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FIELD DEMONSTRATIONS OF HYDROTREATED VEGETABLE OIL AS BIOFUEL FOR GAS TURBINE DECARBONISATION

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ABSTRACT

Uniper is investigating the use of biofuels, including hydrotreated vegetable oil (HVO), to help achieve its goal to make its European power generation carbon neutral by 2035. HVO can offer significant lifecycle CO_2eq emissions reductions compared with fossil diesel or gas oil, and it has been used extensively in compression ignition engines. However, evidence of its use in industrial gas turbines is limited. Therefore, an initial feasibility study was undertaken to identify the gas turbines in the Uniper fleet most suitable for HVO use. Three successful gas turbine field trials were then undertaken, including the world's first demonstration of HVO in a gas turbine in July 2021 in Sweden. Subsequent field trials were conducted in Germany (March 2022) and the United Kingdom (August 2022).

This work captures the preparations, selected results, and key considerations associated with gas turbines using HVO. Performance and emissions indicators (such as NO_x and CO) are compared between fuels and, in some cases, accredited emissions measurements showed marked improvements when using HVO. HVO is shown to be a promising low-carbon replacement fuel for fossil diesel and gas oil in gas turbines. Further work is required to ensure long-term operational reliability, safe handling, material compatibility, and sustainable supply chains.

NOMENCLATURE

BSI	British Standards Institution
CEMS	Continuous Emissions Monitoring System
CHP	Combined Heat and Power
CO_2eq	Carbon Dioxide Equivalent
DLE	Dry Low Emissions
EGHP	Exhaust Gas Horsepower
ELV	Emission Limit Value
Eo1	Eldningsolja 1 ("Light Fuel Oil")
ETIP	European Technology and Innovation Platform
FAME	Fatty Acid Methyl Ester
FTIR	Fourier Transform Infrared
GT	Gas Turbine
HAZID	Hazard Identification Workshop
HEL	Heizöl Extra Leicht ("Light Heating Oil")
HVO	Hydrotreated Vegetable Oil
IEA	International Energy Agency
KWU	Kraftwerk Union AG
LHV	Lower Heating Value
MW_e	Megawatt (electric)
N1	Olympus Low Pressure Shaft Speed (RPM)
OCGT	Open Cycle Gas Turbine
OEM	Original Equipment Manufacturer
ÖVT	Öresundsverket Power Plant
RED	Renewable Energy Directive (European Union)

1. INTRODUCTION

Hydrotreated vegetable oil (HVO), also called hydrogenated vegetable oil, renewable diesel, or green diesel, was first produced commercially in 2007 at Neste's Porvoo, Finland oil refinery, with an annual production capacity of ~218 million litres (Aatola et al., 2009). Since then, global HVO production capacity has increased by nearly two orders of magnitude to just under 20 billion litres per year, with European refiners accounting for over 30% of this capacity (IEA, 2022a). Despite this growth, HVO still remains a relatively nascent liquid biofuel, compared with diesel/gas oil, which has an annual demand of over 1.6 trillion litres (IEA, 2022b), and fatty acid methyl ester (FAME) biodiesel, which has an annual demand of 45 billion litres (IEA, 2022c).

Since its commercial introduction, HVO has been used mainly in the transport market as a drop-in replacement for diesel in compression ignition engines, requiring little to no modification given its similar chemical and physical properties, discussed further in Section 2. Depending on the feedstock used in its production, the lifecycle greenhouse gas reduction from HVO can range from approximately 50% to 90% compared to fossil diesel, with virgin vegetable oil feedstocks resulting in lower CO_2 reductions compared with waste oils and animal fats (Neste Corporation, 2020). For liquid or dual-fuel gas turbines (GTs) with diesel or gas oil capability, HVO presents a potential decarbonisation route for dispatchable power generation. However, the use of HVO in industrial GT applications has rarely been demonstrated. Therefore, it is vital to ensure that a fuel switch to HVO would not negatively affect gas turbine performance, emissions, plant safety, and reliability.

To address these issues, an extensive feasibility study was conducted considering the liquid and dual-fuel capable GTs in the Uniper fleet, which represents approximately 5% of Uniper's European power generation capacity. This study evaluated the existing GT combustion system, fuel handling and delivery system, HVO specification and properties, and local fuel availability for an initial trial and site conversion. The study outcome was a candidate list of locations and GTs suitable for an HVO trial. Following a standard preparation process (discussed in Section 3), HVO was successfully used in short-duration trials in open cycle gas turbines (OCGTs) at Uniper sites in Sweden (Runyon et al., 2023a) and Germany, and at a third-party aeroderivative test facility in the United Kingdom (Runyon et al., 2023b). Details of the GTs used in the HVO trials are given in Table 1. In total, these trials represent approximately 450 MW_e of dispatchable power generation capacity in the Uniper GT fleet, including other Uniper sites where the same GT types with similar combustion system variants are installed.

In addition to the trials undertaken by Uniper from July 2021 to August 2022, only one other trial is known to the authors in the public domain. In November 2021, Siemens Energy and Göteborg Energi demonstrated the use of HVO in a dual-fuel Siemens SGT-800 gas turbine at the Rya Combined Heat and Power (CHP) Plant in Sweden (Vella, 2022). Over two days, an SGT-800 with 3rd generation dry low emissions (DLE) burners was operated with HVO, with similar or lower NO_x emissions than fossil diesel operation. As a result, HVO has been released as an approved gas turbine fuel for Siemens Energy SGT-600/700/800 GTs (24-62 MW_e) with 3rd generation DLE burners (Jöcker, 2022). New build peaking GTs based on HVO operation have also been proposed by Stockholm Exergi in Sweden (Jöcker, 2022) and by SSE Thermal at Tarbert (260 MW_e) and Platin (140 MW_e) in Ireland (SSE Thermal, 2023).

