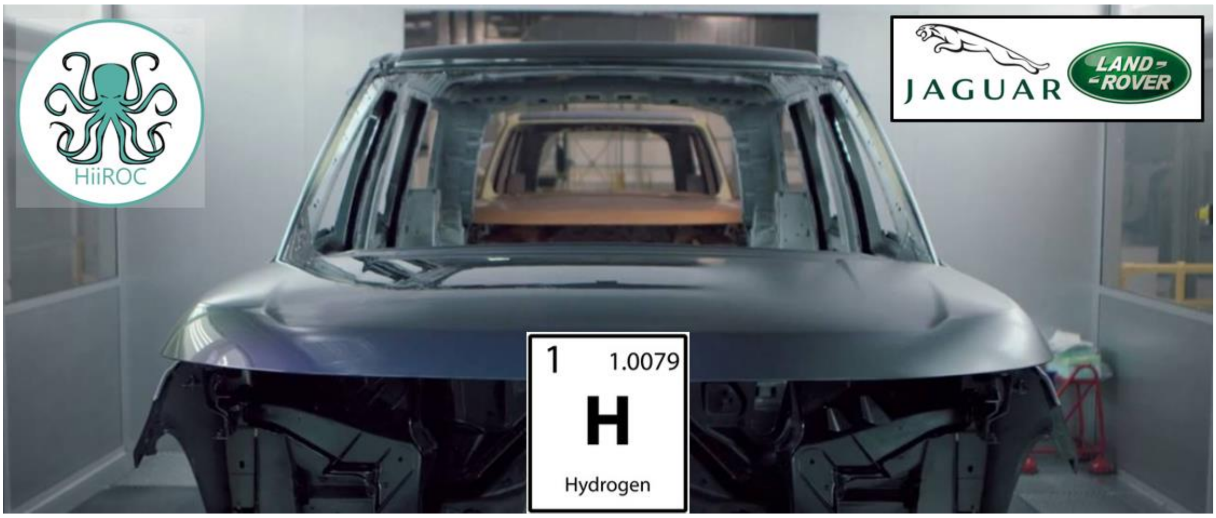
HiiROC-X Developments Ltd

Industrial Hydrogen Accelerator Feasibility Study Stream 2A Summary Report

V001-PM-REP-0001

Department for Energy Security and Net Zero



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Draft 00	27/01/23	Draft	Draft for comment
01	01/03/23	J. Clark	Updated to address Fraser Nash comments as far as practical given the nature of the feasibility study.
02	30/03/23	J Clark	Updated draft following feedback
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Nomenclature

Nomenclature	Definition
The Team or Team or We	HiiROC-X limited, CNG Services, Jaguar Land Rover

Abbreviation

Abbreviation	Definition
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CB	Carbon Black
CHP	Combined Heat and Power
CH4	Methane (Natural Gas)
CO	Carbon Monoxide
CO2	Carbon Dioxide
CPA	Cubic Plus Association
CSL	CNG Services Ltd
DNO	Distribution Network Operator
ESP	Electrostatic Precipitation
GHG	Green House Gas
GWP	Global Warming Potential
H2	Hydrogen
H2O	Water
IHA	Industrial Hydrogen Accelerator
JLR	Jaguar Land Rover
MWh	Mega Watt Hour
NO2	Nitrous Oxides
NOx	Nitrous Oxides
OPEX	Operational Expenditure
R&D	Research & Development
SME	Small to Medium sized Enterprise
TPE	Thermal Plasma Electrolysis
UV	Ultraviolet
VOC	Volatile Organic Compound
WBS	Work Breakdown Structure
W-ESP	Wet Electrostatic Precipitation
WP	Work Package

Normative References

ID	Description	Revision
1	*https://hiiroc.com*	n/a
2	*Ford advances eco-friendly fumes-to-fuel technology (reliableplant.com)*	n/a
3	*(PDF) VOC Emissions from Automotive Painting and Their Control: A Review (researchgate.net)*	n/a
4	*https://birlacarbon.wpenginepowered.com/wp-content/uploads/2020/03/Birla-Carbon-Brochure-Rubber-Products-Guide-v4.pdf*	n/a
5	*Title: "Hydrogen gas curing of waterborne acrylic automotive coatings" Authors: R. Di Venere, A. Mirabile, and V. Sabatino Journal: Progress in Organic Coatings Volume: 79 Pages: 1-6 Year: 2015*	n/a
6	*https://www.thestar.com/business/tech_news/2008/09/29/automaker_harvests_paintshop_emissions.html?rf*	n/a
7	https://digital.library.unt.edu/ark:/67531/metadc673099/m2/1/high_res_d/219518.pdf	n/a
8	Energies | Free Full-Text | Catalytic Hydrogen Combustion for Domestic and Safety Applications: A Critical Review of Catalyst Materials and Technologies (mdpi.com).	n/a
9	Birla-Carbon-Brochure-Rubber-Products-Guide-v4.pdf (birlacarbon.wpenginepowered.com)	n/a
10	Recovered Carbon Black Market Global Forecast to 2028 | The Insight Partners	n/a

1 Executive Summary

The focus of this study was to investigate the feasibility to deploy HiiROC's Thermal Plasma Electrolysis (TPE) technology on industrial paint-shop exhaust gases, to eliminate the toxic Volatile Organic Compounds contained within them, converting these compounds to elemental carbon and hydrogen. The study has researched the feasibility of application to Jaguar Land Rover's (JLR's) paint shop operations in Solihull and broader application to other coating processes within the UK's automotive and manufacturing industries. The TPE technology would replace existing thermal oxidisers, which burn natural gas from the mains to incinerate the Volatile Organic Compounds (VOC) that are in the exhausts from the paint shop ovens. Instead of emitting tonnes of Carbon Dioxide (CO2), the VOC would be converted to hydrogen and elemental carbon, with the hydrogen being available to replace some of the natural gas consumed within the plant, further reducing the CO2 emissions from the site. Table 1 below shows the emissions from the traditional thermal Oxidiser and the TPE per kg of VOC Feed.

	Emissions (kg/kg VOC)	
	TPE	Thermal Oxidiser
CO2		2.2352
C	0.6102	
H2	0.0847	
H2O	0.3051	1.0674

Table 1 - Comparison of emissions from TPE and thermal oxidiser

JLR, as a leading Automotive Manufacturer, operates several vehicle coating applications at its Solihull Plant. The Paint Application Processes include the Mainstream Paint Shop and additional Satellite facilities for 'on-wheels' repairs. Refer to figure 1 below.

These processes require a number of natural gas fired paint curing ovens with high-energy demands (61% of the overall manufacturing sites natural gas demands). The ovens within the main Paint Facility emit a mixture of CO, CO_2, NOx and VOCs. VOCs within the exhaust are oxidised (in a further Thermal Abatement process consuming additional Natural Gas) to reduce VOC content before being emitted. If not treated, high levels of VOCs have negative local environmental effects, including ozone (smog) formation. The Satellite Paint Facilities follow a similar curing process also emitting VOCs.

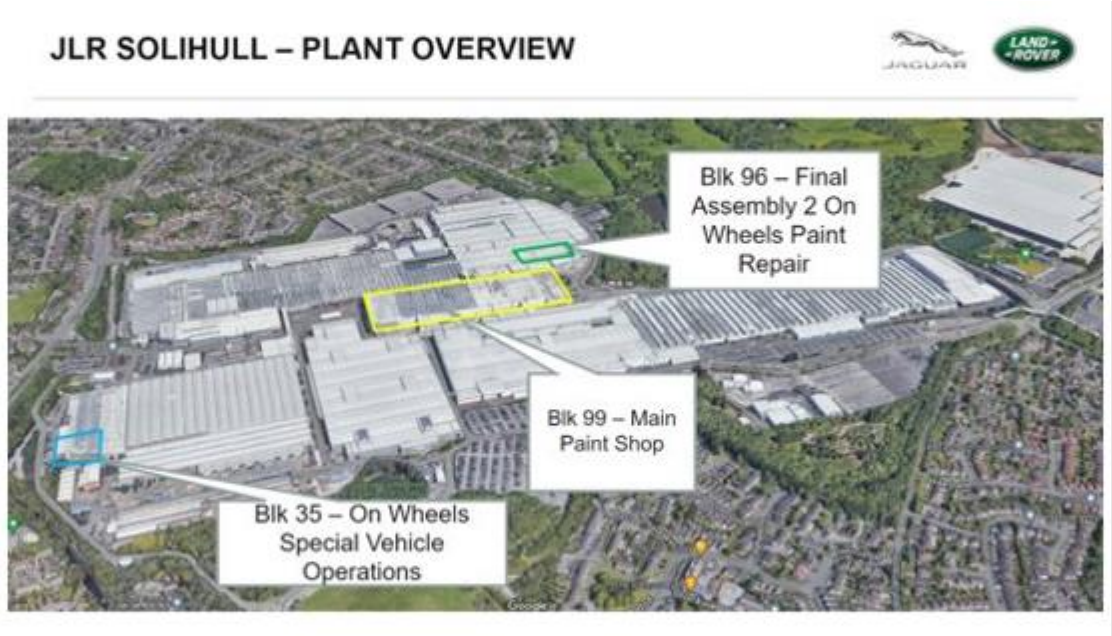

Figure 1 - Jaguar Land Rover Site Layout and Paint shop locations

Current CO_2 emissions are estimated at 38,600te CO_2/yr (refer appendix JLR Solihull Emission summary). HiiROC are developing a novel new technology that uses plasma to break down gasses. This unique, patented process called Thermal Plasma Electrolysis (TPE) uses electricity to create a plasma which splits hydrocarbon gases into solid Carbon Black (CB) and Hydrogen. Whilst the TPE process has so far primarily been applied to natural gas or bio-methane, TPE also works effectively to break down other hydrocarbon gasses into their base components. Exhaust gases from the JLR paint processes contain hydrocarbon VOCs which the TPE process can convert into Hydrogen and solid carbon.

CB is an established valuable commodity widely used in the production of tyres and UV-resistant rubbers and plastics. It is typically produced in specialist fossil-fuel fired furnaces that operate purely to produce CB and so carries significant embedded carbon emissions.

This IHA (Industrial Hydrogen Accelerator) Stream 2A Feasibility study had the key objective of determining the feasibility to extract the VOCs from the JLR paint process exhaust streams, for them to be broken down into Hydrogen and Carbon in the HiiROC TPE system. Further, the study aimed to look to see how the hydrogen generated by the TPE and other sources could be used within the JLR Solihull site.

This study was broken down into eight work packages:

WP1	Management
WP2	Establish a method for recovering VOC Sample from Paint Shop Exhausts
WP3	Testing sample in TPE to prove the concept
WP4	Model Potential JLR Options
WP5	Impact of using H2 in Paint quality; Establish how to blend H2 into site fuel system
WP6	Establish commercial markets for Carbon Black
WP7	Design and costing for IHA Phase 2B
WP8	Review Commercial Opportunities for the technology in JLR site at Solihull

The first part of the study researched the volume and types of VOC present in the exhaust gas streams, and all other gas constituents. Socotec ran several tests to identify the volumes and most commonly occurring types of VOC in the exhaust gases. Work Package 2 (WP2) was focussed on the feasibility of gas extraction and VOC separation. An initial aim of extracting a small amount of the VOCs from the exhaust gas stream for testing in the TPE was technically unfeasible. The temperature, and dilution of the VOCs in the exhaust gases proved this sampling to be unfeasible in the time allocated to Stream 2A, and not commercially viable in terms of cost to cool, capture and transport. Therefore, extensive desktop modelling of an integrated system for extraction and processing via TPE was investigated. A theoretical evaluation of the ability of TPE to reduce the VOC was conducted and it was concluded that TPE would reduce CO_2 emissions due from VOCs by over 90% compared to conventional combustion by Thermal Oxidiser.

To assess the feasibility of separating VOC from the paint oven airstream, five potential extraction techniques were investigated and, while some were technically feasible, the significant heating and cooling requirements meant that the extraction process was commercially unfeasible. It was concluded that, although the HiiROC TPE system remains capable of dealing with the VOC streams and volumes emitted from the entire JLR site in undiluted form, the high level of dilution with air rendered the overall process commercially unfeasible.

Consideration was given to how hydrogen could improve the operations at JLR's Solihull facility (WP5). Hydrogen has been found to improve the painting process in other car plants worldwide[2, 6] and it could be blended with natural gas to reduce the greenhouse gas emissions from the thermal oxidiser. However, to do so would increase the NOx emissions above acceptable levels if the concentration was above 3%, unless it was 100% Hydrogen and not a blend with gas from the grid. Something that has not been explored in detail during this study but is known about by the study team is the ability to have Hydrogen oxidised and release the heat from that process using catalytic combustion. In this case the air and hydrogen are pre-mixed, and the oxidation happens over a catalyst. The temperatures involved in this process are lower than flame combustion keeping below the temperature necessary for NOx formation. If we have a blend of Hydrocarbons in the fuel feed stream, catalytic combustion is less easily achieved[5] (5 *R. Di Venere, A. Mirabile, and V. Sabatino Journal).*

Finally, in WP8 we considered what commercial options there would be for the TPE technology should it be adopted at JLR site in Solihull. We looked at existing fuel gas uses and considered how emissions and costs could be improved if the mains gas was converted to hydrogen in a TPE unit before hydrogen combustion. This would give a financial saving in carbon tax as there would be no CO_2 emissions, and there would also be a commercial return on the carbon black that was manufactured as a by-product.
Adopting this approach will result in increased natural gas costs and electrical power costs to fire the TPE, but these costs can be offset against the reduction in Carbon Tax and the income from the Carbon Black.

