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Enabling Rapid Decarbonisation of Gas Turbine Power Generation with Hydrotreated Vegetable Oil

Jon Runyon[1,*], *Stuart* James[1], *Ben* Broughton[2], *David* Graham[1], *Catherine* Goy[1], *Sam* Duncan[1], *James* Harman-Thomas[1]

[1]Uniper Technologies Ltd., Technology Centre, Ratcliffe-on-Soar, NG11 0EE, United Kingdom
[2]Uniper UK Ltd., Compton House, 2300 The Crescent, Birmingham Business Park, Birmingham, B37 7YE, United Kingdom

Abstract. Hydrotreated vegetable oil (HVO) produced from waste feedstocks offers significant lifecycle CO_2 emissions reduction when used in applications consistent with the European Union's Renewable Energy Directive (RED). Given its similarity to fossil diesel, HVO has been demonstrated in power generation gas turbine (GT) trials as a suitable drop-in replacement fuel. Uniper successfully completed the world's first GT HVO trial in July 2021 and subsequent trials in Germany, the United Kingdom, and Sweden. The most recent trial was conducted on an FT4 aeroderivative GT at Barsebäcksverket (BVT) in June 2024. Additionally, Uniper has converted GT units in Sweden to use HVO. However, long-term operational evidence remains limited. This paper presents an overview of HVO activities using power generation GTs. The carbon intensity and greenhouse gas emissions of HVO for power generation are discussed in line with the RED requirements. Uniper's HVO trial at BVT and experience with HVO GT conversions are described, including performance and emissions results. The development needs and sustainability requirements are discussed to enable further expansion of HVO in power generation. HVO enables a rapid reduction in lifecycle CO_2 emissions and delivers low-carbon, dispatchable GT capacity to complement variable renewable energy sources and provide critical grid services.

1 Introduction

Uniper aims to reduce its Scope 1 and 2 emissions by more than 55% by 2030 compared to 2019 and to become carbon-neutral (i.e., Scope 1, 2, and 3) by 2040. To reduce carbon emissions from existing power generation GT assets, Uniper has investigated the use of hydrogen, carbon capture and storage (CCS), and green fuels (i.e., alternative, renewable, low-carbon fuels). As part of its green fuel investigations, Uniper conducted the world's first gas turbine (GT) field trial using hydrotreated vegetable oil (HVO) in July 2021 [1]. Since then, the power generation industry has shown an increasing interest in the use of HVO as a low-carbon, drop-in replacement fuel for fossil diesel or fuel oil in existing GT assets as well as a suitable fuel for low-carbon, new build GT capacity. Further field trials with HVO have been conducted by various operators in Sweden [2], Germany [3], the United Kingdom (UK) [4], and the United States (US) [5] across a range of industrial and aeroderivative GTs and original equipment manufacturers (OEMs). In addition to conducting short-duration trials, Uniper has installed permanent HVO storage to decarbonise existing GT capacity in Sweden, with Öresundsverket (ÖVT) and Karlshamnsverket (KVT) already completed and Barsebäcksverket (BVT) currently ongoing. A new Siemens Energy SGT-800 was commissioned in HVO service by Stockholm Exergi in Sweden in 2023 [2]. SSE Thermal plans to commission a new Ansaldo Energia AE94.3A GT [6] and three Siemens Energy SGT-800 GTs [7] in HVO service in Ireland in 2027 and 2028, respectively. Further details of global HVO GT projects are summarised in Table 1. The current commercial HVO GT capacity is approximately 225 MW_e from five GTs (i.e., 126 MW_e at ÖVT, 62 MW_e at Värtaverket, and 37 MW_e at KVT). If all GTs of the same type at the sites listed in Table 1 are accounted for, the potential global low-carbon GT capacity operating on HVO is approximately 1.7 GW_e from 38 GTs.

As GT operating experience with HVO is limited, further evidence of the impact of HVO on GT performance and emissions is needed. This is necessary because GT OEMs have focussed recent combustion system developments on gaseous fuels such as natural gas and hydrogen, and liquid fuel operation is less common in general. Additionally, much of the testing completed to date with HVO has utilised conventional, diffusion combustion systems rather than more advanced systems such as lean, premixed, and prevapourised (LPP) [8] combustion systems. To support these developments, this paper provides evidence of HVO experience in industrial and aeroderivative GT applications. The results of Uniper's HVO trial using a Pratt & Whitney (P&W) FT4 aeroderivative GT at BVT in June 2024 are presented along with results from ÖVT and KVT following their conversion to commercial HVO use.

* Corresponding author: jon.runyon@uniper.energy

Table 1. Global gas turbine HVO projects

GT Operator (T/C/P)*	Site	Country	GT OEM	GT Type (Capacity, MW_e)	Year	Reference
Uniper (T)	ÖVT	Sweden	Siemens Energy	V93.0 (63)	2021	[1, 3]
Svensk Kraftreserv (T)	Arendal	Sweden	Rolls-Royce	Avon (15)	2021	
Göteborg Energi (T)	Rya CHP	Sweden	Siemens Energy	SGT-800 (45)	2021	[2]
Uniper (T)	Franken	Germany	Siemens Energy	V93.1 (63)	2022	[3]
Uniper (T)	Taylor's Lane**	UK	Rolls-Royce	Olympus (17.5)	2022	[3, 4]
Uniper (C)	ÖVT	Sweden	Siemens Energy	V93.0 (63)	2023	
Enel (T)	Las Salinas	Spain	GE Vernova	MS6001B (37.5)	2023	
Stockholm Exergi (C)	Värtaverket	Sweden	Siemens Energy	SGT-800 (62)	2023	[2]
Enel (T)	Arona	Spain	Pratt & Whitney	FT8 (25)	2024	
Uniper (T)	BVT	Sweden	Pratt & Whitney	FT4 (21)	2024	
Svensk Kraftreserv (T)	Stallbacka	Sweden	Stal-Laval	GT120 (70)	2024	
Tennessee Valley Authority (T)	Johnsonville	US	GE Vernova	7EA (85)	2024	[5]
Uniper (C)	KVT	Sweden	Rolls-Royce	Olympus (18.5)	2024	
Uniper (P)	BVT	Sweden	Pratt & Whitney	FT4 (21)	2025	
SSE Thermal (P)	Tarbert	Ireland	Ansaldo Energia	AE94.3A (300)	2027	[6]
SSE Thermal (P)	Platin	Ireland	Siemens Energy	SGT-800 (57)	2028	[7]

