NLWA

North London Heat and Power Project

Carbon Offsetting and Abatement

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Abbreviations

Abbreviation	Meaning
AE	Avoided emissions
Arup	Ove Arup & Partners Limited
BAT-AEL	Best Available Techniques-Associated Emission Level
BECCS	Bioenergy with carbon capture and storage
$CaCO_3$	Calcium carbonate
CAPEX	Capital expenditure
CCC	Committee on Climate Change
CCGT	Combined Cycle Gas Turbine
CCUS	Carbon capture use and storage
CHP	Combined heat and power
CIF	Carbon intensity floor
CO	Carbon monoxide
CO_2e	Carbon dioxide equivalent
CO_3^{2-}	Carbonate
COMAH	Control of Major Accident Hazards Regulations
COP26	26th UN Climate Change Conference of the Parties
Defra	Department for Environment, Food and Rural Affairs
EDDiCCUT	Environmental Due Diligence of CO_2 Capture and Utilisation Technologies
EfW	Energy from Waste
EIA	Environmental Impact Assessment
ELV	Emission limit value
EOR	Enhanced oil recovery
ERF	Energy recovery facility
FGC	Flue gas cleaning
FGD	Flue gas desulphurisation
GGR	Greenhouse gas removal
GHGs	Greenhouse gases
GLA	Greater London Authority
Hectare	ha
HCl	Hydrogen chloride
HCO_3^-	Hydrogen carbonate
HF	Hydrogen fluoride
HSE	Health and Safety Executive
HSS	Heat Stable Salts

Abbreviation	Meaning
IBA	Incinerator bottom ash
IBAA	Incinerator bottom ash aggregate
IED	Industrial Emissions Directive
LCA	Life Cycle Analysis
MSW	Municipal solid waste
N_2O	Nitrous oxide
$NaHCO_3$	Sodium bicarbonate
NCV	Net Calorific Value
NLHPP	North London Heat and Power Project
NLWA	North London Waste Authority
NO_x	Nitrogen oxides
OPEX	Operational expenditure
PCC	Post-combustion capture
RAG	Red-Amber-Green
RRC	Reuse and Recycling Centre
RRF	Resource recovery facility
SBTi	Science based target initiative
SCR	Selective catalytic reduction
SDGs	Sustainable Development Goals
SO_2	Sulphur dioxide
SO_x	Sulphur oxides
TfL	Transport for London
UN	United Nations
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
VCS	Verified Carbon Standard
WCC	Woodland Carbon CO_2de
WWF	World Wide Fund for Nature

Executive summary

Introduction

This report provides an overview of carbon dioxide equivalent (CO_{2e}) emission reduction solutions via carbon offsetting and carbon capture use and storage (CCUS) for the Energy Recovery Facility (ERF) part of the North London Heat and Power Project (NLHPP) of the North London Waste Authority (NLWA).

The ERF will treat up to 700,000 tonnes/annum of residual municipal solid waste (MSW) from seven North London boroughs (i.e. Barnet, Camden, Enfield, Hackney, Haringey, Islington and Waltham Forest). The gross electrical output is expected to be 63MWe, and associated district heating output of 35MWth, as a minimum. However, it is expected that the heat supply capacity will be larger than 35MWth.

Legislation, guidance and definitions

The international, national and local legislation, policy and guidance associated with carbon and climate change was reviewed, including the updates to the Environmental Impact Assessment (EIA) Regulations in 2017, which now include climate change as one of the topics requiring assessment.

A discussion of what it means for organisations to be net zero (as defined by the Science Based Targets Initiative) or carbon neutral (as defined by BSI PAS 2060) is also provided. This is to highlight the importance of using an appropriate methodology and communications for NLHPP when setting relevant targets and committing to specific standards and accreditations. It is equally important to clearly define the carbon footprint system boundaries (i.e. ERF, NLHPP and NLWA) when considering target setting.

ERF carbon emissions system boundaries

The carbon emission system boundaries of the ERF are described to define the capital inputs such as the ERF construction, operational inputs including, for example, the delivery of residual MSW to the ERF, and outputs including direct CO_2 emissions in the flue gas, which are contributing to its carbon footprint, and those outputs, for example, extraction of ferrous metals from the incinerator bottom ash that allow the ERF to offset some of its greenhouse gas emissions.

A previous study by Ramboll estimated that the ERF will release fossil carbon comprising 0.455tonnes CO_2e/tonne of waste treated or 318,500 tonnes CO_2e/ annum. Including the offsets for electricity and heat production, and recycling of metals from the incinerator bottom ash, Ramboll report that the net CO_2e emissions of the ERF are 28,000 tonnes/annum, as opposed to the net CO_2e emissions from landfill, which are estimated at 243,000 tonnes/annum.

Additional offsets for recycling of incineration bottom ash aggregate, and potentially air pollution control residues could be considered, which are currently not included in guidance for emissions from waste incineration by the Intergovernmental Panel on Climate Change or in Ramboll's carbon assessment.

Carbon offsetting

Some of the carbon offsetting options explored include afforestation, reforestation, and soil carbon sequestration. All options are qualitatively assessed from a commercial, technical and carbon emissions reduction perspective. Indicative costs are provided for various options, where this information was available.

It is highlighted that to provide tailored recommendations on the carbon offsetting approach for NLHPP, it is important for NLWA to agree on several key areas and approaches including NLWA's carbon targets (e.g. net zero or carbon neutral) and associated standards and accreditations, as well as NLWA's corporate sustainability objectives. It is expected that a combination of carbon offsetting options will be required to be implemented to offset either the net or total CO_2e emissions of the ERF. For instance, a land take of minimum 1,120ha is estimated to be required to offset the net CO_2e emissions of 1,120,000 tonnes generated over 40 years of ERF operation (i.e. 28,000 tonnes CO_2e/annum x 40 years = 1,120,000 tonnes CO_2e). This would include an estimated number of 1,792,000 trees and amounts to a land take of approximately 4% of the total area of the seven North London boroughs. This would cost between £3.4 million and £28 million (as price can vary from £3-25/tonne CO_2e). In comparison, for offsetting 100,000 tonnes CO_2e/annum (i.e. 100,000 tonnes CO_2e/annum x 40 years = 40,000,000 tonnes CO_2e) this would cost between £12 million and £100 million.

The offsetting solution of afforestation and reforestation will be subject to carbon offset credits being available in the market as they are subject to supply and demand market forces. It is likely that the price for carbon offset credits is going to increase as the demand for offsetting is growing. A recent World Bank Group report on the state and trends of carbon pricing states that less than 5% of carbon pricing initiatives are priced at a level consistent with achieving the goals of the Paris Agreement of US$40-80/t$CO_2$ by 2020 and US$50-100/t$CO_2$ by 2030.

Carbon capture use and storage

Some of the carbon capture and use (CCU) options explored include CO_2 mineralisation in construction materials and the use of CO_2 in sodium bicarbonate production. All options are qualitatively assessed from a commercial, technical and carbon emissions reduction perspective. Indicative costs are provided for various options, where this information was available. Case studies of existing energy from waste (EfW) facilities from Norway, the Netherlands and Japan, which have adopted some form of CCUS, either commercially or as a trial were reviewed.

Carrying out a life cycle assessment (LCA) of the proposed CCUS can help determine the level at which CCUS can offer positive environmental impacts. An LCA conducted for EfW showed that it performs better than fossil fuel-based power plants for most environmental impact categories, including its climate change impact potential. However, the quantitative results of an LCA need to be assessed on a case-by-case basis, given the large variety of parameters to be considered, the level of detail required, and the system boundaries set in each case.

If NLWA decides to further consider the development of a carbon capture plant for the ERF, one of the key decisions recommended to be made is determining the potential end-users and the level of CO_2 targeted to be captured. This will heavily influence several key technical decisions, such as the overall size and footprint of the CO_2 capture plant, the size of intermediate storage facility in advance of CO_2 transport from NLHPP, and the selection of CO_2 transport options to the end user.

Based on a high-level estimate, a land take of 2,500-8,500m^2 would be needed for the carbon capture unit, liquefaction, storage and vehicle loading station on-site, based on an assumed CO_2 capture capacity of 100,000-350,000 tonnes/annum. It should be noted that the above estimates are the high-end of the scale (i.e. trying to capture ERF annual direct CO_2 emissions).

The post-combustion capture of CO_2 from the flue gas of the ERF is expensive due to the high deployment costs of the technology and operational costs associated with the extraction, liquefaction, storage and transport of the captured CO_2.

Information on the capital expenditure (CAPEX) for carbon capture plants is limited. Initial discussions with two potential suppliers with experience of CCUS for EfW plants indicates that the CAPEX for a standard modular 100,000 tonnes CO_2/annum plant comprising carbon capture, liquefaction, storage and vehicle loading is approximately £26 million (excluding costs for utility systems, dealing with ground hazards, building, mobile plant, taxes etc).

It is estimated that operational expenditure (OPEX) of capturing the direct CO_2 emissions from the residual MSW on an annual basis (assumed at 100,000 tonnes CO_2/annum) could cost between £0.5-1.6 million/annum. This assumes that the OPEX ranges between 2-6% of the CAPEX of the carbon capture plant. However, both the capital and operational expenditure are very project specific.

Given the significant cost uncertainty associated with carbon capture plants, it is recommended that NLWA undertake a more detailed feasibility study to better define the site-specific constraints and opportunities for developing a carbon capture solution and associated CAPEX and OPEX requirements. In addition, an assessment should be undertaken of the implications of adding a carbon capture plant to the existing consents, permits and approvals already in place for the ERF.

1 Introduction

This report was prepared by Ove Arup & Partners Ltd (Arup) on behalf of the North London Waste Authority (NLWA) and provides a review of the carbon offsetting and carbon capture, use and storage (CCUS) options to address the carbon dioxide equivalent (CO_2e) emissions from the North London Heat and Power Project (NLHPP) Energy Recovery Facility (ERF).

The objective of this report is to explore both short term CO_2e emission reductions solutions via carbon offsetting, as well as longer term solutions via CCUS, as the technology for the latter keeps developing.

The NLHPP will comprise the following elements:

- ERF – to treat up to 700,000 tonnes/annum of residual municipal solid waste (MSW) from seven London boroughs (i.e. Barnet, Camden, Enfield, Hackney, Haringey, Islington, and Waltham Forest). The gross electrical output is expected to be 63MWe, while the district heating output of the ERF is expected to be 35MWth.
- Resource Recovery Facility (RRF) – to sort a variety of reusable and recyclable materials (e.g. plastics, metals) from the incoming residual waste. The RRF will include a Reuse and Recycling Centre for use by members of the public and small businesses.
- Reuse and Recycling Centre (RRC) – a facility for the public to drop-off recyclables and residual waste
- EcoPark House – to serve as a visitor and education centre.

This report focuses on the ERF, which is expected to be the largest contributor of CO_2e emissions on-site and the main element of the NLHPP targeted by opposition groups[1]. However, it is acknowledged that the construction and operation of other project elements (e.g. RRF, RRC, EcoPark House), will also contribute to CO_2e emissions throughout the lifespan of the EcoPark as well as other NLWA services (e.g. operation of transfer stations and other RRCs). Therefore, having a NLWA-wide climate change and carbon management plan will allow the collective and effective targeting of CO_2e emissions reductions.

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[1] Hackney Citizen (2020), *Extinction Rebellion writes to over 400 councillors asking for halt to Edmonton incinerator*, Available at: https://www.hackneycitizen.co.uk/2020/03/11/extinction-rebellion-writes-400-councillors-halt-edmonton-incinerator/ (Accessed 16 March 2020).

2 Carbon dioxide properties and emissions management

2.1 Properties of carbon dioxide

CO_2 is a non-polar chemical compound consisting of two oxygen atoms covalently bonded to a single carbon atom (O=C=O). It is a colourless gas at ambient temperature and pressure, and it is odourless at low concentrations.

The fundamental physical properties of pure CO_2 are listed in Table 1 with reference to the phase diagram given in Figure 1.

Table 1: Physical properties of pure CO_2

Property	Value	Unit	Value	Unit
Critical density	10.63	mol/dm^3	467.6	kg/m^3
Critical pressure	7.38	MPa=MN/m^2	73.8	Bar
Critical temperature	304.25	K	31.1	°C
Critical volume	94.12	cm^3/mol	0.00214	m^3/kg
Density, gas at 32°F/0°C 1 atm	44.9	mol/m^3	1.977	kg/m^3
Density, liquid at -34.6 °F/-37°C, saturation pressure	25,017	mol/m^3	1,101	kg/m^3
Heat (enthalpy) of evaporation at 15°C	16.7	kJ/mol	379.5	kJ/kg
Molecular Weight	44.0095	g/mol	-	-
Solubility in water	0.148	g/100 g	1.48	g/l=mg/ml
Sublimation Point	194.686	K	-78.464	°C
Triple point pressure	0.518	MPa=MN/m^2	5.18	bar
Triple point temperature	216.59	K	-56.56	°C

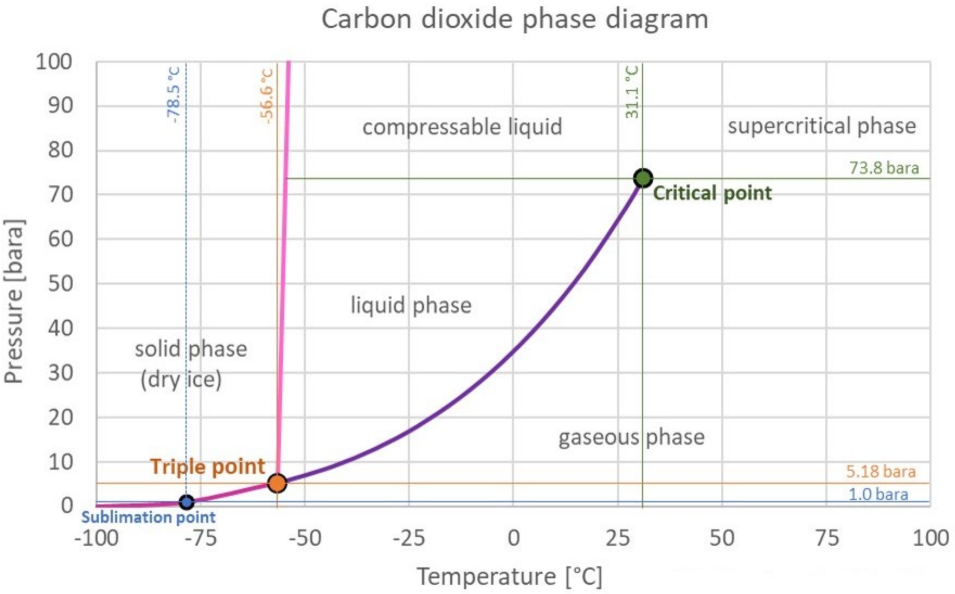

Figure 1: CO_2 phase diagram[2]

At normal atmospheric pressure and temperature, CO_2 exists in the gaseous phase with a higher density than air. For the CO_2 to transform from liquid to gas at constant pressure, heat must be added, as it is required to convert water (liquid H_2O) into steam. Similarly, to transform from gas to liquid, heat must be removed. For temperatures below 31.1°C, an increase in pressure would also result in a transformation from gaseous to liquid phase when the conditions of the CO_2 cross the gas-liquid line. A combination of liquefaction and compression is typically used to transform gaseous CO_2 to liquid CO_2.

The triple point identifies the coexistence of gas, liquid and solid phase. The triple point of CO_2 is at -56.6°C and 5.18 bar. At the right combination of pressure and temperature CO_2 may turn into the solid state commonly known as dry ice. These conditions should be avoided in any CO_2 transportation and storage system.