2. FUEL SPECIFICATION AND ANALYSIS

The first step in evaluating the suitability of HVO for use in these GTs was to compare the existing GT original equipment manufacturer (OEM) fuel specification, current liquid fossil fuel specification, and HVO specification. Subsequently, as part of each trial, samples of the existing fuel and HVO were taken and analysed by laboratories accredited to ISO/IEC 17025. The objective was to ensure HVO compatibility with the site fuel delivery and combustion systems, to measure fuel properties of concern to GT operations not covered in the standard HVO specification (e.g., trace metals such as sodium and potassium), and to provide insights to explain any observed changes in emissions measurements between the two fuels.

In Europe, HVO is typically produced to the EN 15940 standard (BSI, 2019) which stipulates the requirements for paraffinic diesel fuel with a focus on compression ignition engines in automotive applications. The maximum and minimum requirements set out in EN 15940 are very similar to those given in the complementary automotive diesel specification, EN 590 (BSI, 2022), which is why HVO is often considered a drop-in diesel replacement in these applications. There are a few notable exceptions; as compared with EN 590 diesel, EN 15940 HVO has a lower density, lower sulphur content, and higher cetane number. It should also be noted that HVO is chemically unique from FAME biodiesel produced to EN 14214 (BSI, 2021), although the production feedstocks are generally similar.

Across the three HVO trials at Uniper sites, the following liquid fuel standards are used, along with the fuel description:

- Öresundsverket (ÖVT, Sweden) – SS 155410
    - Fuel: Eldningsolja 1 (Eo1) – gas oil
- Franken (Germany) – DIN 51603-1
    - Fuel: Heizöl extra leicht (HEL) – light heating oil
- Taylor's Lane (UK) – BS EN 590
    - Fuel: Diesel

As an example comparison, Table 2 provides selected properties from HEL and Neste HVO samples analysed during the Franken trial. Table 2 also provides the EN 15940 limits. The HVO CO_2 intensity was certified by the supplier, and represents over 90% lifecycle CO_2 emissions reduction when using the fossil fuel comparator of 183 gCO_{2eq}/MJ given in Annex V of the Renewable Energy Directive (RED II) (European Commission, 2018) for bioliquids used for electricity production.

Table 1 *Gas turbine HVO field trials*

GT Operator	Site	Country	GT OEM	GT	GT Capacity (MW_e)	No. GTs at Site	Trial Date
Uniper	Öresundsverket	Sweden	KWU / Siemens	V93.0	63	2	July 2021
Uniper	Franken	Germany	KWU / Siemens	V93.1	63	1	March 2022
Uniper	Taylor's Lane*	UK	Rolls-Royce	Olympus	17.5	8	August 2022
Göteborg Energi	Rya CHP	Sweden	Siemens	SGT-800	45	3	November 2021

*Olympus HVO trial was undertaken at the aeroderivative engine test bed at the Gloucester Jet Test Centre (UK)

Table 2 *Franken trial HEL and HVO analysis results*

Property	Units	HEL	HVO	EN 15940
Density (15°C)	kg/m^3	835.6	780.6	765 – 800
LHV, mass	MJ/kg	42.893	43.86	-
LHV, volume	MJ/litre	35.84	34.24	-
Flash point	°C	56.5	76.5	> 55
Viscosity (40°C)	mm^2/s	3.553	3.013	2.0 – 4.5
Lubricity	µm	-	340	< 460
FAME	%vol	-	< 0.05	< 7
Aromatics	%mass	-	0.7	< 1.1
Sulphur	mg/kg	118	< 5	< 5
Ash	mg/kg	< 0.001	< 0.001	< 0.010
Water	mg/kg	58	21	< 200
Total contamination	mg/kg	-	< 12	< 24
Copper strip corrosion	-	-	Class 1a	Class 1
Oxidation stability	g/m^3	-	< 1	< 25
Cold filter plugging point	°C	-13	-45	-
Hydrogen	%mass	13.6	15.4	-
H:C	-	0.16	0.18	-
Nitrogen	%mass	< 0.5	< 0.5	-
Oxygen	%mass	0.6	0.8	-
Total Acid Number	mgKOH/g	0.07	0.04	-
Chlorine	mg/kg	< 1	0.04	-
Aluminum	mg/kg	< 0.5	< 0.5	-
Barium	mg/kg	< 0.5	< 0.5	-
Calcium	mg/kg	< 0.5	< 0.5	-
Cobalt	mg/kg	< 0.5	< 0.5	-
Iron	mg/kg	< 0.5	< 0.5	-
Lithium	mg/kg	< 0.5	< 0.5	-
Magnesium	mg/kg	< 0.5	< 0.5	-
Manganese	mg/kg	< 0.5	< 0.5	-
Molybdenum	mg/kg	< 0.5	< 0.5	-
Nickel	mg/kg	< 0.5	< 0.5	-
Phosphorus	mg/kg	< 0.5	< 0.5	-
Potassium	mg/kg	< 0.5	< 0.5	-
Sodium	mg/kg	< 0.5	< 0.5	-
Silicon	mg/kg	< 0.5	< 0.5	-
Silver	mg/kg	< 0.5	< 0.5	-
Tin	mg/kg	< 0.5	< 0.5	-
Titanium	mg/kg	< 0.5	< 0.5	-
Vanadium	mg/kg	< 0.5	< 0.5	-
Zinc	mg/kg	< 0.5	< 0.5	-
Copper	mg/kg	< 0.5	< 0.5	-
CO_2eq intensity	gCO_2/MJ	95.1	4.4	-