*T: trial, C: commercial operation, P: planned
**Olympus HVO trial was undertaken at the aeroderivative engine test bed at the Gloucester Jet Test Centre (UK)

HVO is being proven as a solution to rapidly decarbonise dual-fuel and liquid-fuelled GTs with minimal changes to GT combustion hardware, controls, and balance of plant compared with hydrogen or CCS. This significantly reduces the capital expenditure required to decarbonise existing GT capacity. However, this can only be achieved if HVO is produced from appropriate feedstocks and used in applications that are consistent with sustainability regulations. Therefore, this paper first presents a discussion on the sustainability requirements of using HVO for power generation, with a focus on the greenhouse gas (GHG) savings requirements set out in the European Union's revised Renewable Energy Directive (RED II).

2 Sustainability

To date, HVO has been used mainly in the transport sector as a low-carbon, drop-in replacement for diesel, requiring little to no modification to compression ignition engines given its similar chemical and physical properties, discussed further in Section 3. The use of HVO in the transport sector has largely been driven by low-carbon fuel blending and fuel switching requirements in certain countries and regions. For example, as of 1 January 2024, all California fleets are required to procure and only use R99 or R100 renewable diesel fuel (i.e., HVO) in all vehicles subject to the Off-Road Regulation, with some limited exceptions [9]. Therefore, the sustainability requirements for the application of HVO in the transport sector are more advanced and well understood by producers, suppliers, end-users, and regulators. Neste, one of the major HVO producers globally, states that the lifecycle GHG savings from HVO can range from approximately 50% to 90% compared to fossil diesel used in transport applications, with waste feedstocks such as used cooking oils and animal fats resulting in higher CO_2 reductions compared with virgin vegetable oil feedstocks [10]. However, for power generation GTs, commercial HVO use is still a nascent application, as discussed in Section 1. Therefore, the sustainability requirements for use in power generation, particularly related to carbon intensity (CI) and GHG savings, are less well understood across the supply chain.

In the European Union (EU), the utilisation of alternative, low-carbon liquid fuels for power generation, particularly those derived from biological feedstocks, is regulated through the RED II (Directive 2018/2001/EU [11]). For the purposes of this analysis, HVO is considered to fit the RED II definition of a "bioliquid", i.e., a liquid fuel for energy purposes other than for transport, including electricity and heating and cooling, produced from biomass. RED II revised the RED I GHG emissions savings thresholds as shown below, with the critical distinction for bioliquids related to the start date of the production facility.

- GHG savings of at least 50% must be achieved for bioliquids produced in installations in operation on or before 5 October 2015.
- GHG savings of at least 60% must be achieved for bioliquids produced in installations starting operation from 6 October 2015 until 31 December 2020.
- GHG savings of at least 65% must be achieved for bioliquids produced in installations starting operation from 1 January 2021.

This information should be reported by the supplier on any Proof of Sustainability (PoS) certificate that is issued upon transfer of the bioliquid with other details such as carbon intensity, feedstock materials and country of origin, which are required to prove traceability across the product lifecycle.

The methodology for calculating the GHG savings was also revised in RED II to account for the conversion efficiency in processes other than transport. For example, for energy installations delivering only electricity from a bioliquid (e.g., open-cycle or combined-cycle GT), the electrical efficiency first needs to be considered in Equation 1 before calculating the GHG savings in Equation 2.

$$EC_{el} = \frac{E}{\eta_{el}} = \frac{CI}{\eta_{el}} \quad (1)$$

where EC_{el} is the total GHG emissions (gCO2$_e$/MJ) from the final energy commodity, E is the total GHG emissions (gCO_2e/MJ) of the bioliquid before end-conversion (i.e., equivalent to the CI), and η_{el} is the electrical efficiency defined as the annual electricity produced divided by the annual bioliquid thermal input on a lower heating value (LHV) basis. Note that CO_2e is used here to combine the emissions from various GHGs (i.e., CO_2, CH_4, and N_2O) on the basis of their global warming potential by converting these GHGs to the equivalent amount of CO_2. EC_{el} would then substitute for $EC_{B(el)}$ in Equation 2 as follows:

$$GHG\ Savings = \frac{(EC_{F(el)} - EC_{B(el)})}{EC_{F(el)}} = \frac{(EC_{F(el)} - \frac{CI}{\eta_{el}})}{EC_{F(el)}} \quad (2)$$

where $EC_{F(el)}$ is the fossil fuel comparator for electricity production (183 gCO_2e/MJ). As shown in Equation 2, the GHG savings calculation is a function of the CI of the fuel and efficiency (η_{el}) of the conversion process, assumed here to be a GT producing only electricity (in open cycle or combined cycle). RED II states that the contribution of CO_2 emissions in the fuel CI from the combustion of bioliquids shall be zero, but combustion emissions of non-CO_2 GHGs (CH_4 and N_2O) should normally be considered. For the purposes of this analysis, the relatively low CO_2e contribution from CH_4 and N_2O combustion emissions is neglected. Thus, E in Equations 1 and 2 is equivalent to the CI of the HVO at the point of delivery to the power plant, and all combustion GHG emissions are considered to be zero.