2.2 The carbon cycle

Carbon is present in plants and rocks, the atmosphere and the oceans. Carbon therefore moves, or ‘cycles’, between each of these media and is redistributed between carbon ‘sources’ and ‘sinks’.

The carbon in the carbon cycle is found in ‘organic’ or ‘inorganic’ forms. Most of the inorganic carbon exists as CO_2, carbonate (CO_3^{2-}) and hydrogen carbonate (HCO_3^{-}). Organic carbon is found in living or dead organisms, fossil fuels, small deposits in rocks, dissolved in water or dispersed in the atmosphere.

The natural cycles of carbon are disturbed by anthropogenic activity, such as transport and industrial activity, adding more CO_2 to the atmosphere and converting carbon sinks into carbon sources.

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[2] Engineeringtoolbox (2019), *Carbon Dioxide - Thermophysical Properties*, Available at: https://www.engineeringtoolbox.com/CO2-carbon-dioxide-properties-d_2017.html (Accessed 30 April 2020).

The carbon cycle and some ways in which CO_2 can be restored within the cycle are shown in Figure 2.

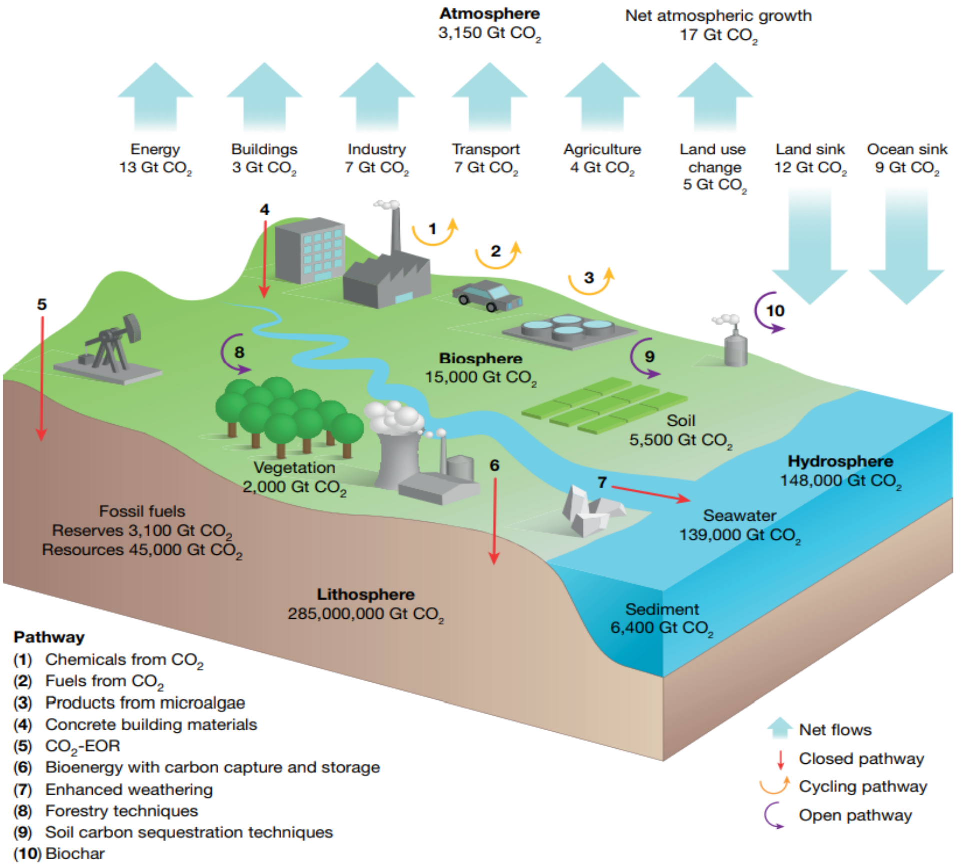

Figure 2: Sinks and sources of CO_2 and potential pathways for restoring the carbon cycle[3]

2.3 Carbon neutrality and net zero emissions

Net zero emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period. Net zero CO_2 emissions are also referred to as carbon neutrality[4].

In September 2019, the Science Based Target Initiative (SBTi), published a discussion paper[5] containing a working definition of net zero, aiming for publication of key principles and draft guidelines later in 2020. Under SBTi's definition, a carbon neutral organisation can offset its emissions through a range

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[3] Hepburn *et al* (2019), *The technological and economic prospects for CO_2 utilization and removal,* Available at: https://www.nature.com/articles/s41586-019-1681-6 (Accessed 12 March 2020).

[4] Intergovernmental Panel on Climate Change (IPCC) (2015), *Special Report: Global Warming of 1.5 ºC*, Available at: https://www.ipcc.ch/sr15/chapter/glossary/ (Accessed 13 March 2020).

[5] Science Based Targets (2019), *Towards A Science-Based Approach To Climate Neutrality in the Corporate Sector*, Available at: https://sciencebasedtargets.org/wp-content/uploads/2019/10/Towards-a-science-based-approach-to-climate-neutrality-in-the-corporate-sector-Draft-for-comments.pdf (Accessed 13 March 2020).

of options, whereas a net zero organisation must use only certified greenhouse gas removal (GGR).

It is important that NLWA sets a target and agrees on appropriate terminology and consistent language for communication. This will assist in providing tailored recommendations for any carbon offsetting solution (dependent on whether certification is required or not) and ensure consistency in communicating the carbon targets of the project.

The carbon neutral and net zero terminology is provided in Table 2.

Table 2: Zero carbon and carbon neutral definitions

Term	Definition	Defined by	Benefits
Net zero	A net-zero organisation will set and pursue an ambitious 1.5°C aligned science based target for its full value chain emissions. Any remaining hard-to-decarbonise emissions can be compensated with certified GGRs.	• Science Based Targets Initiative	• Ambitious carbon reduction target • Reduction required over agreed timeframe • Does not recognise avoided emissions
Carbon neutral	A carbon neutral organisation will measure its carbon footprint and develop and implement a Carbon Management Plan (including a reduction target). Residual emissions will be offset by high quality, certified carbon credits.	• BSI PAS 2060[6]	• Carbon reduction required through efficiency and performance targets • Recognises carbon offsets for residual emissions[7]

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[6] BSI, *PAS 2060 Carbon Neutrality*, Available at: https://www.bsigroup.com/en-GB/PAS-2060-Carbon-Neutrality/ (Accessed 10 March 2020).

[7] 'Residual emissions' are the emissions remaining after all technically and economically feasible opportunities to reduce emissions in all covered scopes and sectors have been implemented.

3 Carbon and climate change legislation, policy and guidance

3.1 Overview

The year 2020 is being hailed as the ‘super year’ for raising ambition on climate change, and the start of a decade of climate action. Through 2020 we will see climate change on the agenda at the World Economic Forum, the World Urban Forum and at Mayoral Summits – all leading up to COP26 in Glasgow, which is expected to be the largest international summit ever hosted in the UK. There are also major summits on oceans and biodiversity, which will further contribute to creating an ambition loop catalysing commitments and action from key actors including nations, regions, cities, business and citizens.

A high-level overview of the main legislation, policy and guidance in relation to climate change and carbon, is given in the sub-sections below, with an emphasis on recent changes (i.e. from 2015 onwards). The aim is to review the main legislation and policy drivers that need to be considered by NLWA and put into practice in its decision making and targets for NLHPP.

3.2 International

In 2015, the UK signed up to the United Nations (UN) Paris Agreement to attempt to limit the global average temperature rise to 1.5 degrees Celsius (1.5°C) above pre-industrial levels.

In 2015, the 17 UN Sustainable Development Goals (SDGs), with their 169 targets, were adopted by Heads of State and Government at a UN summit; these form the core of the 2030 Agenda of the UN. The SDGs balance the economic, social and environmental dimensions of sustainable development, through the 17 Goals, such as Goal 12 Responsible Consumption and Production and Goal 13 Climate Action.

3.3 National

In 2017, a new set of Environmental Impact Assessment (EIA) regulations came into force in England[8] with one of the new topics for assessment being climate change.

In 2017, the Clean Growth Strategy[9] was launched by the UK Government, which sets out a comprehensive set of policies and proposals that aim to accelerate the pace of ‘clean growth’ (i.e. deliver increased economic growth and decreased emissions), via the promotion of low carbon technologies, processes and systems. One of the aims of the Clean Growth Strategy is to demonstrate international

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[8] Town and Country Planning (Environmental Impact Assessment) Regulations 2017.

[9] HM Government (2017), *The Clean Growth Strategy*, Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf (Accessed 21 April 2020).

leadership in CCUS by collaborating with global partners and investing up to £100 million in leading edge CCUS and industrial innovation to drive down costs. The Clean Growth Strategy also sets out the need for the UK Government to work in partnership with industry, through a new CCUS Council, to put the UK on a path to deploy CCUS at scale, and to maximise its industrial opportunity.

In 2018, the 25 Year Environment Plan[10] was published by the UK Government. It sets out goals for improving the environment within a generation, leaving it in a better state than found. It details how government will work with communities and businesses to do this. The 25 Year Environment Plan states that the strengthening of carbon offset mechanisms are targeted to encourage private sector investment and develop markets for domestic carbon reduction. The 25 Year Environment Plan set out the introduction of the Forest Carbon Guarantee scheme, a £50 million government scheme introduced in November 2019, using the existing Woodland Carbon Code[11].

In 2018, the Resources and Waste Strategy for England[12] was published, which sets out a proposed framework for monitoring the success of resource and waste management in England. The framework includes a target to mitigate climate change via reducing greenhouse gas (GHG) emissions from waste. At the same time, the Resources and Waste Strategy targets the improvement of the efficiency and the growth of EfW facilities, to improve the diversion of residual waste from landfill.

In 2019, the Climate Change Act 2008 was amended[13], which sets the basis for the UK Government's approach to responding to climate change. It requires that emissions of CO_2 and GHGs are reduced, and that climate change risks are prepared for. The Climate Change Act legally commits the UK Government to reducing GHG emissions by at least 100% of 1990 levels by 2050.

In 2019, the Net Zero report[14], which was published by the Committee on Climate Change, highlights that '*CCS is a necessity not an option*' and recommends that that the first CCS cluster[15] should be operational by 2026, with two clusters, capturing at least 10 million tonnes CO_2, operating by 2030. However, as they highlight, to achieve net zero targets, larger CCS capacities should be targeted.

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[10] HM Government (2018), *A Green Future: Our 25 Year Plan to Improve the Environment*, Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf (Accessed 21 April 2020).

[11] Forest Carbon (2020), *The Woodland Carbon Guarantee*, Available at: https://www.forestcarbon.co.uk/knowledge-base/woodland-carbon-guarantee (Accessed 21 April 2020).

[12] HM Government (2018), *Our Waste, Our Resources: A Strategy for England*, Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/765914/resources-waste-strategy-dec-2018.pdf (Accessed 21 April 2020).

[13] UK Government (2019), *Climate Change Act 2008 (as amended)*, Available at: http://www.legislation.gov.uk/ukpga/2008/27/contents (Accessed 21 April 2020).

[14] Committee on Climate Change (2019), *Net Zero – The UK's contribution to stopping global warming*, Available at: https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/ (Accessed 21 April 2020).

[15] A group of individual CCS sites.

Delayed availability of CO_2 transport and storage infrastructure may mean higher industry emissions in 2050.

In 2019, the UK Government set out measures to go further in tackling climate change, in response to Committee on Climate Change (CCC) recommendations[16]. Such measures include the provision of £26 million of additional funding for CCUS technology, including an investment of £4.6 million into a facility which will capture and utilise 40,000 tonnes CO_2/annum (planned to be operational by 2021 by Tata Chemicals in a Cheshire gas-fired power plant).

Measures announced in the March 2020 Budget included a new 'CCS Infrastructure Fund' of at least £800 million designed to establish CCS in at least two UK clusters – one by the mid-2020s and one by 2030[17].

3.4 Local

3.4.1 Greater London

In 2018, London's Environment Strategy was published. It is one of the first city plans published to be compliant with the highest ambition of the Paris Agreement 2016. It commits London to be a zero carbon city by 2050.

In 2018, the Greater London Authority (GLA), in its Zero Carbon London: A 1.5ºC Compatible Plan[18], states that London's trajectory to zero carbon by 2050, will encounter residual emissions (estimated at 10% of total emissions), which will need to be offset through CCUS or carbon offsetting.

In 2018, the GLA published the latest iteration of the draft New London Plan, which includes Policy SI2 (Minimising greenhouse gas emissions)[19], stating that major development, including major refurbishment, should be net zero-carbon. This means reducing CO_2 emissions from construction and operation, and minimising both annual and peak energy demand. London's local planning authorities (LPAs) must establish and administer a carbon offset fund (see Section 3.4.2).

The draft new London Plan also includes Policy SI7 (Reducing waste and supporting the circular economy), which promotes waste reduction and landfill diversion, and Policy SI8 (Waste capacity and net waste self-sufficiency), which states that 100% of London's waste should be managed within London by 2026.

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[16] UK Government (2019), *UK to go further and faster to tackle climate change*, Available at: https://www.gov.uk/government/news/uk-to-go-further-and-faster-to-tackle-climate-change (Accessed 21 April 2020).
[17] HM Treasury (2020), *Budget 2020: What you need to know*, Available at: https://www.gov.uk/government/news/budget-2020-what-you-need-to-know (Accessed 17 March 2020).
[18] GLA (2018), *Zero carbon London: A 1.5ºC compatible plan*, Available at: https://www.london.gov.uk/sites/default/files/1.5c_compatible_plan.pdf (Accessed 21 April 2020).
[19] GLA (2018), *Draft New London Plan – Policy SI2 Minimising greenhouse gas emissions*, Available at: https://www.london.gov.uk/what-we-do/planning/london-plan/new-london-plan/draft-new-london-plan/chapter-9-sustainable-infrastructure/policy-si2-minimising (Accessed 30 April 2020).

3.4.2 NLWA waste collection authorities

The GLA published guidance for LPAs to set up Carbon Offset Funds[20] to provide a source of funding for carbon reduction projects across London. They fund emission reductions from existing buildings where achieving carbon savings can be more challenging compared to new buildings. It is estimated that London's Carbon Offset Funds amount to £30-40 million based on a carbon offset price of £60/tonne CO_2. Each one of the London LPAs (which are also waste collection authorities) collects the funds for developments within their area, but the way they implement these funds varies.

Table 3 shows the waste collection authorities comprising the NLWA and the status of their Carbon Offset Payments[21]. Most of the seven waste collection authorities of NLWA have individual carbon policies and targets in place (see Table 4).

Table 3: Carbon offset payments for NLWA LPAs

Waste collection authority	Total sum collected since 1 October 2016	Total sum secured by legal agreement but not collected since 1 October 2016
Barnet	£570	Barnet has a total of £430,131 of carbon offset payments agreed in the Planning Committee Reports which are waiting to have the Section 106 Agreement signed
Camden	£511,373	£2,208,307
Enfield	£75,000	*Information not available*
Hackney	£662,033	£915,217
Haringey	£330,481	£1,498,592
Islington	*Information not available*	*Information not available*
Waltham Forest	£705,828	£666,700

Table 4: Carbon policies of the seven NLWA waste collection authorities

Name of waste collection authority	Carbon policies
Barnet	No available policies
Camden	Reduce CO_2 emissions in Camden from 2005 levels by 80% by 2050[22].

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[20] GLA (2018), *Carbon Offset Funds*; Available at: https://www.london.gov.uk/sites/default/files/carbon_offsett_funds_guidance_2018.pdf (Accessed 23 March 2020).

