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 2023

CESTAP

Competence cEnter in Sustainable Turbine fuels for Aviation and Power

Datum
2024-03-31

Dnr

Projektnr
52683-1

Energimyndighetens titel på projektet – svenska CESTAP (Kompetenscentrum för hållbara turbinbränslen för luftfart och kraft-produktion)	
Energimyndighetens titel på projektet – engelska CESTAP (Competence cEntre in Sustainable Turbine fuels for Aviation and Power)	
Universitet/högskola/företag Faculty of Engineering	Avdelning/institution Heat Transfer / Energy Sciences
Adress Naturvetarvägen 18	
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Nyckelord: Biofuel; gas turbine; jet engine; sustainable aviation fuels; lignocellulose; sustainability analysis, experiments, numerical simulations	

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Preface

During the second year, researchers and industrial partners in CESTAP are setting a high pace towards transformation of the aviation and power generation sectors to run jet engines and gas turbines on sustainable fuels. The affiliated PhD students are more than a year into their activities and have all reached initial milestones in their respective projects. The progress is advanced further by close collaboration with other associated research projects.

Here we briefly summarize some important activities and results from the technical work packages (WP) during 2023. More details can be found in the main section of this report, “Progess and Results”, and in published material listed on the final pages of the report.

Significant progress has been made on establishing the test bed in WP1 “Development and maintenance of the pre-certification test bed”. The testbed comprises a range of experimental facilities working in tandem with chemical kinetics and computational fluid dynamics. Several computational studies analyzing fuel effects on flame properties under various conditions have been published.

Four main topics have during 2023 been addressed by WP2 “Development of turbine fuels from sustainable feedstocks including lignocellulose”: lignin separation from biomass, employing hydrotropic methods and steam explosion pretreatment; converting sawdust into pyrolysis oil; developing a new methanol-to-jet fuel process through ZSM-5 catalysts testing; and, catalyst characterization.

WP3 “Mutual adaptation of turbine fuel and engine technology” focuses on identifying combustion chamber concepts for aviation and stationary gas turbines, that meet future robustness criteria, and ensure low emissions. Work has been performed to establish baselines, model and quantify fuel impacts on spray and flame kinetics, conduct numerical studies on various concepts, and select the most promising ones for testing.

WP4 on “Material sciences” focus on the compatibility of bio-based fuels with aviation and stationary gas turbine materials. Key tasks include evaluating bio-fuels' impact on fuel system lubrication, exploring alternative fuels' interactions with soft materials like elastomer seals, and assessing risks of fuel combustion-related deposits and corrosion. Activities performed in the last year include a study on elastomer interactions.

The ”holistic techno-economic and sustainability analysis” performed in WP5 during 2023 include a literature review on Sustainable Aviation Fuels (SAF) routes, a case study on Methanol-To-Jet (MTJ) SAF, and an analysis of SAF from slurry hydrotreatment of pyrolysis oils and lignin.

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Introduction and background

The world is now experiencing the effects from global warming exceeding the pre-industrial levels by more than 1 °C, and as the climate continues to warm, the perceived changes in the probability and/or scale of extreme weather events will increase as the human influences on these events increase. Combustion of fossil fuels – coal, oil, and gas – are by far the largest contributor to global climate change, accounting for nearly 90% of all carbon dioxide emissions, and over 75%of global greenhouse gas emissions. Fossil-fuel dependent sectors such as aviation, maritime transport, and peak-load and back-up power generation are facing pressure to contribute to the goal of limiting the temperature increase to below 1.5 °C. The International Civil Aviation Organization (ICAO) has embarked on a long-term global goal for international aviation of net-zero carbon emissions by 2050[1]. Whilst continuing to rely on hydrocarbon-based aviation fuels, the ICAO approach provide paths for progressively decreasing greenhouse gas emissions through the application of Sustainable Aviation Fuels (SAF) and liquid hydrogen. This situation is similar for the maritime transport, and peak-load and back-up power generation sectors where hydrocarbon-based fuels are to be replaced by other fuels such as ammonia, hydrogen, metals and/or Hydrogenated Vegetable Oil (HVO).

The aviation and peak-load and back-up power generation sectors depend heavily on continuous combustion engines such as gas turbines and jet engines. These engines both follow the Brayton cycle[2], and consists of a rotating gas compressor, a combustor, where the fuel is injected and combusted in the heated airstream, and a compressor-driving turbine. Jet engines usually runs on kerosene-grade fuels such as Jet A, JP5, JP8, for which they are highly optimized to achieve high performance and safety of operation. Gas turbines are on the other hand optimized for natural gas, diesel, or heavier distillates. The combustion in such engines is aerodynamically stabilized, and even small changes in the fuel properties may have an impact on the flame location, stability, and overall engine performance. In both cases there is potential for using alternative and sustainable turbine fuels. For jet engines these sustainable fuels include Synthetic Paraffinic Kerosene (SPK) from feedstocks such as plants, animal fat, vegetable oil, forest residuals, and algae, produced following either of the seven ASTM approved pathways for alternative jetfuels[3]. For gas turbines, alternative fuels comprise a wider span including hydrogen[4], ammonia[5], alcohol[6], pyrolysis oil[7], Di-Methyl Ether (DME)[8], and HVO[9]. Potential future fuels may also include electro fuels from carbon dioxide or industrial residual gases, water, and renewable electricity.

Alternative fuels usually differ in composition compared to the fossil fuels they are

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[1] ICAO, 2022, "Long term global aspirational goal (LTAG) for international aviation". Available (2024-0318) https://www.icao.int/environmental-protection/Pages/LTAG.aspx.
[2] Cengel Y.A. & Boles M.A.; 2002, "Thermodynamics: An Engineering Approach", McGraw-Hill.
[3] ASTM Standard D1655, Standard Specification for Aviation Turbine Fuels.
[4] Gobbato P., *et al*.; 2011, Int. J. Hydrogen Energy, 36, p 7993.
[5] Valera-Medina A., *et al*.; 2019, Int. J. Hydrogen Energy, 44, Issue 16, p 8615.
[6] Moliere M., *et al*., 2009, ASME GT2009-59047.
[7] Sallevelt J.L.H.P., *et al*.; 2016, Energy Conversion and Management, 127, p 504.
[8] Glaude P., *et al*., 2012, GT2011-46238, p. 649.
[9] Hui X., *et al*; 2012, Fuel, 98, p 176.

to replace as they are synthetically produced. This difference in carbon chain length and chemical structure (i.e. n-, cyclo- and iso-paraffins as well as aromatics) may affect (i) materials compatibility throughout the whole fuel system, (ii) fuels miscibility, (iii) fuels toxicology, (iv) combustion stability and flame anchoring, (v) combustor liner heat loads, (vi) emissions (such as CO, CO_2, NO_X, and soot), and (vi) environmental footprint and overall climate impact. As alternative fuels are synthetically produced, the selection of the feedstock and the production pathways becomes more complex. With SAF as an example, figure 1 illustrates the difference in composition between Jet A and JP5 as well as between fossil fuels and some selected SAF's. The availability and market price of the feedstocks as well as the cost and availability of the materials, components, and energy used in the conversion processes significantly contributes to the higher price of SAF compared to fossil fuels. Moreover, the whole value chain, from feedstocks to fuel, and further on to emissions and climate effects needs to be fully understood and optimized with respect to both cost and sustainability.

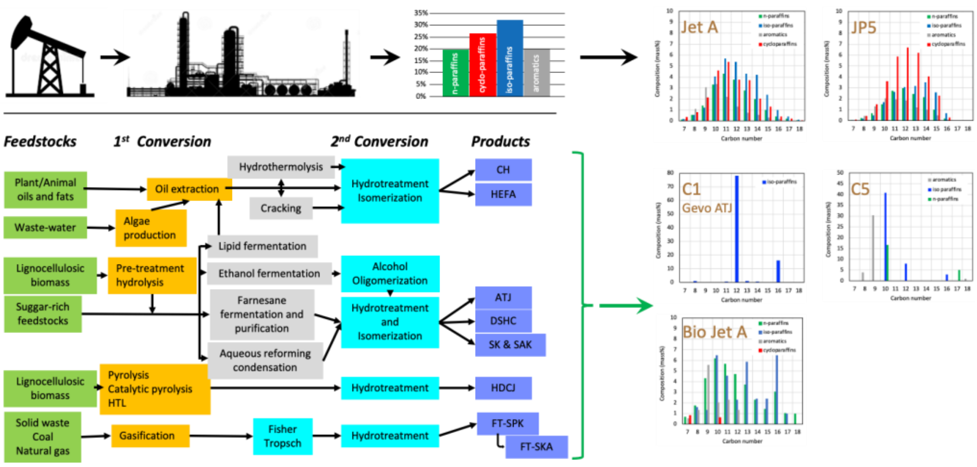


Figure 1. Schematic of fossil and alternative jet fuel production pathways and selected compositions of both fossil jet fuels (Jet A and JP5) as well as three alternative jet fuels.

CESTAP (Competence cEntre in Sustainable Turbine fuels for Aviation and Power) is a competence centre jointly funded by the Swedish Energy Agency, industry, and academia promoting the production and use of sustainable fuels for stationary gas turbines and aviation jet engines. The academic partners include the coordinator, Lund University (LU), Luleå Technical University (LTU), and Research Institutes of Sweden (RISE). The overall objective is to promote the development, use, and function of biofuels for gas turbines and aviation, through research in (i) biofuel development, (ii) physical and virtual testing of the biofuels, (iii) mutual adaptation of biofuel and relevant continuous combustion engine technologies, (iv) materials sciences, and (v) techno-economical and life-cycle studies. In CESTAP not only aviation turbines are included but also turbines for power and electricity generation, thus further contributing to the potential reduction of the global warming but also increasing the resiliency towards supply disruptions.

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. Figure 2 present the roadmap of CESTAP, towards 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.*

During 2023 research and development has progressed in all five technical work packages (WPs) and the activities and results are summarized in the “Progress and Results” section of this report.