Three options were considered for use of the hydrogen produced in the TPE unit.

1. Combined Heat and Power system
2. Using 100% H2 for the fuel to the Thermal Oxidiser
3. Using 100% H2 for the fuel to the paint shop ovens.

The outcome of these studies can be shown in Table 2. There is an overall increase in electrical power and natural gas consumption, but these additional costs are more than offset by the reduction in CO2 emissions and the income that can be generated from the sale of Carbon Black.

	Additional Natural Gas				Additional electric power			Carbon Black			Carbon Tax				
	kg/hr	MW equivalent	cost per kWhr	cost (£/day)	kW	cost per kWhr	cost (£/day)	kg/hr	Value (£/kg)	Income (£/day)	Reduced emissions (kg/hr)	cost (£/Te)	saving	Output	Net Cost (£/day)
CHP	218	3.30052	£ 0.03	£ 2,693.00	-65	£ 0.20	-£ 312.00	164.00	£ 1.00	£ 3,936.00	-	£ 100.00	£ -	750kW heat; 65kw Electricity	-£ 1,555.00
Thermal Oxidiser	197	2.98258	£ 0.03	£ 2,433.58	1800	£ 0.20	£ 8,640.00	439.00	£ 1.00	£ 10,536.00	1,070.00	£ 100.00	£ 2,568.00	Replace existing TO	-£ 2,030.42
Power for Oven	749	11.33986	£ 0.03	£ 9,252.56	7000	£ 0.20	£ 33,600.00	1,800.00	£ 1.00	£ 43,200.00	4,540.00	£ 100.00	£ 10,896.00	25MW heat to paint shop	-£ 11,243.44

Table 2 - Summary of Financial Benefits of Adopting TPE Technology

Taking account of the carbon intensity of electricity supply at 265g/kWh we would have to consider net GHG emissions as follows in table 3 below:

	CO2 Emissions		
	Electricity	TPE process + heat generation	net change
CHP	-17	0	-17
Thermal Oxidiser	477	-1070	-593
Power to oven	1855	-4540	-2685

Table 3 - Overall change in carbon emissions in kg/hr

Swapping both the Thermal Oxidiser and the Paint Shop ovens to H2 supply, with the H2 being manufactured on site using TPE technology, would show an overall reduction in carbon emissions. The CHP, producing 65kW of power, will have a small reduction in greenhouse gas emissions due to the fact that there will be zero emissions from the generation.

All three make commercial sense from an OPEX perspective, however, the two options that provide replacement fuel gas to the Thermal Oxidiser and the Ovens will require significant electrical power increases to the plant. Further conversations will be needed with the distribution network operator (DNO) on the cost of supplying additional electricity to the site. We know that there are current constraints in the area, meaning a significant and costly upgrade will be required. The Thermal Oxidiser at just below 2MW may be feasible, but it is unlikely that the 7 MW required to generate the hydrogen for the ovens would be economically possible.

Further to this, GHG emissions are reduced in carbon black production manufactured this way and not using traditional methods. Table 4 below shows the emissions that could be expected from producing a tonne of Carbon Black traditionally and by TPE. No value is associated to this in Table 1 as this would not be an economic gain to JLR, however it would reduce the global emissions.

Chemical Substance	Oil Furnace Process	HiiROC Process	Emissions avoided for 1kt p.a.
CO_2	2000kg/tonne	0	2,000 tonnes
Carbon disulfide	30kg/tonne	0	30 tonnes
Carbonyl sulfide	10kg/tonne	0	10 tonnes
Methane	25kg/tonne	0	25 tonnes
Acetylene	45kg/tonne	0	45 tonnes
Ethane/Other	2kg/tonne	0	2 tonnes

Table 4 - Carbon Black Emission comparison by Production Method

2 Introduction

The focus of this study is to investigate the feasibility of deploying HiiROC's unique, patented process which uses electricity to create a plasma that splits hydrocarbon gases into solid Carbon Black (CB) and Hydrogen, the Thermal Plasma Electrolysis (TPE) technology on industrial paint-shop exhaust gases. The study has researched the feasibility of application to Jaguar Land Rovers (JLR's) paint shop operations in Solihull and broader application to other coating processes within the UK's automotive and manufacturing industries.

During the paint curing process, in gas fired ovens, Volatile Organic Compounds (VOCs) are released. To ensure that these potentially dangerous vapours do not enter the environment they are incinerated in a Thermal Oxidiser, which is fuelled by Natural Gas. This study hopes to prove that instead of burning natural gas and allowing the VOC's to form a CO_2 emission of ~35-45Te/Year, the VOC can be captured and converted to Hydrogen and Carbon Black in HiiROC's Thermal Plasma Electrolysis (TPE) process. This would go a considerable way to reducing the CO_2 emissions for the painting process, by eliminating them from the VOC vent.

This IHA (Industrial Hydrogen Accelerator) Stream 2A Feasibility study had the key objective of determining the feasibility to extract the VOCs from the JLR paint process exhaust streams and for them to be broken down into Hydrogen and Carbon in the HiiROC TPE system.

2.1 How the Technology Works

HiiROC[1] have developed a novel plasma process to produce Hydrogen in a compact, cost-effective zero-emission manner. The technology has been honed for several years and is now one of the most advanced plasma technologies in the world For the core HiiROC process (hydrogen production) this means that passing through a hydrocarbon efficiently breaks it down into Hydrogen and Carbon (in a solid form as a 'Carbon Black' CB).

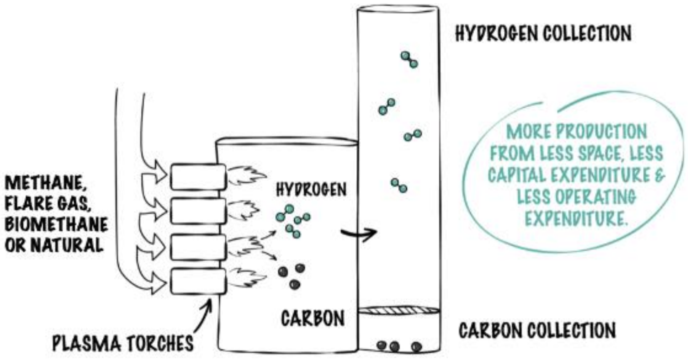

Figure 2 – HiiROC Thermal Plasma Electrolysis Process

The system contains 50 KW plasma torches, which disassemble all gasses that are passed through the system. The electrical field in the plasma torch breaks down the hydrocarbon, but in creating the hydrocarbon plasma the temperature reaches a level where the carbon is vapourised. It is then very quickly cooled in the second reaction chamber.

This patented process is unique for several reasons. It is the electrical field that breaks down the gasses in the torch, not heat. Hence the reason the technology is called Thermal Plasma Electrolysis. This is different to methane pyrolysis – which uses heat to break down the hydrocarbon. By vaporising the carbon in the torch this mitigates issues around carbon condensing within the torch and enables the TPE technology to be a continuous flow process, not a batch process. The TPE technology operates at pressure from 25- 50 bar, which enables unrivalled conversion rates and mass throughput. This means that for the size of the unit, a HiiROC system can create significantly more hydrogen than other similar systems. See table below:

	Monolith	Hazer	C-Zero	Transform Materials	HiiROC
Process	Methane Pyrolysis with minature plasma	Biomethane Pyrolysis	Thermocatalytic Pyrolysis	Microwave Plasma	Thermal Plasma Electroylsis
Focus	Carbon Black	Carbon Black & Hydrogen	Hydrogen	Hydrogen & Acetylene	Hydrogen
Reaction Temperature	Low	Low	Low	?	>6000^{o}C
Ultrafast Reaction	X	X	X	✓	✓
Pressure	Atm	0-8bar	10 bar	?	>50 bar
Footprint$_2$/kgH$_2$/day	2m$_2$	>3m$_2$	0.04m$_2$	>	0.04m$_2$
Coversion Efficiency	97%	60%	70%	90%	>99%
Avoid Catalyst	✓ (no catalyst needed)	X (continuous iron ore feed)	~ (closed loop catalyst)	✓ (no catalyst needed)	✓ (no catalyst needed)
Scale & Capex	Industrial	Industrial	Semi Industrial	Semi Industrial (?)	Modular and Scalable 0.1-1,000 tonnes/ day

Table 5 - HiiROC Competitor Comparison

2.2 Output from the Study

This study was broken down into eight work packages.

WP1	Management
WP2	Establish a method for recovering VOC Sample from Paint Shop Exhausts
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WP4	Model Potential JLR Options
WP5	Impact of using H2 in Paint quality; Establish how to blend H2 into site fuel system.
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WP7	Design and costing for IHA Phase 2B
WP8	Review Commercial Opportunities for the technology in JLR site at Solihull.

As WP4 and WP7 could not be undertaken due to the inability to commercially extract a sample of the VOC’s from the study, there is nothing to report, however the outcomes from the other work along with the results obtained is discussed in this section.

2.3 Develop a Project Charter, Project Plan and Management.

HiiROC developed a set of core objectives for the Stream 2A elements of the IHA programme:

1. Establish a means to measure and analyse waste gas content.
2. Establish and demonstrate an effective solution for capturing and storage of waste gas for processing.
3. Confirm that paint process waste gas produces sufficient hydrocarbon composition for thermal plasma electrolysis.
4. Determine an optimal TPE solution for JLR based on gas volume and outflow location.
5. Establish a viable commercial solution for carbon generated via TPE process.
6. Establish a viable technical solution for the use of hydrogen generated via TPE process.
7. Develop a final proposal that determines the route to exploitation of waste gas conversion at JLR.

From these high-level objectives, eight work packages were developed that would deliver the outcomes needed to achieve the objectives within a defined framework of a Work Breakdown Structure (WBS).

Of the eight packages of work, much of the activity was undertaken by HiiROC, working with other small to medium sized Enterprises (SMEs) and coordinating our activity with JLR.

The HiiROC scope contained Project planning and management, measure, analyse, capture and test waste gases, modelling potential TPE process, high level system design and site deployment, carbon black analysis, sampling, and exploitation routes and finally to define how HiiROC and JLR leverage this learning through dissemination.

JLR's scope was defined as the site planning and infrastructure design to accommodate the proposed TPE process, power, facilities and operations at the Solihull site, research into hydrogen, blending and how we could use hydrogen within the paint process.

In parallel to the scope definition, planning and execution, HiiROC working with JLR and CNG Services developed the risk profile for the project. It became clear to HiiROC from the initial stages of WP2 that the capture of waste gases and the conversion into a format that could be used within the TPE process carried significant risk. The technology for capturing waste gases was novel. As we worked through the feasibility of waste gas capture, it became clear that the risks around this were likely to be realised. The realisation that the gas capture elements were unfeasible in terms of timescales and cost for this phase and in terms of energy efficiency at the operational stage fundamentally changed the approach to how we delivered this phase of work.

With a mid-September starting point and a delivery in late January of all eight work packages, it became clear that without the ability to physically capture and compress the VOCs from the waste gas and proceed to a physical test, much of the work HiiROC could deliver within the timeframe was going to be desktop analysis based. The project team dynamically and reactively changed the feasibility study to remove any deliverables that would no longer be needed and change the final scope in WP 8 to look at other ways HiiROC TPE hydrogen could be used in the JLR facility.

3 WP 2 – Measure, Collect and Test VOCs from waste gas.

3.1 Introduction

The intent of this work package was to obtain a large enough sample of the Volatile Organic Compounds (VOC) to allow them to be processed in HiiROC's Hull facility to prove that the plasma torch could reduce them to Hydrogen and Carbon Black.