As expected, the HVO used in the Franken trial meets the EN 15940 standard to which it was produced and is a FAME-free fuel. Note the HEL sample was tested against the requirements in DIN 51603-1, and therefore some properties (e.g., FAME content) were not measured. HVO has a lower volumetric lower heating value (LHV, vol) compared with HEL, which implies a 4% higher volumetric flow requirement through the fuel delivery system and fuel injectors to achieve the same thermal input to the GT. HVO sulphur content is over 95% lower than HEL, which is expected to reduce SO_2 and particulate emissions as well as corrosion in the fuel delivery system and deposition on hot gas path components. The low water content, low water solubility, and long-term oxidation stability mean that HVO should be suitable for long-term storage while also exhibiting good cold weather properties (Neste Corporation, 2020), all of which is of particular importance for GT grid support applications. Finally, the HVO used in the Franken trial meets the existing OEM liquid fuel specifications, with low trace metal contents in line with the existing HEL fuel. Subsequent HVO analysis from the Rolls-Royce Olympus HVO trial confirms the results obtained here, and in fact all measured trace metals for that particular HVO sample were found to be <0.1 mg/kg.

While the HVO fuel quality shown here is considered to be acceptable for GT operation, it is important to note that HVO is generally being produced as an automotive fuel, and suppliers may be unfamiliar with the additional requirements for GT applications. Therefore, bespoke fuel specifications are likely required which may have requirements more stringent than, or in addition to, the limits set out in EN 15940 (BSI, 2019). In addition, continuous quality monitoring throughout the supply chain may be necessary to ensure that critical properties are maintained within acceptable limits.

3. FIELD DEMONSTRATION APPROACH

For each HVO trial, a standard approach was undertaken to ensure that the trial could be safely and successfully executed, and experience could be shared from one trial to the next to improve efficiency and outcomes. For the ÖVT V93.0 HVO trial in June 2021, considered the first in the world, the approach had to be developed and refined. The authors formed a core group which was the same across all trials. This was important to ensure that the developed approach was consistently used for all the trials, which were held on different Uniper sites with different local staff. A standard approach was necessary for these trials in particular as the GT OEMs were not involved directly. Only in the case of the Rolls-Royce Olympus HVO trial was the GT service provider involved directly to deliver the trial at a third-party test facility in the UK. In that particular instance, this standard approach was still employed, but all steps were completed in conjunction with the GT service provider. This coordination allowed for knowledge exchange between parties to improve the likelihood of a successful outcome as the Olympus trial represented the first use of HVO at the third-party test facility with an engine which was overhauled by the service provider in the months immediately preceding the trial.

In addition to the fuel assessment described in Section 2, this field demonstration approach included the following steps generally undertaken in the order listed although some steps were required to be taken in parallel to ensure timely delivery of each trial (e.g., engagement with local and environmental permitting authorities):

- Pre-trial GT and site assessments
    - Combustion system
    - Ignition system
    - Control and instrumentation system
    - Fuel delivery system
    - Emissions monitoring and mitigation system (e.g., water injection for NO_x control)
    - GT inspection and overhaul history review
    - Site spacing, layout, bunding for temporary fuel storage
    - GT pre-trial inspection, if required
- Test plan development
    - Operating conditions (e.g., start-up, base/part load, shut-down, online fuel transition)
    - Trial duration
    - Estimated fuel quantities
- Hazard identification (HAZID) workshop
    - Definition of subject areas
    - Project presentation
    - Risk identification and mitigation
    - Recommendations
    - Prioritisation
- External stakeholder engagement
    - Local authorities
    - Environmental permitting authorities
    - Fuel suppliers
    - Third-party service providers (e.g., emissions measurement, fuel sample analysis)
    - Grid operators
- Post-trial GT and site assessments
    - GT post-trial inspection, if required
    - Data analysis
    - Internal and external stakeholder reporting

Regarding the test plan and schedule, each trial was completed over 2-3 days, with the first day scheduled for operation with the existing fossil fuel to establish a baseline for GT performance and emissions and subsequent days scheduled for a repeat of test conditions with HVO followed by a brief period of operation to return the GT to service with its original fuel. For the V93.0 and V93.1 trials, this return to fossil fuel service was completed with the GT on load to observe any detrimental impacts in performance or emissions due to an online fuel transition. For the Olympus trial, the first test was conducted with the Jet A-1 fuel available at the test facility rather than the diesel used on site. The return to Jet A-1 service was then conducted after HVO operation. This allowed the GT sufficient cooldown time following the HVO trial to conduct a minor borescope inspection of the combustors, inlet guide vanes, and first stage high pressure turbine blades. Table 3 provides an example of the testing undertaken in the Franken V93.1 HVO trial in March 2022, with approximately three hours of HVO operation in total. The ÖVT V93.0 HVO trial was nearly identical with the exception of the part load conditions at 30 MW_e and an overnight shutdown between Eo1 and HVO operation.