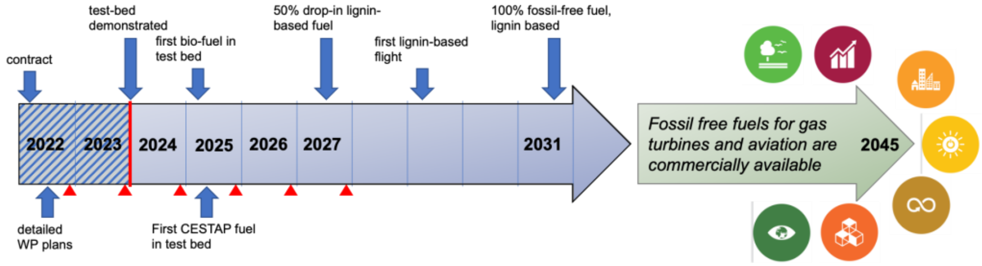


Figure 2. Schematic illustration of the roadmap and vision of CESTAP. The red line across time line symbolizes how far into the projects we are at the writing of this report.

This second year of CESTAP the organizational aspects with meetings in different constellations have taken a form that promote further progress in the research activities, in close connection with industrial partner. The WP leaders have regularly arranged meetings with academic researchers and industrial partners that expressed interest in the WP. About every second month the WP leaders have met to to align activities and report progress. All CESTAP partners have gathered twice for full day meetings with reports from WPs and presentation by selected industrial partners. The Summer Meeting had a technical focus on WP1 but with all partners invited, and the Annual Meeting in late November had a broad scope. Four times during the year the CESTAP Program Council has met, discussing organizational issues and questions of strategic importance to the Centre.

To better understand the partner organizations and to facilitate collaboration the management team during 22-24th of August 2023 visited five partners: Göteborg Energi AB, Preem AB, GKN Aerospace AB, Siemens Energy AB and Saab Aeronautics AB. During the visits the management team got the chance to see test and production facilities, and to discuss research and development needs, and CESTAP activities in particular. Learnings and conclusions from the partner visits are considered very important for how activities within CESTAP are progressed.

Three companies that in 2022 applied to join CESTAP as new partners was after the General Assembly on February 17th 2023 and a *per capsulam* voting procedure accepted as new partner organizations: The Swedish Defense Research Agency – FOI, Alfa Laval Technologies AB, and Desert Ocean AB.

Progress and results

All Work Packages (WPs), including WP4 which had a late start for practical reasons, have made significant progress during 2023. The combined physical and virtual pre-certification test bed have been fully commissioned including numerical simulations, combustion experiments, and detailed fuel characterization. More details on the progress and results follow below for each respective WP.

WP1 Development and maintenance of the pre-certification test bed

Three PhD students are active in this work-package, with the task of establishing and operating the pre-certification testbed. Since the annual report of 2022, the following activities have been conducted.

Table 1. Progression of tasks WP1.

Tasks of WP1	Progression (%)	Comments
Task 1: Simulation models.	85%	On track. Methodology is validated and ready for use.
Task 2: Experimental pre-certification test bed.	85%	On track except for the DESS high-pressure test rig. Small scale test rigs are ready to use.
Task 3: Full scale jet engine test bed.	90%	On track. Ljungbyhed jet engine lab is close to being finalized and a first test run has been performed.

Experimental research

Within CESTAP there is, since October 2022, one dedicated PhD student working with the experimental assignments in WP1. Recently, three related research projects sharing similar tasks, have been started and are now being staffed. This means that since January 2024 the collective experimental capability has been significantly increased. Currently there is one additional PhD and one Postdoc working within the field of sustainable aviation fuels. During the spring of 2024, yet one more PhD student is expected to join the experimental work force. Although the staffing concerns a group of associated projects and is not dedicated to CESTAP, significant synergetic benefits are expected from these collaborations over the coming years. The experimental activities hinge on a number of infrastructures or combustion test facilities that will be briefly described next.

DESS high-pressure test facility

The first facility is the DESS high pressure rig, figure 3, which can operate up to 16 bar and ~800 K. As well-known, the DESS-rig is undergoing an extensive refurbishing program. The two main infrastructures that need substantial repairs or replacement, are the compressor and the air pre-heater. The damaged air compressor has been dismantled and removed from the site together with its 4 m^3 air tank and electric drive. The procurement procedure, aiming at reestablishing the required pressure and mass flow capabilities, is close to being finalized. The electric air-heater was removed from the rig facility and has since been dismantled to assess the damage. After evaluating the options, it was deemed feasible to repair most of the damages and only replace the most severely damaged heating sections. The new and refurbished parts have arrived from the manufacturer and are now being re-installed in the casing. Other required repairs, e.g. of the electrical supply system and the control system, have also been initiated.

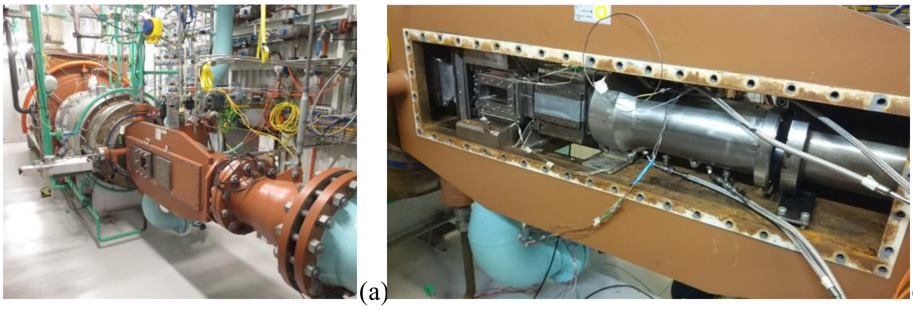

(a) (b)

Figure 3. (a) DESS high-pressure combustion facility. The combustion chamber (b) with optical access is seen in the center. The parts being refurbished are mainly located downstairs in the compressor room.

Small high pressure laminar flame speed test facility

The second facility is the small high-pressure burner that can operate up to 32 bar, figure 4, that will primarily be used for laminar flame speed investigations. Although flame speed measurements were demonstrated in the small high pressure burner last year, some remaining equipment flaws were identified that has now been rectified. The new fuel system facilitating pre-evaporation of liquid fuels, has since been further developed. The initial approach with a Bronkhorst evaporator, has been abandoned and replaced with a bespoke system where heated nitrogen and liquid fuel are introduced in a heated vessel filled with steel pebbles. To prevent condensation, that can lead to accumulation of heavier fractions in the piping system and thus cause alterations to the distillation curve, it is of major importance to keep the vaporized fuel diluted and heated all the way up to the pressurized burner. This was initially achieved by using heated gas sampling hoses. Due to problems with maintaining the temperature it was recently decided to upgrade to new hoses capable of higher temperatures, i.e. up to 525 K. These new hoses are currently being installed. Tests of the reworked system is expected to take place in February 2024, and production runs are anticipated to start in March 2024.

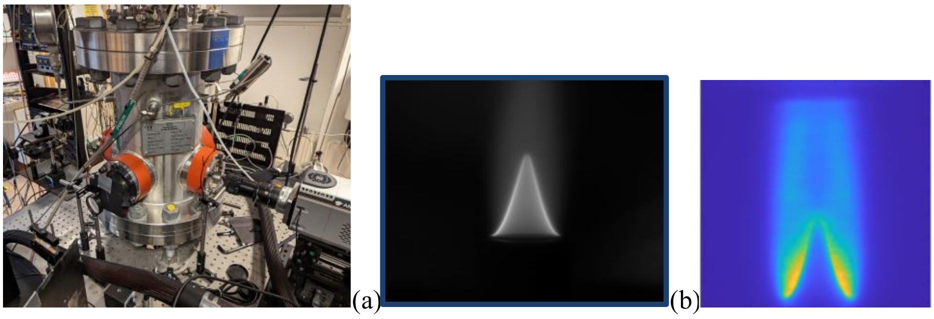

(a) (b) (c)

Figure 4. (a) Small high pressure laminar flame speed test facility, together with two different examples, (b) and (c), of laminar flame images.

Atmospheric combustion test facility

The third facility is the atmospheric combustion rig, figure 5a, which also can provide heated air (~800 K) but only at 1 bar. This facility, which is fully operational and has been used for previous experimental studies, will be used together with at least two burner set-ups: The first configuration is the CECOST burner which is designed to replicate the flow and flame structures in a 4th generation industrial Dry Low Emission (DLE) combustor, figure 5b. The swirl generator of the burner consists of four quarter-cones where the flow enters in a combined tangential/axial/radial direction to create a swirling motion of the air. Gaseous fuel can be injected into the premixing tube using two fuel inlets directed downstream to achieve adequate mixing of air and fuel. Currently we are modifying this set-up to also be able to test liquid fuels. Two optical combustors can be used, one with a cylindrical cross-section having a diameter of 100 mm, and one with a rectangular cross-section with a square cross-section of 100 mm. The second configuration is the Triple Annular Research (TARS) burner which is designed to replicate the flow and flame structures in a modern jet engine fuel combustor. Currently, the TARS burner is being commissioned in the atmospheric combustion rig, and the main tasks include manufacturing a dedicated optical combustion chamber and establishing a liquid fuel supply system. The hardware for this, including a high-pressure dosing pump, fuel storage and flow controller, is recently installed. Preliminary experiments have been conducted and optical investigations are expected to start in March 2024 addressing first combustion of ethanol and Jet A.

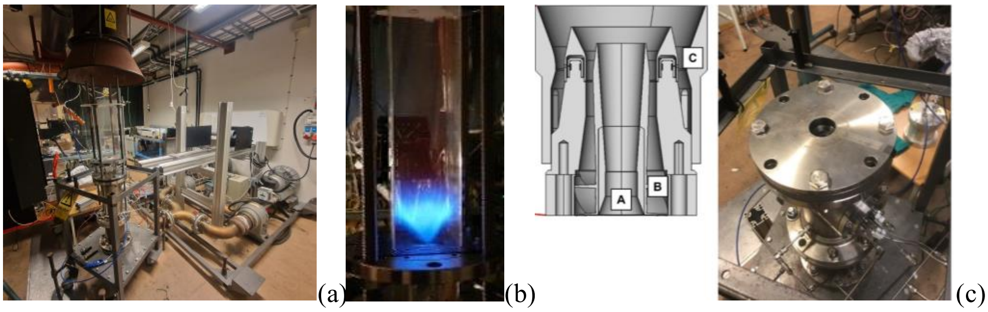


Figure 5. (a) the atmospheric combustion test facility, (b) the CECOST burner in operation with gaseous fuel, and (c) a schematic and the hardware of the TARS burner.