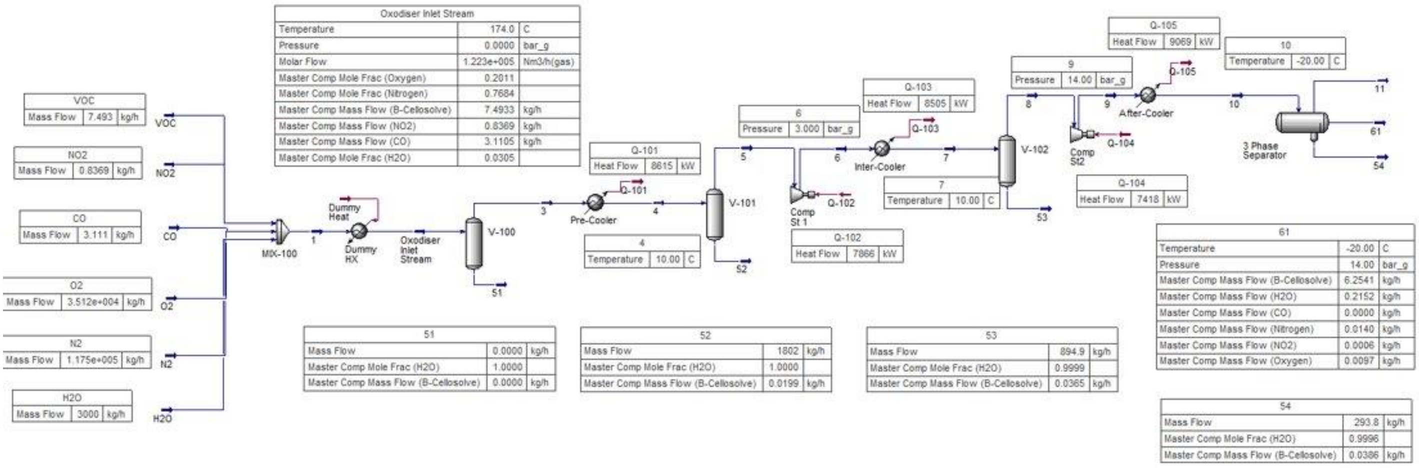
The technology required to do this was considered by an SME, CNG Services Limited (CSL). Because the VOCs are significantly diluted in the air carrying them from the paint shop, large plant would have to be deployed to obtain a small sample. This plant would cool and compress the air and VOC mixture until we get to a point where the VOC would condense, giving us a liquid sample. Therefore, to obtain a sample would require plant that would cost more than was budgeted for in this Feasibility Study and further it would take longer to design, procure and install than there was time in the study schedule. *(Ref Deliverable 2.2 Summary in Annexe)*

Not being able to obtain a sample highlighted the fact that it may not be practical at all to recover the VOC from the air stream that carried them to the Thermal Oxidiser. Consequently, some effort was made to establish what technologies could be deployed to achieve this aim, this is described in some detail below, but suffice to say that none were found. *(Ref Deliverable 2.2 Summary in Annexe)*

Not being able to physically test the VOC in a plasma torch was a set-back for the study, but a desktop analysis was carried out on what the likely outcomes would be and what, if any, modifications would be required to the torches to improve their efficiency to process this feedstock.

3.2 Obtaining a sample from the feed to the Thermal Oxidiser

CSL developed a process design that would allow the VOC laden exhaust stream to be cooled and a liquid sample recovered.



Oxodiser Inlet Stream		
Temperature	174.0	C
Pressure	0.0000	bar_g
Molar Flow	1.223e+005	Nm3/h(gas)
Master Comp Mole Frac (Oxygen)	0.2011	
Master Comp Mole Frac (Nitrogen)	0.7684	
Master Comp Mass Flow (B-Cellosolve)	7.4933	kg/h
Master Comp Mass Flow (NO2)	0.8369	kg/h
Master Comp Mass Flow (CO)	3.1105	kg/h
Master Comp Mole Frac (H2O)	0.0305	

51		
Mass Flow	0.0000	kg/h
Master Comp Mole Frac (H2O)	1.0000	
Master Comp Mass Flow (B-Cellosolve)	0.0000	kg/h

52		
Mass Flow	1802	kg/h
Master Comp Mole Frac (H2O)	1.0000	
Master Comp Mass Flow (B-Cellosolve)	0.0199	kg/h

53		
Mass Flow	894.9	kg/h
Master Comp Mole Frac (H2O)	0.9999	
Master Comp Mass Flow (B-Cellosolve)	0.0365	kg/h

61		
Temperature	-20.00	C
Pressure	14.00	bar_g
Master Comp Mass Flow (B-Cellosolve)	6.2541	kg/h
Master Comp Mass Flow (H2O)	0.2152	kg/h
Master Comp Mass Flow (CO)	0.0000	kg/h
Master Comp Mass Flow (Nitrogen)	0.0140	kg/h
Master Comp Mass Flow (NO2)	0.0006	kg/h
Master Comp Mass Flow (Oxygen)	0.0097	kg/h

54		
Mass Flow	293.8	kg/h
Master Comp Mole Frac (H2O)	0.9996	
Master Comp Mass Flow (B-Cellosolve)	0.0386	kg/h

Figure 3 – PFD of chilling process to obtain VOC sample for TPE trial

The process compresses and cools the gas to obtain a liquid sample. To cool it alone would require significant cryogenic temperatures to be reached, however the saturation point of air as it is compressed, rises, so there is an optimum to be achieved of compressing the exhaust stream and cooling it to a temperature that can be readily achieved without significant refrigeration systems.

The air from the paint shop exhaust is cooled to 10 °C from the oven operating temperature of 174°C, this results in a small amount of water being condensed. The cooled gas is then compressed from atmospheric pressure to 3 barg and again cooled to 10 °C, at this point more water is condensed from the stream. The gas is further compressed to 14 barg and cooled cryogenically to minus 20 °C, this gives us a VOC stream that could be tested in the TPE.

The option wasn't pursued due to cost and schedule constraints. There would be a need to optimise the design, then carry out detailed design work to develop a system that could. This would take a significant time. Then there would the lead time for the equipment items and the time to assemble, test and commission them on site. This would take significantly longer than the 12 months to carry out the work and be deployed at JLR's site. Further it would incur significant CAPEX for a system that would only be used to collect samples for this study and then be redundant with little chance of recovering the capital cost of the equipment and no chance of recovering the costs of designing, building and demolishing the system. There was general agreement from all stakeholders that pursuing this option was not feasible.

3.3 Ongoing Emissions sampling

The waste exhaust gas includes air which is drawn in with the VOCs in the JLR painting and curing processes and is currently gathered in a common waste gas header for the main paint facility. This waste gas header feeds into a thermal oxidiser with the aim of breaking down the VOCs into less harmful components, before being released via a vent stack to the atmosphere. The intent was to ultimately use the HiiROC TPE system to replace the thermal oxidiser using the VOCs as a feedstock to enable the production of hydrogen for use in other applications on the JLR site.

VOCs are not considered greenhouse gases in the same sense as carbon dioxide (CO2), methane (CH4), and other gases that contribute to global warming.

However, VOCs can indirectly contribute to climate change by participating in chemical reactions that produce other air pollutants, such as ozone (O3) and particulate matter (PM), which can have direct and indirect effects on the climate. For example, ground-level ozone is a potent greenhouse gas and a harmful air pollutant that can cause respiratory problems in humans and damage crops.

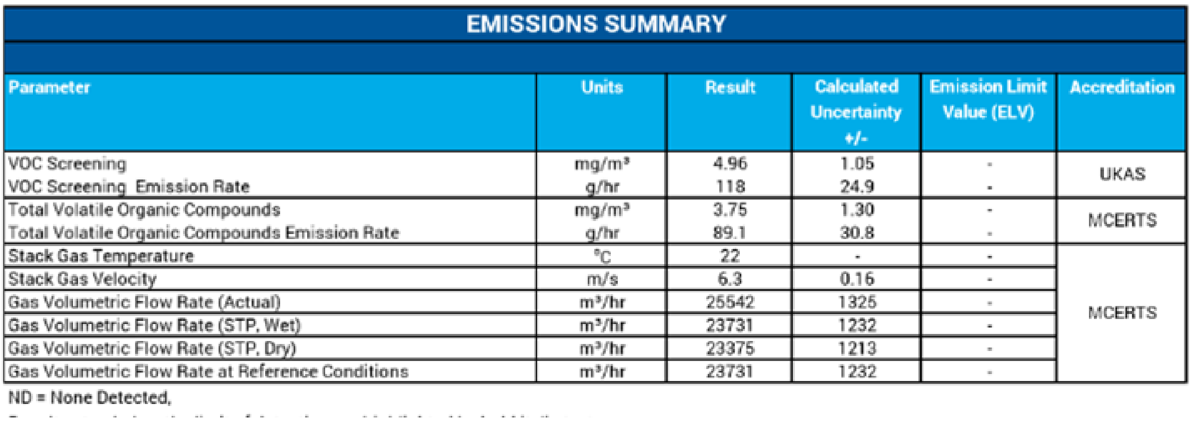
Ozone is a potent greenhouse gas that can contribute to global warming, and it is formed through complex photochemical reactions involving VOCs and other pollutants. Particulate matter can also have indirect effects on the climate by altering the Earth's radiation balance and affecting cloud formation.

The precise quantification of the greenhouse gas effect of VOCs is complex and depends on various factors such as the type of VOC, the concentration, the atmospheric conditions, and the local climate. This means there is no straightforward equivalence between VOCs and CO2e. However, when we identify the most prevalent VOC in the waste gases at JLR, we can ascertain the molecular weight in terms of carbon, and estimate the amount of CO2e that would have been emitted if the VOC were to be oxidised taking the carbon molecule to CO2.

Therefore, reducing emissions of VOCs can have multiple benefits, including improving air quality and reducing the overall impact on the environment and climate change.

Waste gas samples are regularly taken, as part of the JLR site permitting requirements, both upstream and downstream of the thermal oxidiser for the purposes of monitoring VOC emissions to atmosphere. This work is undertaken by a third party, Socotec, which is contracted by JLR. The results are provided by Socotec in the form of

Stack Emissions Monitoring Reports. A Typical report from October 2022 is shown in table 6 below.



EMISSIONS SUMMARY

Parameter	Units	Result	Calculated Uncertainty +/-	Emission Limit Value (ELV)	Accreditation
VOC Screening	mg/m³	4.96	1.05	-	UKAS
VOC Screening Emission Rate	g/hr	118	24.9	-	
Total Volatile Organic Compounds	mg/m³	3.75	1.30	-	MCERTS
Total Volatile Organic Compounds Emission Rate	g/hr	89.1	30.8	-	
Stack Gas Temperature	°C	22	-	-	MCERTS
Stack Gas Velocity	m/s	6.3	0.16	-	
Gas Volumetric Flow Rate (Actual)	m³/hr	25542	1325	-	
Gas Volumetric Flow Rate (STP, Wet)	m³/hr	23731	1232	-	
Gas Volumetric Flow Rate (STP, Dry)	m³/hr	23375	1213	-	
Gas Volumetric Flow Rate at Reference Conditions	m³/hr	23731	1232	-	

ND = None Detected,

Table 6- Typical content of a Stack Emissions Monitoring Report

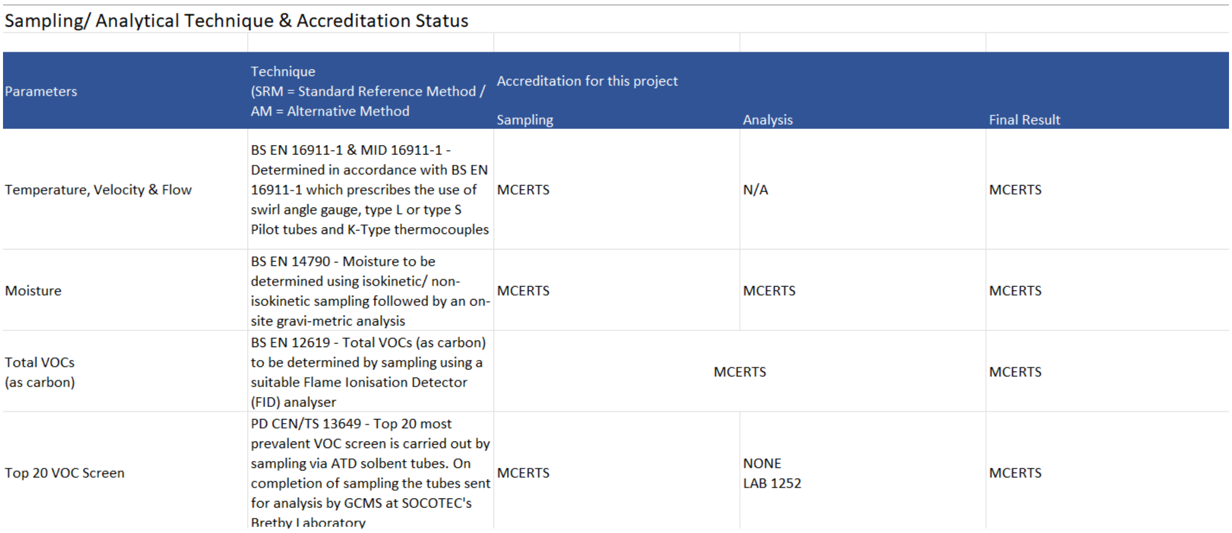
HiiROC and CNG assessed earlier (2021-2022) reports from Socotec which identified the total quantity of VOC's released across the entire range of JLR Solihull based exhaust stacks, both those that are continually monitored and those that are monitored from time-to-time and the results are presented in table 7 below.

	VOC Flow	VOC Flow
	mg/s	kg/hr
Paint Shop	7113.5	25.6
Paint shop unmonitored	46.9	0.2
Satellite	154.0	0.6
Satellite unmonitored	154.0	0.6
Total	7314.4	26.3

Table 7- VOC Emissions by source flowing to thermal oxidiser

3.4 Technologies for recovering VOC from exhaust stream.

The VOCs are carried in a large air stream from the paint shop to the thermal oxidiser. The following (Table 8) details the Socotec sampling techniques used to analyse the exhaust stream.



