately 500,000 tonnes per year of SAF via HEFA.

In parallel, Swedish producers have continued to commercialize upstream intermediates critical for future domestic STF, notably pyrolysis oils and lignin-based streams. Actors such as Envigas and Pyrocell have established commercial pyrolysis-oil production, while RenFuel advances Lignol® (a lignin-based bio-oil), creating options that leverage Sweden's forestry residues and long-standing bioeconomy. The period also saw notable technology milestones and certification progress. Swedish Biofuels obtained ASTM approval for its ATJ-SKA route in 2025<sup>5</sup>.

On the R&D side, CESTAP's Phase I precertification test-bed progressed from development to systematic use, and further to front-line deployment in state-of-the-art research studies, delivering unique research results as outlined in the present report. The testbed was demonstrated in 2024 and completed its first biofuel integration in 2025, evaluating Jet A, Diesel, HEFA-SPK, HVO, and Fatty Acid Methyl Ester (FAME) across a chain of test rigs and simulation models ranging from laboratory

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<sup>1</sup> Energiforsk, 2024, The Potential of Hydrogen in a Swedish Context, Report No. 2024:1011.

<sup>2</sup> IEA Bioenergy; 2024, Implementation of bioenergy in Sweden – 2024 update. Bioenergy Executive Committee.

<sup>3</sup> European Union. Regulation (EU) 2023/2405 of the European Parliament and of the Council of 30 October 2023 on the promotion of sustainable aviation fuels. EUR-Lex; 2023.

<sup>4</sup> <https://www.preem.com/en/about-us/projects/icr-project/>

<sup>5</sup> <https://swedishbiofuels.se/>

flames and atmospheric combustors to a high-pressure sector rig and a full-scale jet engine for emission studies. This provides a coherent pre-certification workflow reducing development risk and accelerates screening of Sweden-relevant fuels.

Looking ahead, Sweden’s PtL activity continues to build: Project Alby targets around 80,000 tonnes per year of SAF via PtL<sup>6</sup>, while Topsoe and Sasol’s FrontFuel demonstrator couples e-electrolysis with Fischer-Tropsch refining from biogas and CO<sub>2</sub> to produce SPK-class fuels. Together with Sweden’s biomass-to-liquids options, these pathways diversify future STF supply and improve resilience.

The start of ReFuelEU Aviation in 2025 provides a concrete demand signal, with volume mandates that rise over time and include sub-targets for synthetic fuels. For Sweden, this sits alongside the national policy direction articulated in recent government propositions that emphasize security of supply, delivery reliability, and cost-effective electrification, aligning well with STF’s dual role in aviation decarbonization and grid resilience for peak-load/backup power. This policy context intersects with a more volatile global energy and trade environment, in which domestically produced fuels and regionally secure feedstocks confer strategic advantages. Sweden’s ability to transform forestry residues, agricultural wastes, and other biogenic streams into certified turbine fuels, backed by test infrastructure and techno-economic/lifecycle analysis, strengthens national autonomy while retaining export options as Nordic production scales.

In sum, the last few years has demonstrated that Sweden now couples policy signals with tangible capacity, technology maturation, and certification progress. By sustaining this trajectory anchored in domestic production, resilient value chains, and rigorous pre-certification, Sweden is well positioned to supply, certify, and operate the STFs required for climate-aligned aviation and reliable power in a more uncertain world. In this report we outline the overall status of the CESTAP project after four years in operation, and summarize the results in each research work package. In the final sections of this document, scientific and technical publications from the CESTAP period from 2022 to 2025 are listed.

## Implementation

To meet the needs of aviation and power production industries, the aim of CESTAP is to develop knowledge and technologies for efficient, sustainable, and cost-effective turbine fuels. 2025 was the fourth year in Phase I (2022 – 2026) of CESTAP, and in the later part of the year an extensive effort involving academic and industrial partners has been to prepare for Phase II. The goals set for Phase I are outlined in Table 1, where the progression at the closing of the fourth year is also given.

**Table 1.** Progression, by end of 2025, of overall goals for CESTAP Phase 1 (2022 – 2026).

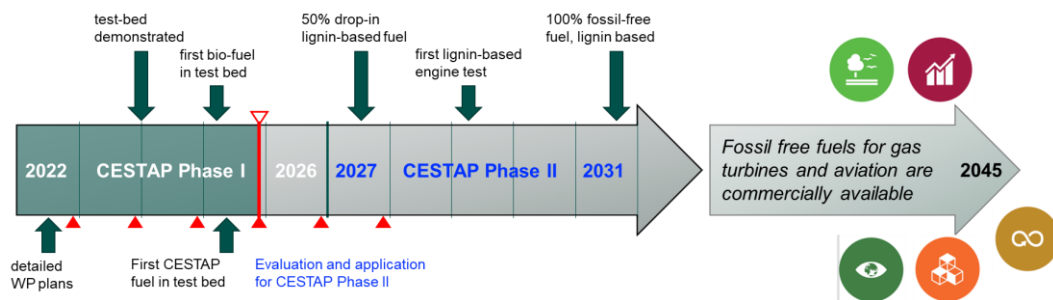
	Goals for Phase I of CESTAP	Progression
1	Establish a validated physical and computational test-bed for pre-certification of turbine fuels.	✓
2	Provide a holistic map, including innovative process path-ways for a range of bio-based turbine fuels, based on the consortium’s experiences, competencies, and demands.	80%

<sup>6</sup> <https://vatgasalby.se/en/the-project/>

3	Demonstrate >2 sustainable bio-based (>1 lignocellulose-based) and cost-effective pilot-scale process-paths to turbine fuels with properties suitable for use in jet engines.	50%
4	Identify and verify >2 sustainable bio-based (>1 lignocellulose-based) turbine fuels, including storage properties and miscibility parameters/limitations.	60%
5	Produce >1 sustainable and cost-competitive bio-based turbine fuel for 50% drop-in use in aviation or power generation engines and verify in tests such as flight or power production.	50%
6	Provide a holistic analysis of the economic and environmental performance of studied sustainable fuel value chains, as benchmarks and including consideration of high-altitude effects.	✓

In Phase II starting in 2027, the centre will continue to strive towards the long term goals outlined in Figure 1 present the roadmap of CESTAP, to realize our vision:

*To transform the aviation and power generation sectors to run continuous combustion engines on 100% sustainable turbine fuels. In addition, the focus is on sustainable turbine fuels from raw material readily available in Sweden, to achieve security of supply.*



**Figure 1.** Schematic illustration of the roadmap and vision of CESTAP. The red line across the timeline symbolizes how far into the projects we are at the writing of this report.

To support the development of competence centra, including CESTAP, the Swedish Energy Agency initiated an evaluation performed by Oxford Research in 2025. The focus was on organizational aspects, communication and outreach, and collaboration between academic and industrial partners.

The evaluation presents a consistently positive picture of CESTAP’s progress and impact. The centre is recognised for strengthening collaboration between partners and for enhancing the employability and competence development of its doctoral students. CESTAP’s ability to create knowledge across the entire biofuels value chain and to link its research activities to broader societal needs and challenges is emphasised as a clear strength. Industry partners underline that CESTAP responds well to developments in the external environment: 81% report that the centre adapts to external trends to a high degree. Equality and non-discrimination are assessed as well integrated, with balanced doctoral recruitment. Learning activities including seminars, annual meetings and joint PhD activities are highlighted as significantly beneficial for both industry partners and the PhDs, who report improved domain knowledge, broader perspectives, and stronger academia-industry connections.

The centre is further commended for its active internal and external collaboration, including conferences, study trips, and accessible communication channels between

partner organisations and the centre’s leadership. Participation levels are high: 7 out of 8 PhDs and all partners have taken part in collaborative activities, and most report substantial competence development.

While the evaluation is strongly positive, potential for further development is identified in a strengthened communication capacity including external outreach, and increased industry-PhD matching. These aspects are taken into account in the preparation for Phase II.

## Progress and Results

The work in the technical Work Packages is generally well in-line with the original work- and time-plan for Phase I. All PhD projects proceed well and a majority of the PhD students within CESTAP are expecting to defend their thesis in late 2026 or early 2027. As evident from the Oxford Research evaluation mentioned above and from the experience of CESTAP researchers and industry, good collaborations are in operation across WP’s, between PhD’s, with associated projects, and between partners. Details on the progress and results follow below for each respective WP.

### WP1 Development and maintenance of the pre-certification test bed

A total of three PhD students are active in this work-package. Initially, the main task was to establish the pre-certification testbed. However, we are pleased to note that, since the previous annual report, the majority of the work performed has shifted towards maintaining and operating the testbed. In this report follows a brief summary of the progress made and the results produced within this work-package during 2025. Overall task progression during the whole project period (2022 – 2026) is briefly summarized in Table 2.

**Table 2.** Progression of tasks WP1.

Tasks of WP1	Progression (%)	Comments
<b>Task 1:</b> Simulation models.	100%	On track. Methodology is validated and in full use since late 2023.
<b>Task 2:</b> Experimental pre-certification test bed.	90%	On track except for the DESS high-pressure test rig which is planned to be operational during 2026.
<b>Task 3:</b> Full scale jet engine test bed.	100%	On track. Ljungbyhed jet engine lab is finalized and a few test runs have been performed on selected larger donated fuel samples.

### *Experimental research*

Within CESTAP there is, since October 2022, one dedicated PhD student working with the experimental tasks in WP1. In addition to this, there are now several related projects on similar topics running in parallel. Since 2024 the experimental capability in the field of SAF, include two additional PhD students and one Postdoc. As a result, this brings critical mass to the experimental efforts, and all contributing researchers and projects are expected to benefit from the synergetic effects introduced through these collaborations. In addition to skillful personnel, the experimental investigations require some highly unique infrastructure. A brief description of the

updates and improvements implemented to the experimental apparatus, can together with some results, be found in the following paragraphs.

*The Lund high-pressure rig*

The work on refurbishing the large high-pressure combustion facility has continued during 2025. The repaired electric air pre-heater, *Figure 2*, has been instrumented with thermocouples and equipped with the necessary electrical wiring before being transported back to the location of the high-pressure rig. The preparatory work before reinstalling the air heater included restoration of the internal sheet metal air guiding panels and remounting them in the heater enclosure. During late fall the heater unit was lifted in place and the pressure holding containment was reinstalled.



**Figure 2.** (a) The electric air pre-heater being instrumented and having necessary wiring fitted, before (b) reinstallation in the Lund high pressure-facility.

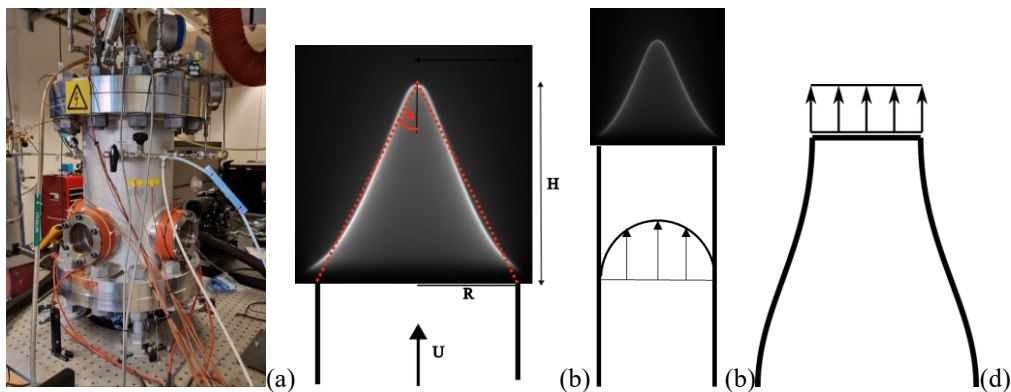
The damaged, oil infused, air compressor was scrapped and replaced by three new units, see *Figure 3*. The decision was to go with oil-free screw compressors that will, not only, be safer to operate, but also bring a major advantage for implementation of optical diagnostic techniques. Since the delivery in December last year, the rest of the compressor hardware installation has been finalized. This includes plumbing for the compressed air, arranging the cooling system and connecting everything to the electricity supply. During the fall of 2025 the system was successfully inspected and pressure tested. The current plan calls for the first on-site tests and control system debugging to be performed in early 2026.



**Figure 3.** The new oil-free compressors were delivered in December 2024 and during the last year the installation including electrical supply, piping for compressed air and cooling water, has been finalized. The door opening to the right connects the compressor room with the switchgear central. To reduce electrical interferences, the separating wall is made of seam welded aluminum.

### Laboratory-scale pressurized burner

This part of the physical test facility was the first to be brought into operation. The base structure, including the pressure vessel (see Figure a) and the pressurization control system, was part of a pre-existing infrastructure. Within the framework of CESTAP, this equipment for pressurized combustion was modified to accept liquid fuels. Although this adaptation turned out to be more complicated than anticipated, it was successfully implemented. After verification measurements with reference fuels, such as n-heptane and ethanol, this laboratory scale high-pressure burner has for the past year, been fully ready for use with aviation like fuel candidates. During the past year, measurements on Jet-A1, HEFA-SPK, MTJ-SPK and HVO have been conducted under different operating conditions.

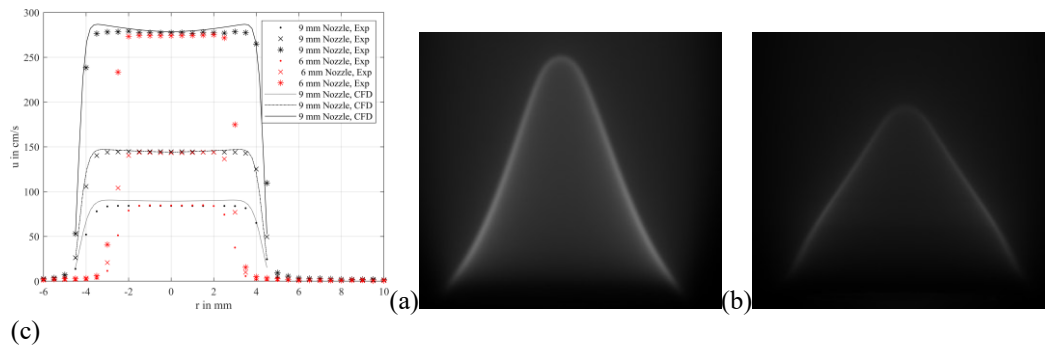


**Figure 4.** The laboratory scale high-pressure vessel (a), mainly employed for performing measurements of the laminar flame speed at atmospheric and elevated pressures. (b) Shape of the conical flame when operated with a “Bunsen-type” straight pipe burner. (c) Illustration showing the gas velocity profile in the burner pipe. The non-top-hat shape shape is causing the just mentioned disturbance of the flame. (d) New burner design, with a tailored spline that promotes a top-hat velocity profile and thus a triangular flameshape.