In addition to the RED II, the EU has set out criteria for sustainable investment with regards to the use of alternative, low-carbon fuels for power generation through the EU Taxonomy [12, 13]. The EU Taxonomy [12] sets out criteria for economic activities such as "Electricity generation from bioenergy" which states that, amongst other criteria, the use of biomass must achieve at least 80% GHG savings using the methodology set out in RED II, and electricity generation installations with a total rated thermal input above 100 MW$_{th}$ must have an electrical efficiency of at least 36% (or apply CHP or CCS) in order to be considered an activity which makes a substantial contribution to climate change mitigation. Additionally, the EU Taxonomy [13] sets electricity CI targets for gas-fired power plants to contribute to climate change mitigation (< 100 kgCO_2e/MWh$_{el}$) and to "do no significant harm" (< 270 kgCO_2e/MWh$_{el}$), with both limits requiring low-carbon fuel blending (e.g., hydrogen).

Figure 1 plots the RED II GHG savings as a function of HVO CI and lines of constant electrical efficiency from 20% up to 64% (i.e., H-class CCGT maximum efficiency). The round dotted line represents the EU Taxonomy target efficiency for bioenergy of 36%.

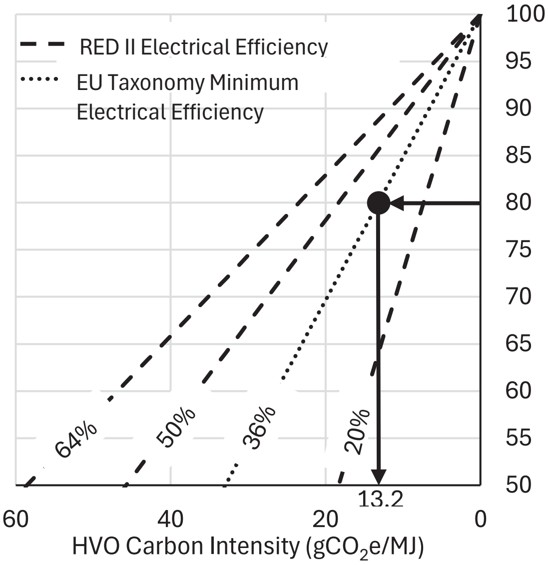

Fig. 1. RED II GHG savings as a function of HVO CI (gCO_2e/MJ) and GT electrical efficiency (%).

From this graph, the maximum allowable HVO CI for a required GHG savings and given GT efficiency can be determined. For example, to achieve a RED II GHG savings of 80% (i.e., the EU Taxonomy target for bioenergy) in an open cycle GT which meets the EU Taxonomy minimum efficiency requirement of 36%, the maximum allowable HVO CI would be 13.2 gCO_2e/MJ. This compares with a typical HVO CI of 11.9 gCO_2e/MJ (given as a total for cultivation, processing, transport and distribution in RED II) when produced from waste cooking oil feedstock, which would meet the requirement. Alternatively, RED II gives a typical CI of 45.8 gCO_2e/MJ if the HVO was produced from virgin rapeseed oil feedstock, which would not meet the EU Taxonomy requirement. Therefore, the selection of HVO as a fuel to meet EU Taxonomy requirements would require a limitation on the allowable feedstocks used in its production. It follows that HVO with lower CI would need to be used in GTs with lower efficiency to achieve the same GHG savings. Alternatively, if the RED II GHG savings requirements presented previously (i.e., between 50% and 65%) are to be met, then HVO with a higher CI could be used than in the given EU Taxonomy example.

The CI of the electricity produced from gas-fired power plants is also set out in the EU Taxonomy in order to reduce their climate impact. Figure 2 plots the electricity CI (kgCO_2e/MWh) as a function of HVO CI and GT electrical efficiency, as given in Equation 3.

$$Electricity\ CI = 3.6 * \frac{E}{\eta_{el}} = 3.6 * \frac{CI}{\eta_{el}} \quad (3)$$

As shown in Figure 2, HVO with the same CI that meets the EU Taxonomy rules for GHG savings and GT efficiency for bioenergy applications (see Figure 1) would exceed the EU Taxonomy electricity CI limit of 100 $kgCO_2e/MWh$ for "climate change mitigation". This highlights an important discrepancy between the EU Taxonomy requirements. To meet the "climate change mitigation" limit with an EU Taxonomy-compliant GT, the maximum allowable HVO CI would be 10 gCO_2e/MJ. Similar to the discrepancy between the RED II and the EU taxonomy GHG savings requirements, this discrepancy between EU Taxonomy activity requirements needs to be further understood and clarified to enable widespread deployment of HVO GT retrofits and new build capacity.

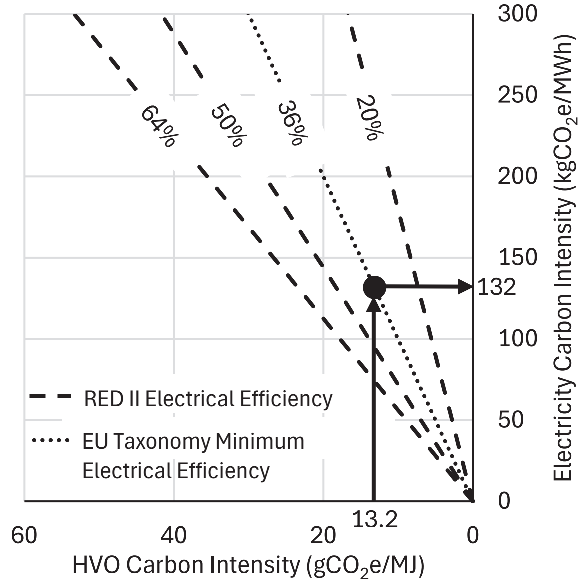

Fig. 2. Electricity CI as a function of HVO CI (gCO_2e/MJ) and GT electrical efficiency (%).