Sampling/ Analytical Technique & Accreditation Status

Parameters	Technique (SRM = Standard Reference Method / AM = Alternative Method	Accreditation for this project		
		Sampling	Analysis	Final Result
Temperature, Velocity & Flow	BS EN 16911-1 & MID 16911-1 - Determined in accordance with BS EN 16911-1 which prescribes the use of swirl angle gauge, type L or type S Pilot tubes and K-Type thermocouples	MCERTS	N/A	MCERTS
Moisture	BS EN 14790 - Moisture to be determined using isokinetic/ non-isokinetic sampling followed by an on-site gravi-metric analysis	MCERTS	MCERTS	MCERTS
Total VOCs (as carbon)	BS EN 12619 - Total VOCs (as carbon) to be determined by sampling using a suitable Flame Ionisation Detector (FID) analyser	MCERTS		MCERTS
Top 20 VOC Screen	PD CEN/TS 13649 - Top 20 most prevalent VOC screen is carried out by sampling via ATD solbent tubes. On completion of sampling the tubes sent for analysis by GCMS at SOCOTEC's Bretby Laboratory	MCERTS	NONE LAB 1252	MCERTS

Table 8 - Socotec Sampling techniques and accreditations

From the Socotec reports carried out in this study we have established that the quantity of VOC entrained can be up to 265mg/m^3, in a flow of 120,000Nm^3/hr of air. This equates to 31.8kg/hr of VOC, entrained in 144tonnes/hr of air. This is because a large volume of air is required to maintain a safe, minimally toxic or flammable environment in the spray booths.

Whether looking at taking a small sample for testing, or for developing a commercial scale operating plant, the process for extracting the VOCs from the waste gas stream would be based on a similar process.

There are several potential processes which could be used that are technically feasible, some of which are generic, and others which would rely on specific supplier information and cooperation. Examples include cooling, compression, membranes, adsorption, etc. The fundamental challenge relates to the relatively large flow rate of "air" (containing VOCs, NO2, CO, and H2O) needing to be processed to capture a relatively small quantity of VOCs, to minimise VOCs released to atmosphere, and to maximise conversion of VOCs to hydrogen.

The team conducted literature searches and thermodynamic modelling and met with industry specialists to identify potential means of separating VOC from the diluted air stream. The technologies can be broken down into four separate areas:

- Adsorption
- biological removal,
- chilling/distillation
- electrostatic precipitation

The outcome of the investigation is summarised in the sections below.

3.5 Adsorption

This is the industry standard solution, as evidenced by the studies from Byong Ro Kim3, and the studies by Ford in 2008[2] .

In a series of email exchanges between HiiROC and VOCzero, who have developed and produced carbon-based adsorption systems, it was advised that the paint shop stream was too large to be accommodated economically by their adsorbers. Furthermore, the JLR Exhaust stream contains a number of VOCs which are not compatible with activated carbon, such as Acetone, Methyl Isobutyl Ketone, Butyric Acid and Butyl Acetate. These substances will act as catalysts for uncontrolled oxidation processes on the activated carbon, which might result in hot-spot formation (local high temperature areas) and potentially fire/explosion, depending on the saturation degree of the activated carbon.

3.6 Biological removal

The Biological removal of the VOC's turns them into biomass, which could be fed to the TPE for conversion to Hydrogen. However, for the biological processes to work, they need the VOC to be separated from the air in the same way as the TPE. It was therefore not considered further.

3.7 Chilling/condensation

The team created a thermo-chemical model using process simulation software AspenTech Hysys v11 and Cubic Plus Association (CPA) physical property package, to prepare a simple preliminary simulation of the paint booth/ventilation system. A visual representation of the chilling/condensation process simulation, along with the process flow diagram and basic site layout is included within Appendices 3, 4 and 5 respectively.

This model assessed the feasibility of chilling the air sufficiently to condense the VOCs which would be drawn from the exhaust stream as a liquid product. A heat and mass balance for the process is included in Appendix 3.

If we were to condense the VOC from the airt stream at 'reasonable temperatures' of minus 20 °C, then we would need significant compression, with minimum compression and keeping within the design temperature allowed by Low Temperature Carbon Steel of minus 39 °C then we get 85% of the VOC to condense. If we were to design a system that was going to condense 99% of the VOC then it is necessary to chill the air to ~-80°C to knock out the majority of the VOCs. All of these options entail a high capital and energy cost and was agreed to be economically impractical.

3.8 Electrostatic precipitation

Our research[3] suggests that Wet Electrostatic Precipitation (W-ESP) is a proven separation technology with capability to capture and separate VOCs. However, our system, operating at 150 °C is 'dry', there being no VOCs in the liquid form. To ensure that the technology had to be 'wet' we contacted Monroe Environmental, and Operational Group for information and guidance, and learned that W-ESP's have a certain capability to remove vapour-phase VOCs from the air, that is when the VOC is in the form of droplets or mist, even fine, invisible mist. They are not, however, able to capture gas-phase VOCs. It is likely that the vast majority of VOC will be in the true gas phase in an airstream of 150°C. To condense the VOC to the point where it forms mists and droplets will require substantial cooling or expansion, both of which are predicted to have high capital and energy cost and therefore are viewed as infeasible.

3.9 Theoretical use of TPE for recovery of VOC

Whilst it was not possible to obtain a sample to test through HiiROC's Thermal Plasma Electrolysis torches to prove that the technology would work, we can consider how it may have performed should a sample have been taken.

The majority (over 90%) of the VOC is understood to be 2-Butoxyethanol, with the chemical formula $C_4H_9OC_2H_4OH$. It contains carbon, oxygen and hydrogen in the following ratios;

Element	Percentage content by mass
Carbon	61%
Oxygen	27%
Hydrogen	12%

Table 9- Split of elements in 2-Butoxyethanol (by mass)

Properties of 2-Butoxyethanol:

Key physical property data used in the assessment:

Molecular Formula: $C_6H_{14}O_2$

Molecular Mass: 118.17

Normal boiling point: 168.4 °C

Freezing point: -74.8 °C

Heat of vaporisation: 57 kJ/mol

Liquid specific heat: 273 kJ/ kmol.K

Heat of formation (gas, standard conditions): 500 kJ/mol (estimate based on similar components, as information not available in literature).

The HiiROC TPE system uses plasma to disassemble the gases that flow through the torch into its base components. The core use case is the breakdown of a hydrocarbon into its base components – hydrogen and carbon.

With some minor modifications to the torch design around cathode and anode it is within the capabilities of TPE to reduce 2-Butoxyethanol to its elements and produce Hydrogen, however it would be optimistic to assume that we could recover the highly reactive oxygen as elemental oxygen. This is most likely to react with the Hydrogen and present itself as water, so the output from the torch is simplistically modelled to be;

Compound	Percentage content by mass
Carbon	56%
Oxygen	0%
Hydrogen	12%
H_2O	15%
CO_2	19%

Table 10 - Product from TPE with 2-Butoxyethanol as feed (by mass)

One plasma torch has a feedstock flow rate of 25 m^3/hour or 18 kg / hr, the VOC content in the feed to the Thermal Oxidisers varies across every test, but they are in the range of 25.6 - 31.8 kg/hr of VOCs. One to two plasma torches would be required to manage the VOC flow rates seen here if they can be extracted from the air that is carrying them.

3.10 Hydrogen Content

The amount of hydrogen contained in the VOC stream (again based on the assumption that whilst the VOC contains several compounds, 2-Butoxyethanol is the predominant component) calculated using simple Stoichiometry is estimated to be 3.2kg/hr in an overall VOC flow of 31.8kg/hr. This represents a hydrogen energy content of 106kW LHV. The energy required to be input to the TPE torch to liberate the hydrogen will need to be established by experiment but based upon our experience with other feedstocks to the TPE such as longer chain hydrocarbons (propane, butane) it can be estimated very crudely to be circa. 70kW. Thus, the use of TPE to treat the VOC retains an overall positive energy return, albeit less than with simpler hydrocarbons.

3.11 CO_2 abatement

The Global Warming Potential (GWP) of 2-Butoxyethanol and the other VOCs is mitigated to CO_2 using the current Thermal Oxidiser scheme. Simply combusting the VOC to completion would release 71kg CO_2/hr into the atmosphere (623tonnes CO_2/yr at 100% utilisation).

Replacing the Thermal Oxidiser with a TPE-based system is calculated to reduce this to 6kg CO_2/hr (52tonnes CO_2/yr at 100% utilisation), a reduction of over 90%. Where 19% of the output is CO_2 (see Table 5) and the VOC flow rate is 31.8kg/hr. These figures assume that all power to the Solihull site comes from renewable sources with zero carbon emissions.

However, to achieve this significant reduction in CO_2 emissions from the VOC's it would need the VOC's to be separated from the air. The work carried out by CSL has shown that the only method of doing this would be to reduce the temperature to -80 °C. This is a cooling of a significant volume of air by 230 °C. To achieve this will need considerable power, which unless we can guarantee 100% renewable energy consumption, is likely to result in higher CO_2 emissions in the wider community.

3.12 Summary

VOC's could be extracted from the exhaust gas, but as they are diluted in a significant air flow, to do so would have needed significant process plant to be deployed involving refrigeration and compression systems. This would have been prohibitively expensive, and the time taken to install would not allow any samples to be taken within the schedule of this study.

The problems associated with extracting a sample would be the same for a full development, therefore alternative technologies were researched. No other viable technology was found to extract the VOC from the airstream to allow conversion to hydrogen.

If the VOC could have been extracted, the TPE Torches would have been able to convert them to hydrogen and black carbon. The yield of hydrogen would be considerably less than would have been expected for simpler hydrocarbon molecules, but it would still release a gas with a higher heating value than the power required to create it – but this doesn't account for the energy use to extract the VOCs

4 WP 3 – Planning site design and operating cycles.

Without the ability to capture VOCs from the JLR waste gas stream or construct a feasible proposal (cost and timescale bound) for the capital equipment, it has not been possible in this phase to develop a detailed site design proposal or consider any regulatory issues as per the baseline scope for the Stream 2A work. Work Package 4 discusses in more detail, based on the learning in this phase, what potential further work HiiROC could pursue that may lead HiiROC and JLR to be able to construct a site design and the planned operating cycles.

5 WP 4 – Model Potential JLR Options

As there were no samples that could be physically tested, HiiROC's engineers established what system would be needed to create hydrogen and Carbon Black from a VOC feed.

Figure 4 is a block diagram that represents the process undertaken by the TPE. The VOC feed would be in liquid form and be vapourised at 250 °C and then there is an exchange of heat with the product stream leaving the plasma torch, before entering the plasma torch to be converted to carbon, hydrogen and oxygen. In reality it is expected that at the temperature we will be operating at there will be no molecular oxygen, as this will readily react with the hydrogen and form water.

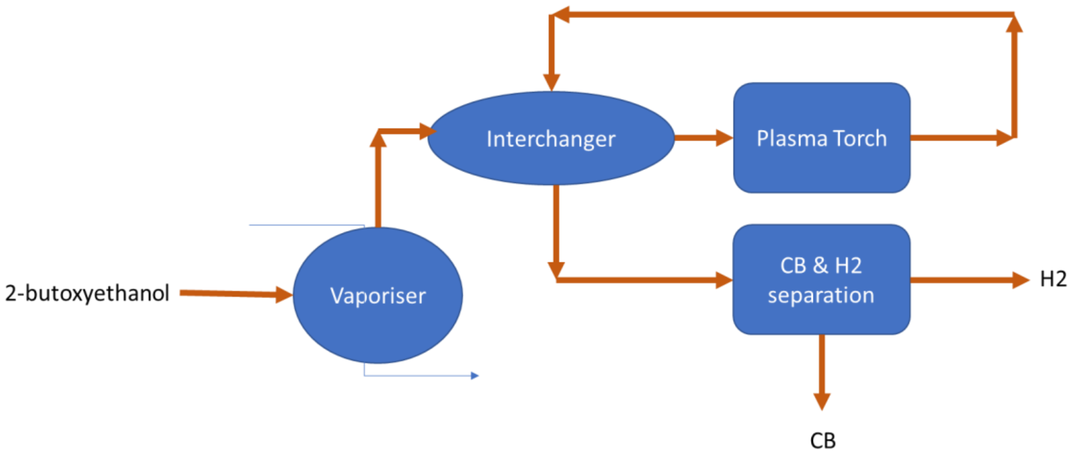


Figure 4 – Basic Flow Diagram

The carbon/hydrogen separation will occur in the standard HiiROC process of entering a cyclonic separator to remove the bulk of the carbon, followed by a filtration system to remove the smaller particles that will be carried from the cyclone by the hydrogen stream.

Analysis of the VOC vapour indicates that the bulk of the VOC is expected to be 2-butoxyethanol, where 1 kg/hr of feedstock would yield 85g/hr of hydrogen, with the capacity to deliver 2.8 kW for every kg of feed. The TPE to create this conversion to hydrogen would consume 1.2 kW of electricity, making the process a net exporter of energy.

6 WP 5 – Impact of Hydrogen on Paint Quality / integration into JLR Site.

6.1 Introduction

Work Package 5 considered the wider implications and opportunities from using the TPE process.

- The effects of using hydrogen in the paint process
- How the Hydrogen generated by the TPE would be blended
- How JLR at Solihull could integrate with the Utility companies that may be supplying hydrogen
- How the use of TPE and Combined Heat and Power plant could benefit JLR.