Although the laboratory high-pressure-burner worked fine, including the metering and pre-vaporization of liquid non-volatile fuels, a slight issue with the resulting flame shape became apparent. In short, the assessment of the laminar flame speed is based on measuring the flame cone angle while carefully governing the flow of fuel and oxidizer. Ideally, the flame should attend a triangular shape. For this to be true, a top-hat velocity profile of the combustible mixture is required. The laboratory high-pressure burner was equipped with a “Bunsen-type” burner, i.e. a long straight pipe. This standard design, however, results in a flame that slightly deviates from a triangular shape as can be seen in **Fel! Hittar inte referenskölla.b**. The reason for this behavior, is the boundary layer close to the pipe walls, as illustrated in **Fel! Hittar inte referenskölla.c**.

There are routines to include the curvature effect when postprocessing the flame speed measurements, but the flow imperfection also causes strain and hence, flame instabilities. As a consequence, it becomes harder to stabilize the flame, especially at elevated pressures. In order to improve the measurement accuracy and to be able to perform testing at higher pressure levels it was decided to address this flaw. A new burner was designed with the aim of achieving a closer to top-hat velocity profile. The core element of the new burner is a pipe with a tailored contraction close to the opening where the flame sits, as illustrated in **Fel! Hittar inte referenskölla.d**. To find the best shape, different spline curvatures, lengths and contraction

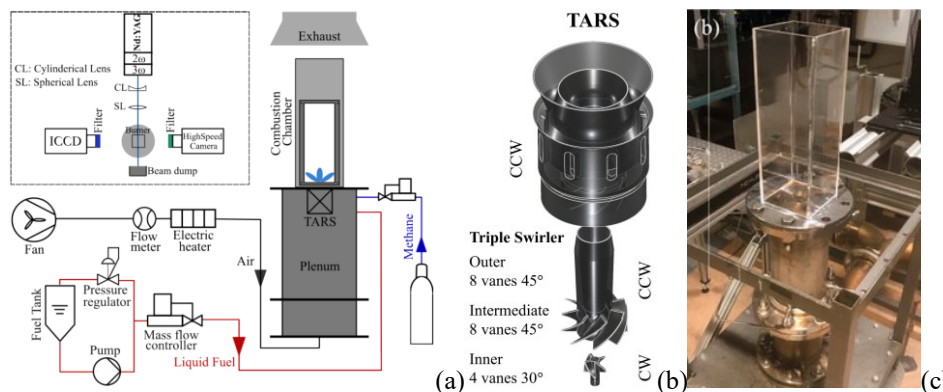
ratios were tested in a Computational Fluid Dynamic (CFD) model. The best combination was singled out and manufactured in two versions, one with a 6 mm and one with a 9 mm outlet diameter. The resulting velocity profiles from these two new burners were then tested through hot-wire anemometry. Figure 5a shows the measured data together with the corresponding calculated velocity profiles, demonstrating very good agreement between modeled and measured velocities for both nozzle sizes. The new burner design produces a flow that has a velocity distribution that closely reassembles a top-hat profile. Flames from the old and new burner designs are presented in Figures 5c and 5d, respectively.



**Figure 5.** Velocity profiles (a) for the two new burners (6 mm and 9 mm) measured through hot-wire anemometry, and (b) and (c) flame shape using the old and new burner design, respectively.

### Atmospheric combustion test facility

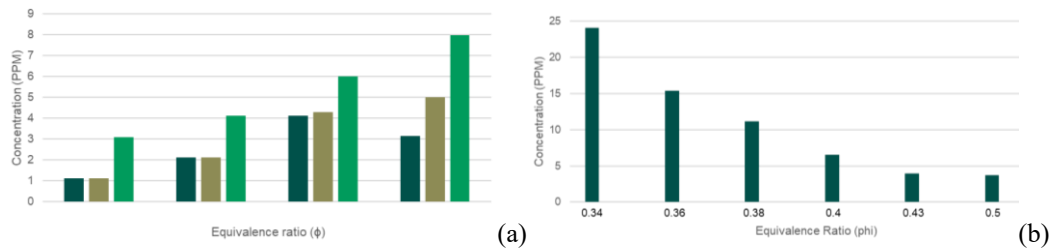
The atmospheric combustion rig uses two low-pressure compressors and electric heaters in parallel to supply pre-heated air (~800 K) to a modular burner-combustor configuration shown schematically in Figure 6a. During the past year this test-rig has been extensively used, configured primarily with the Triple Annular Research Swirl (TARS) burner, Figure 6b, together with a simple can combustor with partial optical access or together with a fully optically accessible rectilinear combustion chamber, as seen in Figure 6c. This particular TARS burner set-up is designed to mimic an aviation jet engine burner for fuel testing.



**Figure 6.** (a) Schematic of the atmospheric combustion test facility, incorporating the TARS burner (b) and different combustors with full or partial optical access.

After successfully debugging initial problems associated with the liquid fuel supply, the atmospheric combustion test facility has been working fine and have delivered results for several different fuels and at different operating conditions. Significant efforts was however initially spent identifying suitable running conditions for

the experiments. At an early phase, the Reynolds ( $Re$ ) number was kept at around 20.000 both for the tests. This in combination with fuel injection through both pilot- and main-fuel supply lines resulted in increasing CO with increasing equivalence ratio,  $\phi$ , as presented in Figure 7a. This behavior is a-typical for an jet engine and indicate either poor mixing or poor recirculation. Tests with increasing  $Re$  number and fuel injection through also only the pilot-supply for Jet A1, resulted in the desired response in CO emissions as can be seen in Figure 7b.



**Figure 7.** (a) CO emissions (in ppm) from the TARS combustor when operated at equivalence ratios of 0.50, 0.55, 0.60, and 0.65 with injection through both the pilot and main-fuel supply lines for Jet A1, HEFA-SPK and HVO, and (b) CO emissions (in ppm) at equivalence ratios of 0.34, 0.36, 0.38, 0.40, 0.43 and 0.50 for Jet A at  $Re=27.000$ .

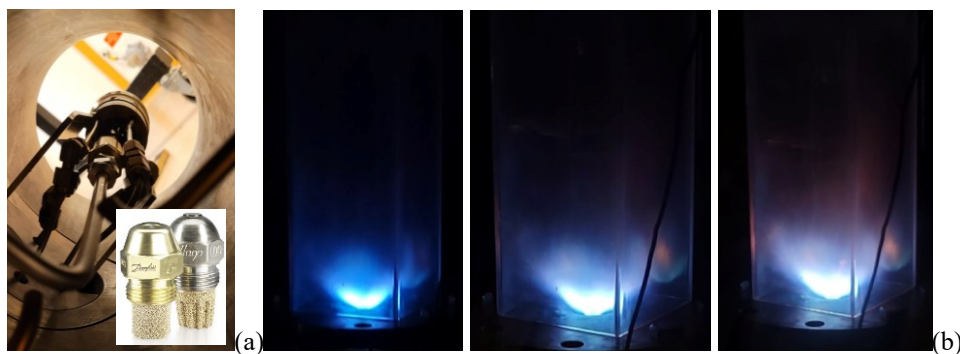
In addition to the reference fuel Jet-A1, several other fuels have been tested in the TARS burner during 2025, including ethanol, n-heptane, iso-octane, HEFA, HVO, and FAME. Fuels like HVO and FAME are not intended as aviation fuels but are relevant as replacements for Diesel for energy producing applications. FAME is significantly less volatile than Jet-A1. In a direct comparison, this results in slower vaporization and therefore also delayed mixing. Images from Jet A1 and FAME experiments can be seen in Figure 8. For Jet A1 the TARS burner was operated at a pre-heating temperature of 250 deg C, and a  $Re$  number of 27.000. For FAME the TARS burner was operated at similar conditions but at varying equivalence ratios, from 0.40 to 0.55. As can be observed in Figure 8, the reduced mixing, as a result of the lower vaporization, the FAME results show a visible increase of soot formation (seen as yellow/orange luminosity from the hot soot particles).



**Figure 8.** The swirl-stabilized atmospheric TARS burner being operated with (a) Jet A1, and (b) FAME at  $Re=27,000$ , at  $\phi=0.40, 0.45, 0.50, \text{ and } 0.55$ .

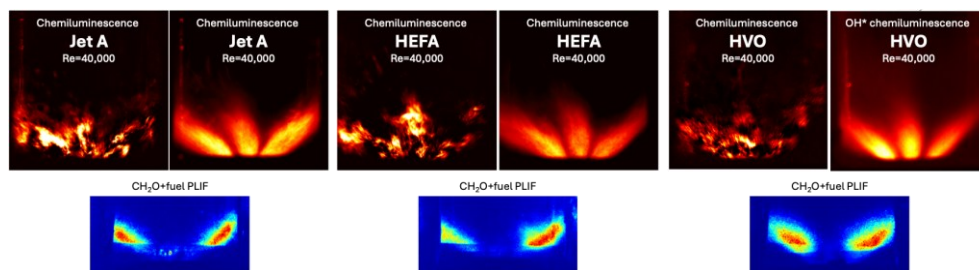
As mentioned initially, the majority of the combustion testing performed 2025 has been conducted on the TARS configuration. The next step in the planned research is to reconfigure the atmospheric combustion rig to adopt the CECOST burner that is designed to replicate the flow and flame structures found in a Siemens Dry Low Emission (DLE) combustor. During the fall of 2025, preparatory work for this transition was performed. The main purpose was to investigate if a fuel spray nozzle

mounted upstream of the TARS burner would provide sufficient vaporization and mixing to operate the TARS with pre-mixed combustion, as will be required by the low-emission CECOST-design. Given the slightly sooty combustion when operating on FAME at this Reynolds number, it would be especially interesting to perform these tests also on a bio-fuel. Since sooty combustion is undesired, both from an emission point of view and from an efficiency perspective it should be beneficial to shift the operating conditions towards more pre-mixed conditions. To test the feasibility of this approach, a separate fuel spray nozzle was placed upstream of the burner according to Figure 9a. The result when operating on FAME can be seen in Figure 9b. When comparing with the TARS configuration using the same fuel in Figure 8, it is obvious that the upstream spray nozzle has a large impact on vaporization and mixing. This is promising for the CECOST application, although, it still remains to be proven that a truly homogeneous mixture is achieved.



**Figure 9.** (a) The physical location of the spray nozzle relative to the TARS burner with an insert showing two examples of the spray nozzles, and (b) FAME combustion with a spray nozzle mounted in the plenum at  $\phi=0.40, 0.45$  and  $0.55$ .

High-speed chemiluminescence imaging, and formaldehyde ( $\text{CH}_2\text{O}$ ) and fuel Planar Laser Induced Fluorescence (PLIF) was performed for Jet A1, HEFA and HVO in order to obtain time-resolved information on flame structure, ignition behaviour, and mixing processes. Chemiluminescence identifies heat-release zones and flame dynamics, while  $\text{CH}_2\text{O}$ /fuel PLIF reveals low-temperature chemistry and pre-ignition regions. Combined, these diagnostics provide a comprehensive picture of how conventional and sustainable fuels differ in evaporation, ignition, and flame stabilisation under realistic spray-combustion conditions. Figure 10 compares instantaneous and time-averaged chemiluminescence images of Jet A1, HEFA and HVO, as well as time-averaged  $\text{CH}_2\text{O}$ -fuel PLIF images. Jet A1 and HEFA behave similarly: the chemiluminescence shows comparable V-shaped heat-release footprints and lift-off with intermittent shear-layer kernels, while the paired  $\text{CH}_2\text{O}$ +fuel PLIF



**Figure 10.** Instantaneous and time-averaged high-speed chemiluminescence images, and time-averaged formaldehyde ( $\text{CH}_2\text{O}$ ) and fuel Planar Laser Induced Fluorescence (PLIF) images for Jet A1, HEFA and HVO at  $\text{Re}=40,000$ .

lobes have similar extent and intensity, indicating broadly comparable evaporation, low-temperature reactivity, mixing, and flame stabilisation. HVO, by contrast, exhibits a smoother, more symmetric chemiluminescence envelope with a more compact heat-release region and fewer small-scale fluctuations; its  $\text{CH}_2\text{O}$ +fuel PLIF appear somewhat broader and more intense around the flame root, with fuel vapour more concentrated near the base, features consistent with shifts in vaporisation and kinetics. Overall, Jet A and HEFA respond nearly equivalently under these conditions, whereas HVO trends toward a wider pre-ignition ( $\text{CH}_2\text{O}$ ) zone.

### *JET-engine test facility*

Within CESTAP's experimental pre-certification suite, the jet engine test facility was designed and built from the ground up. Significant efforts have been spent on design and construction work, both related to the experimental test rig, and to the building housing the equipment. During 2025, this part of the infrastructure has been fully operational and used in CESTAP research campaigns. The turbofan engine has now delivered reference results for Jet-A1 combustion, as well as results for different blend-in ratios of HEFA.

In these experiments exhausts were sampled by a probe placed at the turbine exit and analyzed using an AVL AMA i60 emission analyzer, see Figure 11.

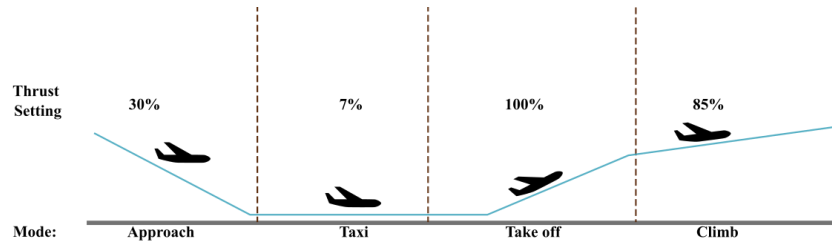


**Figure 11.** To the right, the turbofan engine is seen with its blue bellmouth. To the far left is the AVL AMA i60 emission analyzer, and in the middle is the enclosure for fuel storage and preparation.