[21] GLA (2019). *Carbon Offset Funds Survey Results 2019*. Available at: https://www.london.gov.uk/sites/default/files/2019_cof_survey_results_final_0.pdf (Accessed 16 March 2020).

[22] London Borough of Camden (2019). *Our carbon reduction programme*. Available at: https://www.camden.gov.uk/carbon-reduction-programme (Accessed 16 March 2020).

Name of waste collection authority	Carbon policies
	Key initiatives in Camden's Green Action for Change Plan[23]: • Implement the Carbon Management Programme 2010-20, monitoring and targeting carbon reductions across corporate property, schools, fleet, hostels and street lighting. • Continue to identify and deliver low carbon energy projects in partnership with developers and other organisations in the borough. • Provide advice and support to Camden Climate Change Alliance members to reduce their environmental impact and improve sustainability.
Enfield	The target of reducing carbon by 40% compared with 2009 was met three years ahead of schedule. As a result, a new 60% carbon reduction target by 2025 was set[24].
Hackney	Targets include a 45% reduction in emissions against 2010 levels by 2030 and deliver net zero emissions across its functions by 2040, ten years earlier than the target set by the Government[25].
Haringey	Haringey was the first local authority in the UK to sign the Friends of the Earth pledge to reduce borough-wide emissions by 40% by 2020[26]. The Zero by 2050 report of London Borough of Haringey sets out the following aims: • Improved energy efficiency standards in new and existing buildings. • Embrace and enforce planning policy targeted at energy efficiency and renewable generation. • More efficient and local electricity generation.
Islington	In Islington's Environment Policy the council set out to minimise its carbon emissions from buildings and fleet, as well as maximising renewable energy generation. Islington aimed to reduce carbon emissions from 2005 levels by at least 40% by 2020. They have furthered this by setting out to achieve a net carbon zero Islington by 2030; an ambition that exceeds the national target of 2050 for a net carbon zero UK[27].

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[23] Green Camden (2019) G*reen action for change: Camden's Environmental Sustainability Plan*. Available at: https://www.camden.gov.uk/documents/20142/0/GAFC+Annual+review+2018-final.pdf/4829cf8f-d440-d789-fc5b-2434e3e8633f (Accessed 16 March 2020)

[24] Enfield Council (no date). *Carbon.* Available at: https://new.enfield.gov.uk/services/environment/carbon/. (Accessed 16 March 2020).

[25] Hackney Council (2019). *Hackney Council pledges to reach net zero emissions by 2040.* Available at: https://news.hackney.gov.uk/hackney-council-pledges-to-reach-net-zero-emissions-by-2040/ (Accessed 16 March 2020).

[26] Haringey Council (2019). *Reducing CO2 Emissions.* Available at: https://www.haringey.gov.uk/environment-and-waste/going-green/reducing-co2-emissions. (Accessed 16 March 2020).

[27] Islington Council (2019*). Islington declares climate emergency and makes 2030 net zero carbon pledge.* Available at: https://www.islington.media/news/islington-declares-climate-emergency-and-makes-2030-net-zero-carbon-pledge. (Accessed 16 March 2020).

Name of waste collection authority	**Carbon policies**
Waltham Forest	Over the last ten years Waltham Forest has successfully met the carbon reduction targets set out in their 2008 Climate Change Strategy, which set an overall target to reduce CO_2 emissions by 80% by 2050[28]. Waltham Forest Climate Emergency Commission will inform the Council's Climate Emergency Strategy, following the declaration of a climate emergency[29].

3.5 Future NLWA targets

NLWA runs the Wise Up to Waste Campaign, as part of which they have set up the Waste Prevention Community Fund, to help increase waste prevention activities across London. The Campaign also seeks to improve NLWA's collective recycling rate to 50% by 2020[30].

The North London Joint Waste Strategy was last updated in 2009. The seven North London waste collection authorities have joined forces to prepare the North London Waste Plan, to set out the planning framework for waste management in North London for the next 15 years.

It is important for NLWA to get involved in setting overarching plans and targets for the seven waste collection authorities. Such plans and targets shall be developed in conjunction with climate change and carbon targets, in line with current national and local legislation, policy and guidance, as outlined above.

Setting clear climate change and carbon targets will also ensure that well-informed decisions can be made regarding the reduction of CO_2e emissions from NLHPP, via offsetting and/or CCUS options.

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[28] Waltham Forest Council (2019). *Notice Of Motion - Climate Emergency*. Available at: https://democracy.walthamforest.gov.uk/mgAi.aspx?ID=32233 (Accessed 16 March 2020)
[29] Waltham Forest Council (*no date*). Climate Change. Available at: https://walthamforest.gov.uk/content/climate-change (Accessed 16 March 2020)
[30] NLWA Wise up to Waste, Available at: http://wiseuptowaste.org.uk/ (Accessed 21 April 2020).

4 ERF description

4.1 Process overview

The ERF will use advanced moving grate incineration technology, which is the most widely used technology for residual MSW treatment. It will operate for approximately 8,000 hours/annum, accepting a maximum of 700,000 tonnes of residual MSW/annum, with an average net calorific value (NCV) of 10GJ/tonne.

The combustion of residual waste results in the generation of climate-relevant emissions. These are mainly emissions of CO_2, and to a lesser extent, by at least a factor of 10, nitrous oxides (N_2O), nitrogen oxides (NOx), and ammonia (NH_3). Methane (CH_4) is not generated during normal operation.

The ERF will be equipped with a very high performing combined wet/dry flue gas cleaning (FGC) system. The combined FGC will remove most of the pollutants through an upstream semi-dry system but will also include a downstream polishing scrubber to treat the flue gas further, increasing the FGC's overall performance.

To address emissions of nitrogen oxides (NOx)[31], the ERF will incorporate selective catalytic reduction (SCR), which will reduce NOx emissions to at least 80mg/Nm^3 (daily average) as per the environmental permit. This is less than half of the current Industrial Emissions Directive (IED) emission limit value (ELV) of 200mg/Nm^3. The NOx emissions will also be below the average Best Available Techniques-Associated Emission Level (BAT-AEL) of 50-120mg/Nm^3 for new plant[32]. NLHPP will be one of the first energy from waste (EfW) facilities in the UK to be fitted with SCR technology.

The ERF will recover an estimated 12.2kg/tonne of ferrous metal and 3.4kg/tonne of non-ferrous metal within the incinerator bottom ash (IBA).

4.2 CO_2 emissions

4.2.1 General assumptions

Residual waste is the fraction of MSW that cannot be beneficially recycled for economic, environmental and practical reasons. Residual waste constitutes a significant renewable energy resource that can be recovered through thermal processes, such as EfW.

The composition of residual waste changes over time as consumption patterns, reuse, and recycling performance changes. Based on guidance published by the

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[31] NOx act as indirect greenhouse gases by producing tropospheric ozone which is one of the top five primary greenhouse gases in the Earth's atmosphere.

[32] European Commission (2019), Best Available Techniques (BAT) Reference Document for Waste Incineration, page 496, Table 5.6; Available at: https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC118637_WI_Bref_2019_published_0.pdf; (Accessed 23 March 2020).

Intergovernmental Panel on Climate Change (IPCC)[33], the combustion of 1 tonne of residual waste generates approximately 0.7-1.2 tonnes of CO_2 (see Figure 3). The Environment Agency[34] reports that 0.7-1.7 tonnes of CO_2 are produced for one tonne of MSW combusted.

The measured CO_2 output from the stack is approximately 10% (by volume) with an exhaust flue gas volume of typically $5{,}500m^3$(dry)/tonne of waste and a CO_2 density of $1.9768kg/m^3$, which equates to an emission of 1,087kg CO_2/tonne of waste combusted (i.e. $5{,}500m^3$/tonne x 0.1 x $1.9768kg/m^3$ = 1,087kg CO_2). The content of carbon in CO_2 is approximately 27.3% (i.e. C 12g/mol/CO_2 44g/mol = 27.3) or 297kg carbon per tonne of residual waste.

Based on the IPCC information, the proportion of carbon of biogenic origin in MSW is usually in the range of 50-67% (average 58.5%), and that for non-biogenic carbon of 33-50% (average 41.5%) respectively.

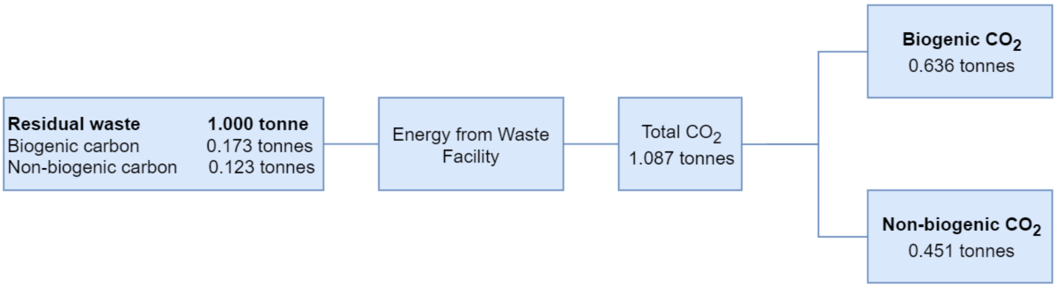

Figure 3: Carbon balance for one tonne of waste

The CO_2 emissions from biogenic sources (i.e. non-fossil based sources) are not included in the carbon assessment for EfW facilities as these are considered renewable sources of carbon. Only the climate-relevant CO_2 emissions are included for the global analysis by the IPCC and Department for Environment, Food and Rural Affairs' (Defra) carbon-based modelling guidance report[35].

4.2.2 System boundaries

In order to make informed decisions regarding the CO_2 emissions to be targeted for offsetting and/or CCUS for the ERF, it is important to have clearly defined system boundaries for the following:

- **NLWA**: Defining the system boundary of the NLWA as a whole (including all of its functions and operations) and subsequently calculating its carbon

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[33] IPCC (2000), *Emissions from waste incineration*, Available at: https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_3_Waste_Incineration.pdf (Accessed 16 March 2020).

[34] Environment Agency (2020), *Pollution inventory reporting – incineration activities guidance note*, Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/869265/Pollution-inventory-reporting-incineration-activities-guidance-note.pdf (Accessed 13 March 2020).

[35] Defra (2014), *Energy recovery for residual waste: A carbon based modelling approach*, Available at: http://sciencesearch.defra.gov.uk/Document.aspx?Document=11918_WR1910Energyrecoveryforresidualwaste-Acarbonbasedmodellingapporach.pdf (Accessed 19 March 2020).

footprint, would help to determine quantitatively the level of contribution of the ERF to the overall carbon footprint of the NLWA.

- **NLHPP**: Defining the system boundary of the NLHPP and subsequently calculating its carbon footprint, would help determine both the level of contribution of the NLHPP to the carbon footprint of the NLWA, but also an informed comparison could be made between its footprint and that of the ERF.
- **ERF**: Defining the system boundary of the ERF (see below) and subsequently calculating its carbon footprint would allow a valid comparison with the footprint of NLHPP and NLWA. This would help determine the significance of the ERF in terms of both its embodied carbon and direct CO_2 emissions. This will inform CO_2 emissions reduction targets. Ultimately, this would help develop the most optimum carbon reduction interventions.

Figure 4 defines the system boundaries of the ERF, including the capital inputs, the operational inputs and the outputs, which should be taken into consideration when estimating the net CO_2e emissions of the ERF (and also the carbon footprint of the ERF as a whole).

The orange boxes on Figure 4 indicate inputs and outputs which add to the overall CO_2e emissions (and therefore the carbon footprint) of the ERF (i.e. burdens). For example:

- CO_2e emissions from transporting residual MSW to the ERF.
- CO_2e emissions in the flue gas conveyed to the atmosphere through the stack of the ERF.

The green boxes on Figure 4 indicate outputs which act as replacements for more carbon intensive alternatives (i.e. offsets). For example:

- Producing electricity from the ERF process and exporting it to the national grid, which offsets the CO_2e emissions from other fossil fuel based electricity production.
- Producing incinerator bottom ash aggregate (IBAA) to be used as secondary aggregate in the construction industry instead of using virgin aggregates.

It should be noted that air pollution control residues (APCr) from the ERF process could be an offset instead of a burden, in case that APCr is diverted from landfill (e.g. by recycling it through the Carbon8 Systems process).

It should be noted that the Ramboll CO_2e emissions study for the ERF (see Section 4.2.3) did not account for either IBAA production or the recycling of APCr, as an offset. Diverting IBA and APCr from landfill via recycling to produce IBAA and concrete blocks, respectively, could marginally reduce the net CO_2e emissions of the ERF. However, for APCr in particular, consideration of the full life-cycle impacts would be necessary to determine the suitability of this solution.

While APCr recycling has not been planned for the ERF, IBAA production from IBA is planned for[36].

As an indication:

- The use of recycled/secondary aggregates (e.g. IBAA) in construction accounts for emissions of 3.2kg CO_2e/tonne as opposed to the use of virgin aggregates, which account for emissions of 7.8kg CO_2e/tonne. This amounts to a saving of 4.6kg CO_2 for every tonne of aggregate[37].
- The Carbon8 Systems process estimates that the CO_2 in the APCr ranges from 11.4% to 34.3% by weight[38].

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[36] North London Waste Authority (2015), *Environmental Statement: Volume 1*, Available at: http://northlondonheatandpower.london/media/0fvjv14c/ad06-02_es_vol_1_lores.pdf (Accessed 27 March 2020).

[37] Department for Business, Energy & Industrial Strategy (BEIS) (2019), *Greenhouse gas reporting: conversion factors 2019*, Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019 (Accessed 27 March 2020).

[38] Carey, P. (*no date*), *Carbon8 Systems*, Available at: http://nas-sites.org/dels/files/2018/02/1-5-CAREY-Carbon8-Systems-NAS.pdf (Accessed 27 March 2020).

