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ASAF

aerobrew Pilot Plant

Metafuels and PSI Team Members in front of the building that will host the Pilot Plant. Source: Metafuels 2024

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The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.

Summary

The Project entails the design, engineering, procurement, manufacture, installation, commissioning, operation, and testing of a pilot plant (PP) based on Metafuels' aerobrew technology which will be capable of taking sustainable methanol feedstock and converting it to Sustainable Aviation Fuel (SAF) at a capacity of up to 50 litres per day. The PP will be housed in a dedicated building at the Paul Scherrer Institut (PSI) site in Villigen, Switzerland. The building has been refurbished and fitted out especially for the purpose.

Metafuels "aerobrew" SAF production technology promises to deliver breakthrough improvements in carbon efficiency and energetic efficiency across the full value chain, with high selectivity to SAF with the corresponding advantages in cost of production and fuel price. The feedstock for the process is green methanol itself produced from green hydrogen and sustainably sourced CO_2. Technology for the production of green methanol is already available commercially although several programmes of research and development are ongoing to further improve the process.

At the time of writing this report, about 11 months after the BfE funding decision, a lot of progress has been made. The detailed engineering of both the PP itself as well as all the interfaces with the building and supporting infrastructure have been completed, including a rigorous safety check and numerous sessions on PP operability. The procurement and design of all equipment is largely completed. Currently the focus is on the fabrication and assembly of six (6) individual skids that will make up the complete PP, their installation in the host building at PSI, and their interface and connection with the supporting infrastructure.

In parallel, preparatory activities for the next phase of the project have been undertaken. This includes hiring and training personnel for the operation of the plant, obtaining the necessary operating permits and a detailed evaluation of the supply chain for chemicals and catalysts needed for the operation. It is also of great importance to collect accurate data at many points throughout the pilot plant including the chemical compositions of various streams. Accordingly, we have developed both sampling and analytic procedures specially for this plant.

A Life Cycle Assessment (LCA) model has been developed which will enable a detailed analysis of environmental impacts to be performed for the SAF product produced at any future location of an "aerobrew" production plant, taking into account both the feedstock and the local electric energy mix as well as all possible transportation alternatives.

The project progress is remarkable given the fact that this type of plant has rarely, if ever, been built before. An integrative and pragmatic approach to problem solving has enabled the project team to address a long list of challenges, ranging from finding suppliers for specialized equipment to ensuring a safe and explosion proof working environment. The multi-disciplinary project team is made up of participants from Metafuels and PSI, extended in part by third party experts. Close co-operation and mutual respect ensure that all views and opinions are discussed, and the best solution is found in all situations.

Project oversight by Metafuels and PSI Management takes place in Monthly Project Report meetings as well as in regular Risk Reviews. The Risk Review process rates the different risks and allows the team to focus on mitigation of the highest rated ones.

The next 12 months are equally exciting, first the installation and hook-up of the plant will be completed, followed by final testing and first operation. During the second half of 2025 results will start to come in and the focus of the project will change from project execution to operational research and development ahead of commercialisation of the aerobrew technology. The SAF produced in the pilot plant will be tested by an expert third party to ensure that it is compatible with the strict rules that apply to any aviation fuel and meets the requirements for a drop in alternative aviation fuel. The plant will also be used to optimize the process and supply data for the improvement and tuning of plant modelling tools.

Zusammenfassung

Das Projekt umfasst die Planung, das Engineering, die Beschaffung, die Herstellung, die Installation, die Inbetriebnahme, den Betrieb und die Erprobung einer Pilotanlage (PP), die auf der aerobrew-Technologie von Metafuels basiert und in der Lage sein wird, nachhaltiges Methanol in nachhaltigen Flugkraftstoff (SAF) mit einer Kapazität von bis zu 50 Litern pro Tag umzuwandeln. Das PP wird in einem eigens dafür eingerichteten Gebäude am Standort des Paul Scherrer Instituts (PSI) in Villigen, Schweiz, untergebracht sein. Das Gebäude wurde eigens für diesen Zweck saniert und hergerichtet.

Die "aerobrew" SAF-Produktionstechnologie von Metafuels verspricht bahnbrechende Verbesserungen bei der Kohlenstoffeffizienz und der Energieeffizienz über die gesamte Wertschöpfungskette, mit einer hohen Selektivität für SAF mit den entsprechenden Vorteilen bei den Produktionskosten und dem Kraftstoffpreis. Der Ausgangsstoff für das Verfahren ist grünes Methanol, das selbst aus grünem Wasserstoff und nachhaltig gewonnenem CO2 hergestellt wird. Die Technologie zur Herstellung von grünem Methanol ist bereits kommerziell verfügbar, obwohl mehrere Forschungs- und Entwicklungsprogramme laufen, um das Verfahren weiter zu verbessern.

Zum Zeitpunkt der Erstellung dieses Berichts, rund 11 Monate nach dem Förderbeschluss des BfE, wurden viele Fortschritte erzielt. Das Detail-Engineering sowohl für die PP selbst als auch für alle Schnittstellen zum Gebäude und zur unterstützenden Infrastruktur ist abgeschlossen, einschliesslich einer strengen Sicherheitsüberprüfung und zahlreicher Sitzungen zur Funktionsfähigkeit der PP. Die Beschaffung und Konstruktion aller Geräte ist weitgehend abgeschlossen. Aktuell liegt der Fokus auf der Herstellung und Montage von sechs (6) einzelnen Modulen, die die komplette PP bilden werden, deren Installation im Gebäude am PSI sowie die Verbindungen zur unterstützenden Infrastruktur.

Parallel dazu wurden Vorbereitungsarbeiten für die nächste Phase des Projekts durchgeführt. Dazu gehören die Einstellung und Schulung von Personal für den Betrieb der Anlage, die Einholung der erforderlichen Betriebsgenehmigungen und eine detaillierte Bewertung der Lieferkette für die für den Betrieb benötigten Chemikalien und Katalysatoren. Es ist auch von grosser Bedeutung, an vielen Stellen in der Pilotanlage genaue Daten zu sammeln, einschliesslich der chemischen Zusammensetzung verschiedener Ströme. Dementsprechend haben wir speziell für diese Anlage sowohl Probenahme- als auch Analyseverfahren entwickelt.

Es wurde ein Ökobilanzmodell (LCA) entwickelt, das eine detaillierte Berechnung der Umweltbelastungen des SAF-Produkts ermöglicht, das an einem beliebigen zukünftigen Standort einer "aerobrew"-Produktionsanlage hergestellt wird, wobei sowohl der Rohstoff als auch der lokale elektrische Energiemix sowie alle möglichen Transportoptionen berücksichtigt werden.

Der Projektfortschritt ist bemerkenswert, wenn man bedenkt, dass diese Art von Anlage bisher nur selten oder gar nicht gebaut wurde. Ein integrativer und pragmatischer Ansatz zur Problemlösung hat es dem Projektteam ermöglicht, eine lange Liste von Herausforderungen zu bewältigen, die von der Suche nach Lieferanten für Spezialausrüstung bis hin zur Gewährleistung einer sicheren und explosionsgeschützten Arbeitsumgebung reichen. Das multidisziplinäre Projektteam setzt sich aus Teilnehmenden von Metafuels und PSI zusammen und wird zum Teil durch externe Experten erweitert. Enge Zusammenarbeit und gegenseitiger Respekt sorgen dafür, dass alle Ansichten und Meinungen diskutiert werden und in allen Situationen die beste Lösung gefunden wird.

Die Projektbegleitung durch Metafuels und das PSI-Management erfolgt in monatlichen Projektsitzungen sowie in regelmässigen Risk Reviews. Der Risikoüberprüfungsprozess bewertet die verschiedenen Risiken und ermöglicht es dem Team, sich auf die Minderung der am höchsten bewerteten Risiken zu konzentrieren.

Die nächsten 12 Monate sind ebenso spannend, zuerst wird die Installation und der Anschluss der Anlage abgeschlossen, gefolgt von den abschliessenden Tests und dem ersten Betrieb. In der zweiten Hälfte des Jahres 2025 werden die ersten Ergebnisse eintreffen, und der Schwerpunkt des Projekts wird sich von der Projektdurchführung auf die operative Forschung und Entwicklung verlagern, bevor die aerobrew-Technologie kommerzialisiert wird. Das in der Pilotanlage hergestellte SAF wird von einem sachverständigen Dritten getestet, um sicherzustellen, dass es mit den strengen Vorschriften kompatibel ist, die für jeden Flugkraftstoff gelten, und die zusätzlichen SAF-Anforderungen erfüllt. Die Anlage wird auch zur Optimierung des Prozesses und zur Bereitstellung von Daten für die Verbesserung und Abstimmung von Simulationen genutzt.

Résumé

Le projet comprend la conception, l'ingénierie, l'approvisionnement, la fabrication, l'installation, la mise en service, l'exploitation et les essais d'une usine pilote (PP) basée sur la technologie aerobrew de Metafuels, qui sera capable de convertir du méthanol vert en carburant d'aviation durable (SAF) à une capacité allant jusqu'à 50 litres par jour. Le PP sera installé dans un bâtiment dédié sur le site de l'Institut Paul Scherrer (PSI) à Villigen, en Suisse. Le bâtiment a été rénové et aménagé spécialement à cet effet.

La technologie de production de SAF « aerobrew » de Metafuels promet d'apporter des améliorations révolutionnaires en matière d'efficacité carbone et d'efficacité énergétique sur l'ensemble de la chaîne de production, avec une sélectivité élevée vers le SAF et les avantages correspondants en termes de coût de production et de prix du carburant. La matière première du procédé est le méthanol vert, lui-même produit à partir d'hydrogène vert et de CO2 d'origine durable. La technologie de production de méthanol vert est déjà disponible sur le marché, mais plusieurs programmes de recherche et de développement sont en cours pour améliorer encore cette technologie.

Au moment de la rédaction de ce rapport, environ 11 mois après la décision de financement du BfE, de nombreux progrès significatifs ont été réalisés. L'ingénierie détaillée du PP lui-même et de toutes les interfaces avec le bâtiment et l'infrastructure locale a été achevée, y compris un contrôle rigoureux de la sécurité et de nombreuses sessions sur l'opérabilité du PP. L'acquisition et la conception de tous les équipements est en grande partie terminée. Actuellement, l’effort est accentué sur la fabrication et l'assemblage de six (6) modules individuels qui constitueront le PP complet, leur installation dans le bâtiment hôte de PSI, ainsi que l’interface et la connexion avec l'infrastructure locale.

Parallèlement, des activités préparatoires pour la phase suivante du projet ont été entreprises. Il s'agit notamment de recruter et de former du personnel pour l'exploitation de l'usine, d'obtenir les permis d'exploitation nécessaires et de procéder à une évaluation détaillée de la chaîne d'approvisionnement en produits chimiques et en catalyseurs nécessaires à l'exploitation. Il est également très important de collecter des données précises à de nombreux endroits de l'usine pilote, notamment en ce qui concerne la composition chimique des différents flux. C'est pourquoi nous avons mis au point des procédures d'échantillonnage et d'analyse spécialement pour cet unité pilote.

Un modèle d'analyse du cycle de vie (ACV) a été développé pour permettre un calcul détaillé des impacts environnementaux du produit SAF fabriqué, et ce pour n'importe quel futur site de production utilisant la technologie « aerobrew », en tenant compte à la fois de la matière première et de la combinaison locale d'énergie électrique, ainsi que de toutes les alternatives possibles en matière de transport.