The engine has so far been operated on three fuels: a conventional Jet A1 (acting as a reference fuel) and two HEFA/Jet A1 blends (1:1 and 3:1 by volume, respectively). The 1:1 blend (50% HEFA) complies with the current HEFA-SPK maximum blend limit in ASTM D7566 (Annex A2) and, once released under D7566, is regarded as ASTM D1655 Jet A-1, whereas the 3:1 blend (75% HEFA) exceeds the D7566 Annex A2 drop-in limit and therefore purposely lies outside the civil-spec Jet A/Jet A-1 requirements as we are interested in understanding (i) how the engine reacts to this fuel blend and (ii) to examine and analyze the emissions from a more aggressive fuel blend. The emission analyzer measures total hydrocarbons (THC), Nitrogen oxides ( $\text{NO}_x$ ), Carbon monoxide (CO) and Carbon Dioxide ( $\text{CO}_2$ ). In addition we are also measuring and sampling soot. The exhaust emissions were collected at four different thrust conditions, Approach (30% thrust), Taxi (7% thrust), Take-off (100% thrust) and Climb (85% thrust), based on the landing and take-off cycle definitions specified by ICAO. The test conditions are specified in Figure 12.

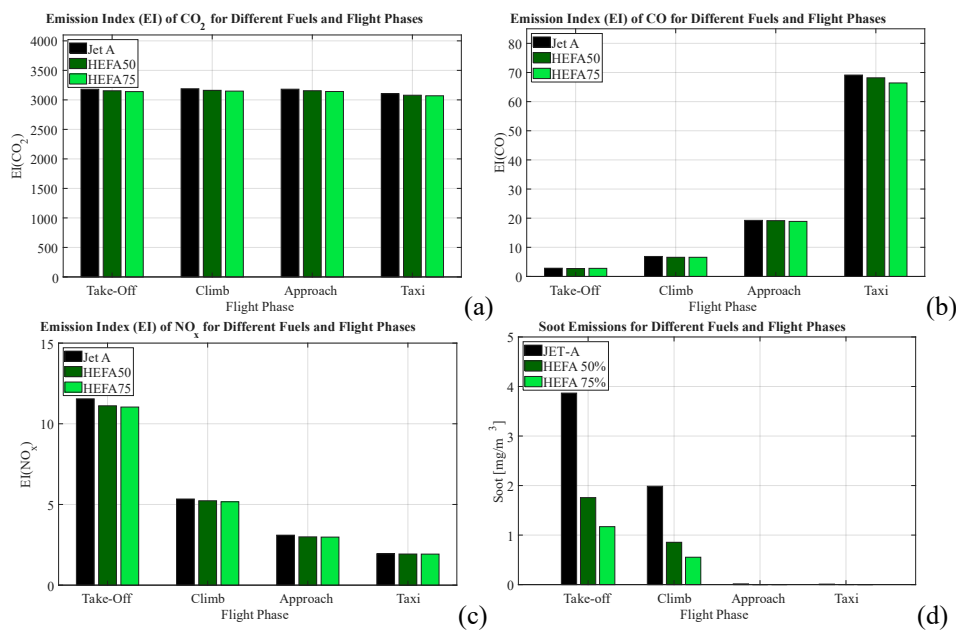
The results for the different cases are shown in Figure 13. As can be seen the relative amount of CO in the exhausts is reduced with increasing load. This is expected from the improved combustion efficiency at higher thermal load. The reverse trend is

observed for the  $\text{NO}_x$ . This is also aligned with expectations due to the strong coupling between  $\text{NO}_x$  and combustion temperature. Soot is only detected at the two highest load point. This is caused by the higher fueling rate resulting in richer zones. The greatest difference between the three fuels is found in soot particle mass. Most likely, the major contributing factor is the decreasing amount of aromatic content with increasing HEFA-SPK blend-in ratio.



**Figure 12.** The operating conditions according to the ICAO protocol. The load settings are specified in terms of percentage of maximum thrust.

Figure 13 comprises four bar-chart panels showing emission indices for  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{NO}_x$  and soot, across the ICAO load points, Take-off, Climb, Approach, Taxi, for Jet A, a 50% HEFA blend (HEFA50), and a 75% HEFA blend (HEFA75).  $\text{CO}_2$  largely follows thrust, peaking at Take-off and declining toward Taxi, with minimal fuel-to-fuel differences as expected for similar heating-value fuels burned at matched operating conditions.  $\text{CO}$  is lowest at high load and higher at low load (Approach and Taxi), reflecting less complete combustion at part power; fuel effects are small, with a slight tendency toward lower  $\text{CO}$  as HEFA fraction increases.  $\text{NO}_x$  is strongly load-dependent, highest at Take-off and dropping sharply thereafter. The fuel blends show a modest reduction versus Jet A1 ( $\text{HEFA75} \lesssim \text{HEFA50} < \text{Jet A1}$ ), consistent with subtle shifts in local temperature and equivalence-ratio distributions. The clearest fuel signature appears in soot: at Take-off (and to a lesser extent Climb) Jet A is highest, HEFA50 is lower, and HEFA75 is lowest, while all fuels approach

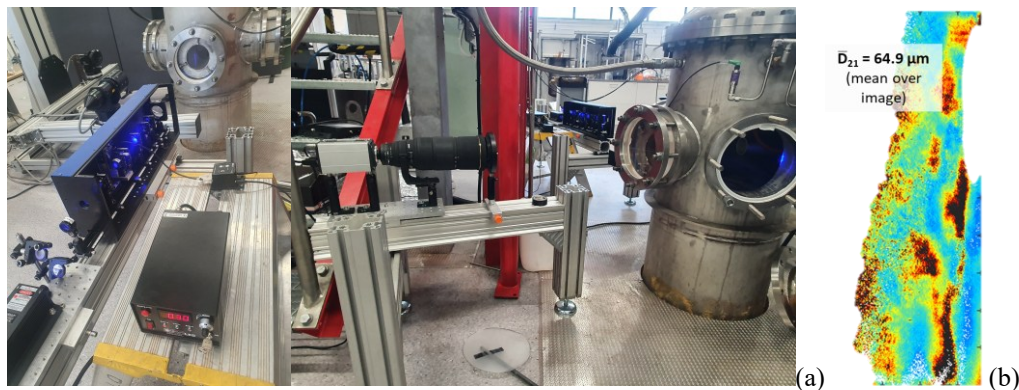


**Figure 13.** Results from the emission measurements performed under conditions corresponding to the ICAO load conditions for three different fuels. (a)  $\text{CO}_2$ , (b)  $\text{CO}$ , (c)  $\text{NO}_x$  and (d) soot particle mass per unit volume.

negligible soot at Approach and Taxi. These trends are well aligned with the lower aromatic content and higher H/C ratio of HEFA that suppress soot precursors and enhance oxidation. Overall, operating condition dominates  $\text{CO}_2$ ,  $\text{CO}$ , and  $\text{NO}_x$  levels, whereas fuel composition dominates soot, with increasing HEFA fraction delivering pronounced particulate benefits and small but favorable  $\text{NO}_x$  changes.

### *Spray test facility*

This spray rig is located at RISE in Piteå. It operates with an atmosphere of pressurized nitrogen gas. The available ambient pressure range is 0 to 10 bar, while the fuel injection pressure can reach around 150 bar. The first fuel spray characterization, using laser diagnostics, within CESTAP was conducted in 2025. In this study, Phase Doppler Anemometry (PDA) was combined with Structured Laser Illumination Planar Imaging (SLIPI) to investigate droplet break-up and size distribution for different fuels, nozzle diameter and pressure conditions. In this first attempt four fuels were tested, methanol, ethanol, HEFA and Jet-A1. Some of the optical diagnostics equipment and the upper section of the spray-rig can be seen in Figure 14a. After the measurement campaign, hosted by RISE in Piteå, followed extensive data post-processing. Without going into the technical details, the results generated, Figure 14b, were unfortunately deemed too unreliable. It should be mentioned that such outcome is not uncommon in experimental activities, especially not in the first attempt. In this case the main reason was temporal instabilities in the spray behavior. It is believed that these issues can be solved with a modified experimental approach, and the possibilities of revisiting this task is being investigated.



**Figure 14.** (a) The pressurized spray chamber at RISE in Piteå during SLIPI spray measurements, and (b) example from the first SLIPI measurements in the RISE spray-rig for HEFA.

### *Chemical kinetics studies*

The work on chemical kinetics is performed in collaboration between researchers at Combustion Physics (at LTH) and Niklas Zettervall at FOI, in close connection to the CFD group at Department of Energy Sciences (LTH). The CESTAP funded work is performed in close collaboration with the project "Combustion characteristics of aviation biofuels" funded by the Swedish Energy Agency 2020-2025, from which one PhD student who has strongly contributed contributed to CESTAP research successfully defended his thesis in 2025.

Real kerosene, gasoline, or diesel grade fuels, fossil or bio-based, consist of hundreds of different hydrocarbons interacting through tens of thousands of chemical

reactions, making them far too complex for direct use in chemical kinetic simulations. A way to approach this is to develop surrogates, mixtures of a handful of components whose properties are representative of real fuels. Surrogates are essential because they allow researchers to model combustion accurately and efficiently. By capturing fundamental characteristics such as molecular weight, functional group distribution, and H/C ratio, a surrogate can reproduce global combustion phenomena: ignition delay, laminar burning velocity, flame extinction behavior, and pollutant formation. This makes it possible to compare fossil fuels, SAF, HVO, FAME, etc. using the same chemical framework, an ability that is crucial in assessing whether new bio-derived fuels can genuinely emulate conventional kerosene in safety-critical environments.

A method for developing surrogates for combustion simulations of aviation fuels has been presented in the thesis by M. Passad<sup>7</sup>. The surrogate mixtures for a range of fuels including fossil Jet A, JP-5 and JP-8 have been modelled using the detailed mechanism from Politecnico di Milan and the compact mechanism by Zettervall & Nilsson<sup>8</sup>, the later developed within CESTAP and employed in different CFD simulation studies presented in the next section.

Surrogates are composed of well-characterized molecules, making results comparable across laboratories and studies. They also support systematic investigations of how different molecular classes, n-alkanes, iso-alkanes, cycloalkanes, aromatics, affect flame chemistry, radical formation, and flame stability. This is especially important for extinction strain rate, a property shown to be very sensitive to transport parameters and fuel diffusivity. Surrogates provide a clean way to attribute combustion behavior to specific chemical structures.

An important activity related to chemical kinetics within CESTAP in 2025 have been studies of transport properties in extinction strain rate simulations. The goal has been to investigate effects of transport data and chemistry on accurate extinction simulations, which has been applied firstly to the well-studied n-heptane<sup>9</sup>, and then to a range of cyclic compounds<sup>10</sup>.

### *Computational Fluid Dynamics (CFD) studies*

To reduce the fuel consumption during physical testing, and hence also the resource requirements and the cost, the physical testing is supplemented also with virtual testing using high fidelity Computational Fluid Dynamics (CFD). Combustion CFD solves the coupled, transient mass, momentum, energy, and species equations to predict reacting flows in e.g. jet engines and gas turbines<sup>11</sup>. Modern solvers advance the reacting Navier-Stokes equations with heat transfer by convection, conduction, and radiation, account for multi-phase spray physics through primary and second-

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<sup>7</sup> Bridging Efficiency and Accuracy in Aviation Fuel Combustion Simulations with Reduced Kinetics. PhD Thesis, Lund University (2025) M. Passad

<sup>8</sup> Zettervall N. & Nilsson, E.J.K. 2024, "A Compact Chemical Kinetic Mechanism for Heavy Fuel Surrogates with n-, iso- and Cyclo-Alkanes, and Aromatic Compounds", ACS Omega, 10, 15471.

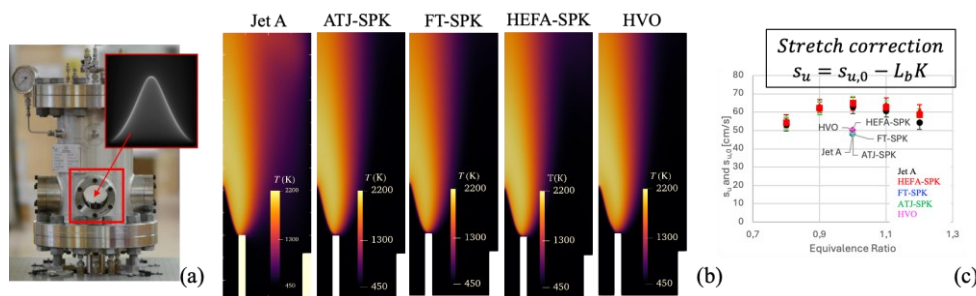
<sup>9</sup> Passad, M. & Nilsson, E.J.K. 2024, "Impact of Transport Data on Extinction Strain Rate of n-heptane Flames". Comb. Flame

<sup>10</sup> The Sensitivity to Transport Parameters in Simulation of Non-Premixed Extinction of Cyclic Hydrocarbons M. Passad, E.J.K Nilsson, Manuscript in preparation

<sup>11</sup> Menon S. & Fureby C.; 2010, "Computational Combustion", In Encyclopedia of Aerospace Engineering, Eds. Blockley R. & Shyy W., John Wiley & Sons.

ary breakup, droplet evaporation, and momentum coupling<sup>12</sup>, and integrate detailed or reduced chemical kinetics<sup>13</sup> with appropriate turbulence and turbulence-chemistry interaction closures to recover flame propagation, thermoacoustic dynamics<sup>14</sup>, emissions, and chemical heat release. Large Eddy Simulation, LES, is the preferred high-fidelity approach for many combustor problems<sup>11</sup>, since it resolves the energy containing flow while modeling only the sub-grid flow, and it can be combined with finite rate chemistry closures<sup>11,12</sup>, combustion chemistry mapping for accelerating the integration of the chemical kinetics<sup>13</sup> and Lagrangian particle tracking for modeling reactive sprays including break-up, atomization etc.