Spray test facility

The fourth facility is the high-pressure spray rig at RISE in Piteå, with complementary laser diagnostic tools, figure 6. The rig is designed to operate with a pressurized nitrogen gas atmosphere at between 0 and 10 bar, and pressure atomization up to around 150 bar. The liquid flow rates are up to approximately 10 l/min. The spray characterization can be made using Phase Doppler Anemometry (PDA).

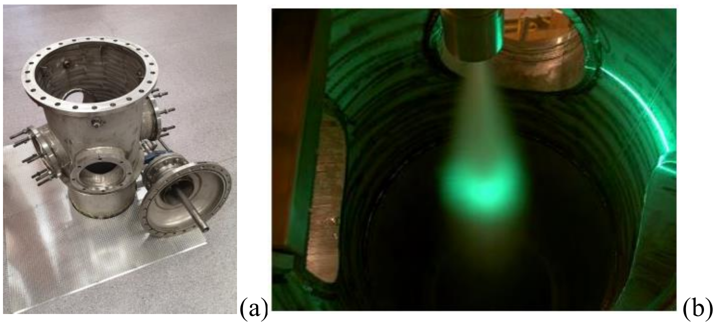


Figure 6. The spray test facility at RISE in Piteå. (a) hardware, and (b) spray testing.

Jet engine test facility

The work of setting up the jet engine test facility at the school of aviation in Ljungbyhed has advanced significantly during 2023. The engine to be used for generating the data is a two-spool, turbofan engine with a thrust of 8.5 kN. The aim is to use this test facility to provide data from operation on both conventional jet fuels and selected bio-jet fuels. An engine test bed has been designed and manufactured in close collaboration with SAAB Aerospace AB. This test bed has been installed in the laboratory and the engine has been mounted to it. SAAB Aerospace AB has been instrumental in commissioning the test bed and transferring knowledge on hos to operate the equipment for different simulated flight conditions. Conditioning of the air flow is critical for the operation of the engine. For this purpose, a bellmouth and an exhaust system have been manufactured and fitted to the engine. Significant efforts have been made to get the mechanical and electrical control and monitoring systems, linking the engine with the control room, in place. A fuel system capable of handling two different fuels in separate tanks is in place. This will serve as the base for testing fuels available in larger quantities. For more exotic fuel candidates, a dedicated fuel supply system designed for small volumes, will be needed. A successful start-up and test run was completed last month. One essential part that must be in place before dedicated engine tests can be performed, is storage and piping for the calibration gases needed for the emission measurement equipment. Applied measurements with data collection for Jet A are expected to start during the spring of 2024. The campaign with bio jet fuel will take place later, pending the availability of the required amounts of neat bio jet fuel or drop-in jet fuel.

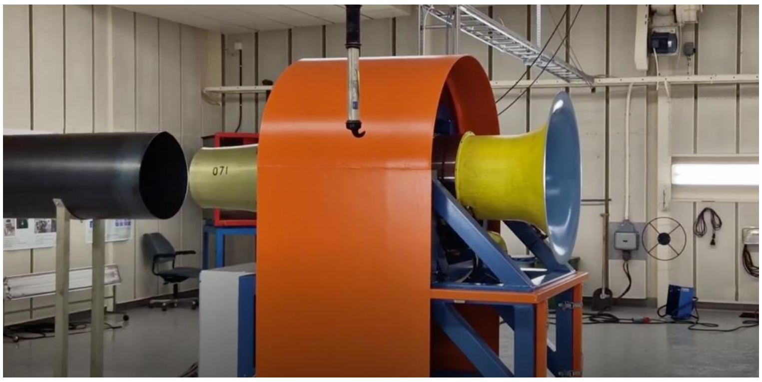


Figure 7. The jet engine test facility.

Chemical kinetics studies

The overall goal for the work on chemical kinetics is to refine the methodology for developing reduced chemical reaction mechanisms appropriate for Computational Fluid Dynamics (CFD) simulations of fuels consisting of a blend of large hydrocarbons. This includes several steps: (i) from a component analysis of the fuel select surrogate components that together represent the complex fuel, (ii) perform a kinetic analysis of combustion properties using detailed chemical mechanisms, and (iii) perform mechanism reduction and validate the mechanism to relevant targets.

The work has during 2023 has had three main parts:

- *Development and analysis of reduced reaction mechanisms for HVO combus-*

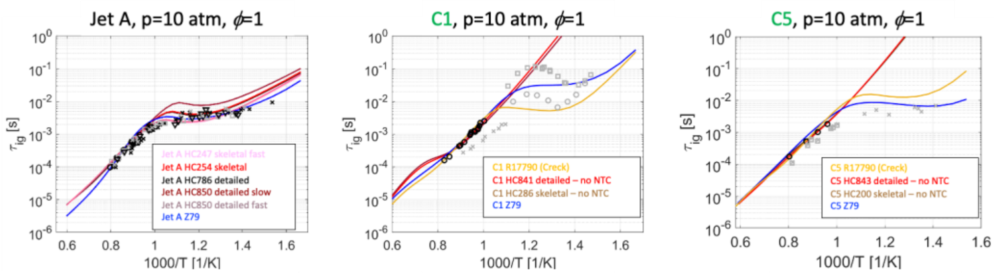
tion, including three mechanisms from the literature and in-house mechanisms of various size. The main challenge is that the combustion chemistry of the heavy hydrocarbons (C_{14}-C_{18}) of relevance for HVO is not well studied. In our work C_{16} iso- and n-alkanes have been selected as a basis for mechanism development.

- *Analysis of the chemistry and transport properties of relevance for extinction strain rate*. These properties are often ignored in the kinetics literature but may be very important for heavy fuels that diffuse slowly. There are two main goals with this work, to get accurate transport properties for use in detailed chemistry, and to understand which chemistry is needed in the reduced representations.
- *Development of surrogate mechanisms for a range of heavy fuels*, including biofuels developed by partners in CESTAP. This is the basis of the methodology, and our approach has been refined and tested.

During the second half of 2023 Topsoe A/S has contributed significantly with data and knowledge related to fuel characterization. This has been used as starting point for dedicated activities in the kinetics and computational part of the pre-certification test bed and may in the future be extended to other facilities.

During 2023 FOI made substantial contributions by further improving the Zettervall *et al*. family of chemical reaction mechanisms, and have provided improved chemical reaction mechanisms for several of the fuels considered in CESTAP such as Jet A, JP-5, ethanol, n-heptane, C1, and C5 as discussed by Åkerblom *et al*.[10]

As an example, figure 8 compares ignition delay time, τ_{ign}, and laminar flame speed, s_u, results from experimental data (symbols), detailed chemical reaction mechanism predictions from the Creck mechanism[11], and small (pathway centric) chemical reaction mechanism predictions from the HyChem[12-13], and Zettervall *et al*.[14-15], family of mechanisms. Both pathway centric reaction mechanism predictions compare well with the experimental data and the detailed reaction mechanism predictions. The most pronounced difference is that the Zettervall *et al*. family of mechanisms can take the Negative Temperature Coefficient (NTC) behavior of C1 and C5 into account which is not yet the case for the HyChem family of mechanisms that are based on high temperature chemistry only. At present reaction mechanism for several other fuels, including HVO and some specific SAF, are being developed.



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[10] Åkerblom A., *et al*., 2024, AIAA 2024-0179.
[11] Ranzi E. *et al*., 2015, Comb. Flame, 162, pp. 1679.
[12] Xu R., *et al*.; 2018, Comb. Flame, 193, p. 520.
[13] Wang K., *et al*..; 2018, Comb. Flame, 198, p 477.
[14] Zettervall, N., Fureby C. & Nilsson E.J.K, 2016, Energy & Fuels, 30, p 9801.
[15] Åkerblom A., Zettervall N. & Fureby C.; 2024, AIAA 2024-0179.

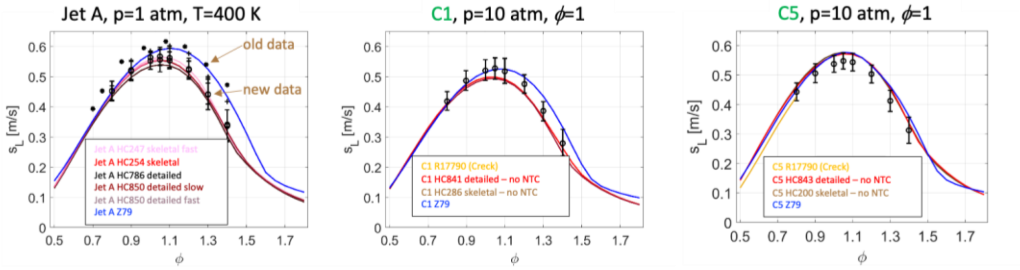

Figure 8. Comparison of ignition delay time, τ_{ign}, and laminar flame speed, s_u, results from experimental data (symbols), detailed chemical reaction mechanism predictions from the Creck mechanism[10], and small (pathway centric) chemical reaction mechanism predictions from the HyChem[11-12], and Zettervall *et al.*[13-14], family of mechanisms.

Diagnostics Development

Experimental flame studies are needed to examine the combustion behavior of the fuels developed in the center as well as for reference fuels. Such experimental studies are generally complicated and generate qualitative and quantitative data as well as knowledge on the complex interactions in the flame. Furthermore, the data sets serve as validation for computational studies. Existing diagnostic tools for flow and flame studies are usually complex, involving lasers and advanced optical set-ups. In order to simplify the diagnostic set-ups the von Karman Institute in collaboration with LTH has developed the Background-oriented schlieren (BOS) technique which is a highly adaptable refractometry technique enabling visualization of transparent gas flows by means of a relatively uncomplicated experimental setup. The acquired image data is processed with an optical flow image processing technique to provide refractive index variations as well as the displacement field, corresponding to a shadowgraphy image. Within the scope of CESTAP this method has been developed for compressible flows[16], and have also been successfully applied to a Bunsen burner flame to perform measurements of CH_4-air laminar flame speed measurements[17]. This techniques provides a faster, cheaper, simpler, and equally accurate method for flame speed measurements compared to existing methods.