Table 3 *Franken trial HEL and HVO operating conditions*

Fuel	**Load (MW_e)**	**Objective**
HEL	---	Start-up and ramp to full load: operability, reliability, and emissions
HEL	55.0	Full load test: performance and emissions
HEL	35.0	Part load test: performance and emissions
HEL	---	Shut-down: operability, reliability, and emissions
90 minute shut-down period		
HVO	---	Hot start and ramp to full load: operability, reliability, and emissions
HVO	54.8	Full load test: performance and emissions
HVO	35.0	Part load test: performance and emissions
HVO	---	Shut-down: operability, reliability, and emissions
105 minute shut-down period		
HVO	---	Hot start and ramp to full load: operability, reliability, and emissions
HVO → HEL	54.0 35.0	On-load (full load then part load) fuel transition from HVO back to HEL. Verify HEL performance and emissions.
HEL	53.1	Full load test: performance and emissions verification
HEL	---	Shut-down: operability, reliability, and emissions

Note that the Franken V93.1 is a dual-fuel GT and that operation with natural gas was also conducted within the same test campaign. As a dual-fuel GT, the Franken V93.1 has different permitted emission limit values (ELVs) for natural gas and HEL. Therefore, the emissions comparison is valid for HEL and HVO, rather than natural gas and HVO, and the natural gas emissions are not relevant to the trial. Additionally, the HEL was not completely drained from the fuel delivery system prior to introducing HVO in the day tank, therefore the initial hot start contained a blend of HEL and HVO. A second hot start was used to demonstrate the start-up capability on pure HVO.

For the Olympus HVO trial, the test conditions were not based on GT load but rather low-pressure shaft speed (N1), following a standard post-overhaul test procedure. This was because the test facility operates the Olympus gas generator coupled to a jet pipe to replicate the restriction of the power turbine installed at the Taylor's Lane site.

Each trial required HVO delivery to the site, with expected volumes (including contingency) determined through the test plan development. Figure 1 provides an example of the temporary HVO storage and delivery system used in the Franken V93.1 HVO trial. Note that the Franken V93.1 liquid fuel injection system relies on the spill-return concept, but the return line to the day tank is not shown in Figure 1. The ÖVT trial setup was nearly identical except for the use of two 50 m^3 HVO tankers, shown in Figure 2. For the Olympus HVO trial, a single 42 m^3 tanker was used without an intermediate day tank.

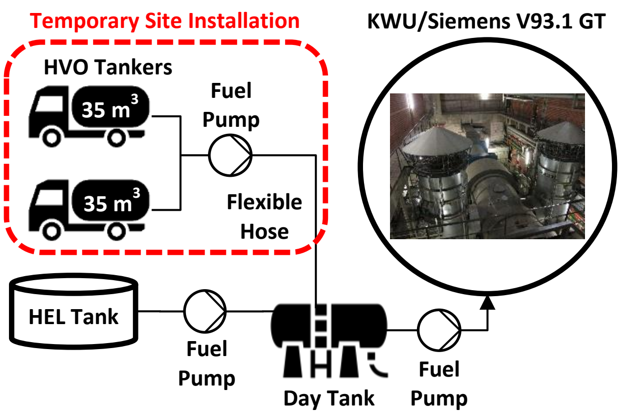

Fig. 1 *HEL and HVO storage and delivery schematic for Franken field trial with inset V93.1 GT photograph*

Fig. 2 *Two 50 m*^{3} *tankers supplying HVO during the ÖVT V93.0 GT field trial*

For the emissions measurements, an accredited emissions measurement contractor was on site at each test location. For the Franken trial, a continuous emissions monitoring system (CEMS) was also in operation in the bypass exhaust stack utilised with the GT operating in an OCGT configuration. For the Olympus HVO trial, emissions monitoring is not normally conducted at the third-party test facility. Thus, a bespoke emissions measurement probe was constructed and placed at the immediate exhaust of the gas generator jet pipe. However, given the layout of the engine test facility and exhaust ducting, this was considered to be a non-standard measurement method and was used for indicative comparison only between Jet A-1 and HVO operation. In each trial, all emissions were referenced to dry, 15%O_2 conditions.

4. RESULTS

In general, the use of HVO was successful across all three trials. No detrimental impacts on GT performance or operation were noted, and no changes to existing combustion hardware or control system parameters were required to allow for successful ignition, synchronisation (ÖVT and Franken only), GT loading/de-loading, stable full load/part load operation, and shut-down. Maximum GT output for each trial was limited by high ambient temperatures (ÖVT), existing exhaust gas temperature control limits (Franken), and fuel supply pump capacity (Olympus), not due to the use of HVO. Exhaust gas emissions were not negatively impacted by the change from liquid fossil fuel to HVO biofuel with all emissions remaining within the existing site ELVs without tuning or changes to water injection rates for NO_x abatement (ÖVT and Franken only). This NO_x behaviour is in agreement with that observed by Siemens Energy in their SGT-800 HVO trial (Vella, 2022). For certain pollutants, such as SO_2, HVO enables significant reductions compared with the liquid fossil fuel. Selected performance and emissions results are given for each HVO trial in the remainder of this section.