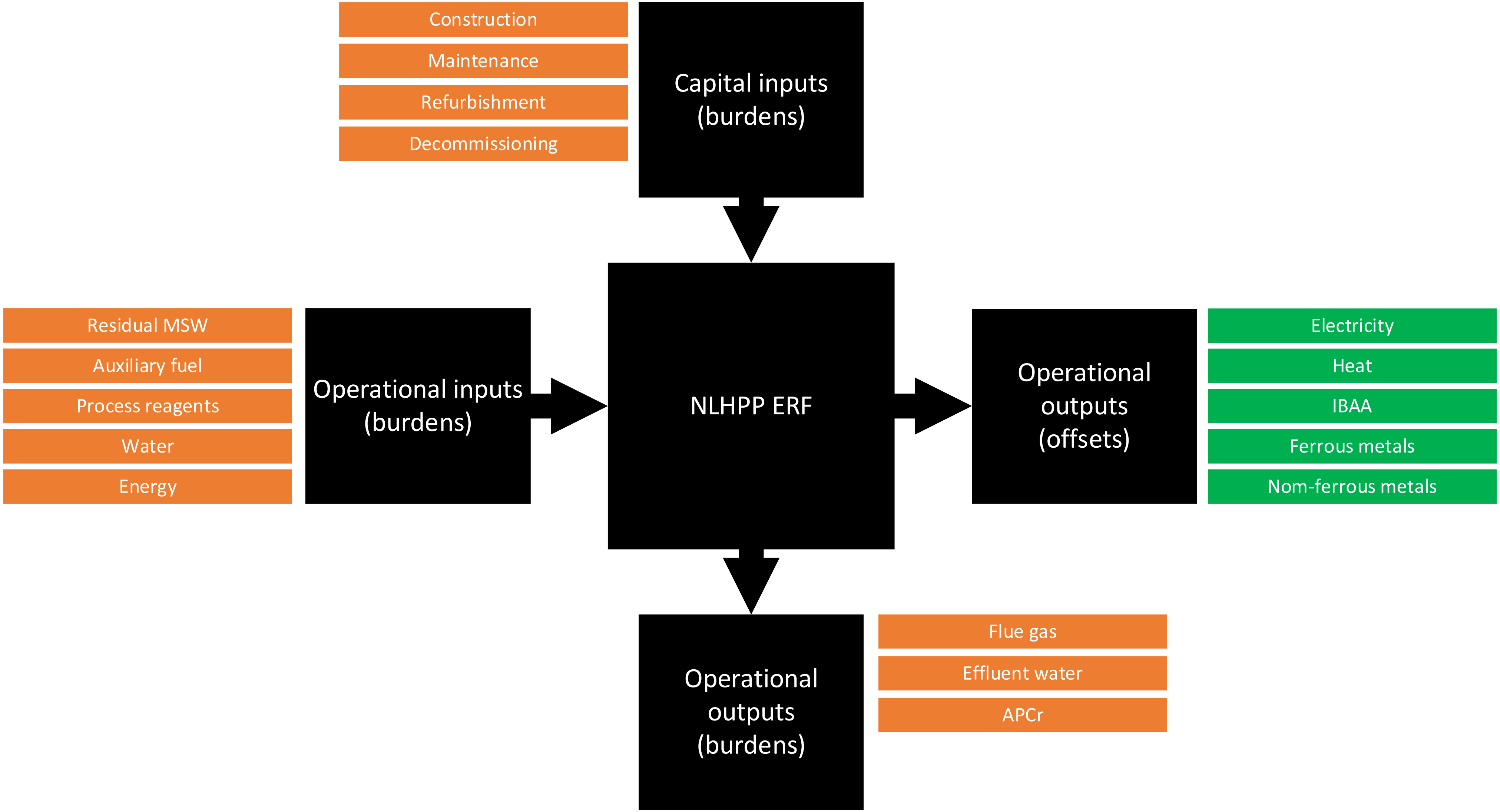

Figure 4: Overview of ERF system boundary

The net CO_2e emissions of the ERF would therefore be determined as shown in Figure 5.

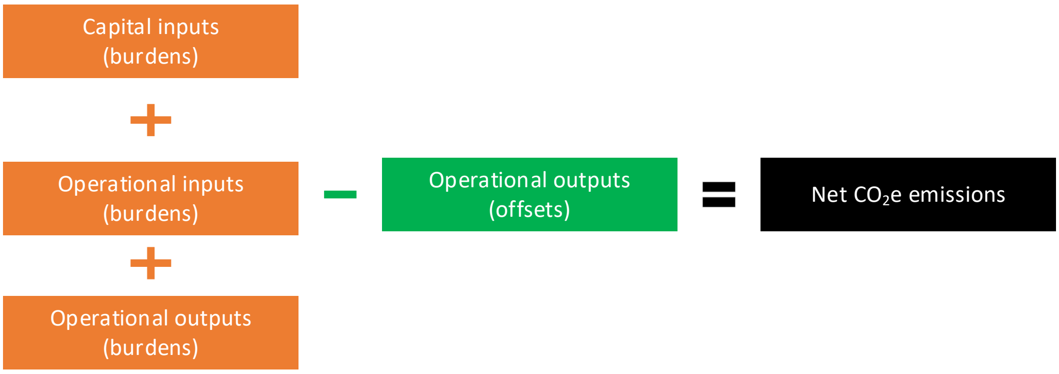

Figure 5: Net CO_2e emissions from the ERF

4.2.3 Ramboll CO_2e emissions study

Ramboll based their CO_2e emissions study of the ERF[39] on Defra's carbon-based modelling guidance report[40]. They assumed that MSW contains 45% of fossil carbon, which is the only carbon source they used in their CO_2e emissions estimate. This is a slightly higher percentage than the average fossil carbon used by the IPCC of 41.5%.

As Ramboll states, they did not include biogenic carbon in the CO_2e emissions because they consider MSW containing biogenic carbon, to be net neutral in terms of CO_2 emissions. This is in line with the Defra carbon based modelling guidance, which states that biogenic CO_2 is considered 'short cycle', as it was recently absorbed by growing matter, as opposed to fossil-based carbon which was absorbed millions of years ago and would be newly released into the atmosphere if combusted in an EfW facility. The IPCC states that there is a distinction to be made between biogenic and non-biogenic carbon when considering carbon emissions from EfW facilities because any net changes in carbon stock of biogenic origin should already covered in the 'Agriculture, Forestry and Other Land-Use' sector category, and should not be reported in the national GHG inventory.

It should be noted that Ramboll did not take into consideration:

- Any CO_2 emissions (including embodied carbon) from capital inputs to the ERF such as construction, maintenance, refurbishment and decommissioning. This is an important component in determining the overall carbon footprint of the ERF and subsequently, the requirement to reduce its CO_2 emissions.
- Additional CO_2e offsets, such as recycling of IBA (to produce IBAA).

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[39] Ramboll (2019), *NLHPP Carbon Impact Screening Edmonton ERF*.

[40] Defra (2014), *Energy recovery for residual waste: A carbon based modelling approach*, Available at: http://sciencesearch.defra.gov.uk/Document.aspx?Document=11918_WR1910Energyrecoveryforresidualwaste-Acarbonbasedmodellingapporach.pdf (Accessed 19 March 2020).

According to Ramboll, the ERF produces a net emission of 40kgCO_2e/tonne of residual MSW, and a total emission of 455kgCO_2e/tonne of residual MSW. Based on the ERF's maximum capacity of 700,000 tonnes of residual MSW, this amounts to:

- Net emissions of 28,000 tonnes CO_2e/annum from the ERF. This is 215,000 tonnes CO_2e/annum less than the net emissions from the landfill of the same quantity of residual MSW, which would be 243,000 tonnes CO_2e/annum.
- Total emissions of 318,500 tonnes CO_2e/annum from the ERF.

4.3 Combined heat and power generation

Operating in combined heat and power (CHP) mode, the ERF will meet the Mayor's current Carbon Intensity Floor (CIF) target of 400g CO_2e/kWh of electricity.

A study was undertaken by Ramboll in 2019 using the GLA's Ready Reckoner tool, which identified that:

- When supplying a 19.1MWth of heat output, the ERF would meet the current CIF target.
- When supplying 54.4MWth of heat output, the ERF would surpass the anticipated future CIF target of 300g CO_2e/kWh.

Following this study, the ERF design was revised to improve energy and carbon efficiency by the addition of an economiser. The economiser allows heat recovery from flue gas cooling, with the recovered heat being used to pre-heat the condensate in the boiler of the ERF.

The heat demand is expected to be at least 35MWth peak output, with gross electrical output being 63MWe. According to the CHP Development Strategy report of NLWA[41], this would provide around 10% of the heat demand in a 5km radius surrounding the NLHPP.

Additional heat export may be provided subject to commercial viability and a heat demand materialising. As demand grows for more local heat supply, the efficiency of the ERF will improve.

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[41] North London Waste Authority (2015), Combined Heat and Power (CHP) Development Strategy, Available at: http://northlondonheatandpower.london/media/r04i55j2/ad05-06_chp_development_strategy_lores.pdf (Accessed 16 April 2020).

5 Carbon offsetting

5.1 Overview

Carbon offsetting is the action of compensating for CO_2e emissions resulting from the release of fossil-derived carbon, by participating in CO_2e reduction schemes designed to reduce the overall emissions of CO_2e in the atmosphere.

Carbon offsetting is a solution to be considered for managing the CO_2e emissions which cannot be otherwise eliminated from the process or activity under question. This is highlighted by the diagram in Figure 6.

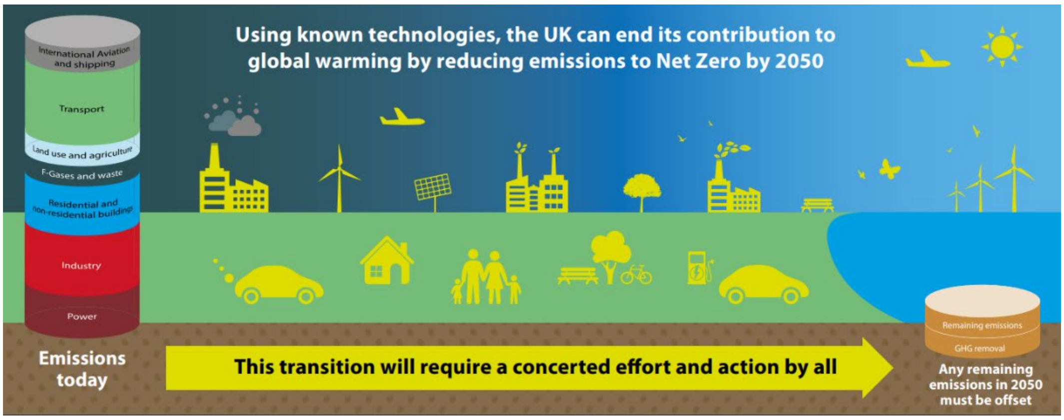

Figure 6: Role of carbon offsetting in achieving carbon neutrality in the UK[42]

Carbon offsets can be divided into three main classifications:

- Avoided natural depletion (e.g. avoided deforestation);
- Avoided emissions (e.g. renewable energy projects, replacing kerosene cook-stoves with solar-powered); and
- Greenhouse gas removal[43] (GGR/sequestration), including:
  a) Natural (e.g. mineral carbonation, ocean alkalinity, enhanced terrestrial weathering);
  b) Engineered (e.g. direct air capture, low carbon concrete); and
  c) Increasing biological update (e.g. forestation, peatland; bioenergy with carbon capture and storage (BECCS)).

Carbon offsets shall be pursued according to environmental integrity and transparency principles, with a strategy for identifying and managing accredited offsetting measures developed. They must be:

- Additional – verify that the project would not have occurred without finance from offsets.

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[42] Committee on Climate Change (2019), *Net Zero – The UK's contribution to stopping global warming*, Available at: https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/ (Accessed 13 March 2020).

[43] GGRs require that CO_2 (or other GHG) is permanently removed from the atmosphere and sequestered.

- Permanent – emissions reduction must be permanent or for a minimum time (e.g. 100 years).
- Measurable – able to quantify the carbon saving accurately.
- Independently audited and verified – for transparency, and to ensure the offset is traceable and cannot be double counted.

5.2 Standards and accreditations

A range of offsetting standards exist across the voluntary carbon offset market, some of which have been criticised for 'greenwashing' due to a lack of quality projects, issues around rigour and accuracy, and reports that projects are 'non-additional' (i.e. would have happened regardless).

Table 5 shows a list of various voluntary carbon offset standards available for offsetting.

It should be noted that the indicative costs provided are very high level at this stage and should not be relied on. The price of offsets can vary significantly according to the amount of carbon that needs to be offset over the project life (i.e. a larger amount may reduce the overall £/tonnes CO_2e cost) as well as other variables such as project location, type of offset, project provider and currency exchange rate.

Table 5: Voluntary carbon offset standards

Standard	Developed by	Indicative cost[44]	Credentials
The Verified Carbon Standard (VCS)	Verra (https://verra.org/project/vcs-program/)	Average price: £1.94/tonne CO_2e	The VCS Program is the world's most widely used voluntary GHG program. More than 1,500 certified VCS projects have collectively reduced or removed more than 200 million tonnes of CO_2e from the atmosphere.
Gold Standard Gold Standard	WWF (https://www.goldstandard.org/)	Average price: £3.88/tonnes CO_2e Offsetting per project can range from £8-17/tonne CO_2e	Established by WWF, The Gold Standard is endorsed by more than 80 NGOs. UN agencies use the Gold Standard for development of their own carbon mitigation.

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[44] Unlocking Potential: State of the Voluntary Carbon Markets 2017 Appendix 7: Detailed Transactional Data by Standard

Standard	Developed by	Indicative cost[44]	Credentials
CCB Standards	Partnership of NGOs including CARE, The Nature Conservancy, Rainforest Alliance (http://www.climate-standards.org/ccb-standards/)	Average price: £3.29/tonne CO_2e	Aims to stimulate land-based carbon reduction activities, improving the wellbeing and reducing the poverty of local communities and conserve biodiversity.
Social Carbon	www.socialcarbon.org	Average price per project: £3.96/tonne CO_2e Estimated premium price for Social Carbon: £1.19/tonne CO_2e	Was developed to strengthen social co-benefits of carbon offsetting projects and enhance active participation of stakeholders. It is typically used in conjunction with carbon accounting standard such as VCS.
UK Woodland Carbon Code	Managed by Scottish Forestry on behalf of the Forestry Commission in England, the Welsh Government and the Northern Ireland Forest Service. (https://woodlandcarboncode.org.uk/)	Average price: £5-15/tonne CO_2e depending on the quantity	Voluntary standard for UK woodland creation projects where claims are made about the carbon dioxide they sequester.
UK Peatland Code	IUCN (https://www.iucn-uk-peatlandprogramme.org/funding-finance/peatland-code)	Average price: £5/tonne CO_2e although general cost information is scarce	Voluntary certification standard for UK peatland projects wishing to market the climate benefits of peatland restoration.

It is generally accepted that best practice for global carbon offsetting requires the selection of offset providers that guarantee Gold Standard offsets, which is an internationally recognised benchmark for carbon offset projects that was created by WWF and other international NGOs in 2003, and is publicly endorsed by partners such as UNFCCC, World Bank Group, UNDP and Fairtrade. The UK Woodland Carbon Code and UK Peatland Code are also robust for UK offsetting projects.

A credible offsetting strategy should also consider the requirements of BS PAS 2060, the internationally recognised specification for demonstration of carbon neutrality. This sets the requirements to be met to demonstrate carbon neutrality through the quantification, reduction and offsetting of GHG emissions.

5.3 Carbon insetting

The concept of carbon 'insetting' is gaining some attention. This commonly takes the form of a fund used to support internal projects to deliver carbon reduction within a company's own supply chain. This is not particularly new, many business corporate social responsibility activities could be described as 'insetting' – essentially uniting procurement, sustainability and carbon reduction. For example, by levying a carbon tax on internal carbon intensive activities, and then reinvesting in practices which help to drive down emissions - or those of the direct supply chain, which in the case of NLHPP could be its waste catchment area, as well as more conventional suppliers.

There is currently no verification standard for carbon insetting.

5.4 Cost benefit appraisal

5.4.1 Overview

Tree planting is a common carbon offsetting strategy. The Woodland Carbon CO_2de[45] (WCC) tool was used to estimate:

- The number of trees and land-take required to offset the ERF's net emissions of 28,000 tonnes CO_2e/annum over 40 years of ERF operation - i.e. net CO_2e emissions of 1,120,000 tonnes (see Table 6).
- The number of trees and land-take required to offset the ERF's upstream and direct emissions of 318,500 tonnes CO_2e/annum over 40 years of ERF operation - i.e. total CO_2e emissions of 12,740,000 tonnes (see Table 7).

It should be noted that while the total emission offsets are also estimated, a carbon offsetting scheme, like the WCC, would be targeting to offset the net CO_2 emissions (see Table 6). This is because these are the remaining CO_2e emissions, not offset by the ERF's operational outputs (e.g. heat production, electricity production and metal recycling) (see Section 4.2.2).