3 BVT HVO Trial

To gather operational evidence to derisk a potential future conversion, an HVO trial was carried out on a P&W FT4 aeroderivative GT at Uniper's power plant in Barsebäck, Sweden in June 2024. The P&W FT4 aeroderivative GTs were commissioned at BVT in 1974 as emergency power supply for the nearby Barsebäck Nuclear Power Plant which is currently being decommissioned. The GTs at BVT are now part of the Swedish disturbance reserve as one of the fastest dispatch plants, reaching peak load within three minutes of synchronisation [14]. BVT consists of two units, G13 and G14, each with a peak capacity of 42 MW_e [15] which operate in a Power Pac arrangement (i.e., each unit consists of two FT4 aeroderivative GTs powering individual Stal-Laval power turbines arranged on opposite ends of a single generator). In total, there are four FT4 GTs in operation at BVT, and only one GT was used for the HVO trial (i.e., one-half of one unit). The P&W FT4 industrial GT was developed from the commercial aero engine, P&W JT4, which powered the Boeing 707 and Douglas DC-8 aircraft [16]. The GT consists of a 15-stage compressor with a 12:1 pressure ratio, a can-annular combustion system, and a 3-stage turbine. The combustion system consists of eight combustor cans with six diffusion fuel nozzles per can (i.e., 48 fuel injectors in total).

For the HVO trial, a recently overhauled GT was installed and tested with fuel oil ("Eldningsolja 1" or "Eo1") and HVO, with the fuel delivery arrangement as shown in Figure 3. HVO was delivered to site by a 20 m^3 road tanker and connected via temporary hose upstream of the low-pressure (LP) Eo1 fuel forwarding system for the unit in operation. The existing GT combustion hardware, control system settings, and fuel delivery system were utilised aside from the temporary hose connection. This was a deliberate decision to prove the drop-in capability of HVO. The trial took place over two days with baseline GT performance and emissions first recorded with Eo1 and then repeated with HVO.

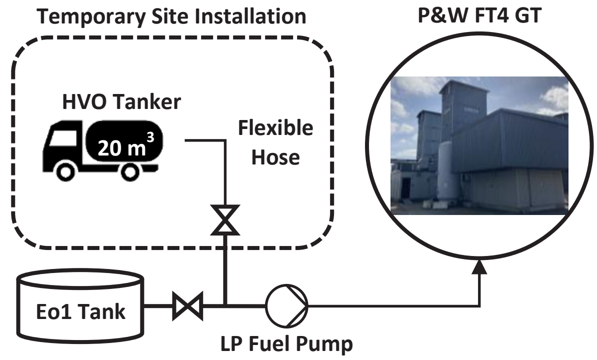

Fig. 3. Eo1 and HVO storage and delivery schematic for BVT field trial with inset FT4 GT enclosure photograph.

Transient and steady-state conditions were demonstrated during the trial following a load path that included start-up, ignition, idle, synchronisation, ramp up to base load, base load, ramp up to peak load, peak load, ramp down to part load, part load, ramp down to idle, cool down, and shut-down. A cold start and ramp to peak load was demonstrated with HVO after an overnight shut-down. Borescope inspections of selected GT combustion cans and injectors were performed immediately before and after HVO operation before returning the GT to Eo1 service. For more information about the general approach taken by Uniper to conducting HVO field trials, refer to the work of Runyon et al. [3].

3.1 Fuel Quality

Fuel samples of Eo1 and HVO were taken during the trial directly from the onsite Eo1 storage tank and the temporary HVO tanker. Figure 4 shows the difference in visual appearance between HVO (left) and Eo1 (right) with HVO appearing clear and colourless. Due to the lack of aromatics, HVO is also significantly less odorous than Eo1. This combination could make HVO leak detection difficult, particularly where it is being handled in close proximity to water (either process or ambient). The fuel samples were then analysed by an accredited laboratory. Table 2 provides selected analysis results from the Eo1 and HVO samples taken during the BVT trial. Table 2 also provides the European standard EN 15940 limits for Class A paraffinic diesel fuel.

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Fig. 4. Visual appearance of HVO (left) and Eo1 (right) samples taken during the BVT HVO trial.

In Europe, EN 15940 is the standard to which HVO is typically produced, with a focus on paraffinic diesel fuel used in compression ignition engines for automotive applications. The requirements set out in EN 15940 are similar to those given in the complementary automotive diesel specification, EN 590, with the exception that 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 fatty acid methyl ester (FAME) biodiesel produced to EN 14214, although the production feedstocks are generally similar. Since HVO is being produced as an automotive fuel, suppliers may be unfamiliar with the additional requirements for GT applications, such as trace metal species. GT liquid fuel specifications likely have requirements more stringent than, or in addition to, the limits set out in EN 15940.

Based on the results in Table 2, the HVO used in the BVT trial meets the requirements of the EN 15940 standard to which it was produced and is free from FAME. HVO has a lower volumetric lower heating value (LHV, vol) compared with Eo1, which implies a 5.5% higher volumetric flow requirement through the fuel delivery system and fuel injectors to achieve the same thermal input to the GT. This could impact on certain balance of plant equipment such as fuel pumps and filters (e.g., higher pressure drop) as well as burners (e.g., higher injection velocity impacting fuel penetration into the air flow) and controls (e.g., changes in fuel control valve position for a given load).