Computational Fluid Dynamics (CFD) studies

During 2023 we have continued to perform numerical simulations of relevant open literature cases to increase our general knowledge about how different liquid fuels perform and to investigate and extend the operational ranges of the simulation models. High-quality experimental investigations of SAF are in short supply and many of those reported in the open literature are incomplete since enough details about either the combustor or the fuels investigated are not made available. This is problematic since it delays and complicates the advancement of the introduction of SAF. The main advantages of performing numerical simulations of different experimental configurations and fuels, besides further validating the models and methods, is building knowledge about how different fuels, with different thermophysical and combustion properties, are injected, vaporize, and combust in different combustors

[16] Cakir *et al.*, 2023, Exp, Fluids, 64, p 11.
[17] Cakir *et al.*, 2024, "Application and assessment of background oriented schlieren for laminar burning velocity measurements", Submitted to Comb. Inst.

at different combustion regimes. This knowledge is particularly useful when attempting to understand how to develop improved SAF fuels and how to improve combustion fuel flexibility.

The Cambridge burner[18] has been further investigated during the year. For this pre-vaporized, premixed, bluff-body stabilized flame experimental results are available for ethanol (C_2H_5OH), n-heptane (C_7H_{16}), Jet A ($C_{11}H_{22}$) and an alcohol-to-jet bio jet fuel C1 ($C_{13}H_{28}$)[16]. We have performed numerical simulations of these four fuels together with two additional fuels, JP-5 ($C_{12}H_{23}$) and another alternative fuel with a flat boiling curve C5 ($C_{10}H_{19}$)[19], using two classes or families of chemical reaction mechanisms. The first family of reaction mechanisms used consists of small detailed reaction mechanisms with about 200-300 reactions[11-12,20-21], whereas the second family of reaction mechanisms used consists of pathway centric reaction mechanisms with approximately 100 irreversible reactions[13-14,22]. The small detailed reaction mechanisms are developed by Stanford University and partners, whereas the pathway centric reaction mechanisms are developed by FOI and LTH together as part of CESTAP. Both families of reaction mechanisms predict the key flame properties such as the laminar flame speed, s_u, and ignition delay time, τ_{ign}, well despite their different size and complexity. Figure 9 shows a schematic of the Cambridge burner together with a volume rendering of the temperature.

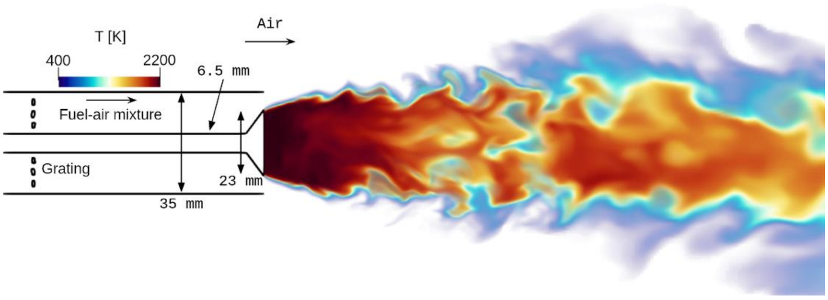

Figure 9. Schematic of the geometry, along with a volume rendering of temperature obtained for Jet A. Note that the pipe is mounted vertically in reality.

GKN Aerospace AB have also successfully performed numerical simulations of this case using similar but slightly different models compared to those used by Lund University. This diversity in modeling provides additional knowledge and further competence to the center, Moreover, GKN Aerospace AB is supporting a master thesis project in numerical simulations of pre-vaporized liquid fuels combustion that is expected to be finalized during mid 2024.

Figures 10a and 10b shows instantaneous and time-averaged formaldehyde (CH_2O) distributions, respectively, describing the reaction zone from experiments (top row), the small, detailed reaction mechanisms (middle row) and the pathway centric reaction mechanisms (bottom row). The simulations all show good agreement with the experimental results with regards to the shape and location of the reaction zone.

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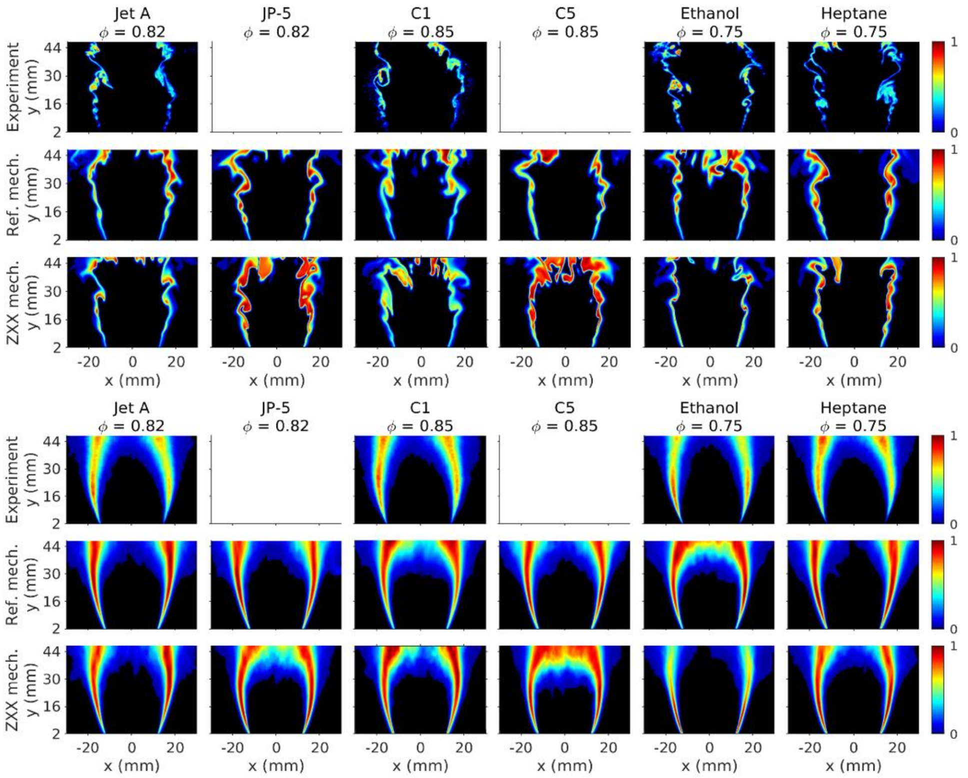
[18] Pathania R.S., Skiba A.W. & Mastorakos E.; 2021, Comb. Flame, 227, p. 428.
[19] Edwards J.T.; 2017, AIAA 2017-0146.
[20] Pichler C. & Nilsson E.J.K.; 2020, Fuel, 275, p. 117956.
[21] Zeuch T., Moreac G., Ahmed S.S. & Mauss F.; 2008, Comb. Flame, 155, p. 651.
[22] Zettervall N.; 2021, Ph.D. Thesis, Combustion Physics, Lund University, Lund.

The Kelvin-Helmholtz instability in the shear layers is clearly visible, as the flame is broadened by the roll-up of turbulent eddies. This behavior is reproduced by the simulations, although the flame wrinkling is not completely resolved. The two reaction mechanism families predict very similar flame shapes indicating that the combustion chemistry is well reproduced as are the mechanisms capabilities to respond to large scale resolved turbulence.



(a)

(b)

Figure 10. Instantaneous (a) and time-averaged (b) CH_2O distributions from the experiments, [6], (top row), small, detailed reaction mechanisms (middle row) and the pathway centric reaction mechanisms (bottom row).

The Timecop burner[23] is a generic single-cup spray combustor operated by DLR Institute of Propulsion Technology to investigate spray combustion at different operating conditions, figure 11. Experimental data is available only for Jet A but at two different operating conditions, and we have used this case to investigate how well we can capture trends due to varying operating conditions (for Jet A) and to assess the potential influence of different jet fuels. Figure 11a shows experimental photographs of the Timecop flame at idle (top) and cruise (bottom) conditions together with results from numerical simulations of the same operating conditions[24]. From both the experiments and the simulations, we find that at cruise conditions the flame is more compact and more intense and is located closer to the burner mouth. The combustion process consists of atomizing and vaporizing the liquid film resulting in a gaseous fuel cloud that mixes with the recirculated combustion products, after which it ignites and burns, resulting in heat release that in turn creates volumetric expansion and temperature increase.

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[23] Meier U., Heinze J., Freitag S. & Hassa, C.; 2011, J. Eng. Gas Turbines Power, 134, 031503.
[24] Åkerblom A. & Fureby C.; 2024, Flow, Turb. and Comb., 112, p 557.

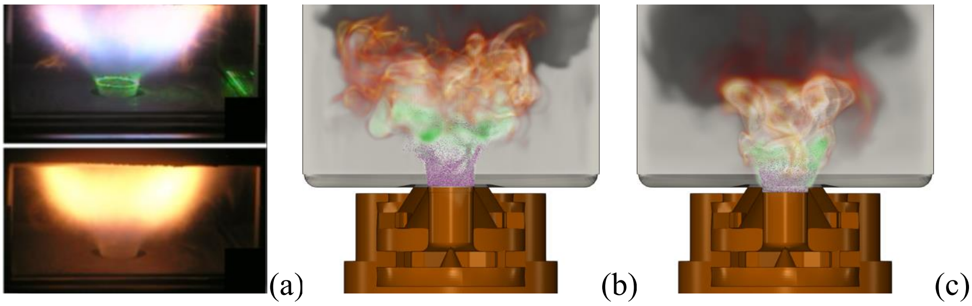


Figure 11. (a) Photographs of the Timecop flame at idle (top) and cruise (bottom) conditions together with numerical predictions of the spray (pink) and vaporized fuel (green), heat release (orange) and CO_2 distribution (gray) at (b) idle and (c) cruise conditions.