5.4.2 Assumptions

Tree planting options vary by tree type, yield class, land availability and the management strategy. The assumptions used to estimate the carbon sequestration requirements and associated costs include:

- The planted trees would be kept over a period of 100 years (although many tree species continue to sequester emissions longer albeit at a much smaller rate);
- Soil carbon and carbon stock before planting of the trees are not included;

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[45] Woodland Carbon CO_2de (2020), *Project carbon sequestration*, Available at: https://www.woodlandcarboncode.org.uk/standard-and-guidance/3-carbon-sequestration/3-3-project-carbon-sequestration (Accessed 17 March 2020).

- Ground preparation such as pre-seeding, tree shelters, fencing or herbicides are not included;
- Emissions from management activities (e.g. thinning) will be negligible; and
- The costs of offsetting the CO_2e emissions via WCC are estimated at £3-25/tonne CO_2e, which has been typical for afforestation and reforestation projects.

The offsetting solution of afforestation and reforestation will be subject to carbon offset credits being available in the market as they are subject to supply and demand market forces. It is likely that the price for carbon offset credits is going to increase as the demand for offsetting is growing.

In addition, a recent World Bank Group report on the state and trends of carbon pricing states that less than 5% of carbon pricing initiatives are priced at a level consistent with achieving the goals of the Paris Agreement of US$40-80/tonne CO_2 by 2020 and US$50-100/tonnes CO_2 by 2030 and is highlighting the need for increasing the carbon pricing to meet the objectives of the Paris Agreement[46].

5.4.3 Results

The total area of the seven North London boroughs is approximately 29,305ha.

As Table 6 shows, the area required for planting the trees to sequester the net CO_2e emissions of the ERF equates to approximately 4-13% of the total land area of the seven North London boroughs.

As Table 7 shows, the area required for planting the trees to sequester the direct CO_2e emissions of the ERF equates to approximately 43-145% of the total land area of the seven North London boroughs.

Table 6: Afforestation requirements for 1,120,000 tonnes CO_2e

Tree type	Spacing of seedlings planted (m)	Number of trees planted	Land take (ha)	Yield class	Management regime
100% Beech	1.2	26,041,667	3,750	2	No thinning
100% Scots pine	1.4	14,285,714	2,800	4	No thinning
100% Douglas fir	1.7	6,228,374	1,800	8	No thinning
33% Sycamore 33% Ash 33% Birch	2.5	1,792,000	1,120	12	No thinning

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[46] World Bank Group (June 2019), State and Trends of Carbon Pricing 2019; Available at: http://hdl.handle.net/10986/31755 (Accessed

Table 7: Afforestation requirements for 12,740,000 tonnes CO_2e

Tree type	Spacing of seedlings planted (m)	Number of trees planted	Land take (ha)	Yield class	Management regime
100% Beech	1.2	294,791,667	42,450	2	No thinning
100% Scots pine	1.4	160,969,388	31,550	4	No thinning
100% Douglas fir	1.7	69,204,152	20,000	8	No thinning
33% Sycamore 33% Ash 33% Birch	2.5	20,240,000	12,650	12	No thinning

Applying the carbon price range mentioned above, the costs of offsetting the net emissions of 1,120,000 tonnes CO_2e would range between approximately £3.4 million and £28 million. The costs of offsetting the total emissions of 12,740,000 tonnes CO_2e would range between £38.2 million and £318.5 million. In comparison, for offsetting 100,000 tonnes CO_2e/annum (i.e. 100,000 tonnes CO_2e/annum x 40 years = 40,000,000 tonnes CO_2e) this would cost between £12 million and £100 million.

However, several factors need to be taken into consideration regarding the costs of offsetting:

- A lack of existing market capacity to offset all the targeted emissions. This also includes the offsetting of only one year of net emissions (i.e. 28,000 tonnes CO_2e/annum). According to WCC[47], the number of afforestation projects in their scheme available for purchasing carbon credits from at the moment, is not sufficient to offset emissions of 10,000 tonnes CO_2/annum (this is approximately one third of the net emissions currently estimated for the ERF). Therefore, it is more likely that investing in more than one carbon offsetting schemes would be required for the ERF.
- The expected increase in market demand for offsetting schemes in the next years will increase the price of carbon offsetting per tonne of CO_2e.

5.5 Carbon offsetting options qualitative assessment

A list of potential carbon offsetting options that NLWA may want to explore further, are described in Table 8.

Table 8 also includes a qualitative assessment against several factors, to provide an indicative overall rating of each option against its associated benefits and costs. It should be noted that the indicative costs provided are very high level at this stage and should not be relied on. The price of offsets can vary significantly according to the quantity of carbon that needs to be offset over the project life (i.e. a larger quantity may reduce the overall £/tonnes CO_2e cost) as well as other

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[47] Phone conversation on 27 March 2020.

variables such as project location, type of offset, project provider and currency exchange rate.

The qualitative assessment is based on a Red-Amber-Green (RAG) ‘traffic light’ system, where:

- An option is scored ‘Green’ against a factor if it is performing well against that factor relative to the alternative options (e.g. relatively low cost of implementation).
- An option is scored ‘Amber’ against a factor if it is performing averagely against that factor relative to the alternative options (e.g. neither too high, neither relatively low cost of implementation).
- An option is scored ‘Red’ against a factor if it is performing weakly against that factor relative to the alternative options (e.g. relatively high cost of implementation).

Table 8: Qualitative carbon offsetting options assessment

No	Name	Description	Benefits	Challenges	Indicative costs[48]	Avoided Emissions (AE) or GHG removal (GGR)	Cost	CO_2e emissions reduction	Availability/ Maturity
1	Energy efficiency	Cogeneration plants (combined heat cooling and power), improving fuel efficiency (i.e. using less fuel per unit of energy generated), energy efficient buildings (cavity wall and loft insulation, heating controls, boiler replacement, window glazing, draught-proofing, external wall insulation etc).	● Cost reduction as well as carbon reduction	● Marginal gains for new technology/buildings which are already very efficient	● Highly variable, as it is dependent on the technology and measures employed	AE	🟩	🟨	🟩
2	Biochar	Biochar is the solid product of the slow pyrolysis[49] of biomass (may include organic waste). Carbonisation decomposes parts of the biomass but retains a large part of its carbon content.	● Biochar can be a replacement for activated carbon ● Biochar can be used for the adsorption of water and air pollutant particles ● Biochar can be used in catalysis (for	● The successful production of biochar requires specific feedstock characteristics (physical and chemical ones) ● Biochar can increase soil dust emissions or	● Depending on the feedstock: predicted range from <£15/tonnes CO_2e to >£200/tonnes CO_2e	GGR	🟨	🟩	🟥

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[48] Greenhouse gas removal - The Royal Society and Royal Academy of Engineering on behalf of the UK government (2018).

[49] Pyrolysis is the thermochemical decomposition of a fuel at elevated temperatures and without the addition of external oxygen.

No	Name	Description	Benefits	Challenges	Indicative costs[48]	Avoided Emissions (AE) or GHG removal (GGR)	Cost	CO_2e emissions reduction	Availability/ Maturity
			syngas upgrading, for biodiesel production and for air pollutant treatment) • Biochar can be used for soil conditioning and helping plant growth • Has lower land and water requirements than other technologies	possess elevated levels of pollutants • The potential health risks of biochar need to be explored further • May still compete for land mass			🟨	🟩	🟥
3	Products from microalgae[50]	Due to their fast growth, microalgae can actively store carbon in the form of biomass. This can then be used in chemical and biotechnological processes to produce precursors for a variety of industrial processes. For instance, they can be used in the production of plastics.	• Microalgae produce a comprehensive variety of bioproducts such as enzymes, pigments, lipids, sugars, vitamins and sterols • May replace fossil fuel-based products	• Multiple factors need to be considered and overcome including: high cost of operation, infrastructure and maintenance, dewatering and commercial scale harvesting • There needs to be a selection of algal	• No indicative costs available	AE and GGR	🟨	🟩	🟥

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[50] Hyper Giant (2019), *Algae is the New Green*, Available at: https://www.hypergiant.com/wp-content/uploads/2019/09/algae_is_the_new_green.pdf (Accessed 10 March 2020).

No	Name	Description	Benefits	Challenges	Indicative costs[48]	Avoided Emissions (AE) or GHG removal (GGR)	Cost	CO_2e emissions reduction	Availability/ Maturity
			(e.g. plastics from crude oil)	strains with high protein content for CO_2 sequestration to be effective • There are limited authentic and reliable data and statistics of microalgae market opportunities which make it difficult to assess their actual potential			🟨	🟩	🟥
4	Oceans as a carbon sink	Supporting the development of microorganism ecologies and biodiversity in the ocean to increase carbon sinks.	• The ocean supports a vast number of organisms and microorganisms (including phytoplankton and cyanobacteria) which can therefore, take up CO_2e and release O_2 via the process of photosynthesis	• As concentrations of CO_2e increase the supply of CO_2^{3-} becomes limited and so the oceans become less and less able to take up CO_2e from the atmosphere • Although there is interest in increasing oceanic carbon storage rates through large-scale nutrient	• Highly variable: can range from £9-450/ tonnes CO_2e dependent on technology and approach (e.g. fertilisation or alkalinity)	GGR	🟥	🟩	🟥

No	Name	Description	Benefits	Challenges	Indicative costs[48]	Avoided Emissions (AE) or GHG removal (GGR)	Cost	CO_2e emissions reduction	Availability/ Maturity
				additions, there is scepticism towards this approach due to the unknown consequences on global nutrient cycles and marine ecosystems			🟥	🟩	🟥
5	Reforestation and afforestation	The planting and cultivation of forests as carbon sinks on land that either previously supported forests (reforestation), or land that is suitable to support new forests (afforestation).	● Trees are tangible and visible carbon sinks ● Wider social and climate benefits - lower air temperatures (by shading), increase rainfall, filter our pollutants and dust, and create habitats for wildlife ● On-site and/or offsite planting	● Mixed scientific opinion on the carbon reduction power of trees ● The albedo effect of planting trees in northern latitudes could promote warming rather than cooling ● Public failure of recent schemes e.g. Turkey[51]	● Price can vary from £3-25/tonnes CO_2e	GGR	🟩	🟨	🟩

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[51] The Guardian (2020), *Most of 11m trees planted in Turkish project 'may be dead'*, Available at: https://www.theguardian.com/world/2020/jan/30/most-of-11m-trees-planted-in-turkish-project-may-be-dead (Accessed 13 March 2020).

No	Name	Description	Benefits	Challenges	Indicative costs[48]	Avoided Emissions (AE) or GHG removal (GGR)	Cost	CO_2e emissions reduction	Availability/ Maturity
6	Renewable energy	Wind farms, biomass energy, biogas digesters, hydro-electric plants, landfill gas capture and utilisation.	• Direct generation (on or offsite) • Provides investments for the development of renewables • Contributes to reduced reliance on fossil fuels	• Carbon associated with some renewable energy infrastructure	• Varies significantly according to technology, location etc	AE	🟩	🟨	🟩
7	Rewilding	Restoring land to its natural uncultivated state to increase carbon sinks.	• Restoring land is tangible and visible carbon sinks • Broader sustainability benefits in terms of biodiversity and habitat restoration • Wider social and climate benefits - lower air temperatures (by shading), increase rainfall, filter our pollutants and dust, and create habitats for wildlife	• Mixed scientific opinion on the carbon reduction power of trees (caution should be applied) • Programmes must be robust in terms of approach and ongoing legacy/ownership to be successful	• An average price of £40/tonnes CO_2e (depends on species, habitat types, location etc)	GGR	🟩	🟩	🟨

No	**Name**	**Description**	**Benefits**	**Challenges**	**Indicative costs**[48]	**Avoided Emissions (AE) or GHG removal (GGR)**	**Cost**	**CO_2e emissions reduction**	**Availability/ Maturity**
8	Urban agriculture	Sequestration of carbon as part of urban food production. CO_2 is removed from the atmosphere and converted to organic carbon through the process of photosynthesis.	• Can help enhance local food security • Offers opportunities for social interaction • Enhances willingness to buy food locally, minimising its carbon footprint • Can help regulate the city's microclimate through additional vegetative and soil cover	• May be susceptible to toxic substances, such as heavy metals (e.g. lead, zinc), with the main sources of pollution being emissions from traffic, industry and sewage • If not operated sustainably, can still be examples of intensive agriculture (using pesticides and fertilisers with negative health and biodiversity impacts)	• No indicative costs available	GGR	🟩	🟩	🟨
9	Soil carbon sequestration	Developing agricultural practices such as conservation tillage, crop rotation and cover cropping to increase the soil carbon content and its effectiveness as a carbon sink, and to support the development of	• Despite the much larger size of the oceanic carbon pool relative to the soil carbon pool, the rate of exchange between the atmosphere and the soil is estimated to	• Changes in soil carbon typically take many decades to occur • Photosynthesis, decomposition, and respiration rates are determined partly by	• No price for offsetting available • Price of implementation ranges from cost to savings	GGR	🟨	🟨	🟩

No	Name	Description	Benefits	Challenges	Indicative costs[48]	Avoided Emissions (AE) or GHG removal (GGR)	Cost	CO$_2$e emissions reduction	Availability/ Maturity
		microorganism ecologies and biodiversity.	be higher than that between the atmosphere and the ocean • There are known ecosystem benefits to be obtained by increasing soil organic carbon, including benefits to water quality and increased food security	climatic factors, most importantly soil temperature and moisture levels., therefore the sequestration may not be as effective in a geography			🟨	🟨	🟩
10	Local community projects	People come together to engage in energy or waste reduction related activities, usually in response to concerns about climate change, inequality and fuel poverty. Projects are designed to have local benefits and are led by local people – and activities can include generating renewable energy, efficiency measures, group buying, and initiatives aimed at changing behaviours.	• Benefits wider than carbon reduction e.g. social value and engagement	• Varying levels of effective project control, benchmarking, target setting and regulation	• Highly variable depending on project type, location etc	AE and GGR	🟩	🟩	🟩

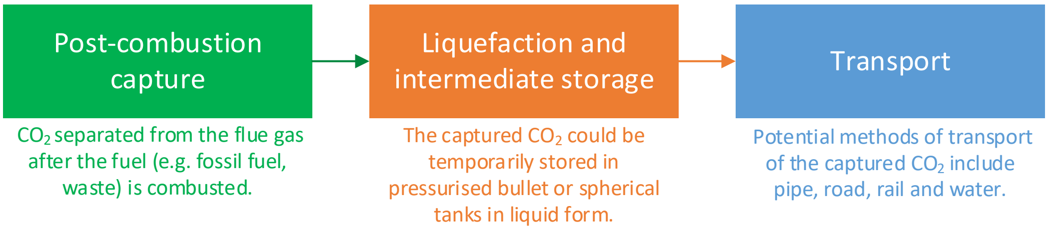
6 Carbon capture, liquefaction and transport

6.1 Overview

CCUS processes potentially relevant to the ERF, involve the capture of CO_2 from the flue gas generated from the ERF process (post-combustion) and emitted via the chimney, and the subsequent use and/or storage of the captured CO_2. CCUS solutions would require investment in on-site infrastructure and identifying appropriate off-site solutions for CO_2 use and/or storage.

This section provides an overview of carbon capture and liquefaction. Further information on the potential uses of the captured CO_2 is provided in Section 7.

An overview of the carbon capture and liquefaction process is given in Figure 7.



CO_2 separated from the flue gas after the fuel (e.g. fossil fuel, waste) is combusted.

The captured CO_2 could be temporarily stored in pressurised bullet or spherical tanks in liquid form.

Potential methods of transport of the captured CO_2 include pipe, road, rail and water.