L'avancement du projet est remarquable compte tenu du fait que ce type de pilote a rarement, voire jamais, été construit auparavant. Une approche intégrative et pragmatique de la résolution des problèmes a permis à l'équipe du projet de relever une longue liste de défis, allant de la recherche de fournisseurs d'équipements spécialisés à à l’assurance d’un environnement de travail sécurisé. L'équipe de projet pluridisciplinaire est composée de participants provenant de Metafuels et de PSI, auxquels s'ajoutent des experts tiers. Une coopération étroite et un respect mutuel garantissent la discussion de tous les points de vue et d’identifier les meilleures solutions dans chaque situation.

La supervision du projet par la direction de Metafuels et de PSI s'effectue dans le cadre de réunions mensuelles de rapport de projet et d'analyse régulière des risques. Le processus d'analyse des risques évalue les différents risques et permet à l'équipe de se concentrer sur l'atténuation des risques les plus élevés.

Les 12 prochains mois seront tout aussi passionnants : l'installation et le raccordement de l'unité pilote seront achevés, suivis des tests finaux et de la première mise en service. Au cours du second semestre 2025, les résultats commenceront à aboutir et l'objectif du projet passera du statut d'exécution à celui de recherche et développement opérationnels en vue de la commercialisation de la technologie aerobrew. Le SAF produit par le pilote sera testé par un expert tiers afin de confirmer sa compatibilité avec les règles strictes s'appliquant à tout carburant d'aviation et sa capacité à répondre aux exigences d'une baisse du carburant d'aviation alternatif. L'unité pilote servira également à optimiser le procédé et à être source de données pour l'amélioration de la modélisation de la technologie.

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List of abbreviations

AtJ	Alcohol-to-Jet
CCU	Carbon Capture and Utilisation
FOAK	First-of-a-Kind
FT	Fischer Tropsch
HAZOP	Hazard and Operability Study
HEFA	Hydrogenation of Esters and Fatty Acids
IATA	International Air Transport Association
LCA	Life Cycle Assessed
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MtJ	Methanol-to-Jet
MtO	Methanol to olefins
OO	Olefins Oligomerisation
PP	Pilot Plant
PSI	Paul Scherrer Institut, Villigen, Aargau
SAF	Sustainable Aviation Fuel
SFOE	Swiss Federal Office of Energy
TRL	Technology Readiness level
UCO	Used Cooking Oil

1 Introduction

1.1 Context and motivation

In 2022, the European Environment Agency published an article on sustainability and mobility entitled "*Imaginary 3: The great decoupling*"[1]. The question for aviation is - how to decouple its future growth from its environmental impact? In large part this means, how can aviation disentangle from its dependence on fossil fuels while remaining affordable?

Aviation is a challenging sector to decarbonise due to weight and size constraints, long innovation cycles, prioritisation of safe operations and since key technologies required to meet the challenge are costly and have not yet been adopted at scale[1].

IATA member airlines plan to achieve their 2050 commitment through a combination of measures: (i) infrastructure and operational efficiencies (3%), (ii) new technology, electric and hydrogen (13%), (iii) sustainable aviation fuel (65%), and (iv) offsets and carbon capture (19%)[2]. Other stakeholders chart similar pathways.

Infrastructure and operational efficiencies are generally low cost, but limited in terms of impact. They include actions such as optimising air space usage and densifying cabins.

The most fuel-efficient aircraft in service today are about 20% more fuel efficient than the aircraft they replace. Accelerating fleet renewal is therefore an important lever. Alternative propulsion such as electric and hydrogen will make only a modest impact by 2050 given typical certification timelines, as well as aircraft lifespan and fleet renewal rates. Range limitation also means they will be limited to certain use cases, e.g. short haul regional aviation.

The major contribution will be made by the use of Sustainable Aviation Fuels (SAFs). By design, SAFs are drop-in solutions, which can be directly blended into existing fuel infrastructure and are compatible with current aircraft. Offsetting and carbon removals will also be needed to remove residual emissions but cannot replace active abatement options.

By 2050 the market demand for SAF is anticipated to grow to around 449 billion litres or 75% of the total aviation fuel market (*IATA base case 2021*)[2]. Today, SAF is available in only very small quantities. In 2023, SAF volumes reached over 600 million litres (0.5Mt), double the 300 million litres (0.25 Mt) produced in 2022 and it is expected to triple to 1.875 billion litres in 2024, equivalent to 0.53% of total aviation fuel demand[3].

Regulation to drive the use of SAF is emerging in various jurisdictions including in the US and in Europe. The need for new and innovative SAF production technologies to meet the growing demand is clear.

To accelerate the production and adoption of SAF, the EU and other jurisdictions are focussing on mandate-based approaches. For example the RefuelEU policy imposes a minimum share of SAF, starting in 2025. In some cases, e.g. EU ETS incentives, or Singapore's flight levy, they are also combining this with mechanisms to support the purchase of SAF. On the other hand, the US uses an incentive-based approach under the Inflation Reduction Act, which has attracted both domestic and European producers. Canada has broadly followed the lead of the US.

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[1] Decarbonizing aviation: Making net zero possible | McKinsey

[2] IATA - Fly Net Zero

[3] IATA - SAF Volumes Growing but Still Missing Opportunities

In addition, ICAO has developed the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)[4]. From 2027 the mandatory phase begins and all international flights will be subject to offsetting requirements.

In the EU, The ReFuelEU[5] Aviation Regulation sets mandates in Article 4 for the proportion of SAF that fuel providers must blend, starting in 2025 at 2% and increasing every five years to a minimum of 70% in 2050. It also includes sub-targets for synthetic SAF, starting at 1.2% in 2030. The evolution is shown in Table 1.

Table 1 Blending mandate of SAF in the EU, under ReFuelEU aviation legislation

Year	2025	2030	2035	2040	2050
SAF	2%	6%	20%	34%	70%
eSAF sub-mandate	-	1.2%	5%	10%	35%

Synthetic aviation fuels, e-fuels or power-to-fuels are fuels made from green hydrogen which in turn is produced through electrolysis of water using renewable electricity as the energy source. This is then combined with sustainably sourced CO_2 as feedstock to produce SAF. Failing to comply with the minimum shares of SAF means fuel suppliers are liable to pay a fine of at least twice the difference between the price of conventional aviation fuel and SAF in that year, with a requirement that the shortfall must be made up in the following reporting period. Switzerland is expected to bring in a similar mandate[6].

In addition, CO_2 emissions from aviation have been included in the **EU Emissions Trading System** (EU ETS) since 2012, whereby airlines operating in Europe are required to monitor, report and verify their emissions, and to surrender allowances against those emissions. Eligible SAF is zero-rated and does not require allowances to be surrendered. Free allowances covering a certain level of emissions from operators' flights per year will be phased out by 2026. Emissions covered are those from flights within the EU/EEA and flights departing to Switzerland and the United Kingdom. The scope of departing flights may be expanded in 2026, depending on the extent to which CORSIA is delivering on the goals of the Paris Agreement. The incentive for SAF use as a result of the EU ETS is equivalent to approx. 250 €/t of fuel at a carbon price of 80 €/tCO_2[7]. There is a linking agreement with Switzerland. Aviation activities in the ETS of Switzerland reflect the same principles as those of the EU ETS.

SAF comes in various types, categorized in accordance with the manufacturing pathway, and sources of feedstock (Table 2). Today the SAF market is dominated by HEFA bio-SAF based on the hydrogenation of used cooking oil, with AtJ expected to gain market share in North America. Power-to-Liquid (PtL) technologies will enter the global market in the late 2020s and gain an increasing share. Other technologies are also being developed including second generation fermentation routes for AtJ.

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[4] Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

[5] ReFuelEU Aviation - European Commission (europa.eu)

[6] SAF Policy Actions | EASA

[7] emission factor under EU ETS is 3.15 tCO_2/t jet fuel

Table 2 Broad categories of SAF types, production routes, and feedstocks

Type	**Pathway**	**Feedstocks**
Bio-SAF	HEFA	Used cooking oil, oil bearing plants, tallow
	Alcohol-to-Jet (AtJ)	Food crops e.g. corn, sugar bearing plants
	Fischer Tropsch	Lignocellulosic (gasification) e.g. biomass municipal Solid Waste
Power-to-Liquid	Fischer Tropsch	Sustainably sourced CO_2/H_2

Each of the identified SAF pathways has relative advantages and disadvantages and face challenges in terms of true sustainability, scalability, performance, and cost (Table 3).

Table 3: Challenges associated with current SAF production technology pathways

Metric	Challenges	Bio-SAF	PtL
Sustainability	Food supply conflict Water Consumption Lifecycle CO_2 footprint	☹	☺
Scalability	Ease of scale up Technology gaps Feedstock availability	☹	😐
Performance	Processing intensity SAF selectivity Yield	😐	😐
Affordability	Cost of production Economies of scale Feedstock flexibility	😐	☹

Broadly speaking the bio-SAF routes, HEFA and AtJ, have the disadvantage of being in conflict with the food and animal feed chain. In the overall value chain they are also consumers of large amounts of fresh water and, counterintuitively, can perform poorly in terms of overall carbon reduction impact especially when taking into account the effects of indirect land use changes. Bio-SAF via Fischer Tropsch (FT) technology suffers from high processing intensity, availability of sustainable biogenic feedstock, and is a non-selective technology converting much of the feedstock into unwanted by-products, impacting on yield and affordability. To increase SAF yield some of the by-products (waxes and heavy oils) require additional processing in a hydrocracking unit adding further to processing intensity.

The PtL route performs well on sustainability depending upon the source of renewable power and sustainably sourced carbon. In addition to the challenges FT technology faces for bio-SAF production, its use as a PtL route suffers additionally from technology gaps due to the need to convert CO_2 to carbon monoxide upstream of the FT unit. The technology to do so, the reverse water gas shift (RWGS) is inefficient, increases carbon losses, and is difficult to scale-up further impacting on affordability.

The conclusion to be drawn from the shortcomings and challenges faced by the incumbent technologies is that there is a need for the development of alternative pathways using the sustainable feedstocks, free from the food/feed conflict, efficiently and which deliver affordable SAF at scale. Metafuels and PSI, through the development and commercialisation of their breakthrough Sustainable Aviation Fuel (SAF) production technology (the subject of this Project), are both motivated by this challenge with our objectives perfectly aligned with the UN Sustainability Development Goals.

The technology being developed by Metafuels and PSI branded “aerobrew” converts sustainably sourced methanol to SAF following the so-called and emerging methanol-to-jet (MtJ) route. Where this methanol is sourced from renewable power (e-methanol) the product is e-SAF providing an alternative to the FT route. Figure 1 shows a side-by-side comparison of the aerobrew MtJ route and FT route for the production of e-SAF.