6.2 Using Hydrogen in the paint process

The painting process is a high energy demand process, requiring circa 25MW of heat for the paint shop ovens. Decarbonising this process would yield significant results in carbon tax reduction, however this cannot be carried out at the detriment to the quality of the painting finish.

Using hydrogen as an alternative fuel for the ovens in the automotive paint baking process does not typically affect the quality of the paint. In fact, a study published in the *Hydrogen gas curing of waterborne acrylic automotive coatings, Journal of Coatings Technology and Research* [55] showed using hydrogen can offer several benefits, such as reducing the curing time and improving the consistency of the finish. However, it is important to ensure that the equipment used for the process is properly designed and operated to avoid any potential safety hazards.

Overall, using hydrogen in the automotive paint process can have positive effects on the consistency and quality of the paint finish. From internal research at JLR, hydrogen should have no negative effect in the paint quality; as the types of ovens employed are indirect heat, (the combustion gases not coming into direct contact with the product) there would be no change to paint quality in this regard. However, the calorific value being lower would alter curing times and other parameters requiring burner changes etc. So, without significant technical modifications, utilising hydrogen as a fuel to the oven burners could impact quality.

There are seven ovens at Solihull, with a total of 120 burners, which could be changed out at a cost of £1.5m to burn a blend of natural gas and hydrogen. However, the value is limited as the maximum blend with natural gas would be 3% Hydrogen, otherwise the NOx emissions will exceed that permitted for the site. However, if the burners were to burn a 100% Hydrogen gas stream, the NO_x problem can be eradicated by pre-mixing the hydrogen and air and using catalytic combustion, allowing the oxidation of the hydrogen at temperatures below those needed to generate NOx (ref 7 & 8) This then challenges the increased cost of the fuel to the burners, which we address in Work Package 8.

6.3 Blending Hydrogen

As we have shown, the TPE technology is not a suitable replacement for the Thermal Oxidiser. The issues surrounding blending the resultant hydrogen with other Hydrogen sources or fuel gas have not been addressed.

6.4 Consideration of the Grid & Utility and Wider Plan for JLR and integration solution

JLR are committed to reduce their carbon emissions and the expectation was that the work we were undertaking here would be a step forward in that direction. As mentioned in WP2, this has not been possible and therefore TPE integration with external utilities is not assessed in detail.

For JLR to maximise the use of renewable electricity there would have to be a major upgrade of their electrical connection to the grid. There is a potential of up to 25MW to be drawn from the local substation, but connection to this would need to be extensively upgraded, which will require a significant amount of CAPEX and is not looked upon favourably. Experience of a recent project requiring connection of 10MW is looking like a connection upgrade cost of ~£15 million. This would be comparable to what we require here.

See Appendix 2 for National Grid map

In time there is a plan to build a Hydrogen Distribution grid; the project will re-use existing gas pipelines and install 2,000 kms of new pipeline. The exact details have not been released yet, but the high-level plans show the pipelines may well pass near to the JLR Solihull site and could potentially be used. This is planned for completion in the early 2030's, but still requires significant hydrogen production to be integrated into the system. Consequently, this cannot be relied upon at this time to deliver a green alternative to the combustion of Natural Gas.

Figure 5 - Proposed Hydrogen pipeline network

6.5 Consideration of hydrogen CHP for onsite energy generation.

At the inception of the study, using the liberated hydrogen from the TPEs, installed to replace the Thermal Oxidiser, to provide fuel to a Combined Heat and Power (CHP) unit was considered an option worthy of further study.

JLR have already tested and successfully used CHP systems at their Solihull site. Currently the CHP system they have at Solihull is not being used. The reason being that as the UK electricity grid decarbonises its electrical generation, the emission profile of using natural gas and burning it in a CHP for heat and power becomes more emissive than just using the grid electricity directly.

A potential solution to this is using 100% hydrogen to fuel CHP's. HiiROC are working with and researching 100% hydrogen CHP systems, primarily with a German company 2G.

Figure 6 shows that if JLR were to consider TPE technology to make hydrogen from natural gas as the fuel to a CHP unit, a 750kW CHP unit could produce 750kW of heat and a net production of 67 kW of electrical power. The system will also produce 164 kg/hr of carbon black with a market value of circa £4,000/day, which would compare to the fuel gas cost of circa £2,750/day. The combined TPE/CHP would generate a net income of £1,250/day; £300k/annum, plus reduce the electrical demand and cost by 67kW, whilst providing 750kW of heat to the plant with no emissions to the atmosphere, directly from this process. The only emissions from the TPE process could be viewed as the upstream fugitive emissions from use of the Natural Gas from the UK grid. The Low Carbon Hydrogen standard uses the figure of 6.293g CO_2e/MJ(LHV) of natural gas consumed, or more easily viewed as 10.25g CO_2e/MJ H2 produced through TPE.

In the below scenario, due to the upstream fugitive emissions of the Natural Gas network, we get the only emission for the process as:

- 218.4kg/hr CH4, which equals 10,483.2 MJ/hr (48 MJ/kg Nat Gas)
- This equates to 65.6kg/hr CO_2e from the upstream emissions.
- Also to be factored in is the counterfactual - where the carbon black is used and displaces carbon black derived from the Oil Furnace process.
- 163.8kg/hr of CB is produced – which is just solid carbon.
- For the full end to end abatement, when considering the electricity as renewable / zero carbon we see:
    - 399kgCO2/hr abated from avoiding the combustion of the natural gas in the CHP
    - In addition we can add in the counterfactual for avoidance of the CB Oil furnace process, we have 163kg/hr CB produced x 2 kg/CO2 per 1kg/CB produced we have 327.6kg/CO2/hr avoided
    - Giving a total of 726kg/CO2/hr mitigated

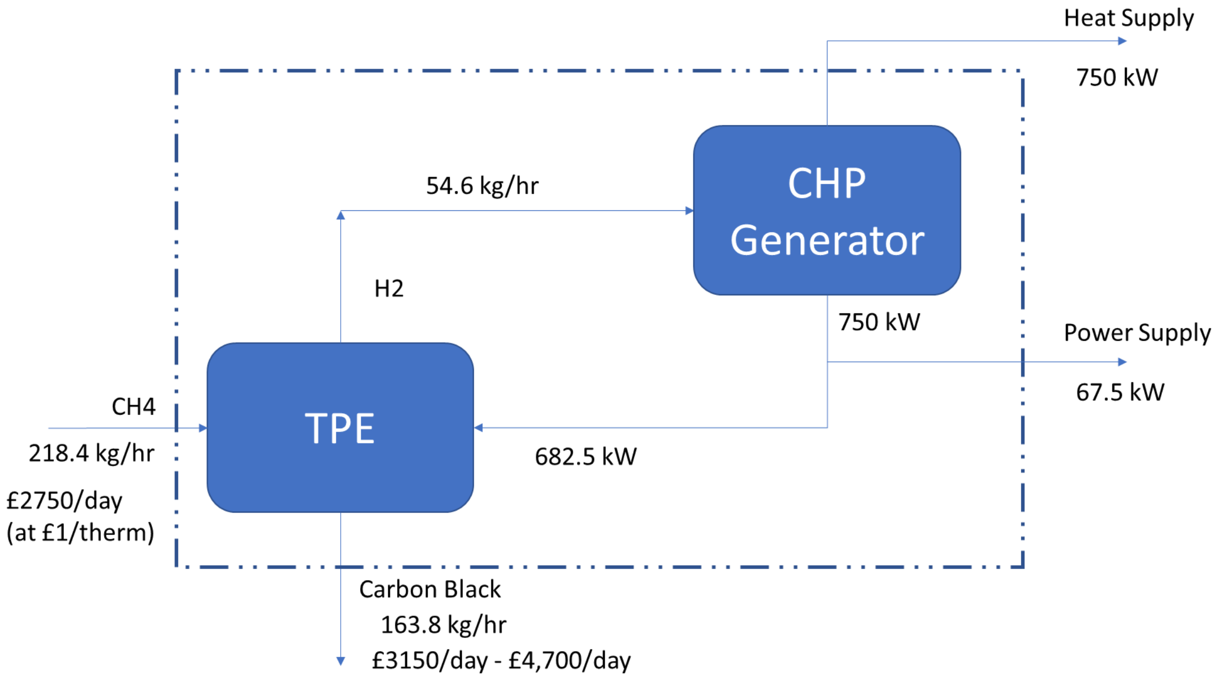


Figure 6 – Potential TPE /CHP System

6.6 Levelized Cost of Hydrogen (LCOH)

Calculating the levelized cost of hydrogen for this project isn't fully possible for several reasons:

- If using the formular LCOH = (TCC + TOC + TFC) / (TR * (1 + r)^OL)
- Where:
  - TCC= Total Capital Costs
  - TOC = Total Operating Costs
  - TFC = Total Fuel Costs
  - TR = Total Revenue
  - OL = Operational lifespan
  - r = discounted rate

The calculation isn't possible to make accurately as the TCC for the project is widely variable. Current production costs of bespoke, one torch pilot units are of a significant magnitude higher than the likely cost when in standardised, commercial production that we will see in 2024 onwards. The targeted unit production volumes for 2024 onward range from the several hundreds of units, up to the potential of many thousands. This could see production costs fall 5 to 10 times from the pilot unit phases – but this remains to be designed and qualified.

Furthermore, the current commercial model for HiiROC is to lease units, and charge a production fee, again will also be based around market factors, and based on the TCC.

The revenue generated from the hydrogen is not required to be accounted for – it is totally consumed onsite. There would however be a revenue stream from the carbon, which from our modelling should be capable of offsetting the cost differential in the swap from natural gas to hydrogen.

7 WP 6 - Establishing what market there would be for Carbon Black.

The HiiROC TPE process produces a wide range of carbon black (CB), that when collected and processed effectively should mean the ability to satisfy several established markets. HiiROC's internal research has shown that the production of a tyre uses 23 different grades of CB[9] consequently, there should be several routes for use of the HiiROC CB within JLR's supply chain.

The HiiROC research suggests that, providing the parameters in the plasma torch stay constant, the type and size of CB will likely stay the same, but again with a wide range of particle size. Whilst the physical carbon sampled from the breakdown of JLR VOCs couldn't be tested, the output of CB is likely to remain within the same parameters. Due to the cooling speeds, temperatures and differing filters throughout the TPE process there is a range of carbon produced allowing for numerous types of CB use cases to be fulfilled. The current research shows that high quality CB will be produced by the TPE system and further research on the TPE design is most likely to allow the particle size of CB to be optimised. Crucially when producing CB (and hydrogen) through the HiiROC TPE system for JLR the carbon will be able to be used within their supply chain creating excellent circularity in the project.

Considering a wider market for Carbon Black[10] there is expected to be a 5.4% compound annual growth rate (CAGR) from 2022 to 2028. The current processes being utilised to produce the CB are highly polluting and there is pressure on current suppliers to reduce their green-house gas (GHG) footprint. Consequently, this is showing a shrinkage in supply. To date the focus on emissions reduction has been on developing production processes that use end-of-life tyres as a feedstock, however these processes do not eliminate GHG emissions, they only offer a reduction. HiiROC's process has no emissions and could easily be adopted to produce all the CB needed for the tyre demand of the existing production line at JLR. JLR globally produces around 500,000 cars, which would equate to 4,000,000 kg/pa of CB, or the maximum output of 34 HiiROC units running 24/7/365. As the table below show's this would therefore offset the emissions of 8,000,000 kg/pa of CO_2e that would have been emitted through the traditional Oil Furnace Process that currently makes CB.

Manufacturing the Carbon Black using a traditional process would result in the emissions contained in table 11 below.

Chemical Substance	**Oil Furnace Process**	**HiiROC Process**	**Emissions avoided for 1kt p.a.**
CO*2*	2000kg/tonne	0	2,000 tonnes
Carbon disulfide	30kg/tonne	0	30 tonnes
Carbonyl sulfide	10kg/tonne	0	10 tonnes
Methane	25kg/tonne	0	25 tonnes
Acetylene	45kg/tonne	0	45 tonnes
Ethane/Other	2kg/tonne	0	2 tonnes

Table 11- Carbon Black Emission comparison by Production Method

8 WP 7 – Design and costing for IHA Phase 2B.

This WP was no longer required due to the unfeasibility of the gas extraction.

9 WP 8 – Review of Commercial Opportunities.

We have looked at the potential to use TPE to convert natural gas into Hydrogen and Carbon Black, with the hydrogen used within the JLR plant.

We identified three possibilities on the JLR site where Hydrogen could replace existing natural gas as the fuel, with the TPE technology generating the hydrogen on site from the existing natural gas connection to the site.

1. Combined Heat and Power
2. Fuel to the Thermal Oxidiser
3. Fuel to the paint shop ovens.

9.1 Combined Heat and Power

As discussed above in WP5 and shown in Figure 6 by adding a hydrogen fuelled CHP unit combined with sufficient TPE torches to provide the fuel, then we could have a unit that consumes 218 kg/hr of natural gas, and produces 67.5 kW of electric power and 750kW of heat to the Solihull plant. It would also produce a valuable product in the form of Carbon Black.

Carbon Black typically sells from 80p/kg to £4/kg [10]. Assuming we could net £1/kg, that would deliver an income of almost £4,000/day. Further the production of 67.5 kW electric power will reduce the import to the site of the same amount, reducing the site electricity costs by £312 per day. The natural gas needed to provide the power and carbon black would typically cost £2,750 (assuming a cost of 100p/therm (3.4p/kWh)).