4.1 ÖVT KWU/Siemens V93.0 (July 2021)

The ÖVT V93.0 GTs were commissioned in 1972. The combustion system consists of two large down-fired silo combustors with four liquid fuel diffusion burners per silo, similar to the V93.1 GT shown in the photograph in Figure 1. This combustion system is generally quite robust and fuel flexible given the diffusion flames and long residence time in the combustor. However, this arrangement promotes NO_x formation, so demineralised water injection is also used to limit peak flame temperatures and reduce thermal NO_x production. Further details on this GT and combustor design can be found in the works of Lienert and Schmoch (1982) and Joyce (1985). For further details on the HVO trial conducted at ÖVT in July 2021, refer to the work of Runyon et al. (2023a).

Using HVO, the GT was successfully started, synchronised, loaded to ~52 MW_e (maximum output, limited by high ambient temperature conditions), de-loaded to 30 MW_e and then shut-down. Following this shut-down, a pure HVO start was successful and an online fuel transition at full load was completed whereby HVO addition to the day tank was stopped and Eo1 filling from storage reinstated. No adverse performance or emissions impacts were observed during this fuel transition, which proved that HVO could be blended with Eo1. HVO achieved the same ramp-up (+MW_e/min) and ramp-down (-MW_e/min) rates as Eo1, which is of particular importance for this GT in the Swedish grid disturbance reserve. A slight increase in the fuel flow control valve position for the same MW_e output was noted when using HVO, which was expected due to the lower volumetric LHV compared with Eo1.

Due to the lack of sophisticated combustor dynamic pressure measurements on this GT, the turbine, compressor, and generator bearing vibration amplitudes are used to infer stable combustion and GT operation. For the turbine bearing, vibrations are normally highest following start-up, and Figure 3 plots the time series of normalised turbine bearing vibration for Eo1 and HVO starts followed by full load operation. Start-up and peak turbine bearing vibration trends are similar between Eo1 and HVO, with HVO resulting in a slight reduction in peak vibration amplitude. This implies similar GT and combustion stability for HVO and Eo1 during start-up, ramp to full load, and full load operation, which was further confirmed visually using combustor sight-glasses during the trial.

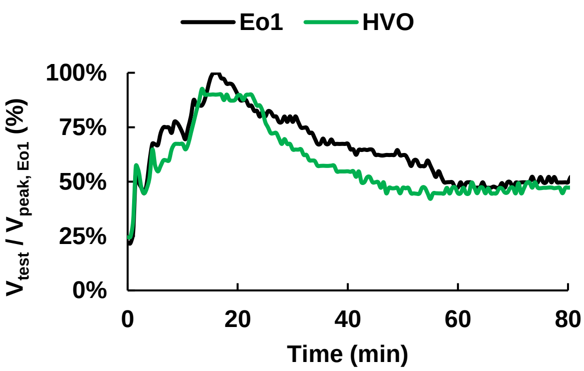

***Fig. 3** Eo1 and HVO turbine bearing vibration measurement (mm/s) normalised by the peak Eo1 vibration measurement (mm/s) following GT start-up.*

The use of HVO in the V93.0 GT results in similar or reduced exhaust gas emissions compared with Eo1 at full load and part load. At each stable operating condition, average emissions were measured for a number of species. Figure 4 provides the percentage change in average emissions during HVO operation (X_{HVO}) compared with Eo1 (X_{Eo1}) at full load and part load conditions, where X is the species given along the x-axis.

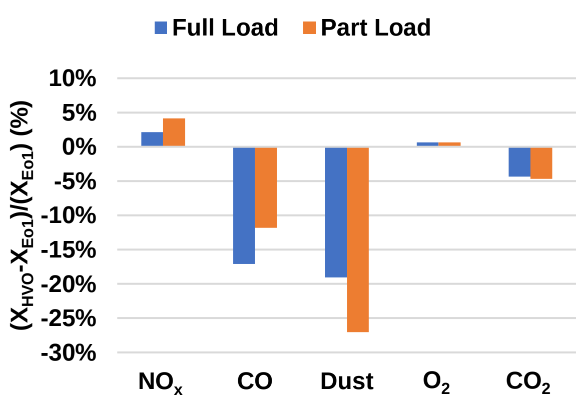

***Fig. 4** Percent change in emissions between Eo1 and HVO in the ÖVT V93.0 GT.*

In addition to the plotted species, SO_2 emissions were also measured, however the results have not been plotted to improve the clarity of the chart. HVO full load and part load SO_2 emissions reduced by 98% and >99%, respectively, compared with Eo1, due to the very low sulphur content of the HVO. CO and CO_2 emissions were observed to reduce when using HVO, likely due to its increased hydrogen content, however the reductions are within the expanded measurement uncertainty of ±22% (CO) and ±8% (CO_2) calculated by the emissions contractor.

NO_x emissions were observed to increase by 2-4% when operating on HVO. This increase is also within the expanded measurement uncertainty (±7%), and therefore no changes to the water injection rate were required for NO_x abatement when operating with HVO. Only the reductions in dust and SO_2 emissions were outside of the average expanded emissions uncertainties of ±16% and ±17%, respectively, which means that the HVO and Eo1 emissions are largely similar with some improvements achieved with HVO use. All emissions remained within existing site ELVs for Eo1 operation (without taking account of the measurement uncertainty). With respect to lifecycle CO_2 emissions, the Neste HVO used in this trial was certified by the supplier for over 90% CO_2 reduction compared with Eo1. Thus, approximately 163 tonnes of CO_2 emissions were avoided during the trial based on the volumes used.