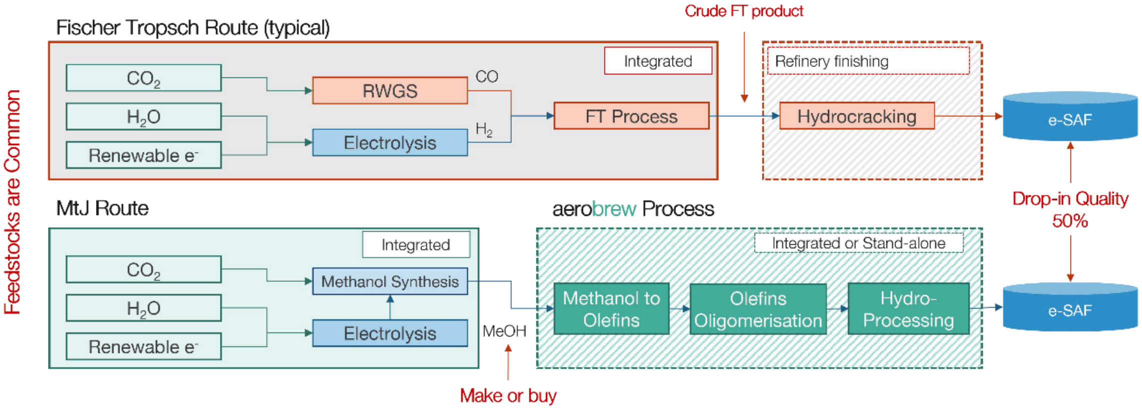


Figure 1 Side-by-side comparison of the FT and aerobrew routes to e-SAF

Both schemes show the pathway from common feedstocks to a common e-SAF 50% drop-in e-SAF. So far none of the FT-based projects to-date have included a designated heavy component hydrocracking unit. This means that crude FT products (oil & waxes) are fed into conventional refinery operation to increase the yield of jet fuel. This adds additional material and energy use, transport processes, and emissions to the SAF supply chain. This expectation also holds true for sun-to-liquid pathways which rely on FT and deliver syncrude at the factory gate.

Table 4 shows the relative performance of the side-by-side comparison using current state-of-the-art FT versus aerobrew, with common boundary conditions.

Table 4 Relative comparison of aerobrew versus FT for the production of e-SAF

Parameter	**aerobrew (expected)**	**FT (current state-of-the-art)**
e-SAF productivity	ca. 80%	ca. 45%
Energy efficiency to e-SAF	ca. 40%	ca. 25%
Cost of Production	x	2x
Scalability	High	Limited
LCA (Carbon Intensity reduction)	Up to 90%	Up to 90%

Compared to FT, aerobrew has a significantly higher productivity. Around 80% of the carbon entering the value chain in the form of CO_2 ends up in the e-SAF product. This compares to around 45% for FT assuming the addition of a hydrocracking unit.

aerobrew also has a significantly higher energetic efficiency. Whereas ca. 40% of the primary energy input from renewable electricity remains in the SAF product, e-FT based processes languish at around 25%. This means that between 50% and 75% more renewable energy is required to produce a litre of e-SAF using FT technology compared to aerobrew. As a result, the aerobrew process has lower renewable energy consumption, and by being more efficient, frees up valuable renewable energy capacity for other products or markets.

The scale up of the FT process is limited by the RWGS step which requires the installation of multiple modular reactors to achieve scale. aerobrew on the other hand achieves scale up through the scale up of equipment sizes.

The effect of the higher productivity, energetic efficiency, and ease of scale up reduce the cost of production for aerobrew SAF to half that of FT, providing significant advantages to the aviation industry as it makes the transition to low carbon fuels.

The aerobrew technology, when processing 100% renewable power and CO_2, can achieve a carbon emission reduction potential of up to ca. 90 % versus the CORSIA benchmark for fossil-based jet fuel. A single commercial scale aerobrew installation, operating on 100 % renewable power and green CO_2 and producing 1000 tonnes of jet fuel per day, will realize an annual saving potential of 1.15 megatons (Mt) of CO_2.

In summary, aerobrew SAF technology promises to deliver breakthrough improvements in SAF selectivity, carbon efficiency, and energetic efficiency with the corresponding advantages in cost of production and fuel price. The feedstock for the process is green methanol which is produced from green hydrogen and sustainably sourced CO_2. Technology to produce green methanol is already available commercially although several programmes of research and development are ongoing to further improve the process. Several green methanol (PtX) production plants are already in planning or underway including from European Energy, with one at Kassø, Denmark, expected to go into operation in Q1 2025, Liquid Wind HIF, ABEL Energy and others.

1.2 Project objectives

The commercialisation of the aerobrew technology involves progressing the technology readiness level from the current TRL4 to TRL9. A successful implementation of the Project will lead to the achievement of TRL 6.

The Project entails the design, engineering, procurement, manufacture, installation, commissioning, operation, and testing of an aerobrew pilot plant (PP) which will be capable of taking sustainable methanol feedstock and converting it to SAF at a capacity of up to 50 litres per day. The PP will be housed in a dedicated building at the PSI site, refurbished and fitted out especially for the purpose.

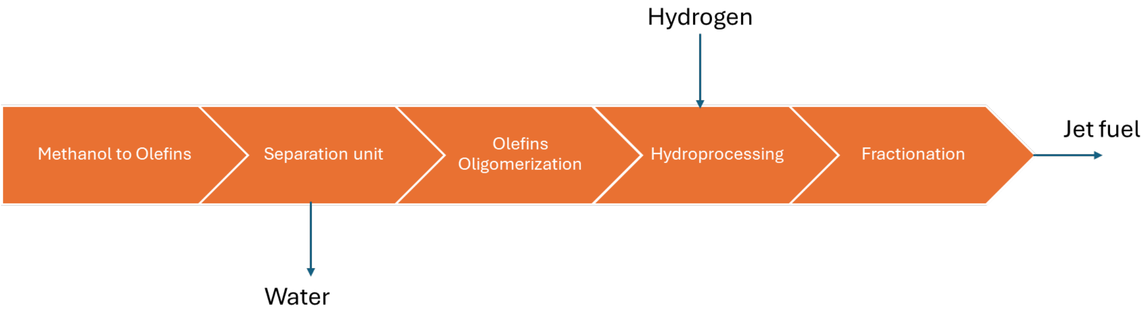


Figure 2: The Methanol to Jet-fuel process currently going through accreditation according to ASTM D4054

The aerobrew process, as installed at the PP, follows the so-called “Methanol-to-Jet” (MtJ) pathway, which consists of four integrated steps, namely, methanol dehydration, olefins oligomerization, hydrotreating, and fractionation, in a continuous operation from methanol feed tank to SAF product tank (Figure 2). The product SAF from the PP will be tested for compliance with the relevant Annex of ASTM D7566 “Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons” expected to be in published and in force during 2025. Compliance with this specification will allow the SAF product from future commercial aerobrew plants to be used as an accredited aviation fuel, by the commercial airlines.

A programme of test campaigns performed on the PP will provide the necessary information, data, and operational experience needed by Metafuels to develop the process simulation tools and engineering design methods to scale-up the technology. The PP will also allow the further development and optimisation of the catalytic systems at the heart of the conversion processes as well as testing of further developments.

Following a successful Project the results obtained, and design tools developed will be used and applied for the realisation of a first of a kind (FOAK) commercial plant with a capacity of approximately 10 t/d that will take the technology to TRL9.

To qualify as SAF under the various regulations in Switzerland, the EU, and elsewhere including under the CORSIA framework, the life cycle assessed carbon intensity (CI) of the SAF must meet certain $CO_{2(eq)}$ reduction benchmarks versus conventional fossil fuel derived jet fuel. The Project will provide the data and LCA framework required to model and calculate the expected CI of the SAF that will be produced using the aerobrew technology following the MtJ pathway. Prospective-LCA will also be used to quantify a broad set of environmental impacts and identify trade-offs between impact categories related to current and scaled-up aerobrew SAF production.

2 Approach, method, results and discussion

For effective project management, the Project is divided into work packages, starting with design and specification of the aerobrew pilot plant (PP), and continuing through procurement, fabrication & assembly and ending in operation, testing, and evaluation.

To ensure clarity and responsibility the work packages have been divided between Metafuels and PSI, where one of the entities has the responsibility and the other has either a reviewing or supporting role. In addition to clarity and responsibility, it also ensures engagement and coordinated team effort along all the work packages.

At the time of drafting of this the interim report, the status of the various work packages, both in-progress and completed, is as follows:

2.1 Pilot Plant Design

The “PP design” work package consists of overall process design, including development of piping and instrumentation diagrams (P&ID), a detailed and structured safety analysis of the design, the so-called HAZOP, as well as detailed design of all vessels and equipment. Further activities include the detailed specification of instruments, valves and other accessories.

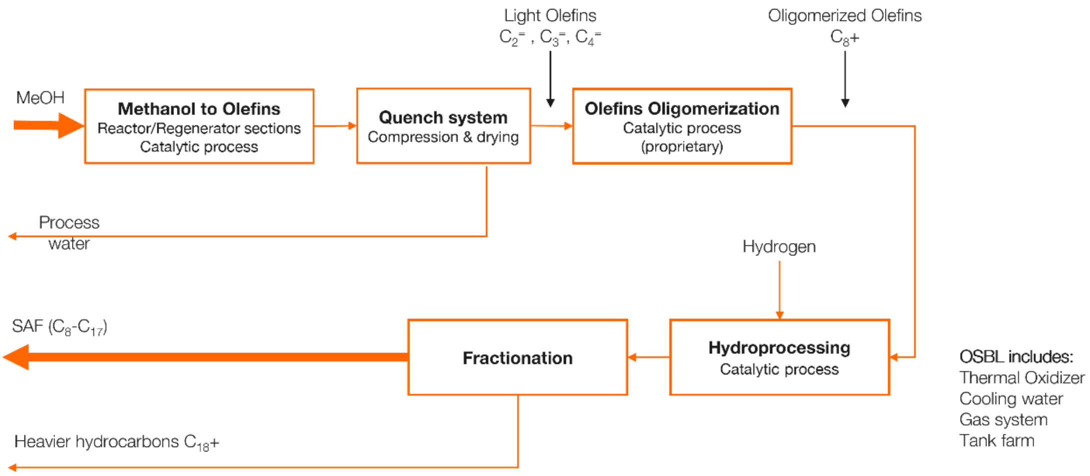


Figure 3 Pilot Plant Process Modules

The PP will be located in a dedicated building at the PSI site in Villigen and as such the design must take into consideration the indoor nature of the facility and the implications for fabrication, installation, operation, maintenance and not least safety. The PP building consists of a PP hall which will house the main processing units of the PP, a control room from which the PP will be operated, as well as connected utility rooms.

For the PP design, and reflecting on the above, it was decided to use a modular fabrication approach. This means that rather than assembling the PP piece by piece inside the PP hall at the PSI site, a so-called “stick-built” approach, the PP is divided into 6 specific modules (Figure 3) which are fully fabricated and assembled remotely at a fabrication workshop. The completed modules include all equipment items like pumps, vessels, heat-exchangers, distillation columns, etc. and other machinery, as well as piping, instrumentation, electrical and instrument wiring and insulation. These modules are then shipped to PSI for installation and hook-up in the PP hall. The advantages of this type of construction are many. Not only will it limit the activities on site, in the relatively confined building space, to placement and interconnection of the modules, it will also allow the individual modules to be tested in a Factory Acceptance Test (FAT) prior to shipment. Work performed at a supplier's premises is less costly than work performed at site since no travel and no accommodation costs are needed. Typically the efficiency and quality of work is better in the purpose built workshop than on site, as space, cranes and other supporting equipment are not limiting factors.

The modules making up the aerobrew pilot plant are the following:

2.1.1.Methanol to Olefins

The methanol to olefins module contains the MtO reactor and the MtO regenerator and their associated equipment. The overall dimensions of the module are: (L x H x W) 3.7 x 5.0 x 1.8 meters with a total weight of approximately 2010 kg.

2.1.2.Quench Cooling

The quench cooling module contains the system which will cool down the olefins from the MtO reactor prior to feeding to the oligomerisation section. The overall dimensions of the module are: (L x H x W) 2.5 x 5.1 x 1.7 meters with a total weight of approximately 2600 kg.

Figure 4 shows the quench cooling model in its fully assembled and post FAT just prior to crating and despatch to the PSI site. Figure 5 shows the same module is it appears in the 3D model of the pilot plant prepared in Aveva 3D plant design software.