HVO sulphur content is more than 99% lower than Eo1, which is expected to effectively eliminate SO_2 emissions as well as reduce deposition on hot gas path (HGP) components. The trace metal content of HVO is lower than Eo1 which is essential for the integrity of GT HGP components in liquid-fuel operation. HVO has a low water content, low water solubility, low oxygen content, and long-term oxidation stability. This means that HVO should be suitable for long-term storage, although experience with long-term storage of HVO in the power generation industry is limited. HVO also exhibits good cold weather properties, which is crucial for a GT operating in the Swedish climate. Finally, the HVO used in the BVT trial meets the existing OEM liquid fuel specifications with the exception of viscosity. However, the HVO result is closer to the OEM limit than Eo1, and no known problems have occurred in the past.

Table 2. BVT trial Eo1 and HVO sample analysis results

Property	Units	Eo1	HVO	EN 15940
Cetane number	-	51.1	> 73.6	> 70
Density (15°C)	kg/m^3	844	781	765 – 800
Aromatics	%mass	22.4	< 0.2	< 1.1
Sulphur	mg/kg	320	< 3	< 5
Manganese	mg/l	0.5	< 0.5	< 2
Flash point	°C	76	83.5	> 55
Carbon residue (10% distillation)	%mass	< 0.10	< 0.10	< 0.3
Ash	%mass	< 0.001	< 0.001	< 0.010
Water	mg/kg	50	40	< 200
Total contamination	mg/kg	3	5	< 24
Copper strip corrosion	"Class"	1A	1A	1
FAME	%vol	0.06	< 0.05	< 7
Oxidation stability	g/m^3	1	2	< 25
Lubricity	μm	390	300	< 400
Viscosity (40°C)	mm^2/s	3.176	3.148	2.0 – 4.5
Distillation (recovered at 250°C)	%vol	31.6	1.6	< 65
Distillation (recovered at 350°C)	%vol	91.6	98.6	> 85
Distillation (95%vol recovery)	°C	363.3	299.8	< 360
LHV, mass	MJ/kg	43.048	43.9	-
LHV, vol	MJ/l	36.3	34.3	-
Cold filter plugging point	°C	-17	-22	-
Hydrogen	%mass	13.4	15.1	-
Carbon	%mass	86.0	84.9	-
Nitrogen	%mass	0.003	0.00011	-
Oxygen	%mass	0.6	< 0.1	-
Total Acid Number	mgKOH/g	< 0.1	< 0.1	-
Chloride	mg/kg	< 1	< 1	-
Calcium	mg/kg	< 0.1	< 0.1	-
Copper	mg/kg	< 0.01	< 0.01	-
Lead	mg/kg	< 0.1	< 0.1	-
Lithium	mg/kg	< 0.1	< 0.1	-
Nickel	mg/kg	< 0.1	< 0.1	-
Potassium	mg/kg	0.3	< 0.1	-
Sodium	mg/kg	0.1	0.1	-
Vanadium	mg/kg	< 0.1	< 0.1	-
Zinc	mg/kg	< 0.1	< 0.1	-

3.2 Performance

The BVT HVO trial demonstrated that the performance of the FT4 gas turbine and Stal-Laval power turbine was not negatively impacted by the use of HVO. All transient and steady state conditions set out in the test plan were achieved, and the generator output (MW_e) was similar between Eo1 and HVO, as shown in Figure 5. Note the longer hold time at the initial load step (~6 MW_e) with HVO to ensure any remaining Eo1 in the fuel system was consumed prior to the HVO emissions tests. Neither fuel was able to achieve the rated peak load of 21 MW_e due to higher ambient temperature conditions in June 2024. There is also a slight reduction in output observed in Figure 5 with HVO due to an increase in ambient temperature (~17°C for Eo1, ~21°C for HVO) from the morning Eo1 start to the afternoon HVO start. Both fuels achieved the required steady-state conditions for emissions measurements at base load (~16 MW_e at a fixed GT exhaust gas temperature (EGT) of 544°C), peak load (~18.5 MW_e at EGT = 580°C), and part load (manually selected as 10 MW_e). At the steady-state conditions shown in Figure 5, the average EGTs and EGT spread were comparable between Eo1 and HVO at similar load conditions. Engine vibration measurements were also within acceptable limits when operating the GT on HVO. On the second day of the HVO trial, a successful cold start and ramp to peak load with HVO was demonstrated, as shown in Figure 6, with a ramp rate of around 26 MW_e/min. Overall, the GT performance and operability on HVO during the trial was determined to be acceptable.

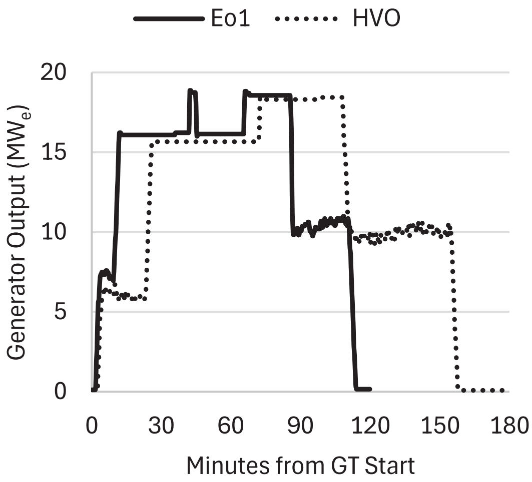

Fig. 5. Generator output (MWe) for Eo1 and HVO load profiles

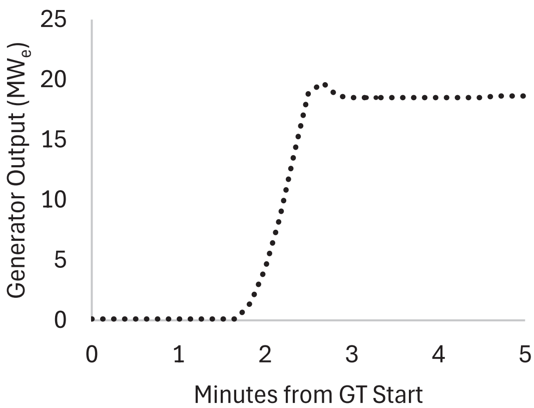

Fig. 6. Cold start, fast ramp load profile achieved by the P&W FT4 GT during BVT HVO trial.