Ref appendix 6

9.2 Fuel to Thermal Oxidiser

Currently the Thermal Oxidiser consumes 389 kg/hr (5,900 kW equivalent) of Natural gas at maximum load which results in the emission of 1,070 kg/hr of Carbon Dioxide.

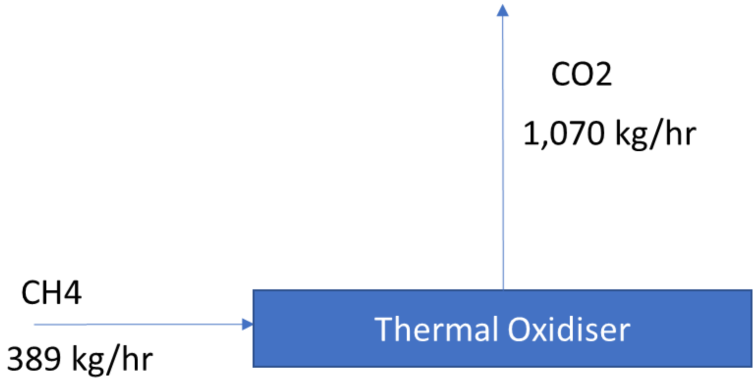


Figure 7 – Current Thermal Oxidiser Flow Diagram

If the natural gas was to be converted to hydrogen and carbon black in sufficient numbers of HiiROCs TPE torches, the emissions would drop and there would be a cash product in the form of carbon black.

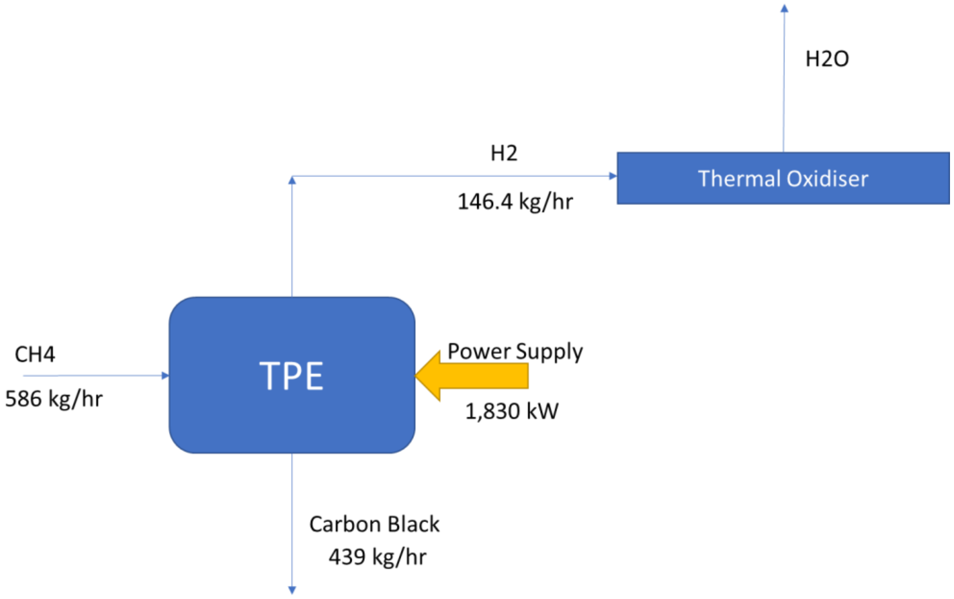


Figure 8 – Proposed reduced GHG Thermal Oxidiser Flow Diagram

To achieve the same heating value of gas entering the thermal oxidiser, the natural gas flowrate will have to increase to 586kg/hr, an increase of 197 kg/hr (approx. 50% increase), which is approximately an increase in costs for fuel of £100/hr (assuming a gas cost at 100p/therm (3.4p/kWh)). There will also be a cost associated with the additional 1.8MW of electrical power which at £200/MWh would be an additional burden of £360/hr. This scheme would therefore require an increase in energy costs of £460/hr or £11,040 per 24 hours.

However, there will be an offset in Carbon Tax and an income from the carbon black. Carbon black selling at £1/kg, would net an income of £440/hr and if we assume carbon tax at £100/te, that would be a total offset of £550/hr; £13,200/day.

Adopting this change would deliver zero carbon emissions from the fuel gas consumed in the thermal oxidiser (there will be a carbon burden from the incinerated VOC) and an improvement in cash flow of £1,680/day.

Item	Cost – current (£/hr)	Cost – with TPE (£/hr)
CH_4 (Natural gas) input (£0.034/kWh)	£200 (5,900 kW)	£300 (8,870kW)
Electricity supply to TPE (£0.20/kWh)	NA	£360 (1,800 kW)
Carbon Black revenue (£1/kg)	NA	-£440 (440 kg/hr)
Carbon cost (£100/t CO_2)	£107 (1070kg CO_2e/hr)	NA
Total	£307	£220

Table 12 - Cost Benefits of firing Thermal Oxidiser with TPE produced Hydrogen

9.3 Fuel to Paint Shop Ovens

Instead of burning natural gas in the paint shop ovens, hydrogen could be generated using HiiROC's TPE torches.

The ovens consume 25MW which can be provided by the combustion of 1651kg/hr of natural gas and would require 600kg/hr of Hydrogen to give the equivalent heat. This production rate of hydrogen is significantly larger than any TPE system considered to date. A typical TPE Torch produces 4.5kg/hr of hydrogen, so a significant upscaling of the technology would be required or a system that contains 134 of the Torches would be required.

134 of the Torches at 50kW each would need a power supply of circa 7MW. It is most unlikely that this additional power could be made available to the Solihull plant at an economic cost, due to the current capacity constraints in the area, getting this connection would potentially be cost prohibitive.

Refer to Appendix 2

Should a system design for the equivalent of 134 torches be possible, and the power available to the plant be increased to allow the ovens to be converted to Hydrogen firing, then the costs contribution can be seen in table 13.

Process	**GHG emissions – current (kgCO2e/hr)**	**GHG emissions – with TPE (kgCO2e/hr)**
Combustion in Ovens	4592.50 (25000 kw natural gas @ 0.1837 gCO2e/kWh)	0 (hydrogen)
Electricity supply to TPE	0	1855 (7MW @ (at 265gCO2/kWh) gCO2e/kWh)
Carbon Black emissions saving vs conventional	NA	-3600 kg/hr (1800kg/hr CB x 2kg CO2 per 1kg CB produced via usual methods)
Total	4592.50	–1745
Overall % emissions reduction: 136% Overall reduction		

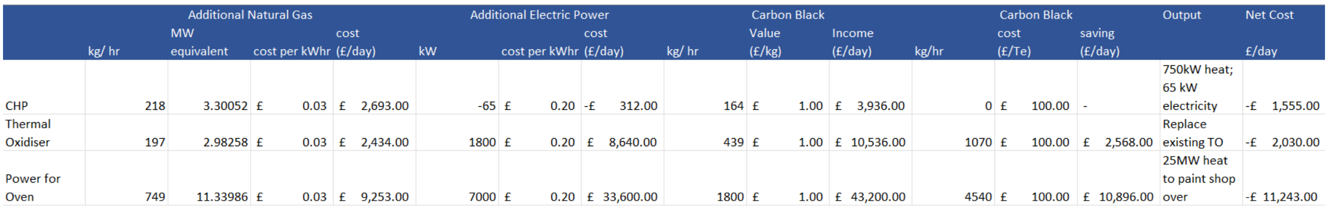
Table 13 - CO2e GHG Emissions of converting Paint Ovens to Hydrogen

Cost contribution	**Cost – current (£/hr)**	**Cost – with TPE (£/hr)**
Natural gas for ovens – 25MW at £34/MWh	850	0
Natural gas for TPR – 36.3MW at £34/MWh	0	1235
Electricity supply to TPE – 7MW at £200/MWh	0	1400
Carbon Black revenue – 1,800 kg/hr at £1/kg	NA	–1800
Carbon cost – at £100/tCO2	450	
Total	1,300	835

Table 14 - Cost Benefits of firing Ovens with TPE produced Hydrogen

10 Summary / Conclusions

A summary of the three options is shown in table 15 below. The cost estimations account for only the operational costs.



	Additional Natural Gas				Additional Electric Power			Carbon Black			Carbon Black			Output	Net Cost
	kg/ hr	MW equivalent	cost per kWhr	cost (£/day)	kW	cost per kWhr	cost (£/day)	kg/ hr	Value (£/kg)	Income (£/day)	kg/hr	cost (£/Te)	saving (£/day)		£/day
CHP	218	3.30052	£ 0.03	£ 2,693.00	-65	£ 0.20	-£ 312.00	164	£ 1.00	£ 3,936.00	0	£ 100.00	-	750kW heat; 65 kW electricity	-£ 1,555.00
Thermal Oxidiser	197	2.98258	£ 0.03	£ 2,434.00	1800	£ 0.20	£ 8,640.00	439	£ 1.00	£ 10,536.00	1070	£ 100.00	£ 2,568.00	Replace existing TO	-£ 2,030.00
Power for Oven	749	11.33986	£ 0.03	£ 9,253.00	7000	£ 0.20	£ 33,600.00	1800	£ 1.00	£ 43,200.00	4540	£ 100.00	£ 10,896.00	25MW heat to paint shop over	-£ 11,243.00

Table 15 - Summary of Financial benefits of adapting TPE Technology

Taking account of the carbon intensity of grid electricity supply at 265g/kWh we would have to consider net GHG emissions as follows in table 16 below:

	CO2 Emissions (kg/hr)		
	Electricity	TPE process and heat generation	net change
CHP	-17	0	-17
Thermal Oxidiser	477	-1070	-593
Power to oven	1855	-4540	-2685

Table 16 - Overall change in carbon emissions in kg/hr

Process	**GHG emissions – current (kgCO2e/hr)**	**GHG emissions – with TPE (kgCO2e/hr)**
Combustion in Thermal Oxidiser	1083.83 (5900 kw natural gas @ 0.1837 gCO2e/kWh)	0 (hydrogen)
Electricity supply to TPE	0	484.95 (1830kW @ 0.265 kg CO_2e/kWh)
Carbon Black emissions saving vs conventional	NA	-393.05
Total	1083.83	91.9

Process	**GHG emissions – current (kgCO2e/hr)**	**GHG emissions – with TPE (kgCO2e/hr)**
Overall % emissions reduction: 91.5% Overall reduction		

Table 17 - CO2e GHG Emissions of Hydrogen to the Thermal Oxidiser

Swapping both the Thermal Oxidiser and the Paint Shop ovens to H2 supply, with the H2 being manufactured on site using TPE technology, would show an overall reduction in carbon emissions and the CHP producing 65kW of power will have a small reduction in greenhouse gas emissions due to the fact that there will be zero emissions from the generation.

The only other emission factor to consider is the upstream fugitive emissions of using the Natural Gas from the grid. The upstream fugitive emissions do form a large part of the HiiROC process, but they are dwarfed by the counterfactual emissions avoided by not using CB produced through the Oil Furnace process.

Table 15 demonstrates that all three options would be potentially economically viable, netting a reduction in OPEX or at least giving a positive cash flow and table 16 demonstrates a reduction in overall GHG from the process. However, the practicalities of adopting the technology are not so straightforward.

There are currently capacity constraints in the electricity network local to the Solihull site. It may be possible to obtain a further 1.8MW supply to allow the Thermal Oxidisers to be converted to H2 burn using TPE technology, however it is unlikely that 7MW increase in supply can be achieved unless there was to be a significant upgrade in the local electricity supply grid. To ascertain whether this is a possibility discussion will need to be carried out with the DNO to determine what plans there are to upgrade the system and in what time frame.

A further consideration, not explored in this analysis, would be the CAPEX for the TPE pilots. At this time the development of these items is very much in the research and development (R&D) phase and the likely cost of the units are unknown. This will be very dependent upon the uptake of the technology. Further to this, HiiROC have yet to establish their business model for delivering the technology to users. Two options are being considered. A direct sale of the system to the end user and a lease basis, where the end user pays a fee to have the system installed and maintained within their site with a levy based upon the volumes of product produced. At this time, we anticipate the design life of the units being greater than 25 years. A cost model will be developed to support the economics of adopting the technology whilst maintaining a favourable cost position.

JLR have indicated that they would like to discuss potential upgrades to the Thermal Oxidiser for both the Solihull site and another site within the group in the 2nd half of 2023 with a view to installing the HiiROC TPE technology and upgrading the Thermal Oxidisers in 2027.

11 Project Information Dissemination Plan

HiiROC have previously presented a high-level overview of the project, and the findings at the IHA dissemination event (27 March 2023). From the success of this session further meetings have been arranged to discuss the TPE technology on waste gas streams with two further businesses.

Further events are being planned with JLR and HiiROC currently, both external conferences, and internal stakeholder and supply chain events.