As a first example of CFD simulations performed as part of the pre-certification work Figure 15 presents Direct Numerical Simulation (DNS) results of the laboratory-scale pressurized burner used to evaluate the laminar flame speeds,  $s_u$ , of candidate fuels. Figure 15a shows the laboratory-scale pressurized burner with an insert showing a typical flame. Figure 15b show DNS results in terms of the temperature distribution for Jet A1, ATJ-SPK, FT-SPK, HEFA-SPK and HVO for simulations using the multi-component reaction mechanism of Zettervall & Nilsson<sup>8</sup> based on surrogate formulations of each fuel. Jet A1, ATJ-SPK, FT-SPK, HEFA-SPK show virtually identical flames whereas HVO result in a marginally different flame. Figure 15c compares experimentally measured and computed values of  $s_u$ . Acceptable agreement is obtained taking into account that the DNS results are not yet corrected for stretch which will increase the values of  $s_u$ .



**Figure 15.** (a) The laboratory-scale pressurized burner, (b) laminar flames from Jet A1, ATJ-SPK, FT-SPK, HEFA-SPK and HVO, respectively, and (c) comparison of experimentally measured and computed laminar flame speeds.

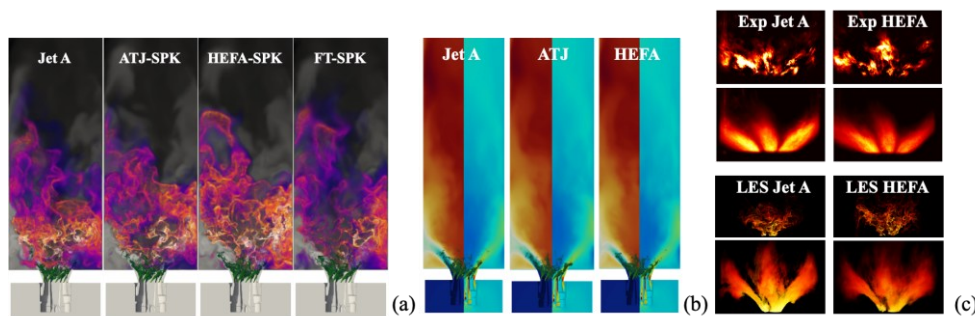
Figure 16 compares predicted spray-flame behavior across conventional and SAF's: Figure 16a presents instantaneous heat-release fields for Jet A, ATJ-SPK, HEFA-SPK, and FT-SPK. All four fuels exhibit qualitatively similar lifted, V-shaped turbulent flames anchored above the injector. The primary fuel-to-fuel differences are in flame-sheet openness and small-scale wrinkling: Jet A appears slightly more compact with locally intense pockets, whereas the SPK's, particularly HEFA-SPK and FT-SPK, show broader reaction zones and finer intermittency. Figure 16b presents time-averaged axial velocity and temperature maps for Jet A, ATJ-SPK, and HEFA-SPK indicating broadly comparable jet development and thermal plumes, with subtle variations. More specifically, Jet A exhibits a slightly warmer and more

<sup>12</sup> Åkerblom A. & Fureby C.; 2024, "LES Spray Combustion Modeling of the DLR Generic Single Cup Combustor", *Flow, Turb. Comb.*, 112, p 557

<sup>13</sup> Vauquelin P., Zhou Y., Åkerblom A., Fureby C. & Bai X.-S.; 2025, "Chemistry Mapping in Reactive LES of Bluff-body Flames using Alternative Jet Fuels", *AIAA.J.*, In Press, <https://doi.org/10.2514/1.J065789>.

<sup>14</sup> Jarfors B. & Fureby C.; 2025, "Large Eddy Simulation of Thermoacoustic Instabilities in Bluff-Body Stabilized Flames", *AIAA* 2025-2488.

concentrated core, while both ATJ-SPK and HEFA-SPK display a modestly wider shear-layer suggestive of enhanced entrainment and a slightly more open flame. Figure 16c shows instantaneous and time-averaged chemiluminescence images demonstrate strong qualitative agreement between experiment and LES for Jet A and HEFA-SPK. Both capture the tri-lobed, lifted topology and its statistical mean, with Jet A showing more pronounced small-scale corrugations in the instantaneous frames and HEFA-SPK presenting more symmetric, wider lobes; overall, the results point to robust cross-fuel similarity in global flame structure while highlighting second-order, fuel-dependent differences in flame-wrinkling, plume width, and intensity localization, and they validate the LES in reproducing both instantaneous features and mean fields across conventional and sustainable blends.

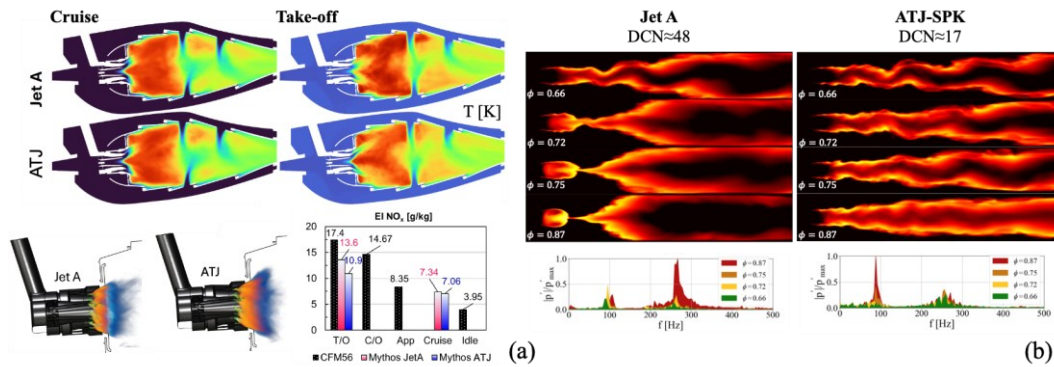


**Figure 16.** Predicted spray-flame behavior across conventional and SAF's: (a) instantaneous heat-release fields for Jet A, ATJ-SPK, HEFA-SPK, and FT-SPK, (b) time-averaged axial velocity (right) and temperature (left) maps for Jet A, ATJ-SPK, and HEFA-SPK, and (c) instantaneous and time-averaged chemiluminescence images from experiments and LES of Jet A and HEFA-SPK.

Figure 17 summarizes activities in associated projects that both leverage CESTAP and return complementary information to it. Figure 17a shows combustion LES results for a virtual jet-engine model developed in the EU project MYTHOS and inspired by the CFM56 engine. Combustion LES were performed for multiple fuels, primarily Jet A1 and ATJ-SPK, across representative operating conditions (Approach, Idle, Take-off, Climb-out, and Cruise) to assess (i) how flow and combustion vary with operating point and (ii) how fuel formulation affects combustion processes and emissions. Fuel-to-fuel differences are most pronounced at very low and very high thrust, whereas at Cruise they are comparatively small. Predicted emissions agree well with CFM56 reference data, indicating that the modeling framework reproduces full-scale engine behavior and captures key operating-condition trends. Figure 17b presents combustion LES for Jet A1 and ATJ-SPK in a simplified flameholder configuration<sup>15</sup>, designed to examine thermoacoustic instabilities and their sensitivity to fuel choice. The most distinguishing feature of the two fuels is the difference in Derived Cetane Number, with Jet A1 having  $DCN \approx 47$  and ATJ-SPK having  $DCN \approx 17$ . For each fuel, the top four panels show predicted line-of-sight OH at  $\phi = 0.66, 0.72, 0.75,$  and  $0.87$ , and the bottom panel shows the corresponding normalized pressure spectra up to 500 Hz. With increasing  $\phi$ , Jet A1 show a transition from an undulating flame shape, determined by the intrinsic relationship between the von-Karman and Kelvin-Helmholtz instabilities, to a strongly pulsating flame shape. The normalized pressure spectrum shifts from having a peak at 90 Hz

<sup>15</sup> Paxton B.T., Fugger C.A., Tomlin A.S. & Caswell A.W., 2020, "Experimental investigation of fuel type on combustion instabilities in a premixed bluff body combustor", AIAA 2020-0174

at  $\phi=0.66$  to having a strong peak in the 260 to 300 Hz band, indicating strong thermoacoustic locking. For ATJ-SPK the undulating flame shape is virtually preserved over the full range of  $\phi$  but with a widening of the flame (due to the increase in flame laminar speed) and a growth of higher frequency undulations. The normalized pressure spectrum stays primarily anchored near 90 Hz with only a modest rise around 280 to 300 Hz, indicating delayed and weaker coupling to the higher-frequency acoustic mode. The observed spectral trends and OH morphologies are in excellent agreement with the experimental data of Paxton *et al*<sup>15</sup>.



**Figure 17.** (a) Jet engine combustion in a virtual jet engine developed in the MYTHOS EU project and (b) incipient thermoacoustic investigations of different fuels (Jet A and ATJ-SPK) for a suite of equivalence ratios

## WP2 Development of turbine fuels from sustainable feedstocks including lignocellulose

The aim of WP2 is to develop turbine fuels from lignocellulosic feedstock. Work package 2 is divided into four tasks, with one PhD student affiliated with each task: Medya Hatun Tanis (Lund University, Faculty of Engineering (LTH)) to Task 2.1, Niklas Bergvall (RISE/LTH) to Task 2.2, Judith Hernandez Cabello (LTU) to Task 2.3, and Jonas Elmroth Nordlander (LTH) to Task 2.4. In addition to the work performed by the academic partners, the industry group is very active in discussions, providing fuel and catalysts samples, upgrading, and performing experiments and analysis work. During 2025, significant progress has been made in WP2. The overall progression of tasks in WP2 is presented in Table 3.

**Table 3.** Progression of Tasks in WP2.

Tasks WP2	Progression (%)	Comments
<b>Task 1:</b> Lignin abstraction and separation.	95%	On track. Gamma-valerolactone (GVL) organo-solv lignin produced and characterized and tested in biorefinery related processes.
<b>Task 2:</b> Development of a process for turbine fuel production from pyrolysis oil and lignin via slurry hydroprocessing.	85%	On track. Candidate SAF produced from pyrolysis oil and delivered to WP1 and WP4 for further testing. Catalyst stability evaluated for the lignin track.
<b>Task 3:</b> Development of a novel process and catalyst for direct conversion of alcohols to	90%	On track. New zeolite catalysts available for testing in 2026. Optimization of the process is ongoing.

turbine fuel components.		
<b>Task 4:</b> Catalyst characterization.	85%	On track. Novel catalysts have been evaluated for hydroprocessing of GVL organosolv lignin. The task proceeds according to plan with regards to characterization of catalysts. The plan for <i>in situ</i> -monitoring of hydroprocessing catalysts has been modified.

### Task 2.1 Lignin abstraction and separation

The aims of task 2.1, managed by LTH, are threefold: (i) to develop an effective fractionation strategy for isolating high-purity lignin from softwood, (ii) to characterize the separated lignin and assess possible end-uses, and (iii) to perform techno-economic analysis of the lignin-first biorefinery concept. The overall goal is illustrated in Figure 18.

The work in Task 2.1 is based on the organosolv fractionation method, that is known to result in high-purity lignin for value-added applications. The molecular weight of organosolv lignin is typically low while the fraction of internal  $\beta$ -O-4 linkages is high, making the lignin highly available for chemical reactions and modification. The organic solvent gamma-valerolactone (GVL) used in this project enables fractionation of the ligno-cellulose while avoiding high-pressurized traditional organosolv methods.

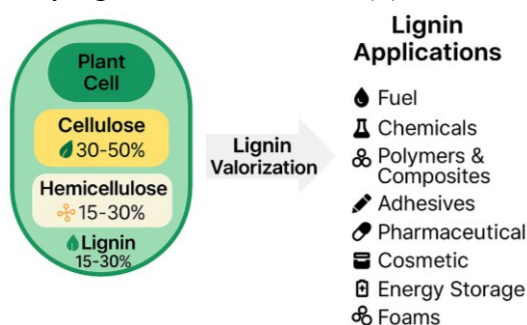


Figure 18. Lignin valorization.

So far, the results have shown that up to 70% lignin recovery can be achieved, with 95 to 99% purity. No cross-peaks associated with hemicellulose-related impurities were detected using 2D HSQC NMR, and the preserved fraction of  $\beta$ -O-4 was up to 47%.

In collaboration with RenFuel, the extracted lignins have been investigated as a feedstock for the Lignol® process, with high bio-oil yields and low yields of insoluble residue observed.

Ongoing work in Task 2.1 includes enhancing lignin recovery as well as solvent recovery and reusability by a salting out phase separation process. Further characterization of the obtained lignin is also ongoing, and market demands for lignin-derived products are being compiled. A techno-economic analysis of the developed lignin-first biorefinery concept is also ongoing.

### Task 2.2 Development of a process for turbine fuel production from pyrolysis oil and lignin via slurry hydroprocessing

Task 2.2, managed by RISE, aims at production of bio-based sustainable aviation fuels from either pyrolysis oil or lignin.

#### The lignocellulosic pyrolysis oil track

Litre amounts of candidate SAF were in this task produced from pyrolysis oil, Figure 19 so called Pyrolysis-To-Jet (PTJ). The pyrolysis oil was, in turn, produced in commercial scale from stem-wood sawdust and was provided by the project partner

VAROPreem AB. To produce the fuel, the pyrolysis oil was hydroprocessed in two steps, first in a slurry reactor and second in a fixed bed reactor. Distillation was used to separate the hydrotreated product into fuel fractions of defined boiling point range. This resulted in a candidate jet fuel fraction having properties in agreement with some important specification criteria for Jet A fuel, Table 4. This PTJ fuel candidate has now been delivered to WP1 and WP4 for evaluation of combustion properties and materials interactions.

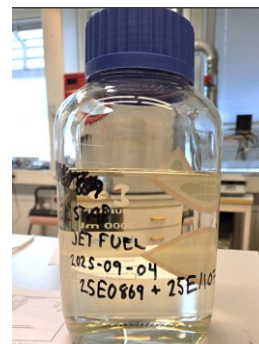


Figure 19. PTJ.

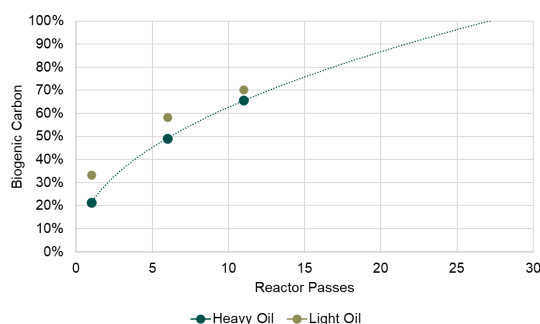
As a first move towards scaling up the pyrolysis oil upgrading methodology described above, the same commercial fast pyrolysis oil was stabilized by one-step hydroprocessing in slurry reactor, similarly as above. This resulted in more than 20 kg of stabilized oil product which was shipped to Topsoe for further hydroprocessing to larger samples of candidate jet fuel using their catalyst technology.