Based on the success of this HVO trial on the V93.0 GT, further work at ÖVT is ongoing to enable HVO use in the GTs and other site assets (e.g., gensets) currently using fossil liquid fuel.

4.2 Franken KWU/Siemens V93.1 (March 2022)

The Franken V93.1 GT was commissioned in 1976. The dual-fuel GT combustion system consists of two large down-fired silo combustors, shown in Figure 1. In contrast to the ÖVT V93.0 GT, the V93.1 GT was upgraded in 1995 with six Siemens hybrid burners per silo featuring natural gas premixing and increased primary zone air flow for improved NO_x performance. The spill-return liquid fuel diffusion injection system is similar to that in the ÖVT V93.0 GT. Water injection is also used for NO_x reduction, but only when the GT is operating on liquid fuel. Therefore, separate ELVs exist for natural gas and liquid fuel operation, and a fuel switch on site from natural gas to HVO would be expected to increase NO_x emissions. At the Franken site, the V93.1 GT exhaust can be used as combustion air preheat in one of the two main utility boilers in a quasi-combined cycle arrangement. However, for the HVO trial, a bypass stack was used to operate the V93.1 in an OCGT configuration.

Much of the experience gained during the ÖVT HVO trial in July 2021 was transferred to the Franken V93.1 trial by the authors. As a result, all of the operating conditions outlined in Table 3 were successfully achieved, including an online fuel transition from HVO to HEL demonstrated with the GT first operating at full load, then while de-loading, and finally operating at 35 MW_e. As the GT exhaust gases can be used as combustion air preheat for a boiler, it was important to also demonstrate operation of the GT in exhaust gas temperature control mode. This was accomplished during the HVO trial as the maximum GT firing temperature is limited for liquid fuel operation compared with natural gas operation. Therefore, the reduction in GT load seen in Table 3 for full load HVO operation (compared with the initial full load HEL test) was the result of the exhaust gas temperature control functionality of the GT when using this fuel as the ambient temperature increased from 2°C (HEL) to 8°C (HVO) to 12°C (HEL) during the trial.

Similar to the V93.0 tests, the start-up ramp rate from synchronisation to full load could be maintained with HVO operation. The load ramp-up (~7 MW_e/min) was nearly identical and full load could be achieved in less than 8 minutes from synchronisation for both fuels. Also in agreement with the V93.0 trial, a slight increase in the fuel flow control valve position for the same MW_e output was noted when using HVO, to accommodate the increased volumetric fuel flow to the burners. Bearing vibration measurements were also comparable between fuels.

The use of HVO in the V93.1 GT results in similar or reduced exhaust gas emissions compared with HEL at full load and part load, with results plotted in Figure 5. Figure 5 shows the percentage change in average emissions during HVO operation (X_{HVO}) compared with HEL (X_{HEL}) at full load and part load conditions, where X is the species given along the x-axis.

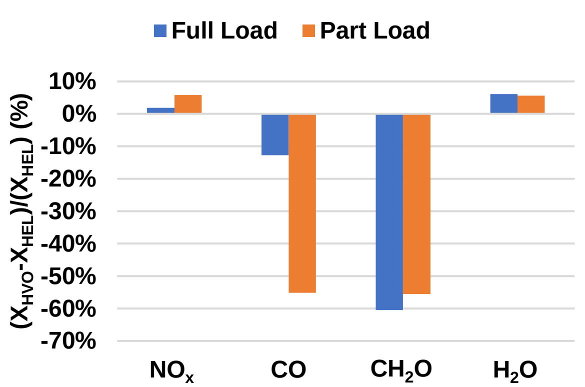

Fig. 5 *Percent change in emissions between HEL and HVO in the Franken V93.1 GT.*

In addition to the plotted species, dust, O_2, and CO_2 emissions were also measured, however the results have not been plotted to improve the clarity of the chart. Both HEL and HVO full load and part load dust emissions were at or below 1.4 mg/Nm^3. Differences between O_2 measurements were less than 0.5% and between CO_2 measurements less than 3%. Formaldehyde (CH_2O) emissions were measured using both an in-situ Fourier-transform infrared (FTIR) analyser and an extractive absorption method analysed post-trial in an off-site laboratory. HVO showed a consistent reduction in CH_2O compared with HEL, although absolute levels measured by FTIR and lab-based measurements were less than 1.0 mg/Nm^3 for both fuels. Similar to the V93.0 trial, a slight increase in NO_x emissions was observed with HVO use, however, this is within the expanded measurement uncertainty of this measurement (±2.5 mg/Nm^3). All emissions remained within existing site ELVs for HEL operation (within the measurement uncertainty). With respect to lifecycle CO_2 emissions, the Neste HVO used in this trial was certified by the supplier for over 95% CO_2 reduction compared with HEL. Thus, approximately 175 tonnes of CO_2 emissions were avoided during the trial based on the volumes used. Based on the success of this HVO trial on the V93.1 GT, further work at Franken is ongoing to validate HVO use in other site assets (e.g., boilers) currently using fossil liquid fuel.