In the experimental studies non-intrusive laser-based diagnostics were made to characterize the fuel and flame dynamics and mean distributions through laser induced fluorescence and chemiluminescence, and from the numerical simulations similar distributions can be obtained. In Figure 12 we compare experimental OH chemiluminescence images with simulated heat release rate for Jet A. Good qualitative agreements is obtained, clearly illustrating that the simulations can capture the trends due to the operating conditions. Furthermore, we also present similar distributions from the numerical predications of the C1 and C5 fuels. Compared to Jet A these fuels are observed to behave somewhat differently as also observed[25]. More specifically C1 behaves rather similarly to Jet A but is burning with a slightly more intense flame whereas C5 shows a longer lift-off.

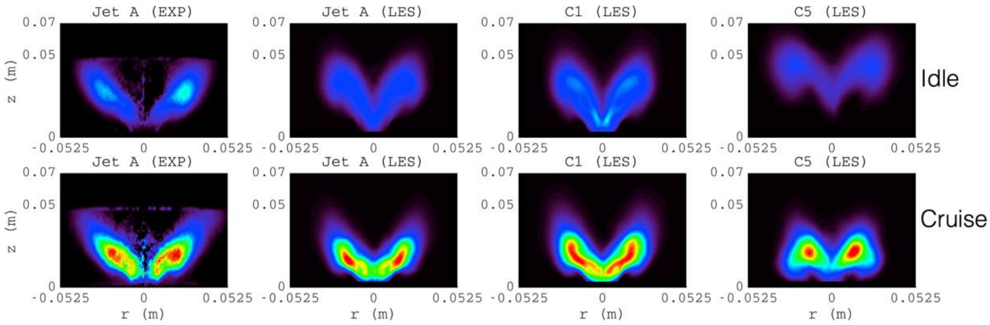


Figure 12. Time-averaged OH chemiluminescence images from the experiments (left panels) of Jet A compared with corresponding numerical images from Jet A, C1, and C1.

In addition, numerical simulations of an afterburner-like geometry[26-27], have been performed with both gaseous and liquid fuels to understand flame stabilization mechanisms and how they change with different fuels. Furthermore, work has been performed on the TARS burner[28], to facilitate its operational use as a test platform for experimental investigations of different liquid fuels.

WP2 Development of turbine fuels from sustainable feedstocks including lignocellulose

LTH, RISE and LTU are all performing various ongoing research activities in WP2.

[25] Stouffer S., *et al.*.; 2017, AIAA 2017-1954.
[26] Sjunnesson A., Henriksson R. & Löfström C.; 1992, AIAA -1992-3650.
[27] Paxton B.T., Fugger C.A., Tomlin A.S. & Caswell A.W., AIAA 2020-0174.
[28] Li G. & Gutmark E.; 2004, AIAA 2004-0133.

The work package is divided into four subtasks with one PhD student affiliated to each task: Medya Hatun Tanis (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. There is also a large industry group which currently engages about 15 of the companies and other organizations of the Centre. In February 2023, a physical work package meeting was held in Luleå (at LTU) and Piteå (at RISE) with participation from both academic and industrial partners. A number of online meetings have also been held during the year, both including the whole WP and in subgroups to discuss more specific questions.

Table 2. Progression of Tasks WP2.

Tasks of WP2	Progression (%)	Comments
Task 1: Lignin abstraction and separation.	75%	Almost on track. Methodology needs further development before scale up manufacture.
Task 2: Development of a process for turbine fuel production from pyrolysis oil and lignin via slurry hydroprocessing.	30%	This activity has been delayed due to competition with commercial assignments during 2023. The plan is to catch up during 2024.
Task 3: Development of a novel process and catalyst for direct conversion of alcohols to turbine fuel components.	75%	On track. Further development of catalyst and process is ongoing.
Task 4: Catalyst characterization.	50%	On track with regard to characterization of used catalysts. The rig for in situ monitoring of hydroprocessing catalysts during reaction is delayed due to needs for reconstructions.

Lignin abstraction and separation

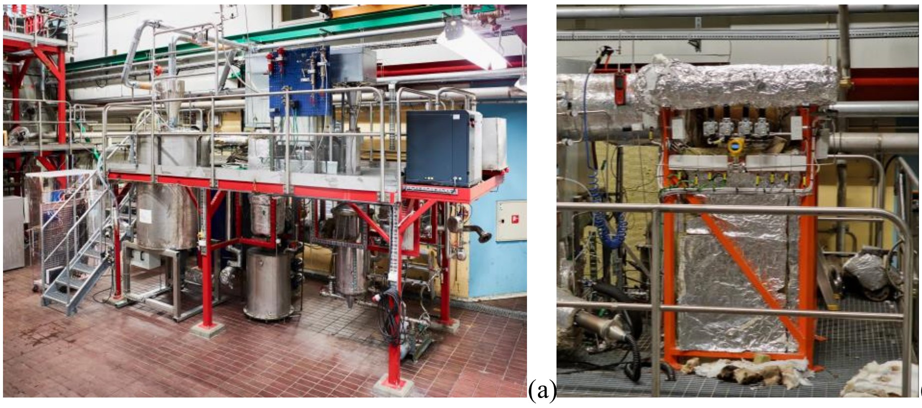
Task 2.1 *Lignin abstraction and separation* is focused on sourcing of lignin and lignin separation from biomass, being a natural starting point for further conversion of the lignin to hydrocarbon-based fuels. The subtask is managed by LTH. During 2023, an experimental study of lignin separation from spruce using hydrotropic extraction has been made. Different hydrotropes, catalysts, and washing conditions for lignin precipitation have been investigated to find optimal conditions for lignin yield and purity. A steam explosion pretreatment step has also been investigated. Precipitated lignin has been characterized on a molecular level using a number of different analytical techniques (e.g. NMR, TGA, SEC and FTIR). A review article[29] on two-step fractionation of lignin was also written as part of the 2023 efforts.

Development of a process for turbine fuel production

In task 2.2 *Development of a process for turbine fuel production from pyrolysis oil and lignin via slurry hydroprocessing* managed by RISE, the pyrolysis pilot plant

[29] Tanis, M.H., Wallberg, O., Galbe, M. & Al-Rudainy, B.; 2024, Molecules, 29, p 98.

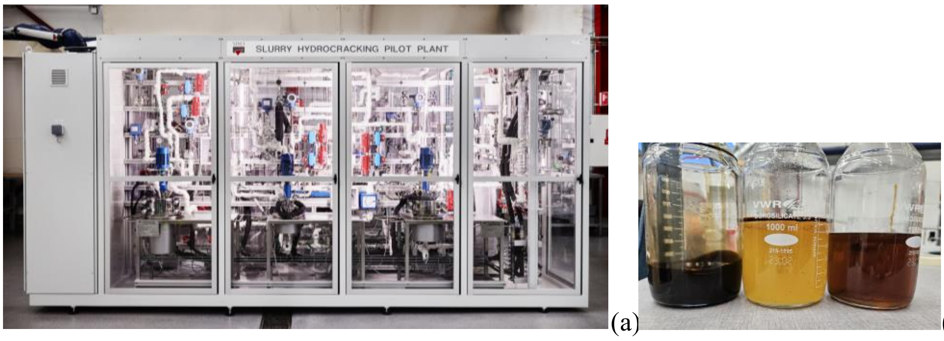
has been re-commissioned after installation of a hot gas filter, figure 13.



(a) (b)

Figure 13. (a) Pyrolysis pilot plant before installation of hot gas filter, and (b) newly installed hot gas filter.

Furthermore, a pyrolysis oil production campaign from saw dust (without the filter) has been successfully performed, and the oil has been distributed to industrial partners for characterization and particle removal tests. The hot gas filter itself is however in need of minor modifications and will be re-commissioned in early 2024. The produced pyrolysis oil has been successfully stabilized via slurry hydroprocessing in continuous mode in the slurry pilot plant, see figure 13, giving about 10 kg of stabilized pyrolysis oil for further conversion. The stabilized oil will be distributed to partners for characterization and further upgrading. A collaboration between CESTAP and the Finnish CaSH (Catalytic Slurry Hydroprocessing) project, managed by VTT, and a joint scientific publication describing successful slurry hydroprocessing of pyrolysis oil is underway. In addition, a vacuum ultraviolet (VUV) detector for fuel sample analysis has been commissioned, and the first SAF and Jet A reference samples have been analyzed using the detector.



(a) (b)

Figure 14. (a) Slurry hydrocracking pilot plant. (b) Samples of heavy oil product (left), aqueous product (middle) and light oil product (right) from stabilization of the produced pyrolysis oil.

Active participation of industry in WP 2.2 during 2023 is exemplified by Alfa Laval Technologies AB, which has contributed with pyrolysis oil characterization studies using hot spin and gyro spin tests to establish the total amounts of solids/sludge, emulsion, and separate liquids in the original pyrolysis oil samples, confirming the poor thermal stability of this type of thermochemical oil intermediates made from lignocellulose. Other examples of important industry partner contributions to WP2 are that Preem AB have provided both fossil Jet A1, HVO and (Rapeseed Methyl

Esters) RME, and that St1 Sverige AB has provided biobased starting material for slurry hydro-treatment experiments constituting a start of the sequence from fractionated solid biomass all the way to hydrocarbon-based candidate turbine fuels.

Development of a novel process and catalyst for direct conversion of alcohols to turbine fuel components

The work to deliver Task 2.3 *Development of a novel process and catalyst for direct conversion of alcohols to turbine fuel components*, led by LTU, focuses on the development of a new methanol-to-jet process and more specifically on the development of new catalysts for this process. The best ZSM-5 catalyst developed so far has during 2023 been used for 1000 hours on stream in a catalyst stability/robustness test. During the first 260 hours of this test, 10 L of bio-methanol (produced at LTU Green Fuels via black liquor gasification) was fed to the catalyst. This resulted in 2.5 L of biobased organic product and 4 L of product from the stability test has been delivered to RISE for analysis and further upgrading.