**Table 4.** Properties of Jet Fuel fraction produced from wood-based pyrolysis oil. Figures in green are inside Jet A specification limits whereas figures in red are outside.

Property	Jet A Specification	Bio-based Jet Fuel Fraction
10 % Distillation	< 205 °C	149
Final Boiling Point	< 300 °C	305
Acidity	<0.10 mg KOH/g	
Aromatics	< 25 vol.%	29.7
Cetane Number	-	33.1
Density @ 15°C	775 – 840 kg/m <sup>3</sup>	848.5
Flash Point	> 38 °C	43
Freeze Point	< -40 °C	- 54
Net Heat of Combustion	> 42.8 MJ/kg	42.81
Smoke Point	> 25 mm or > 18 mm and Naphthalenes < 3 wt.%	17.2
Total Sulfur	< 3000 ppm	3.4
Viscosity @ -20°C	< 8.0 mm <sup>2</sup> /s	4.9

### Converting lignin to biogenic hydrocarbons via slurry hydroprocessing

In the lignin track, Kraft Lignin has been converted to a bio-oil suitable for further upgrading to fuels and chemicals. This was done by dispersing the lignin dry powder in a fossil oil (vacuum gas oil, supplied by VAROPreem AB) to produce a pumpable slurry. This slurry was then processed in the slurry hydroprocessing pilot, converting the lignin to mainly liquid hydrocarbon products. By recycling the catalyst and parts of the liquid product while adding fresh lignin to the process, the fossil oil

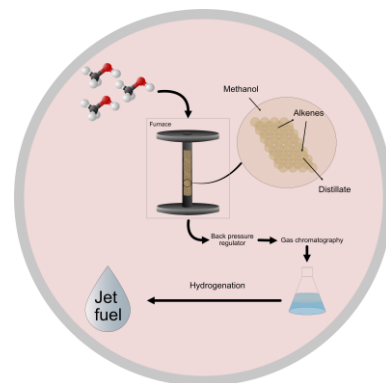


**Figure 20.** Increase in biogenic content with increasing number of reactor passes, showing how the starting oil is being replaced by liquefied lignin components.

was gradually replaced reaching a mixture dominated by biogenic hydrocarbons. Evaluation of the results show that about 80% of the biogenic carbon from the lignin ended up in the liquid oil products, resulting in a rapid increase in biogenic carbon content of the product oils with each reactor pass, **Fel! Hittar inte referenskälla.0.** The bio-oil produced during the later part of the experiment will be subjected to further processing to fuel components during the last year of the project.

### *Task 2.3 Development of a novel process and catalyst for direct conversion of alcohols to turbine fuel components*

This task is managed by LTU, and the work aims at zeolite catalyst development for direct conversion of methanol to turbine fuel components, as shown schematically in Figure 21. As earlier reported, several litres of an aromatic-rich fuel product were produced early in the project, and an exceptionally low rate of catalyst deactivation was observed compared to commercial catalysts. The work in Task 2.3 has since then been focused on optimizing the process and increasing the yield of heavier (jet fuel range) hydrocarbons. Since the start of the project, five catalyst candidates have been developed. Most of the catalysts have been based on the ZSM-5-type zeolite, but also other zeolite frameworks have been investigated. The yield of SAF range hydrocarbons increased by >50% between the first and the second investigated catalyst, and evaluation of the catalytic activity of catalyst No. 3 to 5 is ongoing. All catalysts are being thoroughly characterized.



**Figure 21.** Methanol to Jet.

As the zeolite catalysts have shown selectivity towards producing aromatic hydrocarbons, the synthesized product mixtures show promise for instance as biogenic aromatic blending components to be blended with *e g* mixed aliphatic paraffinic hydrocarbons produced using other (certified) technology track SAF blending components like HEFA-SPK or ATJ-SPK to achieve 100% biogenic complete SAF having all the compound classes represented as found in current Jet A or in fuels following other relevant jet fuel standards like JP5.

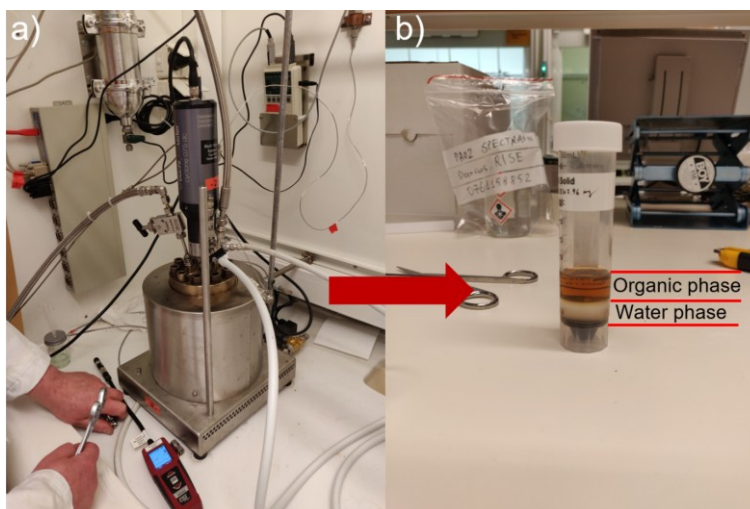
Efforts during the last year of the project will focus on further characterization of different zeolite catalyst candidates as well as SAF component production using catalyst candidates No. 3 to 5.

### *Task 2.4 Catalyst characterization and development*

Task 2.4 is managed by LTH and focuses on characterization of catalysts used in the other tasks of WP2, as well as development and evaluation of new catalysts for hydroprocessing of biobased feedstock. During the project period, this work has led to a deeper understanding of the characteristics of both the molybdenum catalyst used in Task 2.2 as well as the zeolite catalysts used in Task 2.3.

Recent results include a study of three types of novel CuMo catalysts using a model reaction, namely hydrodeoxygenation of anisole (methoxybenzene). This reaction was monitored online at the Balder beamline of MaxIV, giving important insights into catalyst activity and stability.

Hydrodeoxygenation of the lignin produced in Task 2.1 has also been performed, using both traditional sulphided and novel oxide catalysts, Figure 22. The hydro-processing was performed starting from lignin produced in Task 2.1 dissolved in GVL as a solvent.



**Figure 4.** a) Buchi 100 ml batch reactor used for experiments. b) Resulting product (centrifuged).

During the last year of the project, the focus will be on evaluating catalyst activity and characterization results recorded at MaxIV and other synchrotrons, as well as evaluation of the results from the lignin/GVL hydroprocessing.

### WP3 Mutual adaptation of turbine fuel and engine technology

The aim of WP3 is to study different combustion chamber concepts that may be suitable for aviation and stationary gas turbines, that may fulfill the requirements of the future concerning robustness, that may use different green liquid fuels and that may achieve low emissions. The PhD student Alessandro Ercole has been connected to this work package from the beginning of the project and during 2024 an industrial PhD student from Uniper, Rania Torabi Aysf, started as well. They have worked on setting baselines to identify needed improvements, improve modeling capability and quantify fuel effect on spray and flame kinetics together with WP1. Then the aim is to perform numerical studies of improved concepts and down select the most promising concepts for testing. Apart from regular project meetings, there is quarterly WP3 status meetings with all partners that are interested to participate (Lund Uni., RISE, Siemens Energy, GKN, Uniper, Göteborg Energi, SAAB, SKY-NRG). The progression of tasks is shown in Table 3, where the titles have been adjusted to better reflect the most appropriate goals for WP3.

**Table 3.** Progression of tasks WP3

Tasks of WP3	Progression (%)	Comments
<b>Task 1:</b> Investigation of spray characteristics vs fuel flexibility	100%	Spray tests were performed and finished during spring 2025.
<b>Task 2:</b> Investigate combustion technology relevant for stationary GTs	60%	On track and in line with project plan using the CECOST burner.

<b>Task 3:</b> Investigate combustion technology relevant for aviation GTs.	80%	On track and in line with project plan using the TARS burner.
<b>Task 4:</b> Investigate high pressure effect	20%	On track and in line with project plan.

The following activities have been conducted during 2025:

#### *Spray tests to evaluate fuel nozzle performance*

One of the main parameters concerning the effect of different fuels is the spray characteristics when liquid fuel is to be mixed with air upstream the flame, which has a great effect on the downstream flame. Therefore, WP3 has included spray tests at the high-pressure spray rig at RISE, with complementary laser measurements in collaboration with WP1. During 2023/2024 similar spray tests were performed in this rig within the competence center TECH4H2<sup>16</sup>. During 2024 the preparations for the WP3 measurements have been performed and the tests were executed during spring 2025. The down-selection and priority lists of what conditions, nozzles and fuels that were included in this study were approved by the partners attending the WP3 status meetings. The investigation included ethanol, methanol, SAF, Jet A1 and diesel using plain jet nozzles of two sizes. The laser diagnostic technique called SLIPI (Structured Laser Illumination Planar Imaging) was applied that may measure droplet size distribution in a 2D plane for dense sprays. The measurements also included some PDA (Phase Doppler Anemometry) measurements to calibrate the data from SLIPI. The measurement campaign was successful in the sense that all planned measurements were performed, and it was concluded how the SLIPI setup needs to be updated to perform quantitative measurements in next campaign that is planned in next phase during 2027.

#### *Baseline cases for stationery gas turbine (GT) combustion systems*

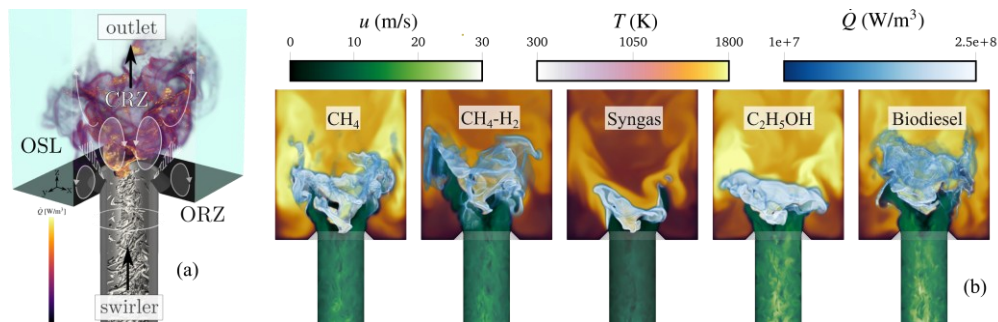
The CECOST burner, originating from the competence center CECOST<sup>17</sup> has been investigated in this part of WP3. It has been selected because it is relevant to the burners used in modern power generation gas turbines, and because it is suitable in size for both atmospheric testing and for the high-pressure rig at Lund University. More specifically, the CECOST burner is a downscaled similar version of the type of burners used in Siemens Energy gas turbines SGT-600, SGT-700 and SGT-800. Previous studies in CESTAP identified the baseline CFD modeling approach, validating it against measurements obtained within the CECOST program. Figure 23a shows a visualization of the premixed turbulent flame from the first round of Large Eddy Simulations. The reaction region in the rectangular combustion chamber is identified by high combustion heat release. When the turbulent swirling flow in the mixing tube reaches the combustion chamber, it induces a Central Recirculation Region (CRZ), an Outer Recirculation Region (ORZ), and an Outer Shear Layer (OSL). Those flow structures play a pivotal role in the flame stabilization mechanism. The findings of the first simulation campaign highlighted how the key flow structures are surprisingly dependent on the choice of turbulent combustion model. Also, it was emphasized how those dependencies should be carefully evaluated in

<sup>16</sup> <https://www.chalmers.se/en/centres/techforh2/>

<sup>17</sup> <https://www.lth.se/cecocost/>

the context of fuel sensitivity studies. The outcome of the campaign was the selection of a baseline modeling methodology for the next simulation efforts, focusing on the effects of alternative green fuels, both gaseous and liquid.

Figure 23b shows five different instantaneous flame structures obtained for three gaseous fuels ( $\text{CH}_4$ ,  $\text{CH}_4\text{-H}_2$ , syngas) and two pre-vaporized, premixed liquid fuels ( $\text{C}_2\text{H}_5\text{OH}$ , biodiesel). The study has a twofold purpose: to extend the validation effort to other cases experimentally tested during CECOST (namely  $\text{CH}_4\text{-H}_2$ , syngas) and to provide insight into the effects of fuel preparation for pre-vaporized, premixed fuels. While gaseous fuels were experimentally tested at atmospheric air temperature, liquid fuels need higher air temperature to ensure vaporization and mixing. At constant mass-flow rate and flame temperature, this results in lower equivalence ratio, higher flow velocity, and generally higher flame speed. Concerning the gaseous fuels cases, the baseline  $\text{CH}_4$  simulations confirmed good agreement with experimental data. However, the hydrogen-enriched methane and syngas simulations proved more difficult because of the more demanding combustion regimes in the first, and of combustion chemistry effects in the second. The pre-vaporized liquid fuels showed similar features to the baseline case, yet with differences in the morphology of the reaction region. Analyzing the entire dataset, the ratio between laminar flame speed and turbulence intensity was found to describe to a good extent some macroscopic features, such as the recirculation region angle and the axial location of peak heat release.



**Figure 23.** (a): Volume rendering of heat release, turbulent structures in the mixing tube, and key flow structures in the stabilization mechanism. (b) Instantaneous volume renderings of heat release, together with temperature and velocity magnitude in the center plane of the combustor. Results for three gaseous fuels, and two pre-vaporized, premixed liquid fuels.

In recent efforts, the combustion modeling and the fuel sensitivity datasets were jointly analyzed to understand fundamental flame-turbulence interactions common to both modeling aspects. The analysis relied on the statistical analysis of fluid-mechanical quantities affected by combustion-induced thermal expansion. It was found that vigorous heat release, either originating from formulations of the models, or from combustion chemistry, statistically favors local flow topologies with turbulence-suppressing effects. This correlates with a distinct flow structure in which the CRZ appears drastically delayed downstream of the heat release region. This cross-analysis at the intersection of combustion models and combustion chemistry isolates common fundamental coupling mechanisms, such as thermal expansion and its impact on turbulence. This offers insight into the physical aspect of the problem while narrowing down some modeling uncertainties.