Figure 7: Overview of post-combustion capture, liquefaction, storage and transport[52]

6.2 Flue gas composition

When capturing CO_2, there is no single compositional or 'quality' requirement for the CO_2 being captured. Pipeline materials, pressure ranges, transportation and storage requirements, as well as specific end usage requirements, all influence an acceptable CO_2 specification. For example, the CO_2 required for use in drink carbonation or packaging (food grade) will be quite different to that acceptable for enhanced oil recovery, or for storage underground.

Transportation requirements are a major factor in setting the target composition of the CO_2 stream. For example, where pipelines are being used for CO_2, care must be taken to avoid corrosion, therefore moisture and oxygen concentrations are important to control. Other gases present in the CO_2 stream may also impact on the phase properties of the CO_2 (see Section 6.6). Health and safety regulations may also be an influence on the acceptable composition (see Section 6.8).

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[52] Adapted from: The Royal Society (2017), *The potential and limitations of using carbon dioxide*, Available at: https://royalsociety.org/~/media/policy/projects/carbon-dioxide/policy-briefing-potential-and-limitations-of-using-carbon-dioxide.pdf (Accessed 13 March 2020).

6.3 Capture

6.3.1 Overview

There are three main routes to capture CO_2 from industrial processes:

- Oxyfuel, where fuel is combusted in oxygen rather than air to produce flue gas that is rich in CO_2. Following additional purification, the CO_2 can then be transported directly to the end user or to storage.
- Pre-combustion, where fuel is decarbonised prior to its use.
- Post-combustion, where CO_2 is removed from the flue gas created from a process.

The nature of the ERF incineration process means that the only suitable capture process is the post-combustion option.

The technology for post combustion removal of CO_2 has been in use for many decades in process industries, most notably for CO_2 removal from natural gas. A focus on this technology and its application at scale has led to considerable advancement in its application to CCS.

The post-combustion capture (PCC) process, which would be situated downstream of flue gas treatment plant (the location and details of tie in with incinerator process would need to be confirmed) of the ERF, is based on the principle of chemical absorption of CO_2 in the flue gas stream by a solvent (see Figure 8). The solvents most commonly used are amine-based solutions but alternatives such as amino acids and ammonia are also being used. Subsequent regeneration releases the CO_2 product stream.

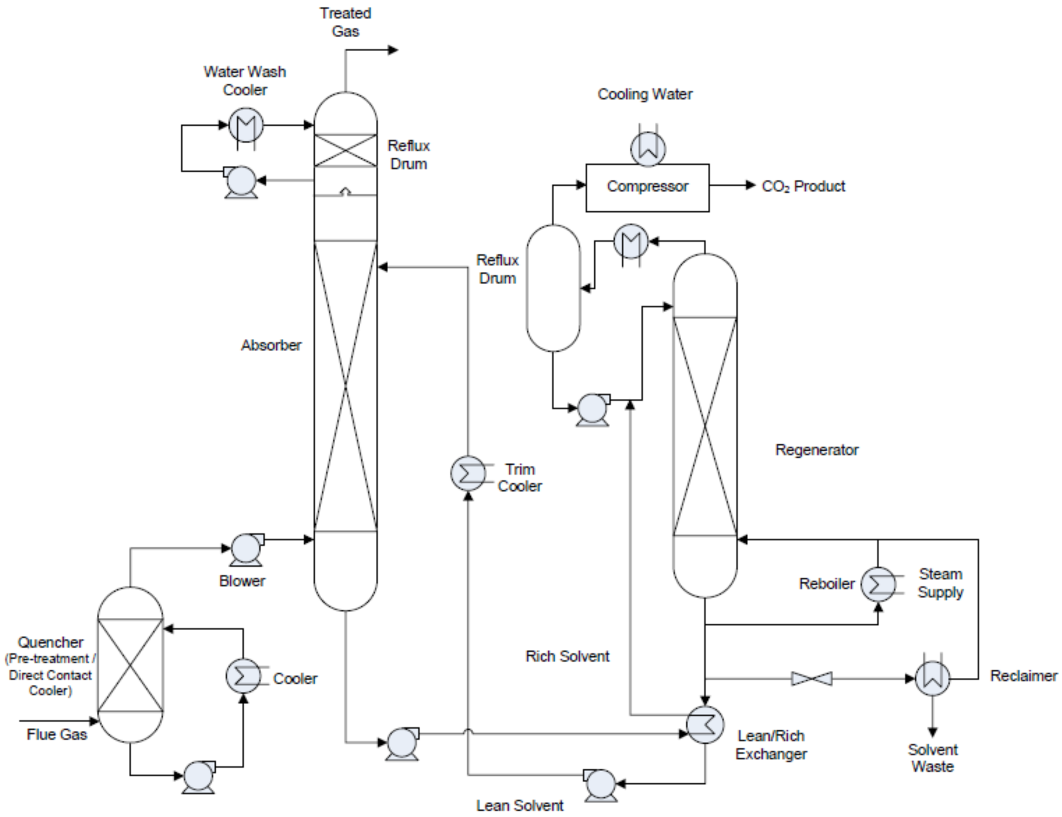

Figure 8: Generic post-combustion capture process

The generic PCC process includes the following main stages:

- Sulphur dioxide (SO_2) polishing and flue gas cooling;
- CO_2 absorption;
- Treated flue gas cleaning/solvent recovery;
- Solvent cross heat exchanger;
- CO_2 regeneration;
- CO_2 product compression; and
- Solvent reclaiming.

6.3.2 Sulphur dioxide polishing and flue gas cooling

After exiting the FGC system of the ERF, the flue gas is initially cooled down to approximately 40°C and most of any residual acid gases (such as sulphuric acid, hydrogen chloride (HCl) and hydrogen fluoride (HF)) are removed. The flue gas entering the carbon capture facility should have low levels of <10mg/m^3 of SO_2, HCl and HF.

The requirement to provide additional flue gas cleaning is highly dependent on the level of FGC provided as part of the EfW process. In the case that further flue gas conditioning is required, a potential solution is to add sodium hydroxide (NaOH) to control the pH value and remove acid gases, while the CO_2 is being cooled to 40°C.

As discussed in Section 4.1, the ERF will be equipped with a high performing FGC system. The specific flue gas composition downstream of the ERF FGC system would need to be investigated to determine the extent of any additional clean up plant that would need to be included at the inlet to the carbon capture facility to condition the flue gas prior to entry into the absorber column.

6.3.3 CO_2 absorption

The flue gas enters the bottom of the CO_2 absorber and flows upwards and out from the top of the absorber. At the same time, the solvent enters at the top of the absorber and flows counter-currently down through the flue gas, over a packed section. CO_2 is absorbed from the flue gas into the solvent. Current technologies are aiming to achieve around 90% removal of CO_2.

6.3.4 Treated flue gas cleaning and solvent recovery

The treated flue gas leaves the absorber through a washing section, to recover vapour phase amine (carried over in the process stream) and amine degradation products, to minimise the amount released via the main stack.

As the flue gas passes through the absorber several compounds and amine species are formed because of solvent degradation and the reaction of the amine with SO_2 and NO_2. The degree of amine degradation will vary depending on the amine chosen and the process conditions. In addition, small amounts of amine in vapour phase will be picked up by the process stream.

Whilst emissions to air of the amine solvents themselves are unlikely to be of significant concern there is a higher degree of uncertainty associated with emissions of amine reaction (degradation) products such as nitrosamines.

For the ERF, further work would be needed as part of the detailed specification and the process design of the system, to select an appropriate solvent and to review and minimise any potential environmental impact.

6.3.5 Solvent cross heat exchanger

The CO_2-rich solvent from the absorber then flows to the regenerator via the lean/rich heat exchanger, where some of the residual heat from the CO_2-lean solvent leaving the regenerator is exchanged with the CO_2-rich solvent entering the regenerator.

6.3.6 CO_2 regeneration

In the reboiler, the solvent is heated up to approximately 120°C to release the CO_2 from the solvent. The CO_2 stream produced exits from the top of the regenerator and is of a high purity due to the selective nature of the solvent. The regenerated solvent (lean solvent) then leaves the bottom of the regenerator and is cooled down in the lean/rich heat exchanger. It may then pass through another cooler to further reduce the temperature before re-entering the absorber to complete a continuous cycle.

An amine-based carbon capture process has a considerable cooling duty and the carbon capture plant itself also requires a significant additional treated water. The water is required for steam supply to the regenerator to allow the CO_2-rich amine to release the CO_2 captured in the absorber. Also, the reboiler operates at around 120°C, therefore, demineralised water is required for the boiler to prevent scaling. Some of the heat demand could be provided by the ERF.

As this is highly plant and process specific, further work is required to determine the exact cooling and water loads for the plant and any consequent wastewater streams.

6.3.7 CO_2 product compression

The captured CO_2 is compressed and dehydrated to condition the process stream for liquefaction, storage and onwards transportation, as required (see Section 6.4).

6.3.8 Solvent reclaiming

An important environmental issue with respect to PCC is the generation of degraded amine waste that must be mitigated or disposed of properly. Degradation products formed by amine-based solvents can include heat stable salts (HSS), non-volatile organic compounds and suspended solids. Typically, these degradation products and heat stable salts exhibit corrosive properties and reduce solvent CO_2 absorption rates. Therefore, reclaiming is required to prohibit accumulation of these degradation products in high concentration in the capture solvent.

Minimising the concentrations of NO_x and SO_2 in the inlet flue gas to the CO_2 capture system should reduce the concentration of HSS in the amine solvent, thus reducing the requirements and waste disposal costs of the reclaiming system.

6.3.9 Solvent selection

Amine solvents have a lower heat requirement in the absorber while still achieving acceptable CO_2 removal efficiencies from the flue gas stream. This reduces the process energy requirements.

There are several different amine solvents that can be used in the capture process and each is more suited to certain flue gas compositions than others. Different amines have different reaction rates and capture loading capacity.

Chemical solvents, such as chilled ammonia and amino acid salts, have been considered for CO_2 removal, however the most developed and currently the only commercially available, is based on CO_2 absorption by primary or secondary alkanolamine solvents (i.e. generic group of amines).

Amine solvents can be impacted by thermal and oxidative degradation due to the high temperatures needed for CO_2 recovery and the contact with species, such as oxygen, NO_x and SO_2 in the flue gas. This could result in loss and carry over of solvent which will require more frequent replacement. Build-up of degradation products will also need to be removed.

The exact composition of the flue gas coming out of the ERF will need to be reviewed and the most appropriate solvent selected. The ideal solvent for a PCC process would have:

- Fast reaction rates;
- High loading capability; and
- Low energy requirements for regeneration.

The choice of solvent will have an impact on the size of the carbon capture plant in terms of primary vessel sizes and overall footprint required. The choice of both carbon capture plant details and solvent type will then impact on the efficiency of the ERF thermal system (see Section 6.9.3).

6.3.10 Selection of PCC process

One advantage of PCC is the ability to retrofit the process equipment to existing facilities without extensive modifications and its design flexibility in new build applications.

There are many variables in the selection of the final PCC process, including the industrial process it is capturing CO_2 from (e.g. EfW) and the concentration of CO_2 in the flue gas.

PCC technology has several strengths and weaknesses as outlined in Table 9.

Table 9: Stremgths and weaknesses of PCC

Strengths	Weaknesses
Can readily be applied as an 'end of pipe' technology with limiting impact on the industrial process.	Due to the requirements solvent regeneration, the energy requirements are high. Whilst this can be lowered through thermal integration, this then increases inter-dependence with the industrial process, or requires that new power and heat production be provided to serve capture.
Well proven in chemical and petrochemical industrial applications and in more recent large utility trials (e.g. Petra Nova, Boundary Dam).	Solvent degradation can be costly – a range of solvents are available to optimise for different flue gas sources.
If calcium based sorbents are used, whilst these are more novel, they do present the opportunity for use of spent sorbent beneficially within the production process as a raw material (in cement production).	The PCC process has the potential to emit trace amounts of amines and amine degradation products to the environment in the treated flue gas.
May allow capture at diverse locations in industrial clusters and centralised regeneration of solvent for CO_2 transport.	Risk that the capital cost for the carbon capture plant and associated requirements on the ERF may not be offset by future carbon pricing.

Strengths	Weaknesses
	Atmospheric emissions and waste treatment are important areas that are not currently fully understand but both have considerable implications for the permitting process of a new carbon capture plant.
	There remains a lack of operational experience of full chain carbon capture systems, which may present a threat to the commercial application of the PCC technology, in common with other capture technologies.

6.4 Liquefaction

Given the quantities of CO_2 likely to be captured from the ERF, and its geographical location, the captured CO_2 would need to be liquified and stored for onward transmission to appropriate end users or remote storage locations.

CO_2 is liquefied through a combination of compression and cooling. This can be achieved through several different methods depending on the temperature of available cooling water or the availability/desirability of an external refrigeration system.

The different liquefaction processes may include:

- Cooling water at <15°C;
- External refrigeration;
- Over-compression and expansion; and
- Combination of above.

A typical liquification process would comprise the following steps:

- **Step 1** – If required, the CO_2 is compressed to approximately 35 bar in several stages, with inter-stage cooling using cooling water. This may not be required if the CO_2 process stream from the capture plant is discharged at a high pressure.
- **Step 2** – The CO_2 stream is then dehydrated. This is achieved through two processes; condensation at cooling stages and by passing it through duplex regenerative adsorption columns to achieve <50 ppm water content.
- **Step 3** – CO_2 is then liquefied either by condensation using an external refrigeration system, or by over-compression to approximately100 bar and expansion to approximately 60 bar (resulting in cooling and condensation), or by compression and cooling against cooling water at <15°C in a heat exchanger to condense the CO_2.
- **Step 4** – The liquid is then distilled to remove ‘volatiles’ (impurity gases such as nitrogen and argon).

- **Step 5** – Expansion to storage pressure of 6.5 bara, resulting in cooling to -52°C. The CO_2 that flashes off during this final expansion is recycled to the appropriate pressure stage in the initial compressor train.

This typical process is illustrated in Figure 9.

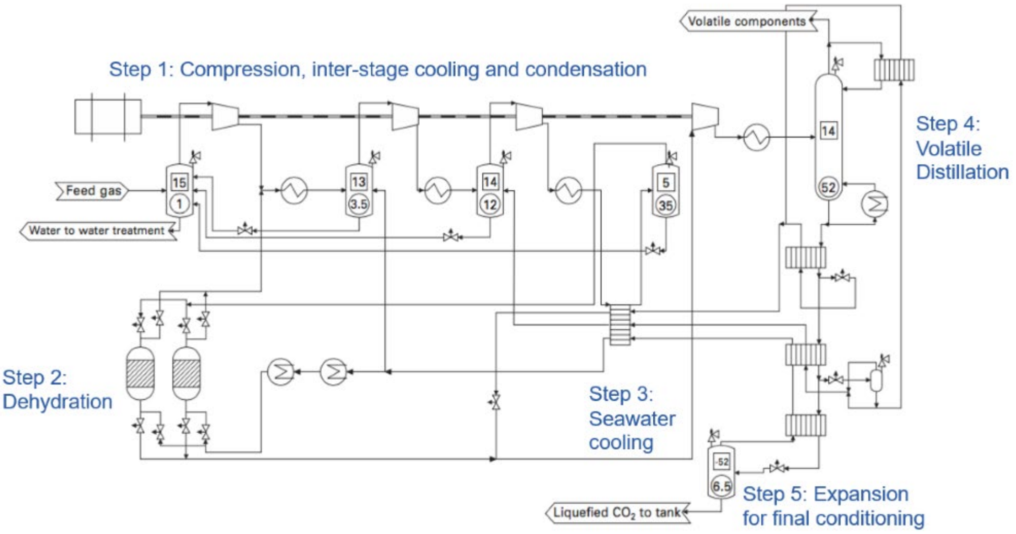

Figure 9: Typical CO_2 liquefaction process by compression, expansion and seawater cooling

The site-specific requirements for the CO_2 liquefaction plant would need to be developed to consider the optimal location, layout and footprint of the plant in relation to the incinerator and capture plant location, any additional utility requirements and connections and how it is connected to the intermediate CO_2 storage facility and export facilities.