Figure 4: Quench Cooling Module during Factory Acceptance Test

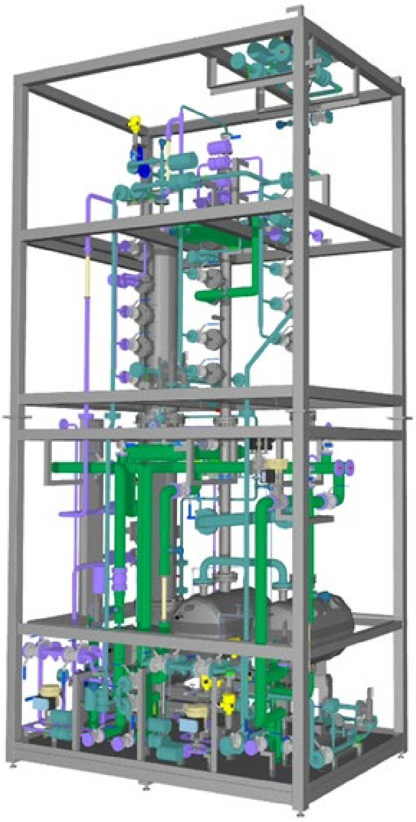


Figure 5: Quench Cooling Module 3D Navis-works model

2.1.3. Compressor and Drying

The compressor and drying module contains the olefins compressor and the olefins drying unit, which removes any residual water remaining from the quench section. The overall dimensions of the module are: (L x H x W) 3.1 x 2.6 x 1.0 meters with a total weight of approximately 1470kg.

2.1.4. Olefins Oligomerisation

The olefins oligomerisation module contains the catalytic reactor for the olefin's oligomerisation stage of the process, including accessories. The overall dimensions of the module are: (L x H x W) 3.0 x 1.9 x 1.2 meters with a total weight of approximately 1980 kg.

2.1.5. Hydrotreatment

The hydrotreatment module contains the catalytic reactor and associated equipment for hydrogen saturation of the olefinic bonds in the oligomers thereby converting them to paraffins,. The overall dimensions of the module are: (L x H x W) 1.0 x 3.4 x 1.0 meters with a total weight of approximately 830 kg.

2.1.6. Fractionation

The fractionation module contains the fractionation column and associated equipment, required to separate the final SAF product from the by-products,. The overall dimensions of the module are: (L x H x W) 2.5 x 6.5 x 1.1 meters with a total weight of approximately 2270 kg.

In addition to the mentioned modules, there are several some equipment items that are installed directly into the PP hall mainly consisting of methanol feed tanks and SAF and by-product rundown tanks.

The PP building itself also needs to be prepared for the receipt, installation, tie-in, and hook-up of the modules which when complete constitutes the complete PP and support facilities ready for operation. The design work for this and site works inside and around the PP hall and building are proceeding in parallel and close coordination with the work on the modules.

A key associated focus area in the development of the building design concept is explosion protection (ATEX). This has required the design and installation of a new ventilation system for

Figure 6: Pilot plant building location at Paul Sherrer Institute (Ost)

the PP building. Other areas of focus include design and installation of the interconnections with the necessary infrastructure such as utilities and operating media, as well as ensuring compliance with all applicable regulations for operation. All key activities for this work package have been completed. Figure 6 shows the location of the dedicated PP building on the left bank of the Aare river.

Figure 7 shows a representation of the dedicated PP building as replicated in the 3D model looking towards the main entrance from the Southwest .

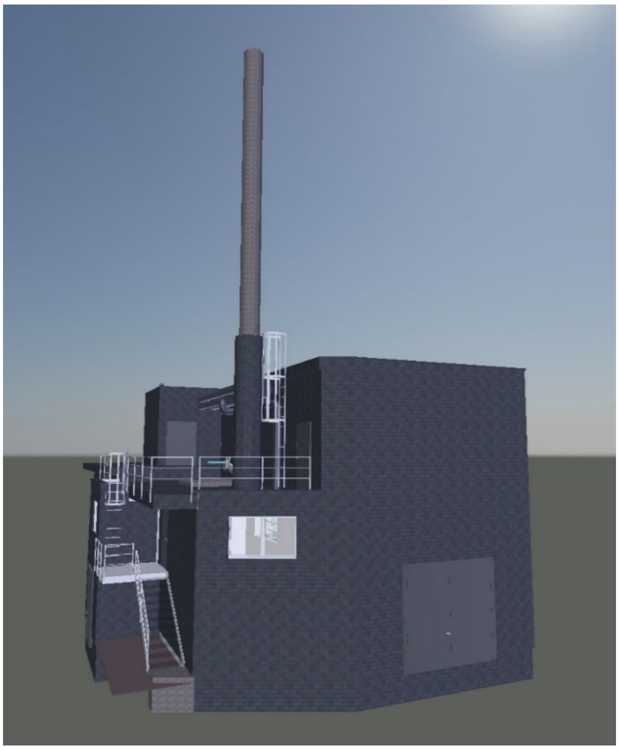


Figure 7: Pilot plant building 3D model

2.2 Catalytic processes

The aerobrew process consists of three heterogeneous catalytic reactions as shown in Figure 3. Catalysts for these three reactions have either been prepared in cooperation with strategic partners or procured from suppliers. The deployed approach is summarised below:

MTO catalyst: For initial campaigns, commercially available catalyst suitable for the production of light olefins from methanol has been procured. The catalyst selection follows from a prior laboratory based screening and pre-testing programme of various formulations conducted outside of the Project. The shaping step for the catalyst is planned to be outsourced to custom manufacturer with suitable facilities. The performance of the MtO catalyst has been shown to be suitable for the application.

OO Catalyst: The OO catalyst is a new and innovative proprietary catalyst based on nanotechnology and materials. Production of catalyst materials has been outsourced to a speciality manufacturer in Switzerland. The finishing steps for the preparation of the catalyst will be completed inhouse. The shaping of the catalyst for initial quantities is planned to be performed inhouse. The performance of the OO catalyst is in line with expectations and supportive of the overall selectivity targets established for the aerobrew technology.

Hydrotreatment Catalyst: The HDT catalyst is a commercially available catalyst selected from laboratory based screening and testing of a number of such catalysts. The supplier will provide the catalyst in a ready to use shaped form. Test have shown that the conversion of olefinic compounds to paraffins proceeds with high efficiency and yield.

These three catalysts will be loaded into the PP and tested for overall performance as a key part of the Project

2.3 PP Procurement

The "procurement" work package covers all hardware, including, equipment and materials required for the aerobrew PP as well as for its installation in the dedicated building at the PSI site.

For the detailed design, fabrication, supply and installation of the modularized aerobrew PP an international invitation to bid (ITB) was issued to companies in Switzerland, The Netherlands, France, Germany and Spain, all with relevant references and experiences in terms of building and instal*ling a turnkey pilot* plant. The successful bidder was a Spanish company Insvatech S.L. (Insvatech) located in the Barcelona region.

Insvatech was responsible for procuring a wide range of equipment, including pumps, compressors, heat exchangers, pressure vessels, and reactors. In addition, Insvatech was tasked with acquiring all necessary instrumentation to ensure the safe and automated operation of the plant. This included temperature, pressure, and level transmitters, flow meters, pressure safety valves, and control valves.

A significant portion of the equipment was manufactured in the Contractor's own workshop, leveraging their in-house expertise. Metafuels was actively involved during the design phase, regularly reviewing the drawings provided by Insvatech. Through this collaborative approach, Metafuels helped ensure safety in design, as well as high standards of quality and process functionality. Special care was taken in the selection of fabrication materials, ensuring suitability of the manufactured equipment for the high temperatures, pressures and media it is exposed to during the operation of the PP. In the case of pressure vessels, the equipment was designed according the AD-2000 Merkblätter, a German technical code used for the design and manufacture of pressure vessels and related equipment. It provides rules for ensuring safety in pressure equipment and is particularly focused on fulfilling the requirements of the European Pressure Equipment Directive (PED). Following fabrication, the equipment was inspected by a notified body, which verified compliance with all relevant regulations, including the PED. As part of this process, the notified body reviewed the complete technical documentation—such as design drawings, material specifications, and mechanical calculations—and witnessed key tests and inspections. Based on this evaluation, CE markings are issued, allowing the pressure vessels to be operated in Switzerland.

Figure 8 shows an example of a mechanical drawing in this case a water storage tank, with the tank as manufactured by Insvatech shown in Figure 9.

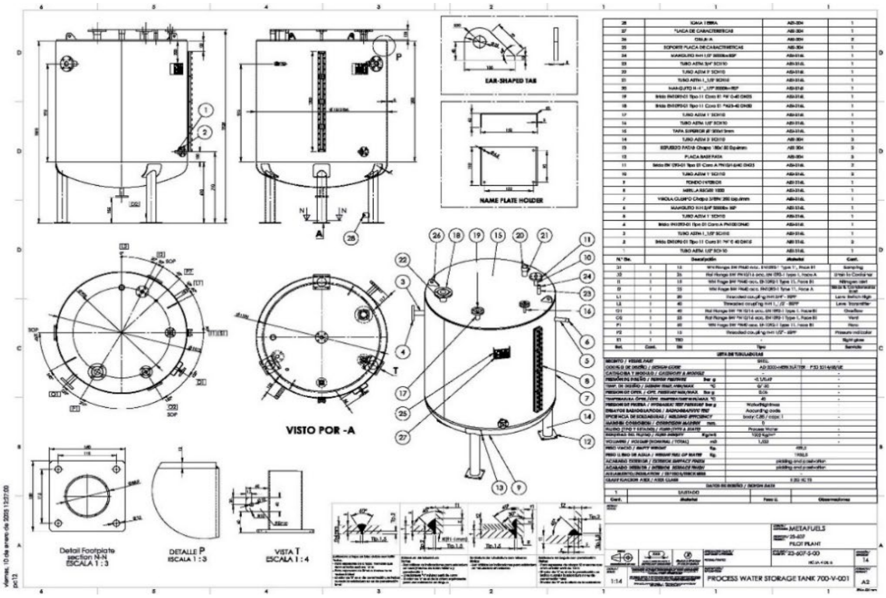
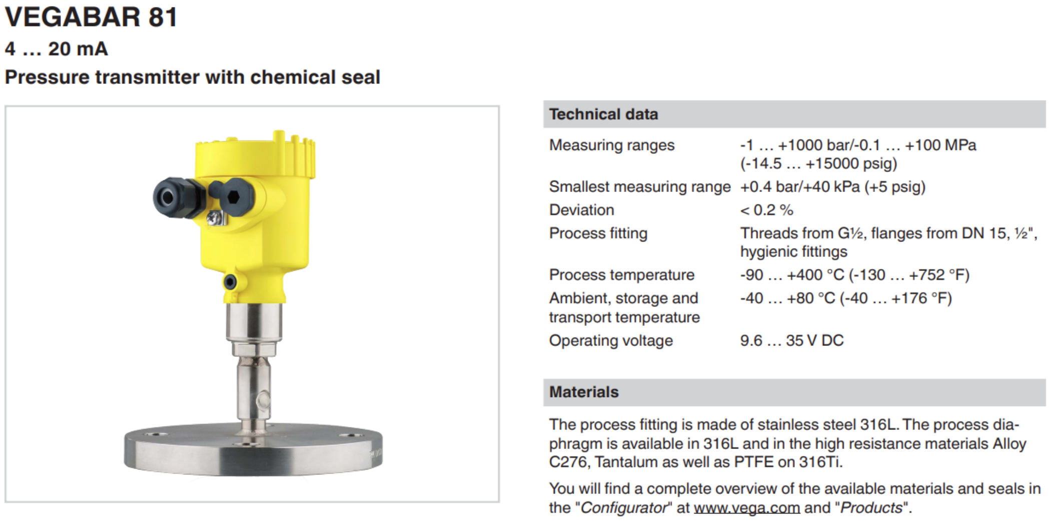


Figure 8: Process water storage tank mechanical drawing as prepared by Metafuels/Insvatech

Figure 9: Process water storage tank manufactured and supplied by Insvatech

For specialized equipment such as pumps and compressors, Insvatech engaged with specialized vendors, providing them with detailed technical specifications and requesting quotations. Upon receiving proposals from such specialized vendors, Metafuels conducted thorough reviews of the vendors' technical documentation, including datasheets, performance curves, material specifications, and compliance with relevant standards. Feedback was shared with Insvatech to ensure alignment with project requirements. This same approach was applied to the procurement of instrumentation and control valves, ensuring consistency in quality, functionality, and integration across all systems.