As input to the baseline cases, Siemens Energy have performed high pressure combustion tests with alternative fuels to quantify the fuel effect that is intended to be compared to the laboratory scale tests. During 2023/2024 there were various tests in the Siemens Energy high pressure rig in Berlin using fuels such as HVO, RME, and methanol complemented with engine tests using HVO in SGT-700, SGT-750 and SGT-800. During 2025 this was followed up using single burner rig and engine tests in Finspång to increase understanding how to increase flame stability during liquid fuel operation, followed by a joint test at Göteborg Energi Rya.

Furthermore, Sydkraft Thermal Power AB / Uniper, has during 2024 performed further testing and implementation of green fuels across their gas turbine sites in Sweden. In June 2024, an HVO trial was successfully conducted on an aeroderivative gas turbine at the Barsebäck (BVT) OCGT site, and the HVO conversion process for the BVT G13/G14 units is underway<sup>18</sup>. In December 2024, the HVO conversion and commissioning of the Karlshamn (KVT) G13 OCGT unit was completed<sup>19</sup>. At Öresundsverket, the first 12-month period of HVO operation was completed on the G24/G25 OCGT units. Further HVO conversions and commissioning are planned for 2025, and any learnings or further research questions that are developed from the increased operational experience is to be shared and explored with CESTAP. The plan is to support these full-scale tests with more fundamental studies, using laboratory facilities and numerical simulations, to provide more detailed understanding, supporting further full-scale tests and optimization.

#### *Baseline cases for aviation gas turbine combustion systems*

A literature study was performed to evaluate baseline options and to investigate potential complementing baselines. The FJ44 combustor is identified as suitable for tests to quantify the effect of different fuels on global level. For detailed experimental and numerical studies in laboratory scale, the TARS (Triple Annular Research Swirler) burner is identified as the best available option. The selected options have been approved with the partners that attend the WP3 status meetings. Experimental and simulation work of the TARS burner using liquid fuels have been initiated in collaboration with the EU Horizon Europe projects MORE&LESS, MYTHOS and Circular Fuels.

Figure 24a shows the digital model of the TARS assembly. Air is forced from a plenum through the outer radial swirler, and through the axial intermediate and inner swirlers. The numerical setup was inherited from the MYTHOS project. It is based on Large Eddy Simulations coupled with Finite-Rate Chemistry (FRC) and Lagrangian Particle Tracking (LPT) to model the spray combustion process.

The initial focus of WP3 on the TARS burner has been on extending the simulation database for Sustainable Aviation Fuels (SAFs) beyond the compact, pathway-centric reaction mechanisms of the Z79 family<sup>20</sup>. To achieve this goal, conventional Jet

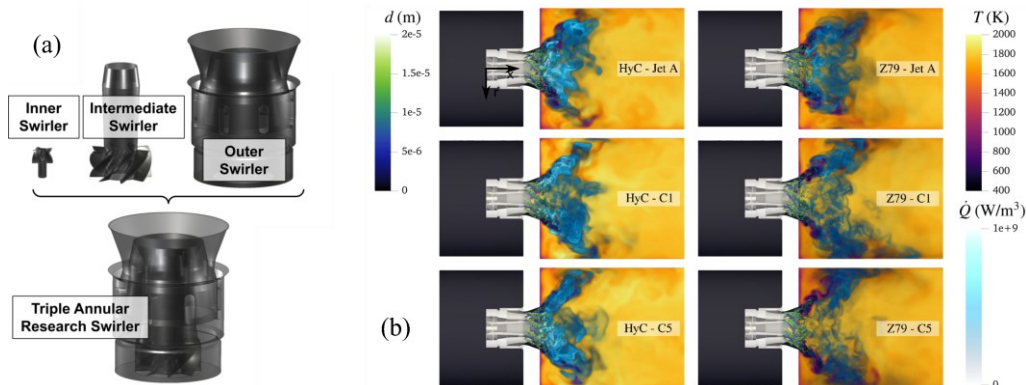
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<sup>18</sup> [https://www.linkedin.com/posts/uniper-se\\_aemverbelastningshantering-activity-7283039429542236160-hwas/?utm\\_source=share&utm\\_medium=member\\_desktop&rcm=ACoAAB8DPUoBVvCRnqKA-TAeDRdz4\\_IYuGFvc2o4&skipRedirect=true](https://www.linkedin.com/posts/uniper-se_aemverbelastningshantering-activity-7283039429542236160-hwas/?utm_source=share&utm_medium=member_desktop&rcm=ACoAAB8DPUoBVvCRnqKA-TAeDRdz4_IYuGFvc2o4&skipRedirect=true)

<sup>19</sup> [https://www.linkedin.com/posts/uniper-se\\_nu-har-ocks%C3%A5-gasturbinen-i-karlshamn-konverterats-activity-7273247596217839616-aTQH/?utm\\_source=share&utm\\_medium=member\\_desktop&rcm=ACoAAB8DPUoBVvCRnqKATAeDRdz4\\_IYuGFvc2o4&skipRedirect=true](https://www.linkedin.com/posts/uniper-se_nu-har-ocks%C3%A5-gasturbinen-i-karlshamn-konverterats-activity-7273247596217839616-aTQH/?utm_source=share&utm_medium=member_desktop&rcm=ACoAAB8DPUoBVvCRnqKATAeDRdz4_IYuGFvc2o4&skipRedirect=true)

<sup>20</sup> Åkerblom A., Zettervall N. & Fureby C.; 2024, "Comparing Chemical Reaction Mechanisms for Jet Fuel Combustion in Simulations of Turbulent Premixed Bluff-Body Burner", AIAA 2024-0179

A1 and two SAF variants, C1 and C5<sup>21</sup>, are simulated using the skeletal HyChem chemical kinetics<sup>22</sup>. The simulations were performed in cooperation with the Circular Fuels project. Figure 24b shows some instantaneous representative snapshots comparing the flame structures in the six cases. The study concluded that combustion chemistry effects across families of reaction mechanisms surpass the fuel-to-fuel variations in the same chemistry framework. Nonetheless, despite the discrepancies in absolute values, several fuel trends are consistent across the two datasets. This confirms LES as an appropriate comparative tool for Sustainable Aviation Fuel assessment, while emphasizing how cross-validation across chemistry model is essential to extract physically meaningful and design-relevant indications.



**Figure 24.** (a) Digital model of the Triple Annular Research Swirler assembly. (b) Instantaneous volume renderings of heat release, together with the spray cloud and the temperature distribution in the center plane. The right and the left column represent HyChem and Z79 results, respectively.

In addition to the impact of chemical kinetics, the impact of the fuels' liquid properties has also been investigated. The different physical properties of the SAF candidates, e.g., density, surface tension, viscosity, boiling point, etc., play a crucial role in the modeled breakup and evaporation processes prior to mixing and combustion. The statistical analysis of the spray data from the Z79 simulations revealed how the thermophysical properties of some SAF candidates, ultimately connected to their composition, can lead to faster atomization and evaporation processes, counteracting the effects of lower reactivity.

Recent simulation campaigns leveraged on a newly developed multi-component reaction mechanism labeled Z153<sup>23</sup>. One of the strengths of the multicomponent approach is capability to isolate and remove biases coming from differences in the base C/O/H base chemical models, focusing on compositional effects of SAF surrogates. The numerical study was performed in parallel with experiments at higher mass flow rate compared to the original round of simulations. The joint effort revealed consistent features and trends of comparable magnitude between simulations and experiment, both in terms of macroscopic flame structure and flame dynamics.

Furthermore, initial numerical simulations of the TARS burner as set up at Lund University were performed by GKN Aerospace. The simulations were done with

<sup>21</sup> Edwards T.; 2017, "Reference Jet Fuels for Combustion Testing", AIAA 2017-0146.

<sup>22</sup> Hai W., Rui X., Kun W., Bowman C.T., Hanson R.K., Davidson D.F., Brezinsky K. & Egolfopoulos F.N.; 2018, "A physics-based approach to modeling real-fuel combustion chemistry – I. Evidence from experiments, and thermodynamic, chemical kinetic and statistical considerations", *Comb. Flame*, 193, p502.

<sup>23</sup> Zettervall N., Nilsson E. J. K.; 2025, "A Compact Chemical Kinetic Mechanism for Heavy Fuel Surrogates with n-, iso- and cyclo-Alkanes, and Aromatic Compounds", *ACS Omega*, 10, p 15471.



fuel candidates during storage and transportation is within the scope of this work package. The work package is divided into the three subtasks, the progression of which are outlined in Table 5 with commenting text containing more detail below.

**Table 5.** Progression of tasks WP4.

Tasks of WP4	Progression (%)	Comments (%)
Task 1: Lubrication	15%	Pending receipt of samples from fuel candidates generated within the centre. Standardized evaluation methodologies are accessible. A literature review is scheduled for completion by the year 2026
Task 2: Soft material interactions.	75%	On track. A method for the rapid evaluation of polymer compatibility with sustainable aviation fuel (SAF) candidates has been published. Swelling performance on fuel candidates to be further investigated 2026.
Evaluation methods Task 3: Deposits and corrosion	50%	Delayed. Plan is to catch up 2026. The primary emphasis for the remainder of WP 4 will be placed on the examination of the storage properties of biofuels Master students starts early 2026.

**Task 1 Lubrication:** The impact of having different fuel properties such as viscosity and assessing potential negative implications on pumps and valves in the fuel system. The fuels under consideration will be investigated, and possible remedies will be sought as part of this work if there is a need for improved lubrication. There are standard test methods measuring lubricity, e.g. ASTM D5001 and Brugger test (DIN 51347-1/2). How lubricity, for fuel candidates, correlates to chemical composition and other physical properties will be further investigated in WP 4.1.

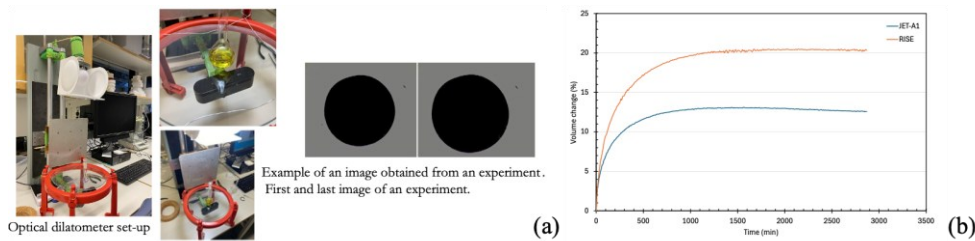
**Task 2 Soft material interactions:** In Task 2, issues related to soft materials will be investigated concerning the suggested fuel qualities. The Master Student Thesis published in Q1 2024 presented an rapid evaluation method for compatibility of alternative jet fuels with elastomer seals. The conclusion from thesis was:

- Volume swell is a one of the most important properties in sealants.
- Volume change equilibrium seems to be obtained in a short amount of time for conventional fuels – first 24 hours.
- Ageing of elastomers is important for simulating elastomers that have been in service.
- Optical dilatometry is a useful way of testing volume change. With a good image processing program, analysis can be done quickly. See figure 26.
- Knowing composition of fuel is important.
- Recommended testing process:
  - Testing the new fuel on both new and “used” elastomers.
  - The fuel should be tested on other materials as well.
  - Higher temperatures for a faster method.

The method employed is based on work made by Graham *et al.*<sup>27</sup> at University of

<sup>27</sup> Graham, J. L. *et al.* *Energy Fuels* **2006**, *20*, 759–765, <https://doi.org/10.1021/ef050191x>.

Dayton in the US.



**Figure 26.** (a) Optical dilatometry set up and sample images, and results comparing Jet A and PTJ

**Task 3 Deposits and corrosion:** High- and low temperature corrosion, chemical stability and deposits will be assessed for selected test fuels. Deposits resulting from the combustion of fuels are normally related to presence of trace metals in the fuel, something which will be carefully analyzed as part of the analytical package in WP 2, where the default scenario is that trace element contents of candidate renewable fuels should be very low. Still, specific metals atoms/ions can work as catalysts causing decomposition of fuel molecules into more reactive components, at lower temperature present at storage, figure 27, causing a FOD/filter problem and at high temperatures causing deposits in nozzles and regulator valves (as worst cases). For fossil fuel Cost-effective standard methods to be applied are ASTM D7111, D8110-17 and UOP 389 as well as the so-called Jet Fuel Thermal Oxidation Test (JFTOT, ASTM D3241). Corrosion is evaluated by microstructural evaluation of material samples soaked in test fuel at elevated temperatures (ASTM D4054). Biofuel introduces new feedstocks, processes and molecules that may require new test methods not used for fossil fuels. An early storage life evaluation of bio-based turbine fuel candidates shall be further investigated in WP 4.3.



**Figure 27.** Fuel storage quality control.

In the year 2025, our primary efforts have been directed towards strategic planning, the delineation of additional project scope, and the recruitment of both researcher and master students.

LTH, RISE, Saab, GKN, Siemens Energy, Topsoe, Svensk Kraftreserv and St1 have been actively involved in WP4 during 2025.

### **WP5 Holistic techno-economic and sustainability analysis**

WP5 centers on a comprehensive assessment of sustainable turbine fuels, emphasizing their benefits as well as associated trade-offs. The evaluation considers key aspects such as production potential, economic viability, and environmental performance.

As described in the overall research plan, the tasks within WP5 are closely linked to the developments in WP2, and include the following specific activities:

1. Literature study on production sustainable aviation fuels
2. Case study for methanol-to-jet (MTJ) SAF production
3. Case study for SAF production from slurry hydrotreatment of pyrolysis oils

#### 4. Engine emissions and high-altitude effects

The following section provides a brief overview of the progress of activities, including any modifications made and additional tasks introduced. The activities are broadly grouped into two main tasks addressing the economic and sustainability performance of SAF, as summarized in Table 5.