6.5 Temporary Storage

Capturing the CO_2 from the flue gas of the ERF is a continuous process. In the absence of a dedicated export pipeline, transportation will be a batch process and so intermediate storage will be required between liquefication and loading to temporarily store the CO_2 prior to dispatch.

The captured CO_2 could be temporarily stored in pressurised bullet or spherical tanks (see Figure 10) in liquid form prior to transportation to a permanent storage location or end user. Liquefying the CO_2 reduces the required volume of tankage required and minimises the footprint of any tank facility. Vacuum insulated (perlite), stainless steel storage tanks can typically store up to 500 tonnes (450m^3) of liquid CO_2 at pressures of around 22 bar.

Figure 10: Various types of CO_2 storage tanks

The required storage capacity to provide enough intermediate volume, with a suitable operational margin, will depend on the rate and continuity of production from the ERF and the type and frequency of transportation to the store or end user.

6.6 Transport

Best practice dictates that the transported CO_2 should be maintained either on the liquid or on the vapour side of the vapour/liquid line running between the triple and critical points but should not cross it. This would result in a biphasic stream, which would affect compression, velocities and other operational factors.

CO_2 can be transported in several ways including by pipeline, road or rail tanker or by ship or barge. Each has its merits depending on the quantities of CO_2 being transported and the distance from the capture plant to the end user or long-term sequestration-site.

Each of the options is discussed below. In the case of non-pipeline transportation methods, suitable loading facilities will be needed which will require an allocation of space and infrastructure within the NLHPP site boundary.

6.6.1 Pipeline

The most efficient and cost-effective way to transport large volumes of CO_2 over long distances is by pipeline in the dense (liquid) phase (above 75 bar at ambient temperatures), where, downstream of the capture stage, the gas is compressed and cooled to the liquid phase. This guarantees the existence of a unique phase and minimises the volume. The CO_2 must be free of hydrogen sulphide and dry, otherwise, the gas can corrode the pipeline. Ideally CO_2 pipelines would be built from stainless steel to lower the risk of corrosion.

However, given the inland location of the NLHPP, and the relatively small volumes of CO_2 being generated as part of the capture process, a pipeline transportation solution is not appropriate and would be prohibitively expensive. There is currently no indigenous subsurface CO_2 storage facility in the UK and so any pipeline solution would need to terminate at a coastal location for onwards transportation by ship to an offshore storage sequestration-site.

6.6.2 Road

Small quantities of CO_2 can be transported by truck (or train) in ISO tank containers (see Figure 11). Each 20ft container tank can transport approximately 20 tonnes ($18m^3$) in vacuum insulated stainless steel pressure vessels at around 22 bar.

Figure 11: Typical ISO tank container

Dedicated road tankers can also be used (see Figure 12).

Figure 12: Typical CO_2 road tanker

An alternative to using large tankers is to transport the CO_2 in racks of smaller gas cylinders. There are three types of gas cylinders suitable for transporting small quantities of gas; high pressure, low pressure and acetylene cylinders. To transport CO_2 a high-pressure cylinder would be used. When transporting the gas cylinders via truck the following guidelines should be met:

- Gas cylinders should only be transported on an open back trailer or in a trailer with a canopy that is separate from the main body of the vehicle.
- Cylinders should be transported in the upright position.
- Cylinders require a support device to prevent rolling and movement.
- Settling time is required before use.

Figure 13 shows the various size cylinders for CO_2 gas transport.

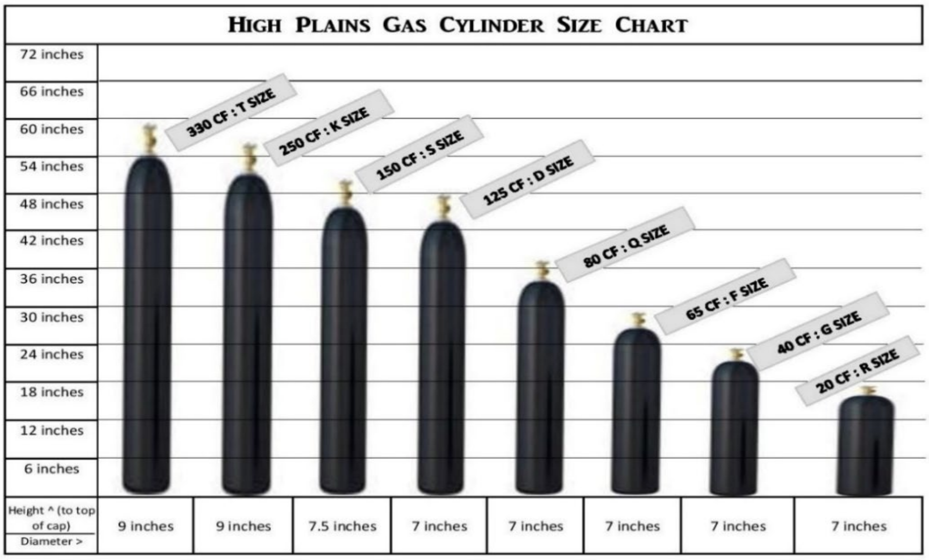

Figure 13: Various sizes of high-pressure cylinders[53]

Typical specifications of a full trailer designed to carry liquid CO_2 is presented in Figure 14.

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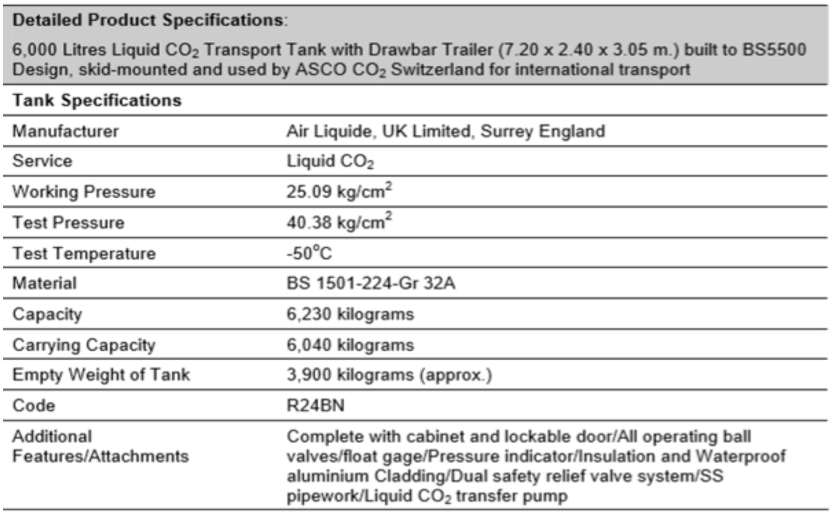
[53] Hpsup. (2019). *High Plains Gas | Supplies for the Welding & Manufacturing Industry*. (Accessed 22 July 2019).



Detailed Product Specifications:	
6,000 Litres Liquid CO_2 Transport Tank with Drawbar Trailer (7.20 x 2.40 x 3.05 m.) built to BS5500 Design, skid-mounted and used by ASCO CO_2 Switzerland for international transport	
Tank Specifications	
Manufacturer	Air Liquide, UK Limited, Surrey England
Service	Liquid CO_2
Working Pressure	25.09 kg/cm^2
Test Pressure	40.38 kg/cm^2
Test Temperature	-50°C
Material	BS 1501-224-Gr 32A
Capacity	6,230 kilograms
Carrying Capacity	6,040 kilograms
Empty Weight of Tank	3,900 kilograms (approx.)
Code	R24BN
Additional Features/Attachments	Complete with cabinet and lockable door/All operating ball valves/float gage/Pressure indicator/Insulation and Waterproof aluminium Cladding/Dual safety relief valve system/SS pipework/Liquid CO_2 transfer pump

Figure 14: Detailed product specifications for liquified CO_2

The advantage of transport by road is that it requires less capital invest in comparison to other modes of transportation. Road transportation is extremely flexible, via road the CO_2 can be transported directly to the desired storage location. Road transportation can also act as a feeder to other modes of transportation such as railways and ships.

The main disadvantage of gas transport by road is the limited capacity available per truck, which results in a linear cost progression for high quantities of fluid (proportional to the number of trucks required), whereas other transport methods show economies of scale.

Over land transportation using discrete tankers, is considered at other sites as part of the CCS chain to deliver the CO_2 to collection-sites or other users. Road or rail tankers could be adopted for transporting the CO_2, either as a gas or liquid. This would be the most appropriate solution for the NLHPP site.

6.6.3 Rail

For transportation by rail tanker (see Figure 15), the CO_2 needs to be liquefied and kept refrigerated to minimize the volume. To reduce the costs of tankers and storage tanks, it is preferable to operate as close to the triple point of -56.6°C/5.2 bar as practically feasible.

Figure 15: Typical CO_2 rail tanker

Typically captured CO_2 can be carried in smaller pressurized containers at a temperature of 21.1°C and pressure of 57.8 bar to minimize the use of multiple small tanks. Otherwise, a larger single pressurized, refrigerated vessel per carriage could be used with a pressure below 17.2 bar at -23.3°C. Smaller tankers are more practical for transporting smaller quantities of CO_2 for food or industrial purposes.

As there is no dedicated railhead at or close to the NLHPP site this is not likely to be a feasible solution to transport CO_2 from the site. The nearest rail line is the line from Ponders End Station to the north to Northumberland Park Station to the south, which runs 450m to the west of the NLHPP site. However, the area between the site and rail line is heavily developed and there is no space available at either the rail line or the site to construct a connection off the mainline and rail head respectively.

The nearest rail yard to the NLHPP site is the TfL London Underground depot at Northumberland Park, 2km south of the site. Construction of a link to this depot would not be possible given the development in the area. This is also a depot for maintenance of London Underground rolling stock and as such would not be suitable in its current configuration to allow loading of CO_2 tankers.

There is a rail yard at Temple Mills, Stratford which services Eurostar rolling stock. This is adjacent to the River Lea, 8.5km along the waterway south of the NLHPP site.

6.6.4 Waterways

The transportation of CO_2 by ship has only occurred in the last 20 years and only for small parcel sizes. Shipment of CO_2 already takes place on a small scale in Europe, where ships transport food-quality CO_2 (around 1,000 tonnes) from large point sources to coastal distribution terminals.

The liquefied and/or refrigerated CO_2 could be transferred to dedicated CO_2 barges at specific marine loading facilities where cryogenic pipelines from the storage location feed specialist cryogenic marine loading arms to fill the ships or barges.

Given the proximity of the Lee Navigation to the facility site it may be possible to use barge transportation to move the CO_2 to end users of a disposal site. For example, as discussed above, it might be feasible to barge the CO_2 from the NLHPP site to the rail yard at Temple Mills for onward transport by rail tanker.

The suitability of the Lee Navigation to provide an exit route to the end users would need to be investigated further to determine whether it is feasible to safely move CO_2 transportation barges along the waterway, considering width and depth restrictions on the waterway itself and height and clearance restrictions from bridges and other infrastructure.

6.7 Site footprint and space requirements

The CO_2 emitted directly by the ERF process is estimated at 439kg CO_2/tonne of MSW. Assuming a maximum efficiency of 90% in the carbon capture process, this equates to 276,500 tonnes of CO_2; equating to an average of 5,320 tonnes/ week (assuming continuous operation over 52 weeks). Liquefying this to -50°C at 20 bar produces 4,600m^3 of CO_2 to transport each week. This would be 266 road tanker movements per week (using 20-tonne road tankers) or 38 road tanker movements per day (using 20-tonne road tankers). This volume of captured CO_2 would require around 12 cryogenic storage tanks (using 450m^3 storage tanks) to hold the liquid CO_2 prior to transportation. It depends on the reliability of the tanker distribution. It might be prudent to have one week's worth of capacity available to allow for downtime with loading facilities or issues with tanker availability.

Based on a high-level estimate, the footprint of an on-site carbon capture, liquefaction and storage plant capturing the CO_2 emissions of the ERF would range approximately between 2,500-8,500m^2. The exact footprint will depend on the technology used, but also on the quantity of CO_2 emissions captured. The estimated footprint range is based on a plant capturing 100,000-350,000 tonnes CO_2/annum (see Figure 16).

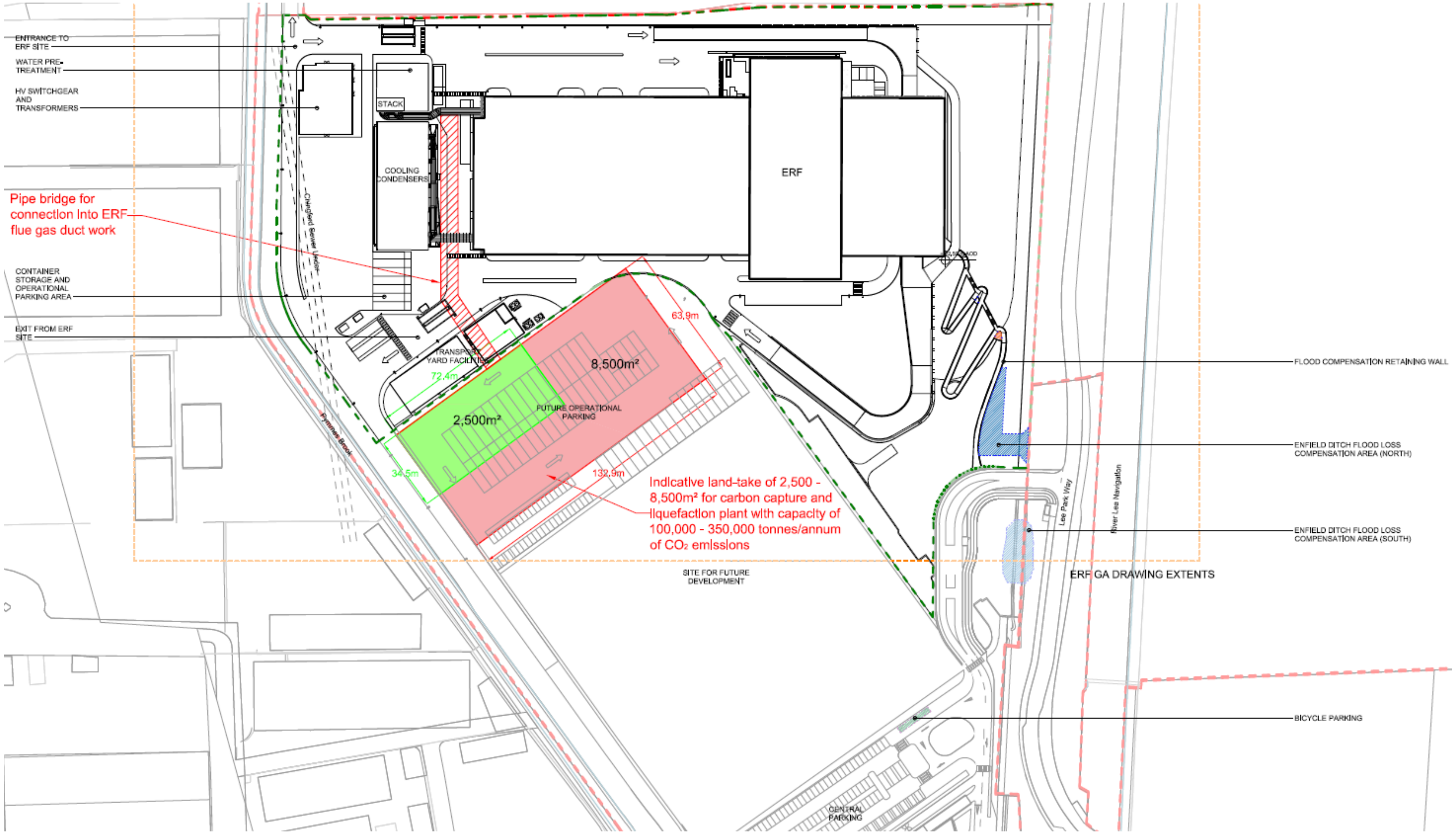


Figure 16: Potential footprints of carbon capture, liquefaction and storage plant[54]

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[54] Based on Grimshaw drawing NLWA DWG No.: NP-GAL-41XX-ZZZ-DR-AR-010003.