3.3 Emissions

The use of HVO in the P&W FT4 GT results in similar or reduced exhaust gas emissions compared with Eo1 at peak load, base load, and part load. At each stable operating condition, flue gas emissions were measured by a certified third-party contractor sampling from the dedicated emissions stack for the GT in operation. Figure 7 plots the percentage change in average emissions during HVO operation (X_{HVO}) compared with Eo1 (X_{Eo1}) at each load condition, where X is the species given along the x-axis measured in mg/Nm^3 at dry, 15% O_2 reference conditions. Note that an extractive dust measurement at peak load with Eo1 was not taken during the trial due to time limitations, and therefore the relative change with HVO does not appear in Figure 7. However, the absolute value of the HVO dust measurement at peak load is nearly identical to that at base load, and so it is likely that HVO would also show a reduction relative to Eo1 at peak load.

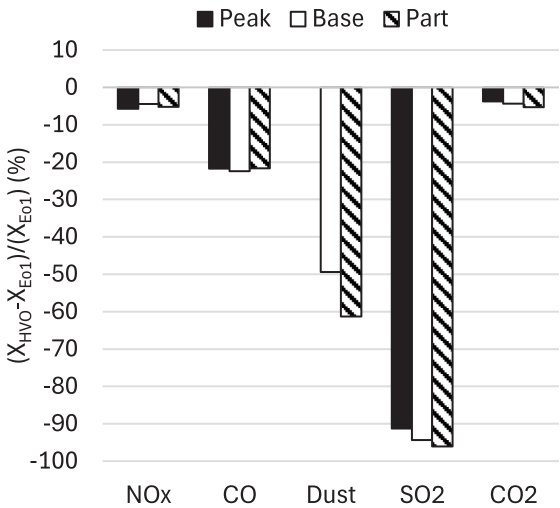

Fig. 7. Percent change in emissions between Eo1 and HVO in the BVT FT4 GT at peak load, base load, and part load.

When operating with HVO, all permitted emissions remained within the existing site emission limit values (ELVs) for Eo1 operation across these load points. Furthermore, Figure 7 shows that NO_x, CO, dust, SO_2, and CO_2 generally reduce at all load conditions when operating with HVO compared with Eo1. These improvements are achieved using the existing combustion hardware and GT control settings. SO_2 emissions reduced most significantly due to the lack of sulphur in the HVO (refer to Table 2). CO and CO_2 emissions were observed to reduce when using HVO, likely due to its increased hydrogen content relative to Eo1. Dust emissions reduced with HVO likely due to its lower aromatics content than Eo1. The reduction in NO_x emissions with HVO is within the expanded measurement uncertainty of the chemiluminescence method utilised (±10%). Other continuous measurements have expanded uncertainties of ±8-9% for CO, ±8% for CO_2, and ±272-410% for SO_2. The measured SO_2 concentrations are near the instrument detection limit, thus a high relative measurement uncertainty is obtained. For the non-continuous extractive dust measurement, the expanded uncertainty ranges from ±19% to ±91% with the uncertainty attributed to filter management accounting for roughly half of the expanded uncertainty.

At part load, HVO use reduces CO emissions by 21%. Therefore, the emissions-compliant turndown of the P&W FT4 GT could potentially be improved with HVO firing, improving the flexibility of the GT. While the higher hydrogen content of HVO will contribute to this, the work of Runyon et al. [1] proposed that HVO may have improved atomisation (and thus, fuel/air mixing) compared with fuel oil due to the similar viscosity, lower surface tension, and higher injection velocity due to the increased volumetric flow through the injectors. Improved fuel/air mixing would tend to promote combustion efficiency, particularly under part load conditions. This could also contribute to the observed reduction in NO_x emissions. However, changes in fuel/air mixing could impact the flame stabilisation location and accelerate combustion hardware degradation. No abnormalities in the combustion hardware were noted during the post-HVO operation borescope inspection, but total operating hours were limited.

Overall, the emissions trends observed during this HVO trial confirm what has been observed in other HVO trials using diffusion combustion systems [1,3,4]. HVO reduces combustion emissions relative to Eo1 while also offering a significant reduction in lifecycle CO_2 emissions.

3.4 Sustainability

The HVO supplier for the BVT trial was certified through a voluntary scheme. Voluntary schemes are recognised by the European Commission to ensure that biofuels, bioliquids, biomass fuels, renewable hydrogen, renewable fuels of non-biological origin (RFNBOs), and recycled carbon fuels (RCFs) are sustainably produced by verifying that they comply with the EU sustainability criteria. For HVO, voluntary schemes verify that feedstock production does not take place on land with high biodiversity or that conversion of land with high carbon content has not occurred to produce feedstock. Other sustainability aspects such as impacts to soil, air, and water may also be considered. To be certified under a voluntary scheme, a participant in the value chain must undergo an external audit to verify the production chain from the origin of the feedstock to the energy used by the fuel producer or trader.