Catalyst characterization

Catalyst characterization is the focus of Task 2.4 *Catalyst characterization*, led by LTH. During 2023, Ni-Mo oxide nanoparticles have been generated and used as a model for active sites in Ni-Mo-based heterogeneous catalysts. Interesting observations have been made. For instance, *in-situ* XPS and *ex-situ* TEM analyses indicate that reduction of the catalyst proceeds via phase separation into separate Ni and Mo phases. This can have important implications on catalyst regeneration and lifetime. MoS_2 nanoparticles of the same type as used in the pyrolysis oil stabilization experiments have also been characterized. Powder XRD results indicate that the main part of the sample is very thin (~1 monolayer) flakes of hexagonal MoS_2.

WP3 Mutual adaptation of turbine fuel and engine technology

The aim of this work package 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. One PhD student is connected to this work package that initially will set baselines to be improved, define modeling 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.

Table 3. Progression of tasks WP3.

Tasks of WP3	Progression (%)	Comments
Task 1: Investigation of thermosacoustics vs fuel flexibility.	10%	On track and in line with project plan.
Task 2: Investigate DLE technology.	40%	On track and in line with project plan.
Task 3: Investigate sequential combustion technology.	0%	On track and in line with detailed project plan.
Task 4: Investigate trapped vortex technology.	0%	On track and in line with detailed project plan.

The following activities have been conducted during 2023:

Baseline cases for stationery gas turbine combustion systems

Up till now the CECOST burner has been investigated in 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. A schematic of the burner and of the combustion chamber is shown in figure 15a. More specifically, the CECOST burner, is a downscaled prototype version of the Siemens Energy SGT-750 burner. So far focus has been on a baseline case, where improved CFD modeling has been performed to confirm the prediction accuracy as compared to the measurement data that were obtained within the CECOST program[30]. Figure 15b shows instantaneous LES results obtained in CESTAP during the combustion model sensitivity analysis. Axial velocity, temperature, and combined OH/CH_2O distributions appear to be significantly influenced by the selection of the combustion model. In particular, PaSR (on the left halves of figure 15b) predicts a more distributed flame compared to the EDC model (right halves), with a remarkably different morphology of the central recirculation region. Figure 15c shows a qualitative, instantaneous distribution of OH* radicals obtained using OH* PLIF. The qualitative agreement with the numerical results in the rightmost panel of figure 15b is satisfactory. Next step is to update the rig to facilitate measurements for liquid fuels and corresponding CFD investigations.

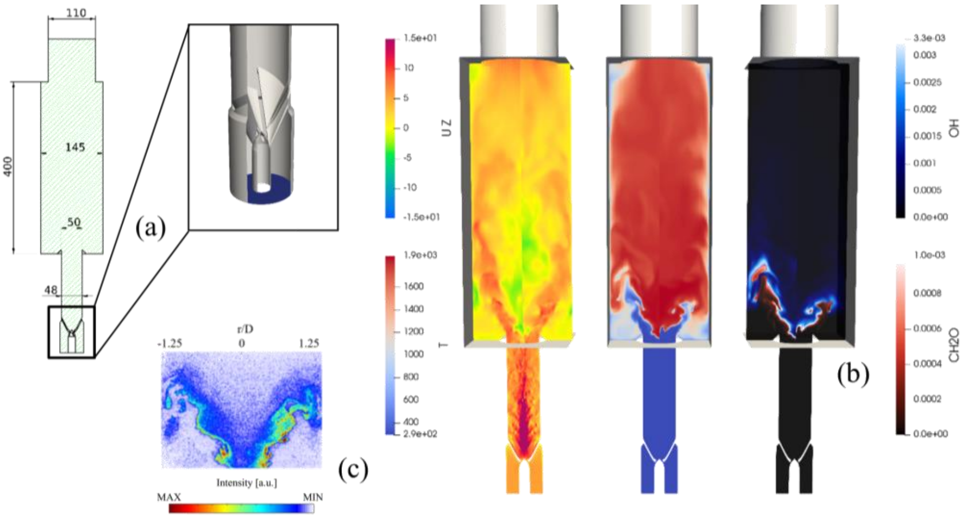


Figure 15. (a) Main geometrical elements of the CECOST burner, and a detail of the axial swirler. (b) From left to right: axial velocity, temperature and OH/CH_2O distributions (blue and red) for PaSR and EDC in the two halves of the combustion chamber (left and right, respectively). (c) Instantaneous experimental OH* PLIF signal.

As input to the baseline cases, Siemens Energy have performed high pressure combustion tests using alternative green liquid fuels to quantify the fuel effect that is intended to be compared to the laboratory scale tests. During spring 2023 the Siemens Energy high pressure combustion rig in Berlin was modified to easier exchange between alternative liquid fuels and during summer SGT-800 burners were tested using RME and methanol. Further, as complement to the successful SGT-800 engine test using HVO during 2022 together with Göteborg Energy at the Rya

[30] https://www.lth.se/cecost

site, during 2023 was performed further SGT-800 engine tests using HVO at Stockholm Exergi and in Finspång.

Furthermore, Sydkraft Thermal Power AB / Uniper have performed full scale tests of HVO in their Öresundsverket plant to progress their strategy in transitioning to green fuels. Similarly, Svensk Kraftreserv AB also performed full scale tests of green fuels in their GT120 assets. Such full-scale tests provide invaluable information about all aspects of fuel adaptation to existing gas turbines and jet engines. 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

An extensive literature study is ongoing 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 but for detailed experimental and numerical studies in laboratory scale, the TARS burner in the Lund atmospheric combustion rig is identified as the best available option. Experimental and simulation work of the TARS burner using liquid fuels have been initiated in collaboration with the EU Horizon Europe projects MORE&LESS[31], MYTHOS[32] and Circular Fuels[33]. The detailed path forward will be further discussed together with particularly the aviation industry partners.

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 will include spray tests at the high-pressure spray rig at RISE in Piteå, Sweden, with complementary laser measurements in collaboration with WP1. Similar spray tests were performed in this rig within the competence center program TECH4H2[34] during autumn/winter and the WP3 measurements are waiting for that campaign and evaluation to finish, in order to get all input needed to finalize the WP3 test planning. This includes down-selection of what conditions, nozzles and fuels that will be included in this study.

WP4 Material Sciences

This WP started during 2023 after being delayed for practical reasons and is since the summer of 2023 led by WP-leader Per-Johan Tolf from SAAB Aeronautics AB. The aim of the work package is, with knowledge about the full certification process and needs, to define and use a set of cost-effective and facile test methods for the characterization of lubricating properties, effects on elastomer materials present in the engine system as well as any corrosive effects of candidate fuels tested against reference as part of the pre-certification test package of CESTAP. Stabilities for storage and transportation of fuel candidates are also part of the scope for this WP,

[31] https://www.h2020moreandless.eu/project/
[32] https://mythos.ruhr-uni-bochum.de/
[33] https://circularfuels.eu/
[34] //www.chalmers.se/en/centres/techforh2/

the progress of which is discussed below.

Progression of tasks WP4.

Tasks of WP4	Progression (%)	Comments
Task 1: Lubrication.	10%	On track since WP4 had a de-lay-ed start for practical reasons. The plan is to catch up during 2024 and onwards.
Task 2: Soft material inter-actions.	20%	On track with tests ongoing.
Task 3: Deposits and corro-sion.	10%	See comment for Task 1.

LTH, RISE, Saab Aeronautics AB, GKN Aerospace AB, Siemens Energy and Topsoe has been actively involved in WP4 during 2023. Fuel candidates manufactured from bio-based (waste) feedstocks like lignocellulosic waste, will inevitably have different chemical compositions compared to the current fossil fuels, with implications for materials compatibility, storage, transportation, and use. Within WP4 the technical feasibility and safety aspects related to material compatibility will be evaluated. To ensure complete compatibility, it is necessary to investigate a range of properties for potential fuel candidates, including lubrication properties, interactions with elastomers (e.g., gaskets), deposits, and corrosion. Another important aspect is storage properties, which is of particular importance for backup gas turbine systems that may rely on stored fuels. The effects of storage and aging on the fuel composition and properties will therefore be studied and safety aspects related to storage and transport of the fuel candidates. For practical reasons, the industry-employed PhD student position available for this WP has not yet been filled and plans and activities for the work package are at present delayed accordingly. One master student thesis regarding WP4.2 (soft material interactions) started in September 2023 at LTH, with technical support from Saab. Two online meetings with the above organizations have been held during 2023.

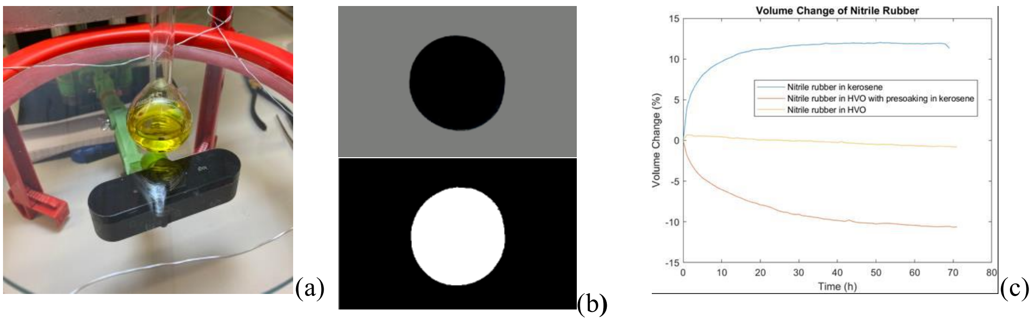


Figure 16. (a) Set up of optical dilatometer. (b) Image processing of o-ring cross sections. (c) Example nitrile rubber elastomer fuel swelling graph.

The work package is divided into the following subtasks:

Lubrication

In 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.

Soft material interactions

In Task 2, *soft material interactions*, issues related to soft materials will be investigated concerning the suggested fuel qualities. The Master Student thesis focusing on compatibility of alternative jet fuels with elastomer seals, started in September 2023. Elastomer material swelling behavior is identified to be the most critical property affected by alternative fuels. Importantly, a rapid test method for characterizing the swelling behavior has been identified.[35] The method is based on work made by Graham *et al*. at University of Dayton in the US and has during the autumn of 2023 been set up in a lab at LTH. The test set up is currently being evaluated using a selected standard elastomer (see Figure 15 above for pictures and selected data obtained).