Examples of specialised equipment pieces are shown in Figure 10 (pressure transmitter) and Figure 11 (pump general arrangement drawing).



VEGABAR 81

4 … 20 mA

Pressure transmitter with chemical seal

Technical data

Measuring ranges	-1 … +1000 bar/-0.1 … +100 MPa (-14.5 … +15000 psig)
Smallest measuring range	+0.4 bar/+40 kPa (+5 psig)
Deviation	< 0.2 %
Process fitting	Threads from G½, flanges from DN 15, ½", hygienic fittings
Process temperature	-90 … +400 °C (-130 … +752 °F)
Ambient, storage and transport temperature	-40 … +80 °C (-40 … +176 °F)
Operating voltage	9.6 … 35 V DC

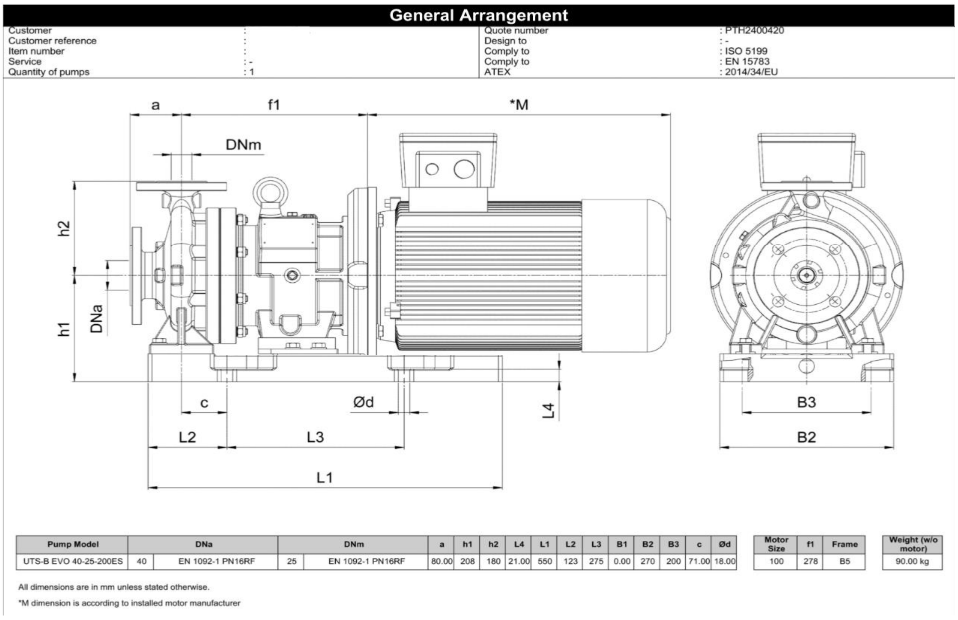
Materials

The process fitting is made of stainless steel 316L. The process diaphragm is available in 316L and in the high resistance materials Alloy C276, Tantalum as well as PTFE on 316Ti.

You will find a complete overview of the available materials and seals in the "*Configurator*" at www.vega.com and "*Products*".

Figure 10: Pressure transmitter specification sheet

Procurement for the infrastructure and other supporting systems required to adapt the PP building and prepare it for the PP installation and operation has been performed mainly through PSI with purchases directly from individual suppliers. This included procurement of the ventilation system, gas supply, exhaust treatment, cooling water systems, and steam generation systems, amongst others. All of these procurement activities have been completed.



General Arrangement

Customer	:	Quote number	: PTH2400420
Customer reference	:	Design to	: -
Item number	:	Comply to	: ISO 5199
Service	: -	Comply to	: EN 15783
Quantity of pumps	: 1	ATEX	: 2014/34/EU

Pump Model	DNa		DNm		a	h1	h2	L4	L1	L2	L3	B1	B2	B3	c	Ød
UTS-B EVO 40-25-200ES	40	EN 1092-1 PN16RF	25	EN 1092-1 PN16RF	80.00	208	180	21.00	550	123	275	0.00	270	200	71.00	18.00

Motor Size	f1	Frame
100	278	B5

Weight (w/o motor)
90.00 kg

All dimensions are in mm unless stated otherwise.

*M dimension is according to installed motor manufacturer

Figure 11: Pump general arrangement drawing

2.4 Fabrication and Assembly

The “fabrication and assembly” work package covers the fabrication and assembly of the different parts of the aerobrew PP at the fabrication workshop of Insvatech in Spain. The PP is designed and fabricated in modular form with each of several modules corresponding to a discrete processing section or unit operation of the overall process. The fabrication of individual components, systems and modules are well under way.

The first module ready for shipment to the PSI site (quench module Figure 4) is expected to be completed during the month of January 2025. All subsequent modules are planned to be shipped to the site with all fabrication and assembly activities completed in Q2 2025.

2.5 Tie-in and integration

The “tie-in and integration” work package will see the PP installed in an the dedicated building at the PSI site. At the time of grant application, the building hosted a large diesel engine test facility. In the meantime, the diesel engine and all auxiliaries have been removed and the building renovated ready for installation of the PP (Figure 12, Figure 13)

Several auxiliary devices (ancillaries) have been ordered and installation of the devices supplied so far has started. In the PP hall itself structural steel has been installed which will support the PP modules Figure 14.

Figure 12: Pilot Plant Building (June 24)

Figure 13: Empty Building (July 24)

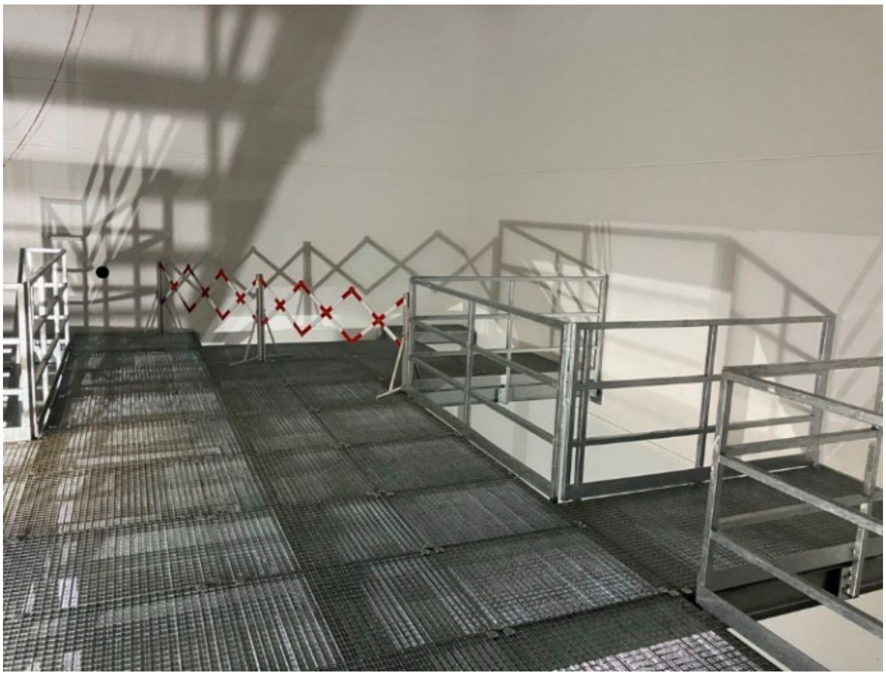


Figure 14: New steel structures ready to host the Demo Plant (January 25)

2.6 Safety Concept

An overall approach to the safety concept for the PP and building has been outlined in Section 2.1. This section describes the tie-in and integration concept based on decisions resulting from the various safety assessment. The concept has been developed with the input of external expertise. The measures are grounded in the characteristics of the existing building, the risk assessment of the modularized PP housed in the building, the design of the PP and the applicable rules and regulations, and legal requirements.

2.6.1. Explosion safety:

a) Definition of ATEX zones:

The entire plant building is classified as Zone 2. Only a provisory Zone 1 is defined where products are transferred to barrels for disposal and only during the transfer process. The designated place for such transfer will have a flexible extraction duct. There is no open handling of methanol feedstock.

b) Ventilation:

The first measure of safety derives from the choice of connections in the PP which ensures a tight plant. The ventilation system ensures the intrinsic air safety of the PP and connected area. The ventilation system to be installed in the PP building has been designed to dilute and extract any potential leaks that may arise from the PP e.g. due to cyclic loading and aging of gaskets as well as small amounts of product escaping during sampling. The ventilation system will ensure the maintenance of an explosion safe atmosphere. The system ensures that the ambient pressure inside the PP hall is lower than the outside pressure and the pressure in connected rooms (e.g., control room, electric installation room). This will ensure a safe access to the plant without plant atmosphere exiting the PP hall. Figure 15 shows a representation of ventilation system and ducting installed in the PP building including the PP hall and connected areas.

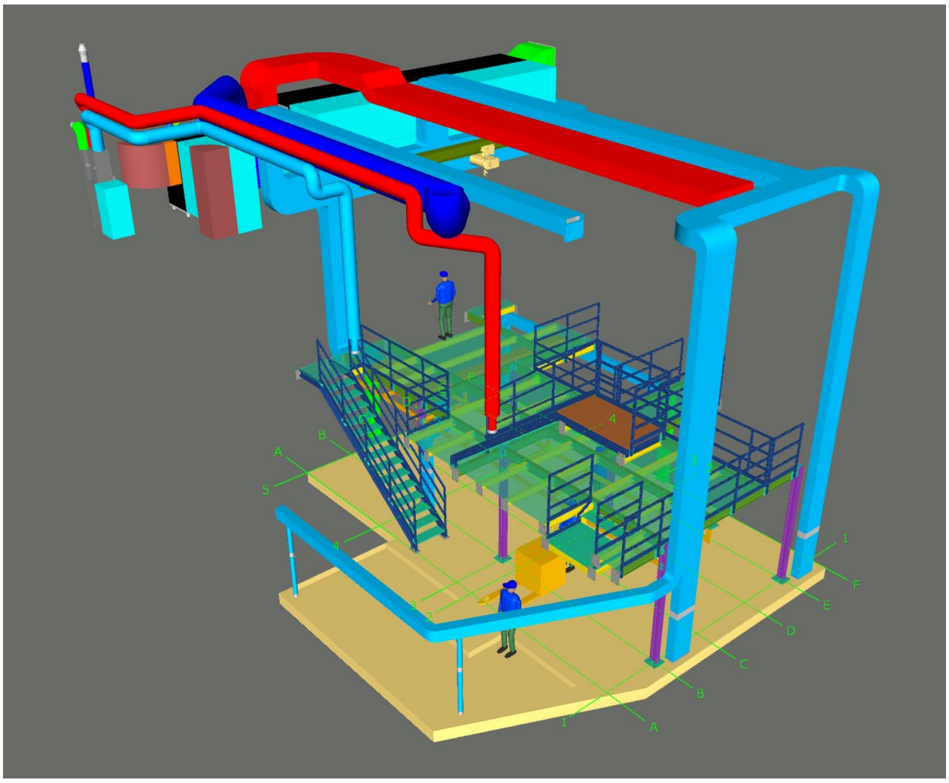


Figure 15: Representation of the ventilation system design from the 3D plant model

c) Gas detection

A gas detection system is designed and will be installed to detect larger loss of fluids due to unforeseen events or malfunctions. The system will operate against thresholds. At the first lower threshold the ventilation ratio will be increased and a warning raised to the operators. At the second higher threshold an emergency stop procedure will activate with an acoustic and optical alarm. In addition an alarm will be sent to call out the gas-brigade. A gas sensor will also be placed in the extraction duct to indicate the presence of leakages that were carried with the normal ventilation flow. This will alert operators to the possibility of a leakage somewhere in the PP and to trigger a manual leak search and to increase attention.

d) Special assessment of hot surfaces

Some of the media in the process require a T3 ATEX temperature class. This means that the maximum allowable temperature of external surfaces exposed to the surrounding air is 200°C. Some sections of the PP operate at temperatures higher than this threshold, and indeed some of their components (for technical reasons), cannot be insulated or shielded meaning that in such cases hot surfaces are exposed to the PP air. This means that measures must be taken to prevent the potential build-up of an explosive atmosphere.