For the HVO delivered to site during the trial, a PoS certificate was provided by the supplier which detailed the following information for compliance with the RED II requirements:

- Lifecycle GHG emissions from extraction or cultivation, land use, processing, and transport and distribution. This is expressed in gCO_2eq/MJ.
- HVO volume supplied
- Raw material (i.e., feedstock) and country of origin
- HVO production country
- Start date of the HVO production installation
- Scope of certification and GHG emissions, e.g., whether the HVO is compliant with EU RED and voluntary scheme requirements
- Scope of certification of the raw material, e.g., does it comply with relevant RED II sustainability criteria, cultivation requirements, indirect land use change criteria, and waste definitions.

Based on the information provided in the PoS, a volume-weighted CI for the HVO used in the trial was calculated to be 4.19 gCO_2e/MJ (equivalent to E in Equation 1). This is indicative of HVO derived from waste feedstocks and is significantly lower than the RED II typical CI for HVO produced from waste cooking oil (11.9 gCO_2e/MJ). To calculate the RED II electrical efficiency (η_{el}, see Section 2) for HVO use across the entire trial load profile, the total electricity produced (46.1 MWh_{el}) during the trial is divided by the total thermal input of HVO used in the trial (205.9 MWh_{th}). This yields a RED II efficiency, η_{el}, of 22.4%. The overall GHG savings from the trial are calculated using Equation 2. For the BVT trial, the RED II GHG savings were 89.8%, which exceeds the RED II GHG savings requirements for bioliquids by almost 50% (i.e., 30%pts), based on the HVO production start date given on the PoS. The GHG savings achieved in this trial also exceed the EU Taxonomy target of 80%.

4 HVO GT Conversions

Following the success of Uniper's HVO trials in Sweden, Germany, and the UK, two sites in Sweden (ÖVT and KVT) have since installed and commissioned permanent HVO storage to decarbonise their GT operations. The conversion of a further site in Sweden (BVT) is ongoing following the successful HVO trial conducted in June 2024 (see Section 3).

4.1 ÖVT G24 and G25

After conducting the world's first HVO trial on Unit G24 at ÖVT in July 2021 [1], a project was initiated to design and install a new, dedicated HVO storage tank to convert operations of ÖVT Units G24 and G25 to HVO whilst retaining the existing Eo1 storage and operational capability. Each unit at ÖVT consists of one, 63 MW_e Siemens V93.0 open-cycle GT which operates in the Swedish disturbance reserve [14, 15] representing a total GT capacity of 126 MW_e. In April 2023, a 100 m^3 storage tank was installed, as shown in Figure 8 [17].

Before filling the tank with HVO for the first time, a similar fuel analysis as shown in Table 2 was conducted, with the sample taken from the supplier's storage tank prior to transport to site by road tanker. This ensured that the initial HVO delivery met the required GT liquid fuel specification in addition to the requirements of the fuel standard to which the HVO was produced (i.e., EN 15940). Cold commissioning of tank protection systems, fuel valve positioning, and instrumentation was conducted during the summer of 2023.

Fig. 8. Installation of new dedicated HVO storage tank for G24 and G25 at ÖVT.

In September 2023, Units G24 and G25 were commissioned in HVO operation from the dedicated HVO storage tank. ÖVT G24 and G25 were the first GT units in the Uniper fleet and the Swedish disturbance reserve to convert to HVO.

Further GT operational and maintenance experience with HVO has been obtained at ÖVT over the past 18 months, including annual emissions testing conducted with HVO and silo combustion chamber inspections. The performance of the GTs has been consistent between Eo1 and HVO across seasonal ambient condition variation using the same combustion hardware and GT control settings. No significant findings were made during the combustor inspections.

Figure 9 shows a comparison of the full load NO_x emissions from the July 2021 G24 HVO trial [1] with annual emissions tests on G24 and G25 from November 2022 and November 2023. The measured NO_x emissions (mg/Nm^3, dry, 15% O_2) are normalised by the site NO_x ELV. The 2022 annual emissions test was conducted with Eo1, and the 2023 annual emissions test was conducted with HVO following the conversion.

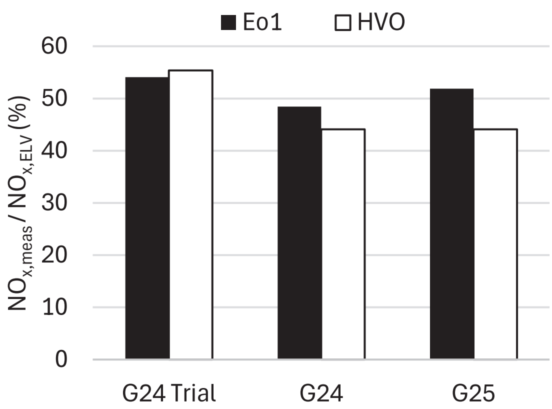

Fig. 9. ÖVT G24 and G25 relative NO_x emissions at full load as a function of the fuel type.

As shown in Figure 9, NO_x emissions with HVO and Eo1 are well within the site's permitted ELV. The G24 trial NO_x emissions are higher than the 2022 and 2023 annual tests due to higher ambient temperatures. Additionally, while the G24 HVO trial demonstrated a slight increase in NO_x emissions with HVO (within the measurement uncertainty), a comparison of the 2022 and 2023 annual emissions tests shows a more substantial reduction in NO_x with HVO. This trend will be monitored during future annual emissions tests to determine if optimisation of NO_x water injection is possible, but it can be concluded that HVO has not significantly increased NO_x emissions in the ÖVT GTs. HVO emissions results from the 2023 annual test also confirmed a number of trends relative to Eo1 from the 2021 G24 trial [1], namely:

- Greater than 95% reduction in SO_2 emissions.
- Reduction in dust emissions.
- Reduction in CO emissions.
- Reduction in flue gas CO_2 emissions.

These improvements are mainly the result of the fuel quality of HVO and are achieved using the existing GT control settings (e.g., no change in water injection rate).