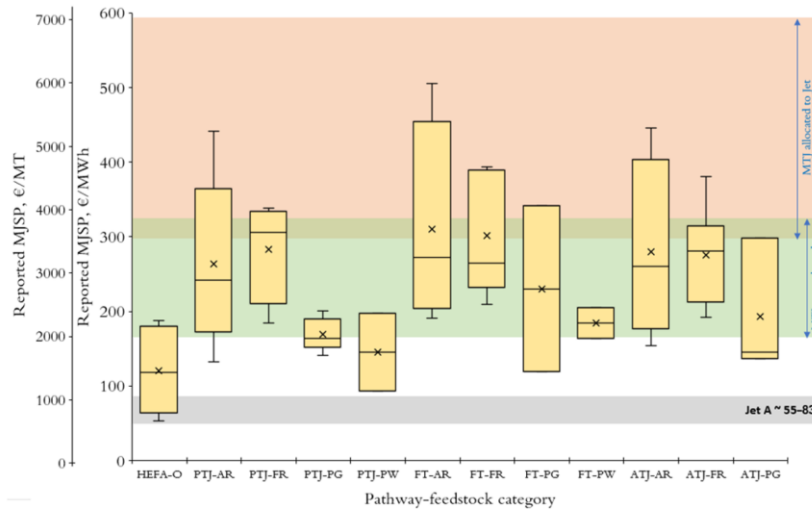
**Table 5.** Progression of tasks WP5.

Tasks of WP5	Progression (%)	Comments
Task 1: Techno-economics of biofuel production	85%	<p>A systemic review and meta data analysis of MJSP across relevant SAF value chains (published, 100%)</p> <p>The completion of the MTJ evaluation in Task 2 depends on the developments currently ongoing in WP2 (postponed pending data confirmation)</p> <p>System study on pyrolysis to jet (PtJ) based on fuels developed in WP2 (manuscript ready for submission, 90%)</p> <p>To align with Zeenat's PhD timeline and benchmark against ASTM approved FTJ value chains, the methanol supply chain developed for MTJ in Task 2 is currently used in a technoeconomic comparative assessment of the MTJ (via olefins) and FTJ value chains in the Swedish context (manuscript under preparation, 60% complete)</p>
Task 2: Sustainability of biofuel production and use	60%	<p>On track and this task is partly dependent on emissions data from tests in WP1. As part of the systems assessments, emissions related to SAF production and use (assuming complete combustion) are estimated for comparison against fossil comparators.</p>
Task 3: Holistic analysis of biofuel alternatives	65%	<p>This task aims to translate the results of the economic and environmental assessments of SAF value chains (Tasks 1 and 2) into the broader ambitions and objectives of CESTAP.</p>

**Task 1.** Zeenat Farooq, a PhD student at LTU conducted a comprehensive literature review and meta-analysis of the techno-economic performance of commercially available SAF pathways based on sustainable, non-food feedstocks. The study evaluates 52 greenfield and 42 integrated configurations and the results are published in peer review journal. Results show that high production costs remain a key barrier, with MJSP commonly used but difficult to compare due to inconsistent TEA assumptions. Based on harmonized data, HEFA ranks lowest in MJSP, followed by PTJ, ATJ, and FT, though results are highly context-dependent. By-product credits, feedstock costs, capital estimates, and financial assumptions are identified as major drivers of cost variability and improvement potential.

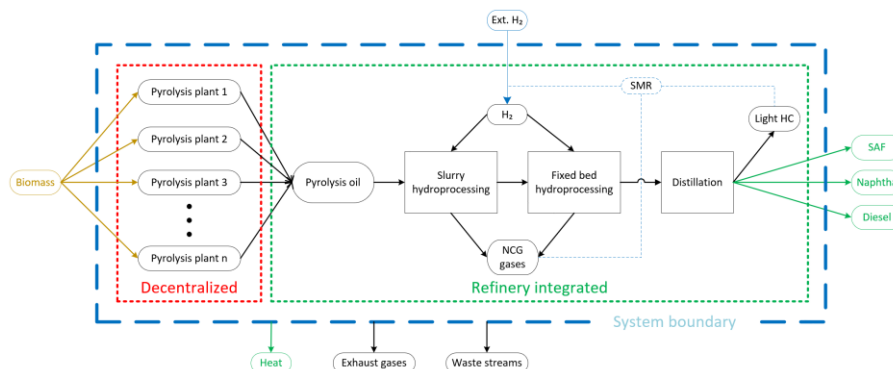
**Task 2.** Work on the direct MTJ pathway began in 2022 and was expanded in 2023 to include renewable methanol production and downstream upgrading. A simplified Aspen Plus® model was developed to generate mass, energy, and carbon balances and to estimate MFSP. In this configuration, unreacted methanol was recirculated, light gases were assumed to replace fossil gas, and naphtha was treated as a saleable

product. Preliminary results show that production costs are dominated by renewable methanol, particularly CAPEX and feedstock (biomass/electricity) costs, while conversion costs are comparatively low. Evaluating MJSP across all liquid products provides a more representative cost estimate than allocating costs solely to the distillate fraction. Further action on this activity is currently on hold, pending the results of ongoing catalyst testing in WP2. A summary of the MJSP is presented in Figure 28, including the preliminary results for MTJ.



**Figure 28.** Compilation of reported MJSP for comparable SAF production pathways. The shaded area represents the range of production costs for MTJ tracks evaluated in this project (light green: MFSP allocated to all liquid fuel products and light red: MFSP allocated to jet fraction). *AR* – agricultural residues, *FR* – forest residues, *O* – oil feedstock, *PW* – process waste, *ATJ* – alcohols-to-jet, *PTJ* – pyrolysis-to-jet, *FT* – Fischer-Tropsch, *HEFA* – hydroprocessed esters and fatty acids.

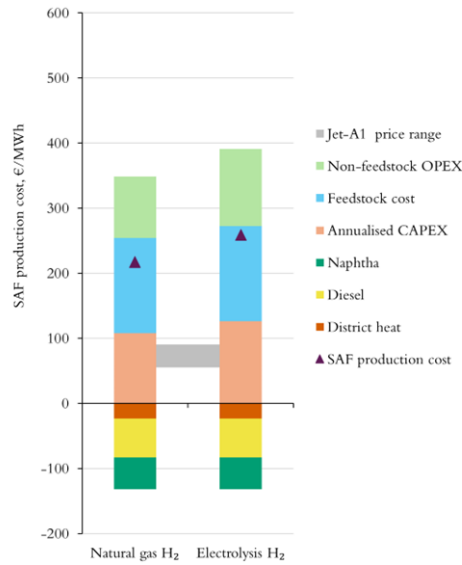
**Task 3.** Based on the results of Task 1, forest-based Pyrolysis-To-Jet (PtJ-FR) pathway shows strong economic competitiveness, positioning it as a promising route for utilizing Swedish forest resources in SAF production. Figure 29 shows system boundary used for valorizing sawmill byproducts into SAF.



**Figure 29.** System boundary for evaluating PtJ-FR developed within CESTAP.

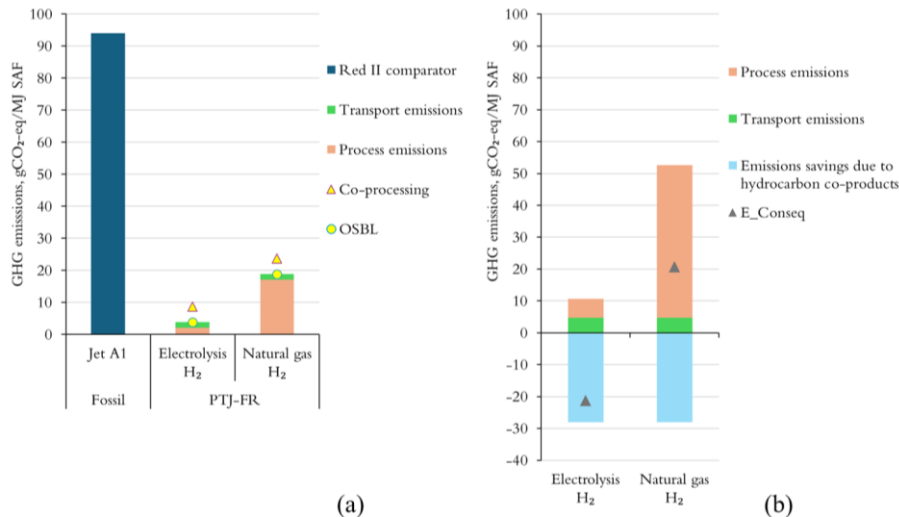
Figure 30 compares the SAF production cost breakdown for two hydrogen supply configurations: natural gas reforming and electrolysis. In both cases, feedstock cost and annualised CAPEX are the dominant cost components, followed by non-feedstock OPEX. For the natural gas H<sub>2</sub> case, the production cost is around 218 €/MWh, whereas switching to electrolysis increases the cost to roughly 260 €/MWh. The higher cost in the electrolysis scenario is mainly driven by increased CAPEX and

non-feedstock OPEX associated with electrolyser investment and electricity consumption. Revenues from co-products (naphtha, diesel, and district heating) provide notable cost credits in both scenarios, partially offsetting total production costs. Among these, naphtha generates the largest credit, followed by diesel, while district heating contributes a smaller but noticeable reduction. Despite these credits, total SAF production costs remain well above the indicated Jet A1 market price range in both cases. Overall, the results highlight that H<sub>2</sub> supply choice influences production cost, with natural gas reforming offering lower near-term costs and electrolysis increasing costs but potentially improving environmental performance.



**Figure 30.** PtJ production cost for valorizing sawmill by-products, 100 kTPY SAF capacity.

Figure 31 presents the emission performance of PtJ-FR. Accordingly, the CO<sub>2</sub> emissions performance of the PtJ value chain shows substantial reductions compared to the RED II fossil comparator (94 g CO<sub>2</sub>-eq/MJ) under both hydrogen supply options, Figure 30a. In the attributional RED II assessment, electrolysis H<sub>2</sub> results in very low emissions (~3 to 5 g CO<sub>2</sub>-eq/MJ), while natural gas H<sub>2</sub> leads to higher but still significantly reduced emissions (~18 to 22 g CO<sub>2</sub>-eq/MJ), with process emissions dominating and transport contributing only marginally. Figure 30b shows consequential GHG emissions with system expansion approach in which co-products and excess energy streams were assumed to displace equivalent fossil-based products in the wider energy system. Specifically, renewable naphtha and diesel were assumed to substitute their fossil counterparts on an energy-equivalent basis, while excess heat delivered to district heating displaced the average Swedish district heating mix. Under this expanded system boundary, avoided emissions from hydrocarbon co-products provide significant credits. In the electrolysis H<sub>2</sub> case, these credits exceed the remaining process and transport emissions, resulting in net negative GHG emissions per MJ of SAF. In the natural gas H<sub>2</sub>, higher process emissions reduce the overall benefit, but the displacement of fossil hydrocarbons still lowers the net GHG intensity compared to the attributional result. This consequential perspective demonstrates that co-product valorization and system integration are critical for capturing the full climate mitigation potential of the PtJ pathway.



**Figure 31.** CO<sub>2</sub> emissions performance: PtJ value chain valorizing sawmill byproducts; (a) Emissions performance of SAF against fossil comparator, (b) Emissions performance for expanded system boundary (including impact of co-product hydrocarbons, diesel and naphtha, and excess heat)

## WP6 Exploitation and Implementation Plan

During 2025, the activities within the Exploitation and Implementation work package focused on strengthening the link between fundamental research outcomes and industrial applications within CESTAP. Close interaction with industrial partners was maintained throughout the year to ensure continued relevance and early identification of results with implementation potential.

Research results generated within the centre were actively disseminated through joint workshops, technical meetings, and scientific publications. Several project outcomes were integrated into ongoing industrial development activities and used as input for pilot-scale studies and process evaluations.

The centre management team coordinated exploitation-related activities in close collaboration with academic and industrial partners. Particular emphasis was placed on supporting competence development, facilitating knowledge transfer, and aligning research activities with long-term sustainability and energy transition objectives.

During 2025, efforts were made to strengthen the long-term development of the centre. This work included continuous identification of promising research directions, further strengthening of existing collaborations, and ongoing development of strategies to ensure long-term industrial and societal impact beyond the initial funding period. Overall, the work package progressed according to plan and continues to provide a solid foundation for long-term implementation and impact within CESTAP.

## WP7 Dissemination and Outreach

WP7 is the work package for communication and dissemination, within CESTAP as well as to stakeholders outside the Centre. As stated in the Program Description for CESTAP, WP7 includes activities that ensure that the project results are collected and disseminated, including attendance at major scientific dissemination events; disseminate the knowledge developed during the course of the project; promote the results to the wider international community and arranging a strong and

fruitful collaboration with other relevant projects.

Two physical all partner CESTAP meetings have been arranged during 2025:

- The 2025 CESTAP Summer Meeting was held at Lund University on May 22<sup>nd</sup>, with research presentations mainly by PhD students. The meeting had 42 attendants from 18 partner organizations.
- The 4<sup>th</sup> CESTAP Annual Meeting was hosted by RISE in Stockholm on November 20-21, with 49 participants from 21 partner organizations. Four industrial partners presented their work on biofuels. The WP leaders presented the status of research progress in relation to overall goals and anticipated timing.

An activity for PhD students have been the preparation for the summer meeting. Students belonging to each WP together with affiliated students from partner projects, met several times in the months before the meeting to prepare the presentations as a team. Their task was to get acquainted with the overall goals of CESTAP and put their own work in the context.

## Doctoral Degrees

Bora O. Cakir 2024 “Optical Diagnostics with Background Oriented Schlieren – A practical perspective on reactive and non-reactive flow scenarios”, Lund University, Dept. of Energy Sciences, 2024-10-25.

Arvid Åkerblom, 2025 “Large Eddy Simulations of Alternative Jet Fuel Combustion”, Lund University, Dept. of Energy Sciences, 2025-06-12.

Martin Passad, 2025 “Bridging Efficiency and Accuracy in Aviation Fuel Combustion Simulations with Reduced Kinetics”, Lund University, Div. of Combustion Physics, 2025-12-19.

## List of Publications from CESTAP 2022 – 2025

### Journal Publications

Åkerblom A., Pignatelli F. & Fureby C.; 2022, “Numerical Simulations of Spray Combustion in Jet Engines”, *Aerospace*, **9**, p 838.

Cakir B.O., Lavagnoli S., Saracoglu B.H. & Fureby C.; 2023, “Assessment and Application of Optical Flow in Background-oriented Schlieren for Compressible Flows”, *Exp. Fluids*, **64**, p 11.

Åkerblom A., Zettervall N., Passad M., Ercole A., Nilsson E. & Fureby C.; 2024, “Numerical Modeling of Chemical Kinetics, Spray Dynamics, and Turbulent Combustion towards Sustainable Aviation”, *Aerospace*, **11**, p 31.