12 Appendices

12.1 Appendix 1 - JLR Summary and recommendations

Deliverable 2.2:

•CNG Services Ltd (CSL) have been awarded a contract by HiiROC to provide support services relating to the capture of volatile organic compounds (VOCs) from waste gases produced at the Jaguar Land Rover (JLR) site in Solihull, UK

•The aim is to capture VOCs from JLR waste gases using the HiiROC HiiQ Thermal Plasma Electrolysis (TPE) technology to produce sustainable hydrogen from the captured VOCs

•The CSL scope of work was to understand the feasibility of waste gas collection, and if feasible support HiiROC in the collection of sample(s) for testing at HiiROC facilities in Hull, UK

•Available information has been gathered, including previous waste gas sample analysis carried out by Socotec for JLR emissions monitoring requirements

•A site visit to JLR facilities in Solihull, UK was carried out by HiiROC and CSL to better understand where the VOCs were produced, the current method of capture and disposal, and to identify:

a) If and how appropriate samples of JLR waste gas could be taken for testing at HiiROC facilities in Hull, UK, and,

b) How a potential site-based HiiROC TPE process could potentially be integrated into the existing JLR site and facilities (in preparation for subsequent phases of this project)

•Following initial review of data available from JLR including historical waste gas analysis, clarification with HiiROC on gas sample requirements, and visual inspection of existing JLR site and facilities, HiiROC and CSL agreed that it would not be economically feasible for the engineering design, procurement and construction of a process solely to take samples of waste gas for testing, within the budget and time constraints of this feasibility study phase. The reasons for this decision are discussed in the following slides but the primary issue is the high volume of air in the process

•Following the decision that waste gas sampling at JLR for testing by HiiROC was not economically feasible, HiiROC and CSL discussed potential alterative scopes of work that would be beneficial at this stage, and the recommendation is to add to the scope of work as follows:

a) Further, more-detailed sampling and analysis of JLR waste gas to be carried out to get a more detailed breakdown of components in the waste gas stream

b) Identify potential process technologies for the commercial capture of VOCs from the waste stream, evaluate technologies, and agree a preferred technology

c)Carry out an initial concept / feasibility study design and produce a report for the commercial scale plant

•HiiROC commissioned Socotec to carry out further sampling and more detailed analysis of the JLR waste gas, but the results have not been made available at the time of writing this report – therefore this report is based on the same assumptions regarding the waste gas analysis as the previous initial feasibility report

•CSL carried out some research into potential technologies that might be suitable for this project and identified that the process offered by VOCZero could be a viable option and contacted VOCZero to request further information and a quote. VOCZero have recently provided a quote and further information, but due to the challenging timescales of this phase of the project there is insufficient time to evaluate the quote and seek clarifications from VOCZero

•The feasibility design herein is based on a *preliminary system concept* using simple open-art processes and equipment, but is probably not the most suitable or preferred process, subject to further evaluation of the VOCZero process

•The following have been produced for the *preliminary system concept* and are included herein:

a) Preliminary Process Flow Diagram

b) Preliminary Layout Drawing; a footprint of 90m x 46m has been indicated

c) Preliminary CAPEX estimate; circa £15million ± 50%

d) Preliminary OPEX estimate; circa £4.5 million p.a. maximum in Year 1 falling to circa £2.2 million p.a. minimum in Year 6

e) Preliminary Project Schedule; circa 18 to 24 months

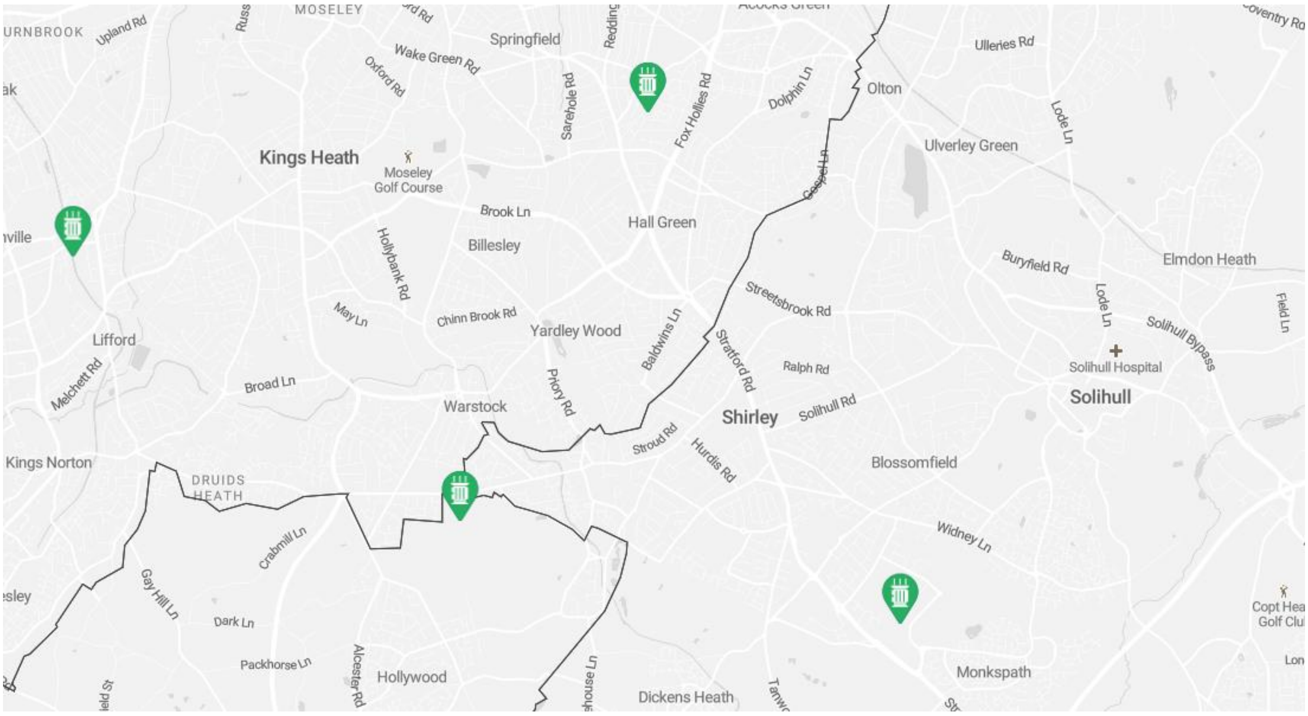
•Based on initial review of the unchecked/unchallenged VOCZero information it appears that the VOCZero could be a suitable process alternative to the *preliminary* *system concept* design detailed herein, and could well be more attractive in terms of CAPEX, OPEX and footprint. However, we will not know this for sure without carrying out further evaluation and clarifications with VOCZero

•It is recommended that:

a) Further more-detailed sampling and analysis of JLR waste gas to be carried out to get a more detailed breakdown of components in the waste gas stream

b) Using the revised gas analysis mentioned above, identify potential process technologies for the commercial capture of VOCs from the waste stream, evaluate technologies including the *preliminary system concept* and the VOCZero process, and agree the preferred technology

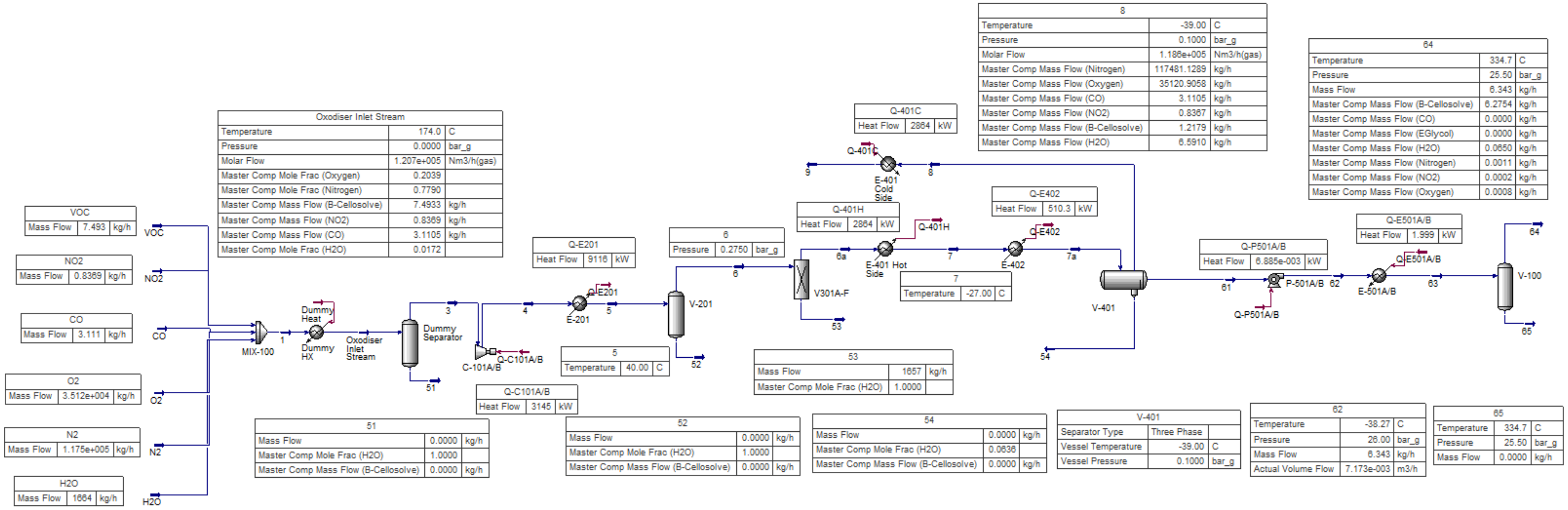
12.2 Appendix 2 - Local Network Sub-Stations local to Solihull



Source ref:

https://www.nationalgrid.co.uk/our-network/network-capacity-map-application

12.3 Appendix 3 - Preliminary System Concept – Simulation



VOC		
Mass Flow	7.493	kg/h

NO2		
Mass Flow	0.8369	kg/h

CO		
Mass Flow	3.111	kg/h

O2		
Mass Flow	3.512e+004	kg/h

N2		
Mass Flow	1.175e+005	kg/h

H2O		
Mass Flow	1664	kg/h

Oxodiser Inlet Stream		
Temperature	174.0	C
Pressure	0.0000	bar_g
Molar Flow	1.207e+005	Nm3/h(gas)
Master Comp Mole Frac (Oxygen)	0.2039	
Master Comp Mole Frac (Nitrogen)	0.7790	
Master Comp Mass Flow (B-Cellosolve)	7.4933	kg/h
Master Comp Mass Flow (NO2)	0.8369	kg/h
Master Comp Mass Flow (CO)	3.1105	kg/h
Master Comp Mole Frac (H2O)	0.0172	

51		
Mass Flow	0.0000	kg/h
Master Comp Mole Frac (H2O)	1.0000	
Master Comp Mass Flow (B-Cellosolve)	0.0000	kg/h

Q-C101A/B		
Heat Flow	3145	kW

Q-E201		
Heat Flow	9116	kW

5		
Temperature	40.00	C

6		
Pressure	0.2750	bar_g

52		
Mass Flow	0.0000	kg/h
Master Comp Mole Frac (H2O)	1.0000	
Master Comp Mass Flow (B-Cellosolve)	0.0000	kg/h

53		
Mass Flow	1657	kg/h
Master Comp Mole Frac (H2O)	1.0000	

Q-401C		
Heat Flow	2864	kW

Q-401H		
Heat Flow	2864	kW

7		
Temperature	-27.00	C

Q-E402		
Heat Flow	510.3	kW

8		
Temperature	-39.00	C
Pressure	0.1000	bar_g
Molar Flow	1.186e+005	Nm3/h(gas)
Master Comp Mass Flow (Nitrogen)	117481.1289	kg/h
Master Comp Mass Flow (Oxygen)	35120.9058	kg/h
Master Comp Mass Flow (CO)	3.1105	kg/h
Master Comp Mass Flow (NO2)	0.8367	kg/h
Master Comp Mass Flow (B-Cellosolve)	1.2179	kg/h
Master Comp Mass Flow (H2O)	6.5910	kg/h

54		
Mass Flow	0.0000	kg/h
Master Comp Mole Frac (H2O)	0.0636	
Master Comp Mass Flow (B-Cellosolve)	0.0000	kg/h

V-401		
Separator Type	Three Phase	
Vessel Temperature	-39.00	C
Vessel Pressure	0.1000	bar_g