4.2 KVT G13

In August 2022, Uniper conducted an HVO trial on a Rolls-Royce Olympus aeroderivative GT in an engine test facility in the UK [3, 4]. GT performance and emissions measurements confirmed the suitability of HVO as a fuel for the Olympus GT, however, power generation using HVO could not be demonstrated in the test facility (i.e., an exhaust nozzle is attached to the GT to simulate the backpressure of the power turbine). Following this successful trial and the HVO conversion experience gained at ÖVT, a project was initiated to install a dedicated HVO tank to decarbonise the operations of Unit G13 at KVT in Sweden [18]. Similar to the installation at ÖVT, the installation of the new tank at KVT enables the site to retain its existing Eo1 storage and operational capability. KVT G13 consists of two, 18.5 MW_e Rolls-Royce Olympus GTs used as gas generators for a single 37 MW_e power turbine and generator. KVT G13 also operates in the Swedish disturbance reserve and, similar to the aeroderivative GTs at BVT, it is typically one of the first units to be dispatched [14]. In December 2024, KVT G13 was commissioned on HVO supplied from the new storage tank (shown in Figure 10). This represents the second site in the Uniper fleet and Swedish disturbance reserve to be converted to HVO. The hot commissioning tests also demonstrated power generation from Olympus aeroderivative GTs for the first time.

Fig. 10. New dedicated HVO storage tank for KVT G13.

HVO was successfully utilised at KVT G13 with the existing GT combustion hardware and control system settings. The impacts of the HVO fuel conversion on emissions will be assessed during future annual emissions tests. Among numerous starts and load profiles executed during the HVO commissioning, Figure 11 provides an example of a warm, fast start to peak load achieved with HVO, demonstrating a ramp rate of around 34 MW_e/min with acceptable engine vibrations.

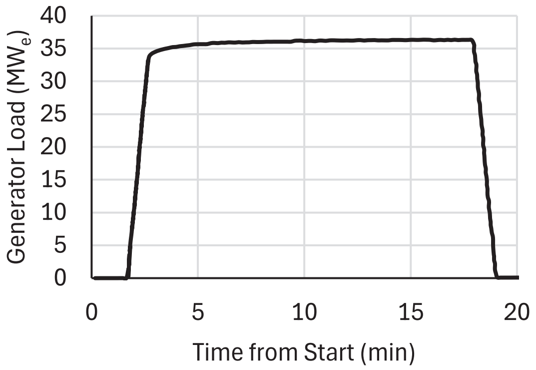

Fig. 11. Fast ramp load profile achieved during HVO commissioning of KVT G13 Olympus GTs

4.3 BVT G13 and G14

Based on the results of the HVO trial conducted at BVT in June 2024 (see Section 3), a third conversion project has since been initiated to install a dedicated HVO storage tank at BVT to decarbonise the operations of G13 and G14 [18] while retaining the existing Eo1 storage and capability. Figure 12 shows the installation of the new HVO tank on site in December 2024. Commissioning of BVT G13 and G14 in HVO service using this new tank is anticipated in 2025.

Fig. 12. Installation of new dedicated HVO storage tank at BVT.

5 Conclusions

Since Uniper first tested HVO in a GT in July 2021, industry interest in its use to decarbonise dispatchable power generation has increased significantly for both retrofit and new build installations. HVO enables rapid decarbonisation of liquid fuel and dual-fuel GT capacity in the short-term with lifecycle GHG savings of approximately 90% demonstrated when calculated in accordance with the methodology set out in the RED II.

However, the use of HVO in GTs is still a nascent application for this fuel, with most experience to date instead occurring in the transport industry. Therefore, field trials are essential 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 performance, emissions, and reliability compared with long-established liquid fossil fuels such as diesel and fuel oil. To address this need, the authors have detailed a successful trial and commercial conversions to HVO in Uniper's GT fleet. HVO has been demonstrated as a low-carbon, drop-in replacement fuel for liquid fossil fuel in these GTs using the existing hardware and control system settings. This significantly reduces the time, cost, and unavailability while converting existing GT capacity and retains the ability to use fossil fuels if required. Other positive factors from HVO use have been identified such as use of existing transport and storage infrastructure and similarities with current fuel handling and safety procedures. HVO also reduces key permitted emissions such as SO_2, dust, and CO, improving local air quality relative to diesel or fuel oil.

In this work, the authors have also detailed the crucial sustainability requirements related to CI and GHG savings associated with the use of HVO in power generation applications. This has been presented in the context of both the EU RED II regulations and the EU Taxonomy and identifies a key discrepancy between the GHG savings requirements of each regulation. Discrepancies are also identified within the EU Taxonomy between bioenergy applications and requirements for carbon reductions from gas-fired power generation for climate change mitigation. Regardless of the EU regulation under consideration, it is likely that only HVO derived from waste feedstocks will meet the necessary sustainability criteria for use in GT power generation.

Additional development needs for the use of HVO in GTs include extending its use to more advanced combustion systems such as dry LPP systems, long-term operability and impacts on maintenance intervals, and a systematic evaluation of quality impacts from feedstock variation and long-term storage. Further work is also required to raise awareness amongst regulators and policy makers of the role that HVO can play in the future energy system to complement other dispatchable power generation technologies and variable renewable energy sources.

HVO enables rapid decarbonisation of existing liquid fuel and dual-fuel GT capacity in the short term while other low-carbon solutions are developed, such as hydrogen and CCS which require more extensive infrastructure and are more challenging to retrofit. HVO can also be used as either a pure fuel or blended with diesel or fuel oil, providing further flexibility in the short term while maintaining fossil fuel capability for security of supply. Through trials and commercial retrofits, Uniper has demonstrated that HVO will have a role to play in achieving its carbon neutrality target by 2040.

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