Deposits and corrosion

In Task 3 *deposits and corrosion* high- and low temperature corrosion 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 causing a storage/FOD/filter problem and at high temperatures causing deposits in nozzles and regulator valves (as worst cases). 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). Test methods identified for early evaluation of bio-based turbine fuel candidates shall be further investigated in WP 4.3. Test methods identified for early evaluation of bio-based turbine fuel candidates shall be further investigated in WP 4.3.

WP5 Holistic techno-economic and sustainability analysis

WP5 deals with comprehensive examination of sustainable turbine fuels, emphasizing on the benefits and trade-offs. The assessments consider aspects such as production potential, economic viability, and environmental impact. Both current (fossil) and future (hydrogen and electric) alternatives will serve as benchmarks in this evaluation.

Progression of tasks WP5.

Tasks of WP5	Progression (%)	Comments
Task 1: Techno-economics of biofuel production	40%	On track and plans are aligned with case studies in WP2

[35] Graham, J.L. *et al*.; 2006, Energy Fuels, 20, p 759.

Task 2: Sustainability of bio-fuel production and use	10%	On track and this task is partly dependent of emissions data from tests in WP1.
Task 3: Holistic analysis of biofuel alternatives	30%	On track and collaboration with Swedavia has started on system aspects of SAF from an infra-structural and logistics perspec-tive.

As outlined in the overall research plan, the activities stated for the first two years of the project, 2022 and 2023, include:

1. Literature study on production sustainable aviation fuels, delayed from 2022.

2. Case study for Methanol-To-Jet (MTJ) SAF production.

3. Case study for SAF production from slurry hydrotreatment of pyrolysis oils and lignin.

Literature review of techno-economics of bio-fuel production

Zeenat Farooq, a PhD student at LTU, has conducted a comprehensive literature review evaluating the technoeconomic performance of commercially available SAF production routes in the short or medium term. These routes are based on sustainable and cost-effective feedstocks. The findings are scheduled for submission to a peer-reviewed journal in Q2 2024. In her research, Zeenat examined 52 greenfield and 42 integrated process configurations. According to the analysis, integrating SAF production through Fischer Tropsch (FT) and Pyrolysis to Jet (PTJ) pathways into existing biorefineries reduces the Minimum Jet Fuel Selling Price (MJSP) compared to greenfield scenarios. The study identified challenges with current Techno-economic analysis (TEA) methodologies which can impact the accuracy of technoeconomic results. The treatment of byproduct credit in the different methodologies can significantly skew MJSP estimates. Additionally, methodological choices play a crucial role in determining the fixed operation cost parameter, thereby affecting overall operational expenses and MJSP. Reproducing commonly used technoeconomic performance indicators, specifically MJSP, for 52 greenfield cases revealed areas where TEA methodology or variables (Capex, Opex, feedstock cost, by-product revenue) strongly influence the variability in MJSP. Regression analysis on these cases demonstrated that the influence of TEA input variables on MJSP is route-specific. For the FT route, MJSP showed the highest sensitivity to Total Capital Investment (TCI). By-product credit was found to have more potential in reducing MJSP for Alcohol to Jet (ATJ). However, the analysis of 52 greenfield cases indicated wide variations in operating costs and by-product credit, suggesting interactions between these variables that may affect MJSP. To deepen the understanding, a supplementary harmonization analysis was conducted, adopting a common value for each input variable across all cases in each route to isolate its effect. The results highlighted the complex interplay between operational expenses and by-product credit, emphasizing the need to find an optimal balance between the two for optimizing SAF production costs. The analysis further positioned the FT route as superior in several metrics compared to ATJ and PTJ routes. A summary of SAF production cost reported in the literature and reproduced in this study is shown in figure 17.

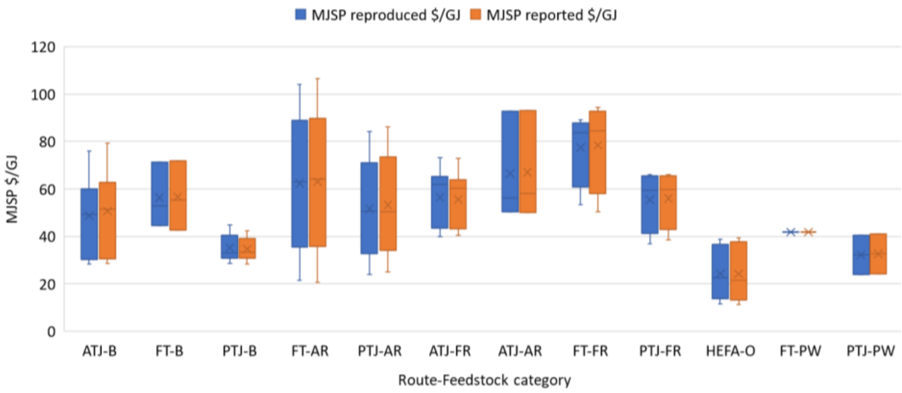


Figure 17. Reported and reproduced SAF production cost, Farooq *et al*. (2023, manuscript under preparation). AR – agricultural residues, FR – forest residues, O – oil feedstock, PW – process waste, B - other lignocellulosic biomass, ATJ - alcohols-to-jet, PTJ - pyrolysis-to-jet, FT -- gasification + Fischer-Tropsch, HEFA - hydroprocessed esters & fatty acids.

Sustainability of biofuel production and use

The work on methanol-to-jet track initiated in 2022 was further developed in 2023 to include upstream (renewable methanol production) and downstream (catalytic conversion and hydrotreatment). A preliminary systems model for the methanol-to-finished distillate process chain was established by integrating results from methanol-to-jet project along with data from the open literature. The model facilitated the derivation of mass and energy balances, which were subsequently employed for estimating production costs. The carbon, mass and energy balance results derived from the model implemented in Aspen Plus is shown in figure 18. The model assumed the recirculation of unreacted methanol, incrementally adding the methanol-to-product yield to 100%. The gases (C_2-C_4) produced were assumed to substitute fossil gas in the integrated refinery, while the light liquid fraction (C_5-C_7) was considered for sale as a feedstock for renewable gasoline (naphtha). It is noteworthy that the gas, although theoretically convertible into a liquid product by recirculation to the reactor with the zeolite ZSM-5 catalyst was not considered in this context due to time constraints. Further catalyst development and the impact of recirculation on the performance of the catalyst will be studied under CESTAP WP2. Regarding excess heat generated from the process, an assumption was made that it is comparable to that in the methanol-to-gasoline process, and it can replace steam produced from fossil gas in the refinery.

Production cost or Minimum Fuel Selling Price (MFSP) was evaluated as economic indicator, with adjustments made to raw material costs and CAPEX to align with 2021 levels. The production of renewable methanol, i.e., eMeOH, BLG-MeOH and BMG-MeOH, was based on previous work conducted at RISE[36]. Two allocation methods were employed: (1) MFSP was calculated for all liquid fuel products (bio-distillate/jet fuel intermediate plus naphtha), and (2) naphtha was treated as a saleable by-product of the bio-distillate. The cost assessment of bio jet fuel focused solely on the distillate component derived from methanol, excluding the isomerized HEFA component. The resulting production costs were benchmarked against reported costs from various renewable jet fuel production routes, as identified through

[36] Mesfun S. *et.al*. Energies **2023**, 16, p 7436.

the comprehensive literature review reported in activity one, figure 16.

Figure 18 illustrates the resulting production costs (MFSP), depicting the distribution among various cost components. The figure highlights that the majority of the production cost for the final product stems from the expenses associated with renewable methanol production, with the costs of converting methanol into renewable hydrocarbons being relatively modest. The methanol cost is, in turn, dominated by capital cost (CAPEX) and raw material cost (biomass and/or electricity). The figure assumes an electricity price of €59/MWh[37] and a biomass price of €17.5/MWh.[38] Methanol concepts with low electricity usage, such as black liquor and biomass gasification without electrolysis, yield the lowest total cost. At an electricity price of €40/MWh combined with a biomass price of €25/MWh, hybrid concepts become comparable to pure gasification cases.

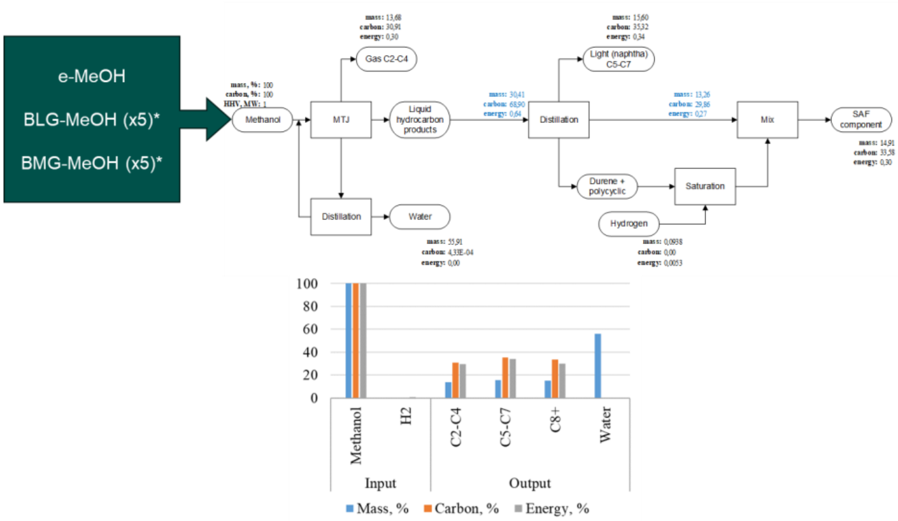


Figure 18. Schematics for SAF production via methanol-to-jet track used for the technoeconomic evaluation. e-MeOH – captured CO_2 based methanol (via a reverse water-gas-shift process), BLG-MeOH – Black liquor gasification-based methanol, BMG-MeOH – Biomass gasification-based methanol.