During operation some of the media inside the process equipment are at temperatures higher than their own ignition temperature, but in total absence of any oxygen. Any leak of such media (for instance through flange gaskets) would lead to a spontaneous ignition at the leakage point, but consequently not to the build-up of an explosive atmosphere.

Small leakages from the PP will be diluted by the ventilation system preventing a build-up of an explosive atmosphere.

The remaining risk in relation to hot surfaces is a loss of containment by bursting of a vessel or by a tube rupture releasing significant amounts of media, building an explosive atmosphere that could reach a hot surface at a different place in the plant. This risk has been reduced during HAZOP to an acceptable level by defining appropriate design values of pressurized equipment and implementing safeguards to prevent operating conditions being reached that could lead to loss of containment. The assessment of such scenarios has been performed in a conservative way.

2.6.2. Fire safety:

a) The PP building and components have been assessed for the required fire resistance level of 60 minutes (building, doors, windows) and actions implemented.

b) Fire detectors (smoke and temperature) will be installed at two levels in the PP building. Sensors will activate an emergency stop procedure an acoustic and optical alarm and send an alarm to call out the fire-brigade according to the fire protection procedures defined at PSI.

c) Hand fire extinguishers and a first action water hose will be installed.

2.6.3.Goods handling:

The different kind of goods and materials to be handling have been analysed and appropriate measures have been defined for personal protection. These include the following:

a) Ex-protection ventilation and an additional flexible extraction point in the area of open product and byproduct handling.

b) The design of the feedstock methanol transport containers have been enhanced in coordination with the vendor to allow closed handling (leak-free-quick-connectors and connection of volume compensation gas line). The transportation containers will allow for a safe methanol transfer to the PP methanol feed tanks according to the safety concept. Figure 16 shows the methanol connection for safe transfer of methanol from transportation container to the feed tank. Figure 17 shows the methanol delivery concept inside the PP hall.

c) The specification of personal protection equipment required to enter the plant especially during sampling activities.

d) The adoption of temporary measures to prevent methanol entering the canalization for environmental and safety reasons. These measures are taken despite the risk of incidents while onloading the container from the truck being very small due to the certified methanol transport containers of the vendor.

The safety concept is now close to being finalized. As a final step, the process team will explain each process step module for module to the PSI safety officer to ensure that no relevant detail has been missed.

Risk analyses have also been performed for the individual auxiliary systems.

Figure 16: Methanol safe transfer connection

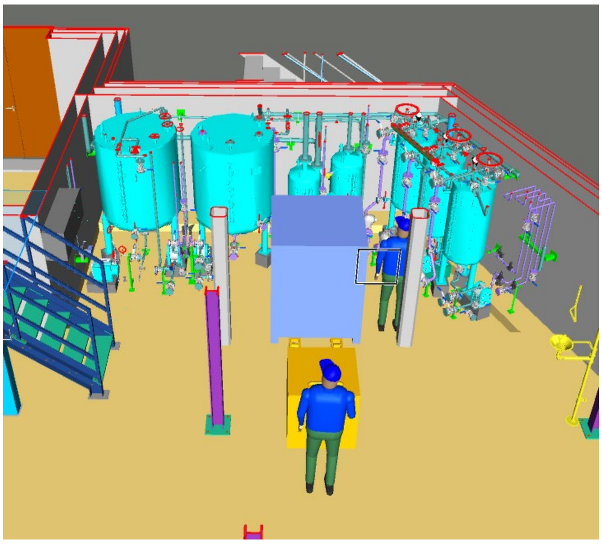


Figure 17: Methanol Delivery Concept inside the Building

2.7 Sampling and Analytics

2.7.1. Sampling system

A concept for the aerobrew PP has been created (Figure 18) and which is reflected in the P&IDs. The sampling system will consist of a sampling valve placed directly in the line, that will collect a small volume of a sample, and two collection vessels.

By rotation of the sampling valve a sample will be collected from the line. By further rotation the collected sample will be discharged, into a first metal collection vessel where the pressure is reduced. Depending on the pressure, temperature, and composition of the sample, phase separation may occur. The sample will be left to cool to ambient temperature, before the next valve opens and the liquid flows by gravity into a graduated glass tube, allowing the volume of the liquid to be determined. The glass tube will then be disconnected, and small quantities of the gas and liquid will be collected for analysis by micro-GC and GC-MS/FID.

Two of the sampling valves have been ordered, with delivery expected in March 2025. The metal collection vessels have already been delivered, and other small parts are pending.

2.7.2.Analytics

The analytical part focused on the development of a derivatization method for structural characterization based on soft ionization of olefins. The Paternò−Büchi (PB) - ultra high-performance liquid chromatography - high resolution mass spectrometry (PB-UHPLC-HRMS) approach has been adopted.

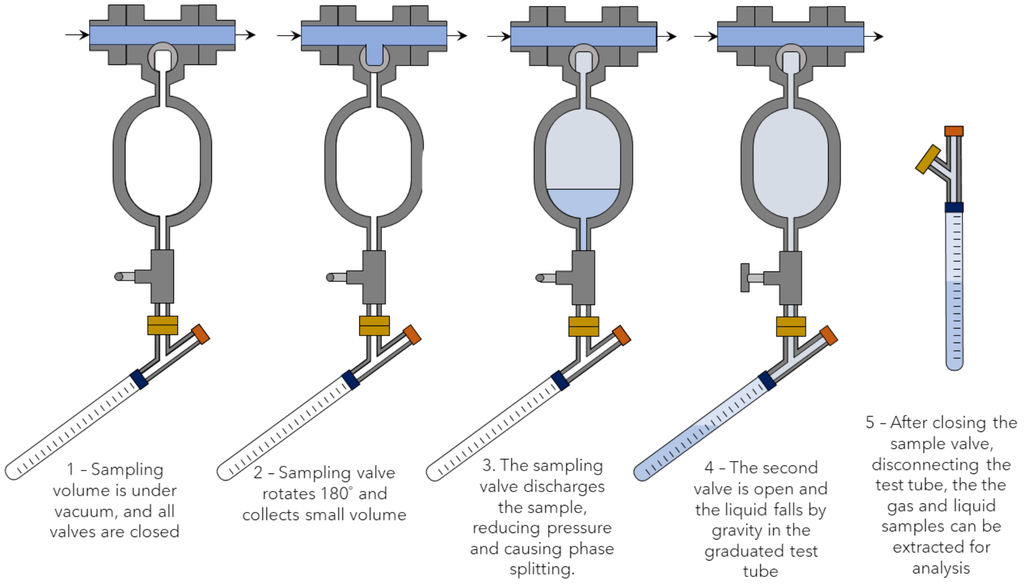


Figure 18: Sampling valve operation concept

2.8 Architectural planning

The structure and architectural planning for the different installations has been completed. The application for the building permit to carry out civil work and other upgrading activities has been submitted (Baugesuch). This includes environmental aspects like the proper disposal of the purged gases through an oxidizer and the existing stack to comply with air pollution regulations.

The civil work, building adaptation and utilities installation activities on site are closely co-ordinated with the PP fabricator to ensure a smooth and trouble-free installation of the PP modules and interconnections with the infrastructure and utilities.

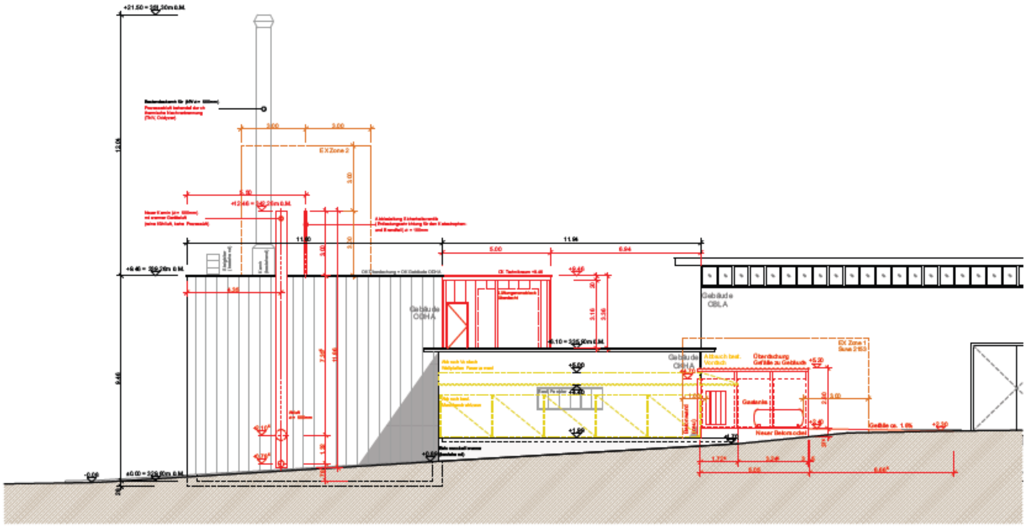


Figure 19: Architectural drawing of the PP building from the Southeast

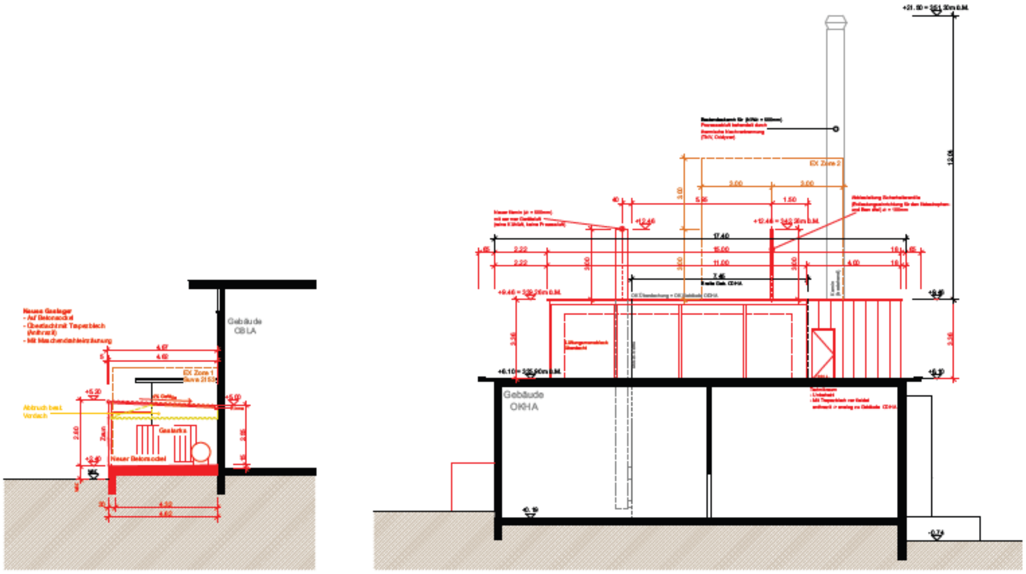


Figure 20: Architectural drawing of the PP building (left bottle storage, right view from Northeast)

2.9 Permits and Permissions

There are various permits and permissions required for the PP, as well as requirements that need to be followed.