4.3 Taylor's Lane Rolls-Royce Olympus (August 2022)

The Taylor's Lane Olympus aeroderivative GTs were commissioned in 1979 and are operated in pairs as gas generators exhausting into a single power turbine. The combustion system consists of eight can-annular combustors, each with a single pressure-assisted, diffusion liquid fuel atomiser firing in the axial flow direction of the GT. The Olympus GT combustors are significantly smaller than the V93.0 and V93.1 GTs used in the preceding HVO trials. Further details about the aeroderivative Olympus GT and its combustion system can be found in the work of McKnight (1979). For the HVO trial, a recently overhauled engine was tested with Jet A-1 fuel and HVO in a dedicated aero engine test facility in the UK. A new low-pressure fuel delivery system was developed to feed HVO directly from the road tanker to the engine without intermediate storage. For further details from the Olympus HVO trial in August 2022, refer to the work of Runyon et al. (2023b).

A standard post-overhaul test procedure was employed for the trial using OEM acceptance limits for various performance criteria (e.g., exhaust gas horsepower (EGHP), exhaust gas temperature spread, specific fuel consumption, and vibrations) as a function of N1. HVO was successfully used for engine start-up, shut-down, and N1 speeds equivalent to idle, synchronisation, base load, and peak load conditions. Olympus EGHP performance results are plotted in Figure 6, with Jet A-1 and HVO test results normalised by the OEM overhaul acceptance limit. The Jet A-1 and HVO EGHP results are nearly identical. All other OEM acceptance limits were successfully met whilst using HVO in the test facility.

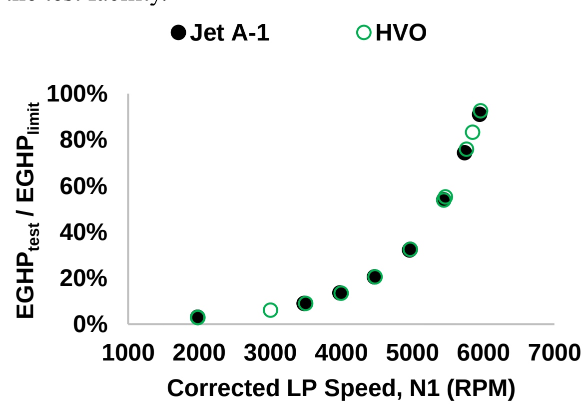

Fig. 6 *Olympus Jet A-1 and HVO normalised EGHP results as a function of N1.*

Emissions measurements at the test facility were carried out by Uniper engineers using FTIR and standard multi-gas analysers, with results shown in Figure 7. The sample arrangement was non-standard and therefore more significant variation in the results is to be expected compared with the exhaust gas stack measurements made at ÖVT and Franken. However, similar trends can be seen in the results plotted in Figure 7 for N1 conditions equivalent to base load (5800 rpm) and peak load (6000 rpm). All measured permitted emissions remained within existing site ELVs (without taking account of the measurement uncertainty).

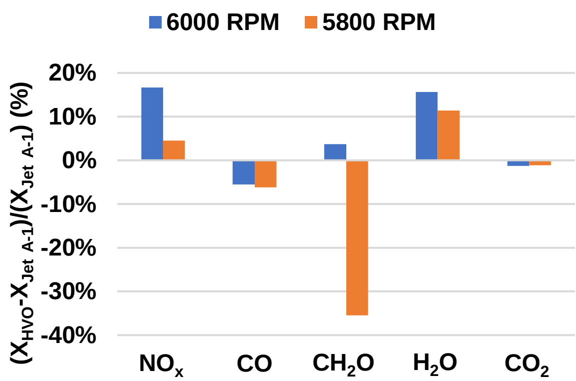

Fig. *7 Percent change in emissions between Jet A-1 and HVO in the Olympus GT at two N1 conditions.*

Based on the success of this HVO trial, further work is ongoing at Taylor's Lane to enable HVO use in the Olympus GTs and other assets (e.g., diesel engines).

5. FUTURE CONSIDERATIONS

While the results from these three field trials are encouraging for the use of HVO in low-carbon, dispatchable GT power generation, each trial demonstrated only a few hours of HVO operation with limited volumes stored on site for a short duration. These trials were unable to highlight any potential long-term impacts that HVO use might have on the associated GTs and fuel supply systems, and therefore a number of additional considerations are necessary to ensure its safe, reliable use in the future.

First, HVO is generally produced to a fuel specification (EN 15940 in Europe or ASTM D975 in the United States) which targets compression ignition engine applications. Many heavy-duty diesel engine manufacturers (e.g., Caterpillar, Cummins, MAN, Volvo, MTU) have approved HVO for use in some or all of their engines (Neste Corporation, 2020). HVO approval is not yet common from GT OEMs. Also, EN 15940 does not limit certain properties which are of importance to GT operation, such as trace metal species. It is encouraging that initial sample analyses show that HVO produced in accordance with EN 15940 should meet GT OEM fuel specifications. However, HVO producers and suppliers may not be familiar with the quality requirements for GTs and may be unwilling to guarantee that those properties can be met for each fuel delivery. As a result, continuous HVO quality analysis may be necessary to determine the variability of these properties long-term.

Second, as the use of HVO in transport applications is more well-established, this presents significant competition for limited HVO volumes and pressure on waste feedstock supplies. While it is encouraging that HVO production capacity is increasing globally, this is largely due to renewable transport fuel blending targets set in legislation such as RED II (European Commission, 2018). Furthermore, HVO can also be upgraded to sustainable aviation fuel (ETIP Bioenergy, 2020), and therefore producers may begin to shift production towards the aviation sector, placing further supply pressure on HVO for industrial GT use.