As shown in figure 19, a significant portion of the formed renewable hydrocarbons comprises lighter fractions (gas or naphtha). Treating these as by-products to the distillate fraction in the economic analysis can result in a misleading production cost (right graph). Therefore, considering the MFSP for all liquid fuel products (left graph) provides a more accurate indication of actual production costs, especially considering considerable market demand for renewable hydrocarbons, including renewable naphtha/gasoline.

[37] Wetterlund E. Oral communication. This is a projected average spot price of electricity on Nordpool.
[38] This biomass average price is reported for instance in a report from the Horizon 2020-project Clara (Chemical Looping Gasification for Sustainable Production of Biofuels), by Raúl Pérez-Vega, Idoya Goñi, Ibai Funcia, Nadine Gürer, Frank Radosits "Deliverable D7.1 Cost Estimation for biomass feedstock supply" 27th of April 2022, available at https://clara-h2020.eu/wp-content/uploads/2022/05/CLARA_D7.1_Cost-estimation-for-biomass-feedstock-supply_v01.pdf.

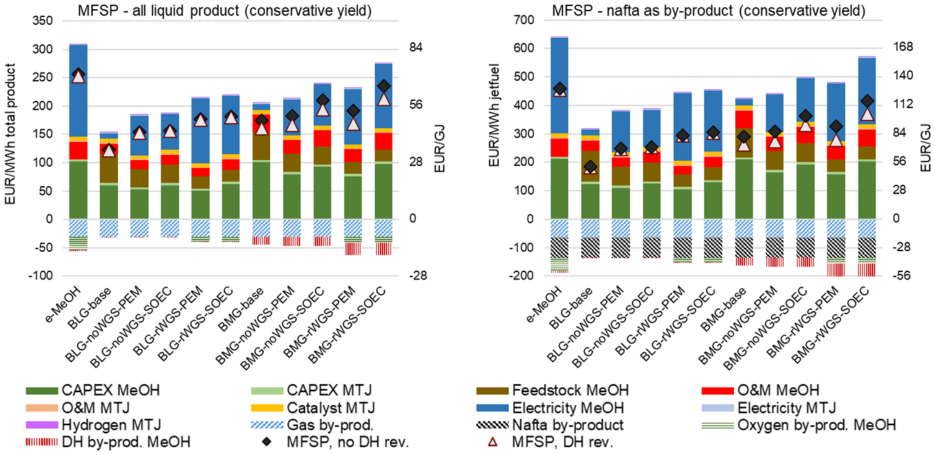


Figure 19. Resulting cost distribution and cost of production (MFSP) for the analyzed scenarios, with different production concepts for renewable methanol. Left: MFSP calculated for all liquid products; Right: MFSP for only bio-distillates with naphtha as a by-product.

Figure 20 summarizes reported renewable jet fuel production costs for comparable production pathways, relative to the economic findings from this study (shaded area). The publication costs exhibit a considerable range within most production routes. Similarly, the MFSP spread for the studied concept in this project is largely influenced by variations in methanol production costs. Nonetheless, the resulting cost is comparable or superior to the most relevant Sustainable Aviation Fuel (SAF) production concepts, such as FT-FR and PTJ-FR. Optimizing process conditions or polymerizing the C_2-C_4 fraction to achieve a higher yield to liquid hydrocarbons could likely further enhance the MFSP of this project's concept. However, additional process step costs have not been considered here, and the yield from the C_2-C_4 fraction to C_{8+} has not been experimentally studied yet.

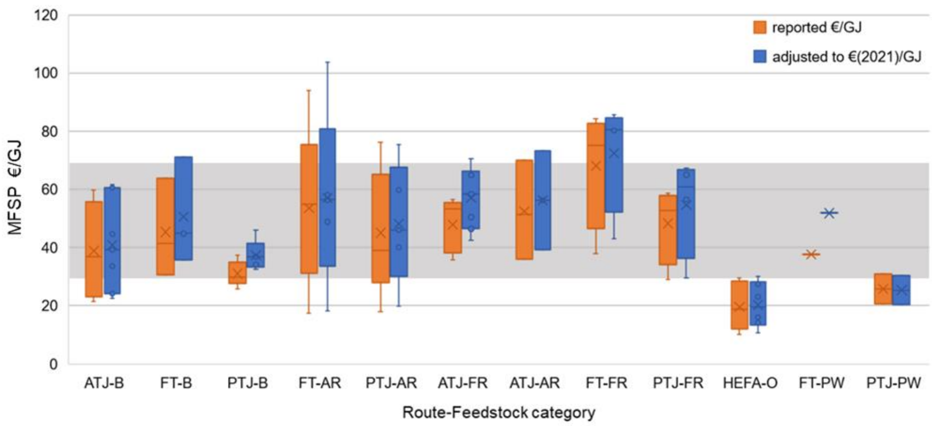


Figure 20. Compilation of reported production costs for comparable sustainable aviation fuels (SAF) production pathways (adapted from Farooq *et al*. (2023, manuscript in progress). The shaded area represents the range of production costs from this study (MFSP calculated for all liquid fuel product). AR – agricultural residues, FR – forest residues, O – oil feedstock, PW – process waste, B – other lignocellulosic biomass, ATJ – alcohols-to-jet, PTJ – pyrolysis-to-jet, FT – gasification + Fischer-Tropsch, HEFA – hydroprocessed esters & fatty acids.

Two manuscripts are currently being prepared by chemical engineering division at LTU in connection to WP2. One focuses on the experimental work related to methanol-to-jet, while the other addresses the performance of catalysts. The systems aspects, techno-economics of methanol-to-jet including the production of renewable methanol, will be prepared for a separate publication in Q3/Q4 2024 by energy division at LTU and RISE. Zeenat, who will take a lead on this task, is on parental leave until June 2024.

Holistic analysis of biofuel alternatives

The evaluations of pyrolysis oil and lignin tracks are scheduled for Q2/Q3 2024. In this context, we anticipate leveraging synergies with other projects to share experimental data. RISE will commence the systems assessments promptly upon the availability of experimental data.

WP6 Exploitation and Implementation Plan

Work Package 6 (WP 6) has focused on Intellectual Property Rights (IPR) assessment within our Competence Centre. Key achievements include a draft of the sustainable plan for the pre-certification test bed in collaboration with WP1 as well as strategic discussions with LU Innovation. The pre-certification test bed plan is still in progress, but the framework for a comprehensive and sustainable plan has been laid. The plan should be further developed and fine-tuned in parallel with the development of the experimental work of the pre-certification test bed.

WP 6 collaborates with Universities and RISE to identify and address potential patent opportunities, ensuring future commercial rights. In our regular meetings, the Work Package leaders report on a comprehensive overview of outcomes achieved within their respective packages and the identification of potential patentable elements. The aim is to ensure that all valuable research findings are appropriately covered by IPR, contributing to the long-term protection and commercial success of the center's innovations.

WP7 Dissemination and Outreach

WP7 is the work package for communication and dissemination, within the Centre as well as to stakeholders outside the Centre. As stated in the Program Description for CESTAP, WP7 include 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.

Routine activities in WP7 is the sharing of information within the Centre, with the Sharepoint site as the internal sharing platform. A quarterly Newsletter is sent by email to all involved personnel in the partner organizations, informing about recent and upcoming activities.

In 2023 the PhD students in the Centre finalized the introductory course in March during a two-day visit to the partner LTU. A second PhD course given by CESTAP was on Gas Turbine technology, held in Lund during the first week of December, by Prof. Magnus Genrup

Two meetings have been arranged in 2023:

- Summer Meeting in Ljungbyhed on June 14th, including a visit to the Jet Engine Lab. The meeting had some focus on WP1 activities and partners. The meeting had 40 attendants from 15 partner organizations.
- The second CESTAP Annual Meeting was held in Lund on November 28th, with 50 participants from 21 partner organizations. This was a full day with reports on scientific progress from the WP leaders and talks by five representatives from the industrial partners.

List of Publications from CESTAP 2022 – 2023

Fureby C.; 2022, "Paving the Route Towards Green Aviation with Hydrogen and Biojetfuels – A Numerical Study using OpenFOAM", OpenFOAM and Combustion Webinar 2022-11-25, SNU, Singapore.

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

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

Passad M., Åkerblom A., Pignatelli F., Nilsson T., Nilsson E.J.K. & Fureby C.; 2022, "Predictions of Spray Combustion using Conventional Category A Fuels and Exploratory Category C Fuels", AIAA-2023-1486.

Hatun Tanis, M. Vercoutere, E., Al-Rudainy, B. & Wallberg, O.; 2023, "A Comparison of Lignin Extraction: One- and Two-Step Fractionation", Poster at the CESTAP Annual meeting 2023.

Cakir B., 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.

Hernandez Cabello, J. 2023, "Conversion of bio-methanol to jet fuel on zeolite-based catalysts", Poster at the CESTAP Annual meeting 2023.

Ercole, A. & Åkerblom A. 2023, "Large Eddy Simulations of Alternative and Conventional Gas Turbine Fuels", Poster at the CESTAP Annual meeting 2023.

Dullovi, E.; 2023, "Evaluating the compatibility of alternative jet fuels with elastomer seals", Poster at the CESTAP Annual meeting 2023.

Farooq Z.; Furusjö E.; Mesfun S.; Cabello J.H.; Hedlund J. & Wetterlund E.; 2023, "Techno-economic Assessment of Methanol-to-Jet Pathway", 31st European Biomass Conference & Exhibition (EUBCE), 5-9 June 2023, Bologna, Italy.

Åkerblom A. & Fureby C.; 2023, "LES Modeling of the DLR Generic Single-Cup Spray Combustor: Validation and the Impact of Combustion Chemistry", Flow, Turb. and Comb., 112, p 557.

Ercole A.; 2023, "LES of Turbulent Premixed Flames in Model Gas Turbine Burner: Influence of Combustion Model", Nordic Flame days 2023, November 29-30, Trondheim, Norway.

Fureby C.; 2023, “Sustainable Turbine fuels for Aviation and Power”, SARC Annual Meeting, Saltsjöbaden, June 8-9.

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.

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

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

Cakir B.A., Sanned D., Prakash M., Brackmann C., Richter M. & Fureby C.; 2024, “Application and assessment of background oriented schlieren for laminar burning velocity measurements” Submitted to Comb. Inst.

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