The manufacture and storage of products that are subject to the Mineralölsteuer has to take place in an authorised facility. An application was submitted to the Bundesamt für Zoll und Grenzschutz and the confirmation was received on 28th January 2025.

In addition the right procedures are being put in place to manage the VOC Lenkungsabgabe, Mineralölsteuer and CO_2-Abgabe. The methanol feedstock is subject to the VOC Lenkungsabgabe. Given that it is converted into products rather than ending up in the atmosphere it is possible to apply for an exemption and receive a refund. The products are subject to Mineralölsteuer if used as fuel in transport or to CO_2-Abgabe if the products are disposed and used for energy purposes.

2.10 Environmental sustainability: Life Cycle Assessment (LCA)

When launching a novel technology it is important to understand the environmental benefits and impacts it potentially brings along with it. This Project includes a work package to assess the environmental implications of producing SAF from sustainable methanol according to the methanol-to-jet (MtJ) pathway (see section 1.2) practiced by Metafuels. It uses the well-established and ISO-normed method "Life Cycle Assessment" which looks at the whole supply chain, and can provide insights into scaling up the technology by adopting a prospective approach.

The LCA in this project has the following goals:

1. **Quantification of the environmental impacts** related to the production and use of synthetic jet fuel via the (future scaled-up) aerobrew MtJ fuel pathway including the identification of trade-offs with other environmental impact categories.
2. Definition of **environmentally optimal system configurations**: evaluation of various supply chains of feedstock (CO_2, H_2, MeOH) and possible distribution chains, and identification of optimal system configurations. This includes evaluation of potential hydrogen and CO_2 producing sites including their renewable energy supply and their use of land, water and raw materials.
3. **Certification**: Evaluation as to whether greenhouse gas reduction goals as requested for SAF certification can be reached, and under which circumstances.

The LCA model is set up with open source python packages, namely the LCA software Brightway and the “premise” package for prospective LCA. The development of both open source packages was heavily driven by members of the Laboratory for Energy Systems analysis at PSI.

A user interface built into the LCA model will allow various supply chains, sensitivities, and certification implications to be explore. The system is shown in Figure 21. Each shaded box comes with life cycle inventories modelling the processes involved, with geographical and temporal attributes, and with variability in technical choices and other relevant parameters.

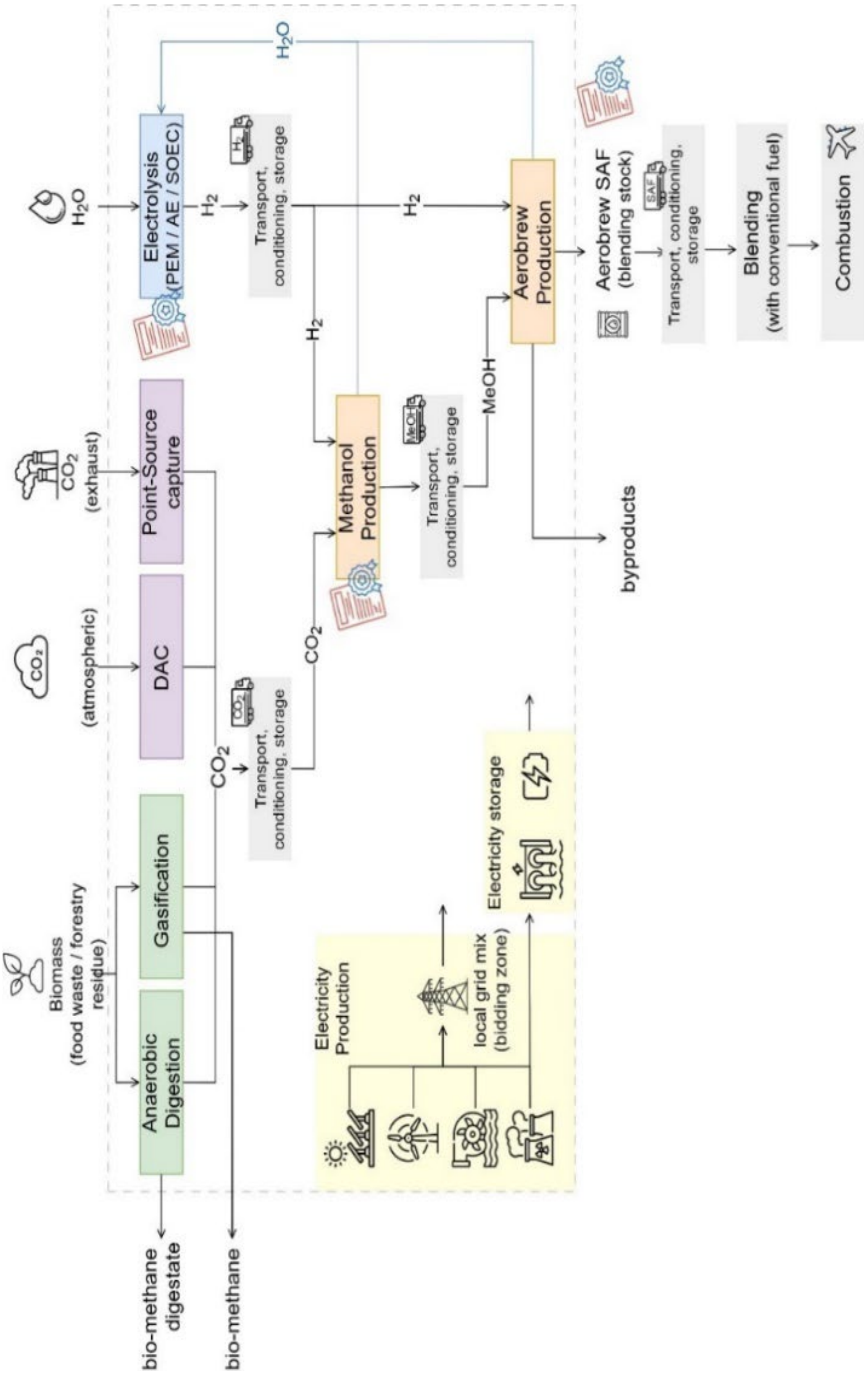


Figure 21: Product system modelled in the LCA work package.

The geographical scope is currently Europe, with feedstock sourced primarily in Europe. Global supply chains may also be evaluated at a later stage as the model develops. The temporal scope spans from the first-of-a-kind plants expected to come on-stream from 2028 through to 2050 in line with net zero goals until 2050 in the aviation sector.

Life Cycle Inventory (LCI) data for the processes upstream of the aerobrew SAF production step are taken from literature or previous project work at PSI. The aerobrew process is modelled primary with data from Metafuels and PSI Project partners. Blending and handling of the SAF is based on literature data, estimations, and input by Metafuels or other stakeholders in the blending chain. Background data are taken from the ecoinvent database(https://ecoinvent.org/).

The Life Cycle Impact Assessment (LCIA) is done using the European “Environmental Footprint v3.1” method. A focus will be given to impacts on climate change, use of water and land, ozone depletion, particulate matter formation, and raw materials use.

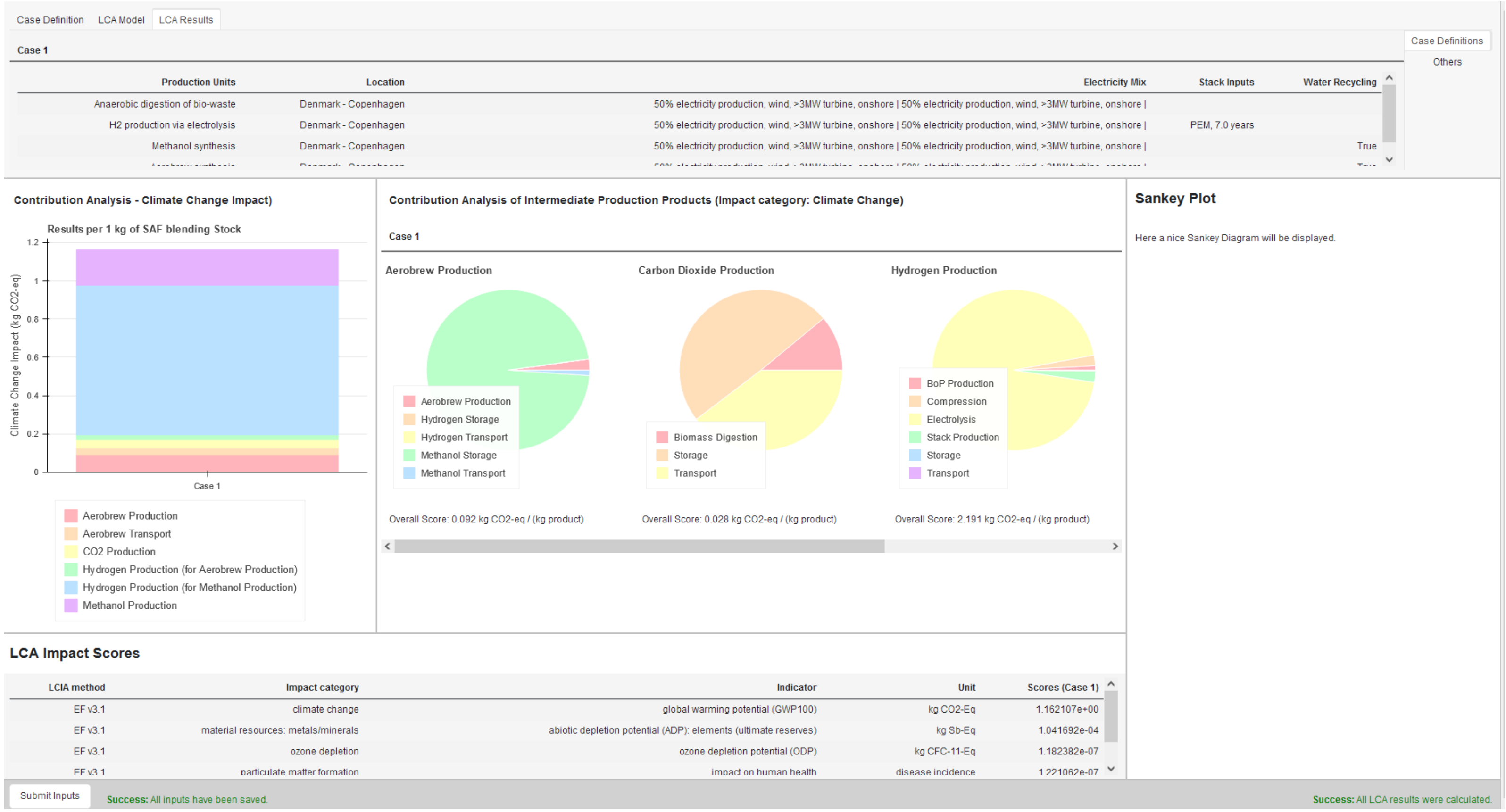
The first preliminary results calculated with the collected Life Cycle Inventories (LCI), the LCA model and the proof-of-concept user interface are in line with previous LCA studies done at PSI and available in literature. For instance, the production of feedstock and SAF in Denmark in the year 2020 with 100% onshore wind electricity leads to a greenhouse gas emissions level of ca. 1.2 kg CO_2(eq)/kg SAF blending stock, which is a significant reduction compared to the 3.9 kg CO_2(eq)/kg fossil jet fuel.