Third, as HVO becomes more widely available, supplier certification is necessary to ensure its lifecycle CO_2 reduction and the traceability and sustainability of its production feedstocks. In Europe, this certification must include lifecycle CO_2 emissions reductions calculated using the appropriate comparator from RED II (European Commission, 2018) for the application. Lifecycle CO_2 reduction percentages are often calculated and quoted today by suppliers using the transport fuel comparator (94 gCO_{2eq}/MJ) rather than the comparator for bioliquids used for electricity production (183 gCO_{2eq}/MJ), which may be more appropriate for GTs and must include the electrical efficiency as shown in Annex V of RED II (European Commission, 2018). Another comparator (80 gCO_{2eq}/MJ) is to be used for the production of useful heat, as well as for the production of heating and/or cooling. Regarding HVO production feedstocks, RED II (European Commission, 2018) requires that CO_{2eq} savings from bioliquids used for electricity, heating, and cooling shall be at least 70% until the end of 2025 and at least 80% thereafter. This requirement impacts on the possible feedstocks for HVO production as virgin vegetable oil feedstocks result in default RED II CO_2 savings of around 50%, while waste cooking oils and animal fats achieve over 70% (Neste Corporation, 2020). According to ETIP Bioenergy (2020), palm oil was one of the largest global feedstocks for HVO production in 2020. Some HVO producers such as Neste have announced plans to reduce the share of conventional palm oil in its feedstock to zero by the end of 2023 (Neste Corporation, 2023). Stakeholder acceptance of HVO use in GTs will rely heavily on certified CO_2 savings and sustainable feedstocks.

Fourth, the long-term use of HVO in GT applications, particularly for fuel switching, must be done with regard for personnel and process safety. While many of its properties are similar to existing fossil diesel, gas oil, or heating oil, HVO is free from aromatics which can have two key safety impacts. First, according to Neste Corporation (2020), the lack of aromatics may shrink some elastomeric seal materials which were swollen previously due to exposure to aromatic or FAME containing fuels. In the trials described, this was not considered an issue due to the short exposure time of seal materials to HVO and the return of the liquid fuel systems to standard operation after using HVO. However, this issue is of particular importance for future fuel switching applications, which could be addressed through a materials audit of the fuel handling system, replacement of elastomer seal materials, and enhanced monitoring of specific components during HVO operation. Second, due to the lack of aromatics, HVO is essentially odourless. Combined with its clear appearance, this may make leak detection more difficult, particularly if HVO handling is in close proximity to GT cooling water or water injection systems. Additional leak detection or material identification methods may be required.

Finally, as HVO is an emerging fuel and operational data with GTs is limited, any impacts on long-term reliability and maintenance intervals are yet to be determined. There is little evidence from the trials to suggest that HVO should have a detrimental effect on GT reliability, availability, or maintenance, and in fact may improve some of these aspects compared with fossil fuels due to its low aromatic, sulphur, and ash content, as shown in Table 2. However, it may be necessary to reduce GT inspection intervals initially after fuel switching to obtain baseline degradation conditions before a decision is made to revert to the standard liquid fuel operation inspection interval.

6. CONCLUSIONS

HVO presents an immediate opportunity for the decarbonisation of dispatchable GT power generation, including both retrofit and new build installations. However, the use of HVO in GTs is still an emerging application for this fuel. Therefore, field trials are vital to building experience while also demonstrating to relevant stakeholders, such as environmental permitting authorities and grid operators, that using HVO in GTs will not negatively impact on emissions, performance, and reliability compared with long-established liquid fossil fuels. In this work, the authors have detailed three successful HVO field trials across multiple Uniper European GT sites and demonstrated that HVO should be suitable for long-term use in these assets. HVO offers the potential to reduce lifecycle CO_2 emissions by over 90% for approximately 450 MW_e of GT capacity, including other Uniper sites where the same GT types with similar combustion system variants are installed.

HVO has been demonstrated as a drop-in replacement fuel for fossil diesel, gas oil, or heating oil in these GTs without requiring hardware or control system changes. Therefore, fuel switching can be achieved rapidly and with limited capital investment while other low-carbon GT fuels are developed (e.g., hydrogen, ammonia, biomethane, or e-fuels). HVO could therefore serve as a bridging fuel in the energy transition for GTs due to its ability to be used as a pure fuel or blended with diesel, gas oil, or light heating oil in any quantity. Existing assets can also retain their existing fossil fuel capability for security of supply. It is encouraging that Siemens Energy has released HVO as an approved fuel for the SGT-600/700/800 GTs (Jöcker, 2022), and it is anticipated that further approvals will be granted as more experience is gained. As noted in Section 5, long-term reliable GT operation and HVO quality still need to be monitored, in particular for retrofit applications and as the HVO production feedstocks continue to evolve.

As a result of the success of the trials detailed here, HVO is considered a promising low-carbon biofuel for use in GTs to help Uniper achieve its goal to make its European power generation carbon neutral by 2035. Further activities are underway and additional short-term HVO trials on other Uniper GTs, gensets, and boilers in both power generation and CHP applications have recently been completed or are at advanced stages of planning.

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