Q-P501A/B		
Heat Flow	6.885e-003	kW

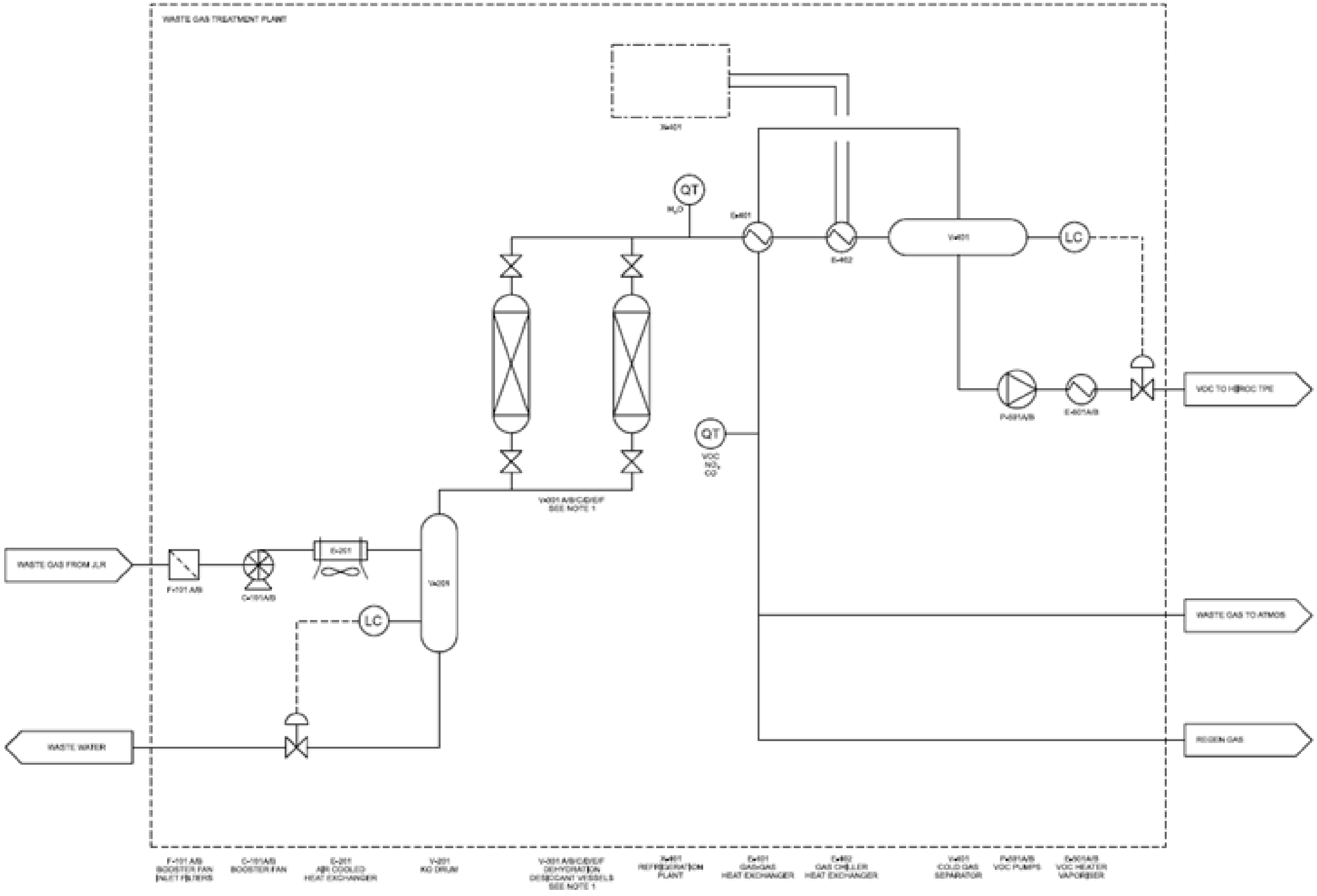
62		
Temperature	-38.27	C
Pressure	26.00	bar_g
Mass Flow	6.343	kg/h
Actual Volume Flow	7.173e-003	m3/h

Q-E501A/B		
Heat Flow	1.999	kW

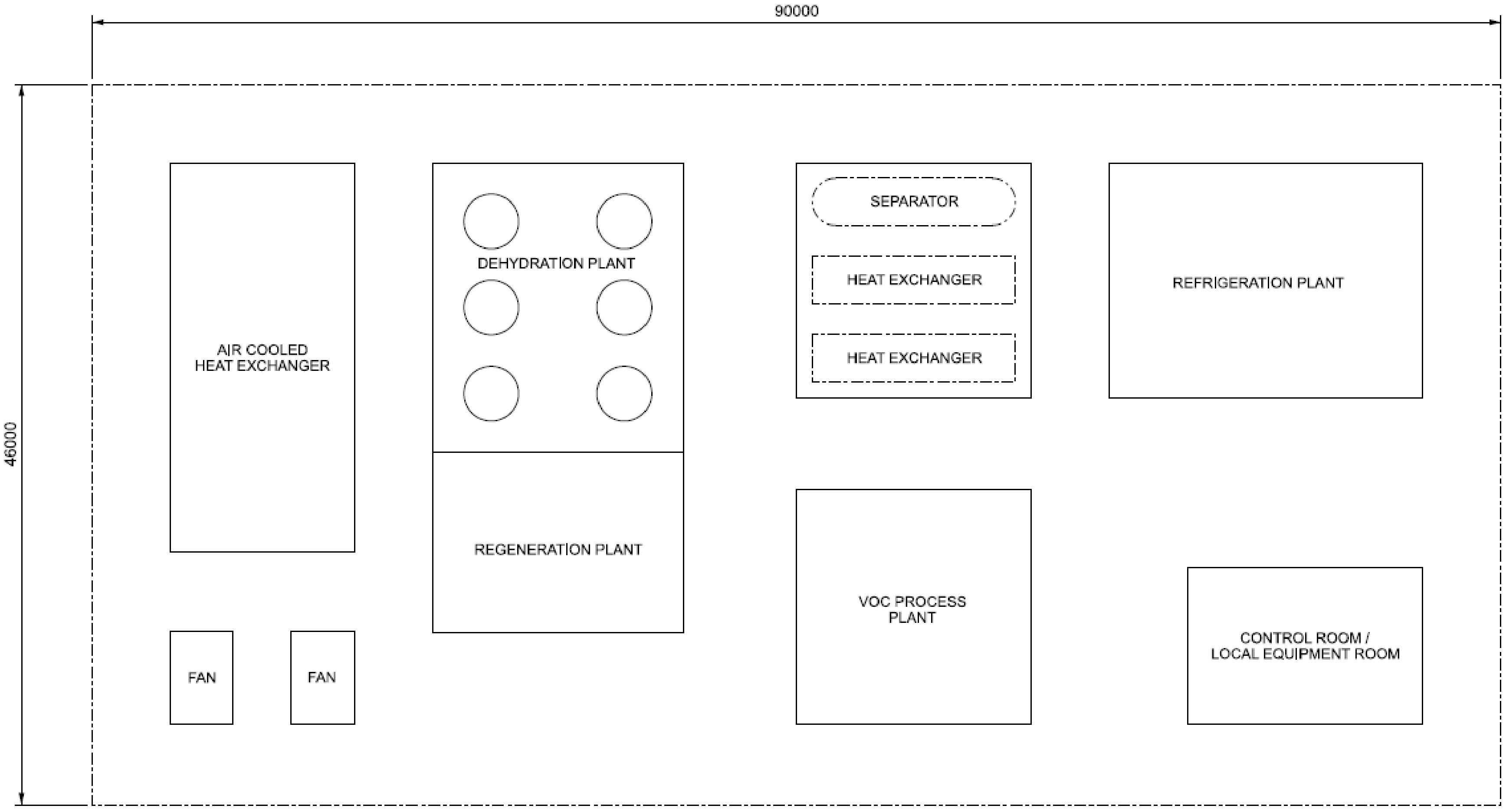
64		
Temperature	334.7	C
Pressure	25.50	bar_g
Mass Flow	6.343	kg/h
Master Comp Mass Flow (B-Cellosolve)	6.2754	kg/h
Master Comp Mass Flow (CO)	0.0000	kg/h
Master Comp Mass Flow (EGlycol)	0.0000	kg/h
Master Comp Mass Flow (H2O)	0.0650	kg/h
Master Comp Mass Flow (Nitrogen)	0.0011	kg/h
Master Comp Mass Flow (NO2)	0.0002	kg/h
Master Comp Mass Flow (Oxygen)	0.0008	kg/h

65		
Temperature	334.7	C
Pressure	25.50	bar_g
Mass Flow	0.0000	kg/h

12.4 Appendix 4 - Preliminary System Concept – Process Flow Diagram



12.5 Appendix 5 - Preliminary System Concept – Site Layout



12.6 Appendix 6 – Energy Costs

Figure 10 shows the historic costs of gas in the UK[1]

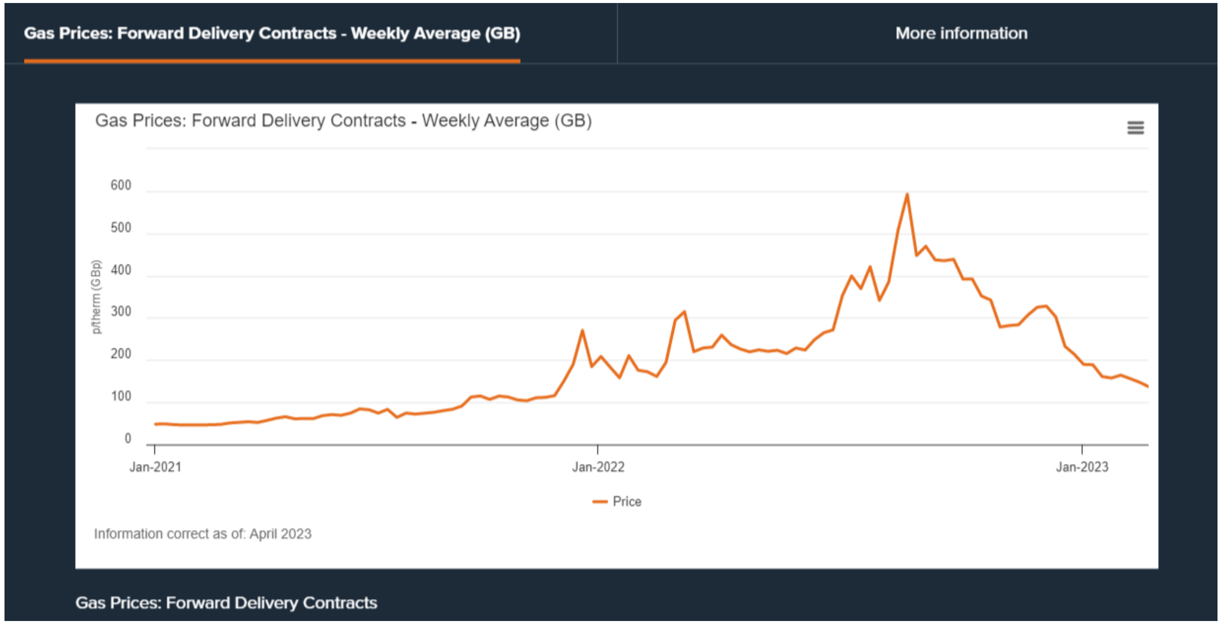


Figure 90 - historic wholesale price of gas in UK

Further electricity prices are shown in Figure 2, from the same reference as Figure 1.

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[1] https://www.ofgem.gov.uk/energy-data-and-research/data-portal/wholesale-market-indicators

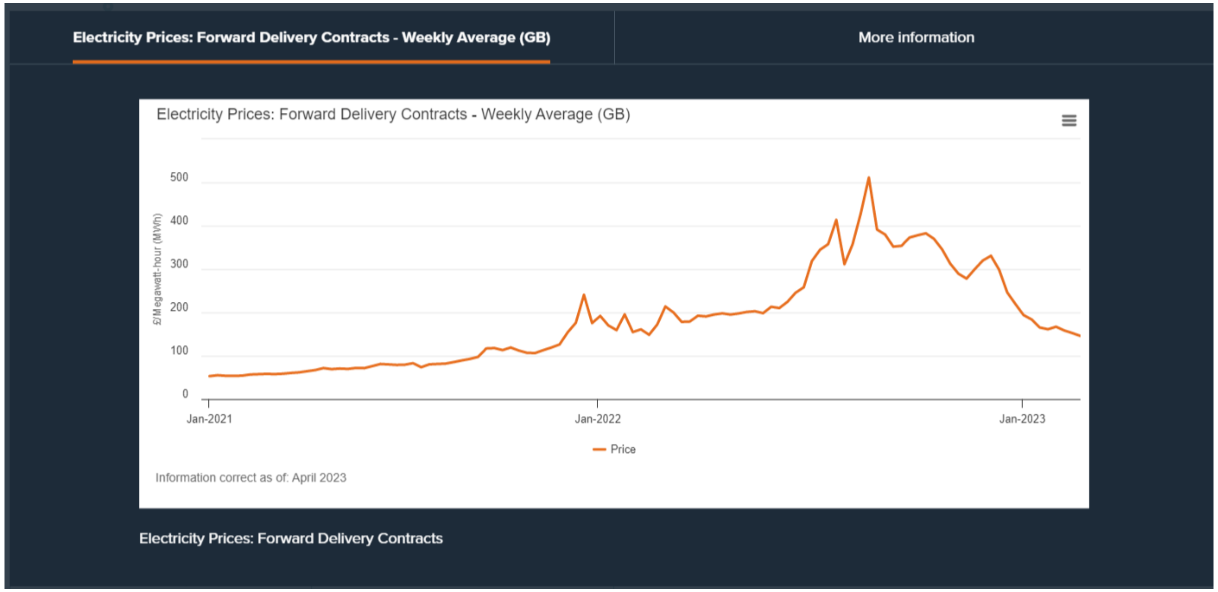

Figure 11 - historic wholesale price of Electricity

For the purposes of this study we have assumed that gas will cost 100p/therm (3.4p/kWh) and that electricity will cost £200/MWh

[1] https://www.ofgem.gov.uk/energy-data-and-research/data-portal/wholesale-market-indicators