Figure 22 shows the user interface in the proof-of-concept version of the LCA model. The LCA results can be seen at the very left together with the contributions of the main production and feedstock supply steps, while the pie charts at the right allow a deep-dive into the individual production steps for the production of SAF (based on aerobrew), CO_2, and H_2. Technical choices from the case definition are shown in the table at the top. LCA impact scores for a chosen set of LCIA categories are shown at the bottom.

Although the aerobrew process itself has not yet been modelled in detail, it is expected that the conversion from methanol to jet fuel will only be a minor contributor to the total environmental impacts. The production and supply of hydrogen and carbon dioxide as well as the jet fuel combustion are expected to represent the hotspots in the majority of the environmental impact categories.

The LCA model allows for flexible evaluation of various SAF supply chains and production locations. It includes supply of renewable electricity including storage required for continuous operation.

Also modelled is feedstock conditioning for storage and transport, the storage and transport of products which include transport distances and losses (emissions) during storage and transport (see Figure 21). Further, prospective LCA is possible with the LCA model through the coupling of background and foreground data with scenario results from Integrated Assessment Models (IAMs), which is done using the open source premise package. This is important as SAF production will only be scaled up in future and thus be deployed in a fast and heavily changing world depending on the climate mitigations which may be adopted by humanity.



Production Units	Location	Electricity Mix	Stack Inputs	Water Recycling
Anaerobic digestion of bio-waste	Denmark - Copenhagen	50% electricity production, wind, >3MW turbine, onshore | 50% electricity production, wind, >3MW turbine, onshore |		
H2 production via electrolysis	Denmark - Copenhagen	50% electricity production, wind, >3MW turbine, onshore | 50% electricity production, wind, >3MW turbine, onshore |	PEM, 7.0 years	
Methanol synthesis	Denmark - Copenhagen	50% electricity production, wind, >3MW turbine, onshore | 50% electricity production, wind, >3MW turbine, onshore |		True

Contribution Analysis - Climate Change Impact)

Contribution Analysis of Intermediate Production Products (Impact category: Climate Change)

Overall Score: 0.092 kg CO2-eq / (kg product)

Overall Score: 0.028 kg CO2-eq / (kg product)

Overall Score: 2.191 kg CO2-eq / (kg product)

Sankey Plot

Here a nice Sankey Diagram will be displayed.

LCA Impact Scores

LCIA method	Impact category	Indicator	Unit	Scores (Case 1)
EF v3.1	climate change	global warming potential (GWP100)	kg CO2-Eq	1.162107e+00
EF v3.1	material resources: metals/minerals	abiotic depletion potential (ADP): elements (ultimate reserves)	kg Sb-Eq	1.041692e-04
EF v3.1	ozone depletion	ozone depletion potential (ODP)	kg CFC-11-Eq	1.182382e-07
EF v3.1	particulate matter formation	impact on human health	disease incidence	1.221062e-07

Success: All inputs have been saved.

Success: All LCA results were calculated.

Figure 22: Visualisation of LCA results in the proof-of-concept version of the user interface.

3 Conclusions and outlook

Since the award of the BFE grant significant progress has been made in the realisation of the Project. The combined Metafuels and PSI teams have worked diligently to make the Project a success. All of the work streams that constitute the overall Project are progressing well.

Design of the PP has been largely completed along with most of the procurement activities. Fabrication of the modules comprising the processing steps of the aerobrew process is well advanced as is the preparation of the PP building for installation of the modules.

The project implementation continues in full swing with multiple PP modules and ancillary devices and systems planned to be delivered and installed within the PP hall during Q1/Q2 2025. The site acceptance test (SAT) of the PP and installed facilities and subsequent start of operations are targeted for Q2 of 2025.

4 National and international cooperation

4.1 National

a) SUVA have been involved in the safety assessment of the aerobrew PP and ancillary systems.

b) PSI is a key partner in refuel.ch, collaborating with various stakeholders and maintaining direct scientific connections related to sustainable fuels production. Metafuels is an industrial observer within refuel.ch.

c) Metafuels is collaborating with a specialty company in the Swiss chemical sector.

4.2 International

a) Metafuels is involved in the ASTM accreditation of the Methanol-to-Jet pathway for SAF.

b) The MtJ pathway to produce synthetic aviation fuels is currently undergoing accreditation in accordance with the ASTM D4054 “Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives”. A task force has been formed to conduct the process of which Metafuels is a member. The task force has produced research reports conducted to assess the performance and operational characteristics of MtJ derived fuels from competing providers. These reports are undergoing scrutiny by the Federal Aviation Authority (FAA) of the USA, and the participating original equipment manufacturers (OEMs).

c) Upon approval of the reports by the FAA/OEMs a proposed draft MtJ specification for inclusion as an annex to ASTM 7566 “Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons” will be put to ASTM members for balloting which is expected to take place in 2025. Following a positive ballot the MtJ pathway will be formally added to the relevant annex to D7566 as an accredited pathway.

d) Metafuels is also consulting with a specialty company in the European chemical sector.

5 Publications and other communications

Metafuels & PSI have communicated the progress on the implementation of the aerobrew PP as well as the grant of funding by the Swiss Federal Office of Energy using their regular communication channels as well as presentations at various industry events. Some notable examples include:

a) Press release dated 30 July 2024 announcing the grant. This press release was widely picked up by media and has been included in the first issue of Metafuels newsletter "Fuel Up".

b) Presentation on 27th of May 2024 at IATA Energy Forum in Vienna, Austria.

c) Presentation on 12th September 2024 at European Venture Fair, Zurich organised by Emerald Technology Ventures

d) Presentation on 3rd October 2024 at the World Hydrogen derivatives conference in Copenhagen, Denmark.

e) Article in Forbes authored by energy and ESG analyst Gaurav Sharma. The article is based on an on-site visit and interview conducted at PSI

f) Press release on the main PSI website: Sustainable aviation fuel from the PSI campus | News & Events | PSI

g) PSI Technology Transfer website: PSI and Metafuels: Pioneers for Sustainable Aviation Fuel | Industry | PSI

h) 5232 Magazine Issue #2 2024: Climate Neutral Air Travel: Is It Possible? 5232 — The magazine of the Paul Scherrer Institute 2/2024 by Paul Scherrer Institut - Issuu

6 References

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[2] International Air Transport Association, “IATA to achieve net zero carbon emissions by 2050,” IATA Pressroom, Oct. 4, 2021. [Online]. Available: https://www.iata.org/en/pressroom/pressroom-archive/2021-releases/2021-10-04-03/.

[3] European Commission, “ReFuelEU Aviation: Sustainable aviation fuels,” European Commission - Transport, 2024. [Online]. Available: https://transport.ec.europa.eu/transport-modes/air/environment/refueleu-aviation_en.

[4] Carbon Off-setting and Reduction Scheme for International Aviation (CORSIA), https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx.

7 Appendix

Figure 23 shows a complete view of the PP from the 3D model

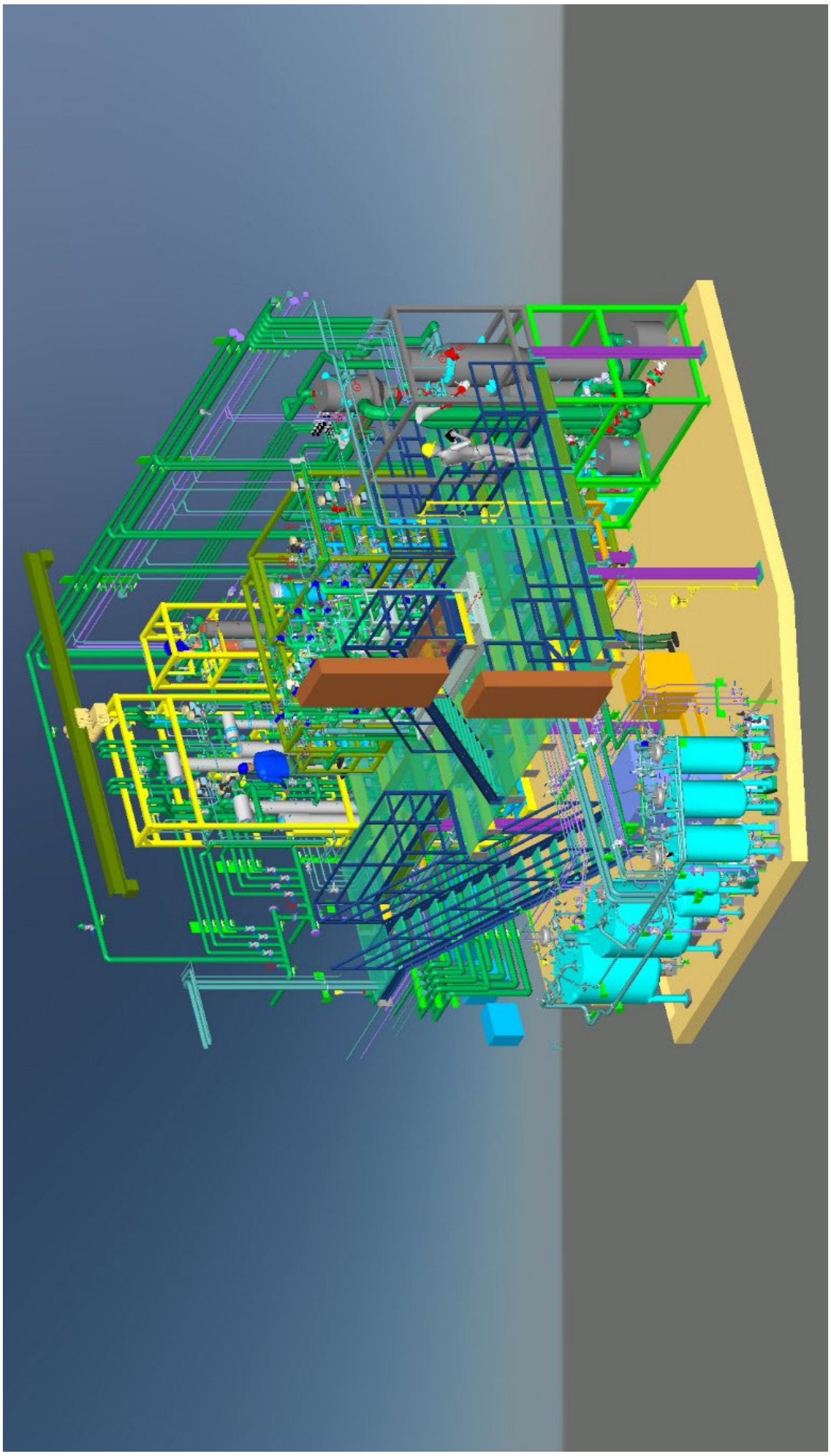

Figure 23: 3D Image of the Pilot Plant Source: Metafuels 2025