Åkerblom A. & Fureby C.; 2024, “LES Spray Combustion Modeling of the DLR Generic Single Cup Combustor”, *Flow, Turb. Comb.*, **112**, p 557.

Hatun Tanis M., Wallberg O., Galbe M. & Al-Rudainy B.; 2024, “Lignin Extraction by using Two-Step Fractionation: A Review”, *Molecules*, **29**, p 98.

Cakir B.O., Lavagnoli S., Saracoglu B.H. & Fureby C.; 2024, “Sensitivity and Resolution Response of Optical Flow based Background Oriented Schlieren to Speckle Patterns”,

Meas. Sci. Tech., **35**, 075201.

Åkerblom A. & Fureby C.; 2025, “LES Modeling of Sustainable and Conventional Aviation Fuel in the Cambridge Premixed Bluff-body Burner”, *Comb. Flame*, **272**, p 113895.

Cakir B., Sanned D., Prakash M., Brackmann, C. Richter M. & Fureby C.; 2025, “Application and Assessment of Background Oriented Schlieren for Laminar Burning Velocity Measurements”, *Exp. Thermal and Fluid Sci.*, **163**, p 111357.

Ercole A., Lörstad D. & Fureby C.; 2024, “Large Eddy Simulations of Turbulent Premixed Swirling Flame using Finite Rate Chemistry and Different Combustion Models”. *Flow Turb. Comb.*, **114**, p 1377.

Åkerblom A., Zettervall N. & Fureby C.; 2025, “Comparing Chemical Reaction Mechanisms for Jet Fuel in Turbulent Premixed Combustion Simulations”, *AIAA.J.*, **63**, p 3676.

Åkerblom A. & Fureby C.; 2025, “LES Modeling of the DLR Generic Single-Cup Spray Combustor: Comparison of Exploratory Category C Jet Fuels”, *Flow, Turb. Comb.*, **114**, p 1315.

Vauquelin P., Zhou Y., Åkerblom A., Fureby C. & Bai X.-S.; 2025, “Chemistry Mapping in Reactive LES of Bluff-body Flames using Alternative Jet Fuels”, *AIAA.J.*, In Press, [doi.org/10.2514/1.J065789](https://doi.org/10.2514/1.J065789).

Tanis M.H. Vercoutere E., Galbe M., Al-Rudainy B. & Wallberg O.; 2025, “A Comparative Study of Lignin Recovery Conditions Using GVLOrganosolv and Lignin Characterization”, *ACS Sustainable Chemistry & Engineering*, **13**, p 8457

Passad, M. & Nilsson, E.J.K. 2025, “Impact of Transport Data on Extinction Strain Rate of n-heptane Flames”. *Comb. Flame* **280**, p 114238

Zettervall N. & Nilsson, E.J.K. 2024, “A Compact Chemical Kinetic Mechanism for Heavy Fuel Surrogates with n-, iso- and Cyclo-Alkanes, and Aromatic Compounds”, *ACS Omega*, **10**, 15471.

Zettervall N. & Nilsson, E.J.K.; 2026 “Evaluation of Single Component Kinetic Mechanisms for Aviation Fuels Combustion”, submitted to *ACS Omega*

Tanis M.H.; Al-Rudainy B. & Wallberg O., 2026, “Lignin Recovery from Norway Spruce using Steam Pretreatment and Hydro-tropic Extraction”, *Holzforschung*, **80**, p 136.

Tanis M.H. Vercoutere E., Galbe M., Al-Rudainy B. & Wallberg O.; 2025, “A Comparative Study of Lignin Recovery Conditions Using GVLOrganosolv and Lignin Characterization”, *ACS Sustainable Chemistry & Engineering*, **13**, p 8457.

Elmroth Nordlander J., Bergvall N., Sala S., Reinsdorf O., Kahnt M., Turato E., Beech J. P., Johansson Ac-C., Sandström L. & Blomberg S.; 2025 “Detailed characterization of in situ-generated MoS<sub>2</sub> nanoparticles for the hydrodeoxygenation of pyrolysis oil”, *Renewable Energy* **263**, 125530,

Bergvall, N., Minidis, A., Bernlind C., Sandström, L., Hedberg, M. H. & Blomberg, S. “Production of Sustainable Aviation Fuel by Slurry and Fixed Bed Hydroprocessing of Fast Pyrolysis Bio-Oil”, Submitted for publication in peer review journal *Fuel*.

Farooq Z., Wetterlund E., Mesfun S. & Furusjö E.; 2025, “Uncovering the economic potential of sustainable aviation fuel production pathways: A meta-analysis of techno-economic studies.” *Energy Conversion and Management*, 341, 120076, <https://doi.org/10.1016/j.enconman.2025.120076>

## Conference Publications/Presentations

Åkerblom A.; 2022, “The Impact of Reaction Mechanism Complexity in LES Modeling of Liquid Kerosene Combustion”, 33<sup>rd</sup> Congress. of the Int. Council of the Aeronautical Sciences, 4-9 Sept., Stockholm, Sweden.

Fureby C.; 2022, “Paving the Route Towards Green Aviation with Hydrogen and Biojet-fuels – A Numerical Study using OpenFOAM”, OpenFOAM and combustion Webinar 2022-11-25, SNU, Singapore.

Farooq Z., Wetterlund E., Mesfun S. & Furusjö E.; 2023 “Techno-economic Assessment of Methanol-to-Jet (MTJ) pathway”. Poster presentation at EUBCE 2023.

Tanis M.H., Vercoetere E., Al-Rudainy B., & Wallberg O.; 2025, "Lignin recovery from Norway spruce by  $\gamma$ -valerolactone organosolv", 33rd European Biomass Conference & Exhibition (EUBCE), Valencia, Spain, 9-12 June 2025, poster presentation

Åkerblom A., Zettervall N. & Fureby C.; 2024. “Comparing Chemical Reaction Mechanisms for Jet Fuel Combustion in Simulations of a Turbulent Premixed Bluff-Body Burner”, AIAA 2024-0179.

Fureby C. & Hedberg M.; 2024, “Sustainable Turbine Fuels for Aviation and Power”, IS-ABE-2024-072, ISABE, Toulouse, France, 22-27 Sept.

Pignatelli F., Subash A.A., Richter M., Sanned D. & Fureby C.; 2024, “Experimental and Numerical Investigation of Sustainable Aviation Fuels on a Helicopter Combustion Chamber”, ISABE-2024-174, ISABE, Toulouse, France, 22-27 Sept.

Cakir B.O., Sanned D., Vauquelin P., Prakash M., Hannappel J.-P., Subash A., Richter M., Bai X.-S. & Fureby C.; 2024, “Experimental and Numerical Investigations of a Swirl Stabilized Jet Engine Combustor”, 34<sup>th</sup> Congress of the Int. Council of the Aeronautical Sci. (ICAS), Florence, Sept. 9-13.

Ercole A. Lörstad D. & Fureby C.; 2024, “Turbulent Combustion Model Sensitivity in LES of a Gas Turbine Combustor”, 19<sup>th</sup> Int Conf. on Num. Comb. Kyoto, Japan.

Vauquelin P., Cakir B.O., Fureby C., Bai X.-S., Richter M., Subash A.A., Prakash M. & Sanned D.; 2024, “Numerical Investigation of the Fuel Flexibility of a Typical Aero Engine Swirl Stabilized Flame”, 19<sup>th</sup> Int Conf. on Num. Comb. Kyoto, Japan.

Cakir B.O., Vauquelin P., Sanned D., Prakash M., Subash A.A., Richter M. & Fureby C.; 2024, “Numerical Investigation of the Fuel Flexibility of a Typical Aero Engine Swirl Stabilized Flame”, 19<sup>th</sup> Int Conf. on Num. Comb. Kyoto, Japan.

Vauquelin P., Cakir B.O., Sanned D., Prakash M., Hannappel J.-P., Subash A.A., Richter M., Bai X.-S. & Fureby C., 2025, “Large Eddy Simulation of a Model Jet-Engine Swirl-Stabilized Flame Using Sustainable Aviation Fuels”, AIAA 2025-0163.

Vauquelin P., Zhou Y., Åkerblom A., Fureby C. & Bai X.-S.; 2025, “Multidimensional Chemistry Coordinate Mapping for Large Eddy Simulations of a Turbulent Premixed Bluff-Body Burner”, AIAA 2025-2485.

Jarfors B. & Fureby C.; 2025, “Large Eddy Simulation of Thermoacoustic Instabilities in Bluff-Body Stabilized Flames”, AIAA 2025-2488.

Vauquelin P., Cakir B.O., Sanned D., Prakash M., Hannappel J.-P., Subash A., Richter M., Bai X.-S. & Fureby C.; 2025, “Large Eddy Simulation of a model Jet-Engine Swirl-Stabilized Flame using Sustainable Aviation Fuels”, AIAA 2025-0163.

Tanis M.H., Vercoetere E., Al-Rudainy B., & Wallberg O.; 2024, "Lignin recovery from Norway spruce by two-step fractionation", 20th International Conference on Renewable

Resources and Biorefineries (RRB), Brussels, Belgium, 5-7 June 2024, oral presentation.

Tanis M.H., Vercootere E., Al-Rudainy B., & Wallberg O.; 2024, "Lignin recovery from Norway spruce into value-added components", 11th Nordic Wood Biorefinery Conference (NWBC), Örnsköldsvik, Sweden, 15-17 October 2024, oral presentation.

Farooq Z., Wetterlund E., Mesfun S., Bergvall N. & Ma C.; 2025, "Techno-economic analysis of biomass fast pyrolysis with ex-situ slurry hydroprocessing of bio-oil to jet fuel", To be presented at SDEWES, 20<sup>th</sup> conference on sustainable development of energy, water and environment systems, Oct 05-10, 2025, Dubrovnik, Croatia.

Mesfun S., Farooq Z., Ma C., Hed E., & Wetterlund E.; 2025, "Carbon, cost and climate performance screening of bio-electrofuel value chains relevant for unlocking SAF production in the Nordic context", Abstract submitted for ICSAR 2025, 1<sup>st</sup> conference on sustainable aviation research, July 9-11, 2025, Dublin, Ireland.

Hernandez Cabello, J, Yu L. & Hedlund J.; 2026, "Highly Stable Defect-free HZSM-5 Nanocrystals for Enhanced Conversion of Biomethanol to SAF Components", 10th International Conference on Catalysis and Chemical Engineering (CCE-2026), 9-11 March 2026, Boston, United States,. Oral presentation.

Bergvall, N. & Sandström, L. "Continuous pilot scale hydroprocessing of kraft lignin", 21st International Conference on Renewable Resources and Biorefineries (RRB), Turku, Finland, 2 - 4 June 2025, oral presentation.

Reinsdorf, O., Bergvall, N., Sandström, L. & Hedberg, M. "SAF Production by Continuous Mode Hydroprocessing of Fast Pyrolysis Bio-Oil", 1st International Conference on Sustainable Aviation Research (ICSAR), Dublin, Ireland, 9 - 11 July 2025, oral presentation.

Vauquelin P., Ercole A., Åkerblom A., Hannappel J.-P., Bai X.-S. & Fureby C.; 2025, "Numerical Analysis of Sustainable Aviation Fuels: Spray, Evaporation and Combustion from a Typical Aero-Engine Fuel Injector", 1<sup>st</sup> Int. Conf. on Sustainable Aviation Research., 9-11 July, Dublin, Ireland.

Ercole A., Gupta P., Hannappel J.P., Prakash M., Sanned D., Vauquelin P., Åkerblom P., Richter M. & Fureby C.; 2025, "Experimental and Computational Studies of Spray Combustion with Fossil and Sustainable Aviation Fuels", 1<sup>st</sup> Int. Conf. on Sustainable Aviation Research., 9-11 July, Dublin, Ireland.

Jarfors B. & Fureby C.; 2025, "Large Eddy Simulations of Thermo-acoustic Instabilities for Bluff-Body Stabilized Flames", Symposium on Thermoacoustics in Combustion: Industry meets Academia, (SoTiC 2025), Sept. 8-11, 2025, Trondheim, Norway,

Vauquelin P., Ercole A., Åkerblom A., Hannappel J.-H., Bai X.-S. & Fureby C.; 2025, "Numerical Analysis of Sustainable Aviation Fuels: Spray, Evaporation and Combustion from a Typical Aero-Engine Fuel Injector", ILASS Europe 2025, 33<sup>rd</sup> Conference on Liquid Atomization & Spray Systems, 31 Aug. - 4 Sept., Lund, Sweden.

Vauquelin P., Ercole A., Hannappel J.-P., Bai X.-S. & Fureby C.; 2025, "Large Eddy Simulation of Sustainable Aviation Fuels Flames from a Tripple Swirler: Comparing Compact and Skeletal Chemical Reaction Mechanisms", 16<sup>th</sup> Int. Conf. Combustion Technologies for a Clean Environment, May 25-29, 2025, Lisbon, Portugal.

Ercole A., Lörstad D. & Fureby C.; 2025, "Analysis of Swirling Premixed Flames in Model Gas Turbine Burner: Ranging Fuels and Operating Conditions using Large Eddy Simulations", Nordic Flame Days, Copenhagen, Denmark, Nov. 26-27.

Hannappel J.P., Prakash M., Brackmann C., Fureby C. & Richter M.; 2025, "Design of a Burner with Variable Nozzle Geometry for the Measurement of Laminar Burning Velocities at Elevated Pressure", Nordic Flame Days, Copenhagen, Denmark, Nov. 26-27.

Prakash M., Gupta P., Hannappel J.-P., Sanned D., Henrysson S., Subash A.A., Fureby C., Heimdal Nilsson E. & Richter M.; 2025, “Characterisation of Emissions from a Jet Engine using Alternative Aviation Fuels”, Nordic Flame Days, Copenhagen, Denmark, Nov. 26-27.

Vauquelin P., Donndorf J., Lo Presti F., di Mare F., Bai X.-S. & Fureby C.; “Design, Simulation and Virtual Certification Assessment of a Medium Range Aeroengine Combustion Chamber”, Nordic Flame Days, Copenhagen, Denmark, Nov. 26-27.

Fureby C.; 2025, “A Scandinavian Perspective on SAF”, AIAA Aviation, Sustainable Aviation Workshop AERO-04, July 22.

# PARTNERS