While it is not a strict requirement, it is an advantage to locate the carbon capture plant in close proximity to the EfW stack. This will reduce CAPEX and OPEX, due to the reduced ducting costs and reduced power which would be needed to overcome the friction losses in the longer flue gas duct.

The equipment required to capture CO_2 is likely to require significant space in addition to the space required for the ERF. In general, the additional space required will be highly dependent on the type of capture technology proposed and whether the ERF has been designed to enable capture to be integrated efficiently into the new plant design or whether it will be a retrofit. The required footprint must consider health and safety, as well as permitting and consenting requirements.

Assessments of the appropriate space to be set aside will depend on:

- The type of carbon capture technology;
- Ensuring the safe storage of chemicals such as the amine solvents;
- Avoiding congestion on-site for safety both during construction and operation; and
- Future progress in capture technology design which may lead to more compact options if decisions on deployment are delayed.

In practice the positioning of capture capture-related plant will be influenced by the layout of the ERF. The layout will need to be configured so that:

- Treated gas (with reduced CO_2) can be returned to the existing stack or a new stack.
- Duct work length for flue gas to pass from the ERF to the capture plant is minimised. The size of ducting is likely to be large to accommodate the large volumes of low CO_2 concentration flue gas being passed to the capture plant.
- An area is provided for absorbers, desorbers, heat exchangers and reboiler, together with ancillary equipment, possibly including booster fans.
- Efficient sourcing of steam to be supplied to the desorber reboiler, and for condensate to be returned. This may require the provision of additional plant if this is not directly available from the ERF.
- An area for CO_2 drying and compression is appropriately positioned considering that the compressed CO_2 will need to leave the site at a specified point.
- An area for additional cooling capacity or a source of cooling water is available. The energy requirements of the capture process are high and a large increase in cooling duty above that of the ERF will need to be accommodated.
- An area for auxiliary services, demin plant, accommodation etc. is available in appropriate locations.
- There is space provision for additional flue gas cleaning and CO_2 quality conditioning equipment if required.

An amine based process has a considerable cooling duty, with the main cooling demands within the CCS process comprising:

- Flue gas DCC cooler.
- Lean solution to absorber cooler.
- Stripper overhead cooler.
- CO_2 compression intercoolers.

Typically, this additional cooling requirement takes the form of modular low level cooling towers, although spare cooling capacity in the ERF plant, could reduce or eliminate the need for space to construct such cooling infrastructure.

The carbon capture plant itself will also require significant additional treated water.

Consideration must also be given to the space requirements during construction of the capture plant, particularly if it is retrospectively constructed. The laydown area requirements and temporary working areas will need to be allowed for and managed appropriately.

6.8 Health, safety and environmental considerations

There will be several impacts that the capture technology will have on the environment which are additional to the impacts of the main ERF.

Post-combustion capture technology involves separation of CO_2 from flue gas produced by an air-blown, fuel-fired boiler. As well at the separated CO_2, nitrogen, water and residual oxygen are the main diluents, accompanied by trace amounts of sulphur oxides (SO_x) and NO_x.

Several species are formed within the capture process because of solvent degradation and the reaction of the amine with SO_2 and NOx. Any species present in the solvent has the potential to be emitted to air in the treated gas if appropriate control measures are not utilised. It is therefore essential that these species are identified and characterised and that the potential environmental impact of the species is investigated to control emissions to an acceptable level and to comply with any overall levels and constraints that the ERF must operate within.

Careful selection of solvents and management of the capture process will minimise the potential for carry over of solvent.

CO_2 is not currently defined as a dangerous substance under the Control of Major Accident Hazards Regulations 1999 (COMAH) or as a dangerous fluid under the Pipelines Safety Regulations 1996[55].

Operational CCS is likely to bring other potentially dangerous substances onto the site depending on the capture technology and actual process applied, as different capture technologies may require large inventories of amines, ammonia or oxygen. Where carbon capture sites use dangerous substances in quantities above

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[55] Health and Safety Executive (HSE) (*no date*), *Major hazard potential of CCS*, Available at: https://www.hse.gov.uk/carboncapture/major-hazard.htm (Accessed 16 April 2020).

a certain threshold, COMAH will apply to the whole site. In these cases, the site operator will be required to submit a safety report to the Health and Safety Executive (HSE).

Therefore, once the carbon capture process is defined, a determination process would be required to establish whether COMAH would apply, and whether any additional safety provisions would be required.

6.9 Cost benefit appraisal

6.9.1 Overview

According to the Global CCS Institute, there are 19 large-scale carbon capture facilities in commercial operation worldwide, while there are four more in construction, 10 are in advanced development and 18 are in early development[56].

The PCC process is expensive due to the high deployment costs of the technology and operational costs associated with the extraction, storage and transport of the captured CO_2.

Costs are mainly a function of:

- The size of plant;
- In terms of flue gas to be treated;
- The extent of CO_2 capture from the process;
- How the carbon capture plant is integrated into the EfW facility;
- Where energy consumed by the process is to be supplied from; and
- Other operating costs, such as solvent reclamation and replacement.

However, as discussed in Section 3.3, there are opportunities for funding a potential CCUS project through national funds; something which is worth exploring further.

6.9.1 Carbon taxation

As the UK has legislated to reduce its net carbon emissions to zero by 2050, it is critical to set a number of policy instruments to achieve this. Carbon pricing, which is effectively the implementation of the polluter pays principle for CO_2 emissions, may be implemented in the UK in the form of a carbon tax.

Such carbon taxation may go beyond the scope of the UK ETS, which is a cap-and-trade system and covers power stations but not EfW installations. For instance, carbon taxation for EfW facilities is in the process of being introduced in the Netherlands.

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[56] Global CCS Institute (2019), *Global Status of CCS*, Available at: https://www.globalccsinstitute.com/resources/global-status-report/ (Accessed 30 April 2020).

If such carbon taxes are introduced, it will be another incentive to ensure that NLWA reduces CO_2 emissions from the ERF. Planning for such reductions from an early stage (i.e. carbon capture readiness), will ensure that informed decisions are made and the solutions identified are both effective, as well as financially and technically viable.

6.9.2 CAPEX

There is limited information on the actual CAPEX of PCC for EfW plants. Some public domain information suggests that the deployment cost for CCUS are currently as high as €3,000-5,000/tonne of waste treated, which is 15-20 times higher than the EU Emissions Trading System (ETS) carbon price of approximately €20/tonne[57].

Initial discussions with two potential suppliers with experience of CCUS for EfW plants indicates that the CAPEX for a standard modular 100,000 tonne/annum plant comprising carbon capture, liquefaction, storage and vehicle loading is approximately £26 million (excluding costs for utility systems, dealing with ground hazards, building, mobile plant, taxes etc).

6.9.3 OPEX

The main elements contributing to the OPEX of the PCC plant include:

- Cost of utilities (water, power);
- Cost of amines (typical 0.2kg/tonne CO_2);
- Annual maintenance cost; and
- Additional personnel (i.e. plant manager and one person to support and follow-up the plant) assuming no additional control room operators assuming that the carbon capture plant would be operated from the central EfW control room.

The main penalty with the deployment of CCS is the loss of efficiency in base plant (e.g. the EfW) due to the additional parasitic load for the carbon capture plant, and this loss of power will need to be translated to a cost to deploy. There are additional fixed costs in terms of staffing and maintenance.

The amount of efficiency loss relative to the base facility is dependent on the base facility technology. The net power efficiency of the power plant due to PCC, drops by 8-12%, on average[58].

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[57] Refinitiv (2018), *Will high European carbon prices last?,* Available at: https://www.refinitiv.com/perspectives/market-insights/will-high-european-carbon-prices-last/ (Accessed 17 March 2020).

[58] Wienchol, P., Szlek, A. and Ditaranto, M., (2020), *Waste-to-energy technology integrated with carbon capture–Challenges and opportunities*. Energy, p.117352.

The carbon capture plant of the Fortum Oslo Varme EfW facility[59] (see Section 8.2) requires a power input of 15.4MWe and the CO_2 conditioning, storage and loading facility requires a power input of 6.4MWe.

For state-of-the-art coal fired plants the net power efficiency is decreased by approximately 9%, while for lignite fired plants the loss is about 10%.

The net power efficiency of a combined cycle gas turbine (CCGT) plant would be reduced by around 7%. For example, a typical CCGT plant operating at around 59% efficiency with a net output of around 910MWe, would see a 120MWe drop in output with the introduction of an amine-based PCC system (i.e. a reduction in efficiency to around 51%).

The power demand of the carbon capture plant is mainly for the regeneration of the amine solution and the CO_2 compression. The impact of carbon capture is highly dependent on the industrial process and the concentration of CO_2 in the flue gases. Therefore, the actual power demand for a system attached to the ERF, would need to be determined from a more detailed assessment of the system to be deployed.

The plant OPEX will be project specific. Annual fixed costs are shown to be variable, but in the range of 2-6% of the CAPEX of the plant. Public domain information shows variable OPEX, primarily energy related, and are likely to be €35-50/tonne CO_2 for gas fired power plant applications and around €20/tonne CO_2 for coal fired plants.

It is estimated that capturing the direct CO_2 emissions from the residual MSW on an annual basis (estimated at 100,000 tonnes/annum of CO_2) based on a carbon capture plant CAPEX of £26 million could cost between £0.5-1.6 million/annum (assuming an operational expenditure range between 2-6% of the plant CAPEX).

However, both the capital and operational expenditure are very project specific. The NLWA should undertake a more detailed feasibility study to better define the site-specific constraints and opportunities for developing a carbon capture solution on-site and the associated CAPEX and OPEX requirements.

6.9.4 Life cycle assessment

Life cycle assessment (LCA) can be used as a metric to assess the actual environmental benefits of carbon capture. Since carbon capture is an energy and material intensive process, it is unclear whether it allows for a net reduction of environmental impacts from a life cycle perspective.

An LCA was conducted as part of the 'Environmental Due Diligence of CO_2 Capture and Utilisation Technologies' (EDDiCCUT) project on coal fired and gas

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[59] Fortum Oslo Varme AS (*no date*), *Carbon capture from Waste-to-Energy in Oslo*, Available at: http://task41project5.ieabioenergy.com/wp-content/uploads/2017/11/Stuen.pdf (Accessed 17 April 2020).

fired power plants with different carbon capture technologies (i.e. different amine solvents and Oxyfuel) deployed based on a per kWhe basis[60].

However, the quantitative results of an LCA need to be assessed on a case-by-case basis, given the large variety of parameters to be considered, the level of detail required and the system boundaries set in each case.

6.10 Technology providers

According to Vision Gains' CCUS 2019 market report[61], the top 20 companies in the CCUS market in 2019 comprise a range of suppliers with expertise in carbon capture technology, liquefaction technology and companies active in the oil and gas industry sector.

Arup approached to technology providers with experience in carbon capture associated with EfW facilities including Aker Solutions and Tecno Project Industriale (TPI) to obtain some more detailed project information.

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[60] Orregioni *et al* (2016), *Comparative environmental life cycle assessment of oxyfuel and post combustion capture with MEA and AMP/PZ - Case studies from the EDDiCCUT project*, 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland.

[61] Vision Gain (2019), *Top 20 Companies in Carbon Capture and Storage 2019*, Available at: https://www.visiongain.com/report/top-20-companies-in-carbon-capture-and-storage-2019/ (Accessed 30 April 2020).

7 Carbon use and storage

7.1 Overview

Carbon capture and use (CCU) is the process of capturing CO_2 to be recycled for further use.

Tackling CO_2 emissions requires keeping CO_2 away from the atmosphere indefinitely. Therefore, for the purposes of addressing climate change, it is important that the captured and liquefied CO_2 is stored away from the atmospheric carbon cycle, and without any human intervention, for as long as possible (e.g. for 1,000 years, and preferably for 10,000 years).

If the captured CO_2 is stored away from the atmosphere for a much shorter period (i.e. for days or years) the issue of CO_2 emissions to the atmosphere is effectively only delayed.

On the other hand, capturing CO_2 for use (i.e. CCU), has a number of advantages, as it is a means of:

- Turning a waste product into a useful commodity. As explained by the Global CCS Institute, CCU allows businesses to think about single-use carbon as a thing of the past and is a way to engage in the circular economy.
- Creating new markets and offering opportunities for investment in industrial innovation and manufacturing.
- Decoupling economic growth from CO_2 emissions.
- Providing a solution to industrial facilities (e.g. EfW) without cost-effective access to CO_2 transport and storage infrastructure.

7.2 CCU options

An overview of the main CCU options is given in Figure 17.

Consumer brands are now looking at carbon as a viable feedstock for the chemicals, polymers, and other materials that go into their products and supply chain executives are engaging with companies operating CCU facilities.

A number of companies have developed technologies to permanently store CO_2 in building materials and chemical products, such as:

- The Canada-based CarbonCure[62] uses CO_2 sourced from industrial emitters. The technology is retrofitted into existing concrete plants, and equipment injects the CO_2 into a hopper or central mixer. Once injected into the wet concrete mix, the CO_2 reacts with calcium ions from cement to form a nano-

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[62] Forbes (2019), *CarbonCure Technology Says Goodbye To Carbon Dioxide, Hello To Greener Concrete*, Available at: https://www.forbes.com/sites/jeffkart/2019/02/23/carboncure-technology-says-goodbye-to-carbon-dioxide-hello-to-greener-concrete/#433121ae7311 (Accessed 30 April 2020).

sized calcium carbonate ($CaCO_3$) mineral that becomes permanently embedded in the concrete.

- Solidia[63]developed a sustainable concrete curing technology, curing concrete with CO_2 instead of water.
- Blue Planet[64] uses its patented Liquid Condensed Phase (LCP™) Technology to convert CO_2 into CarbonMix™ building and highway materials.
- BluePlanet bubbles waste gases from California's largest power plant at Moss Landing through seawater, collecting CO_2. Around 90% is removed and then combined with minerals in the water to create limestone.
- CO_2Concrete LLC[65] uses CO_2Concrete technology which turns CO_2 emissions into CO_2Concrete™ products that can replace traditional concrete.

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[63] Solidia, Available at: https://www.solidiatech.com/solutions.html (Accessed 30 April 2020).
[64] Blue Planet, Available at: http://www.blueplanet-ltd.com/ (Accessed 30 April 2020).
[65] CO2Concrete LLC, Available at: https://www.co2concrete.com/ (Accessed 30 April 2020).

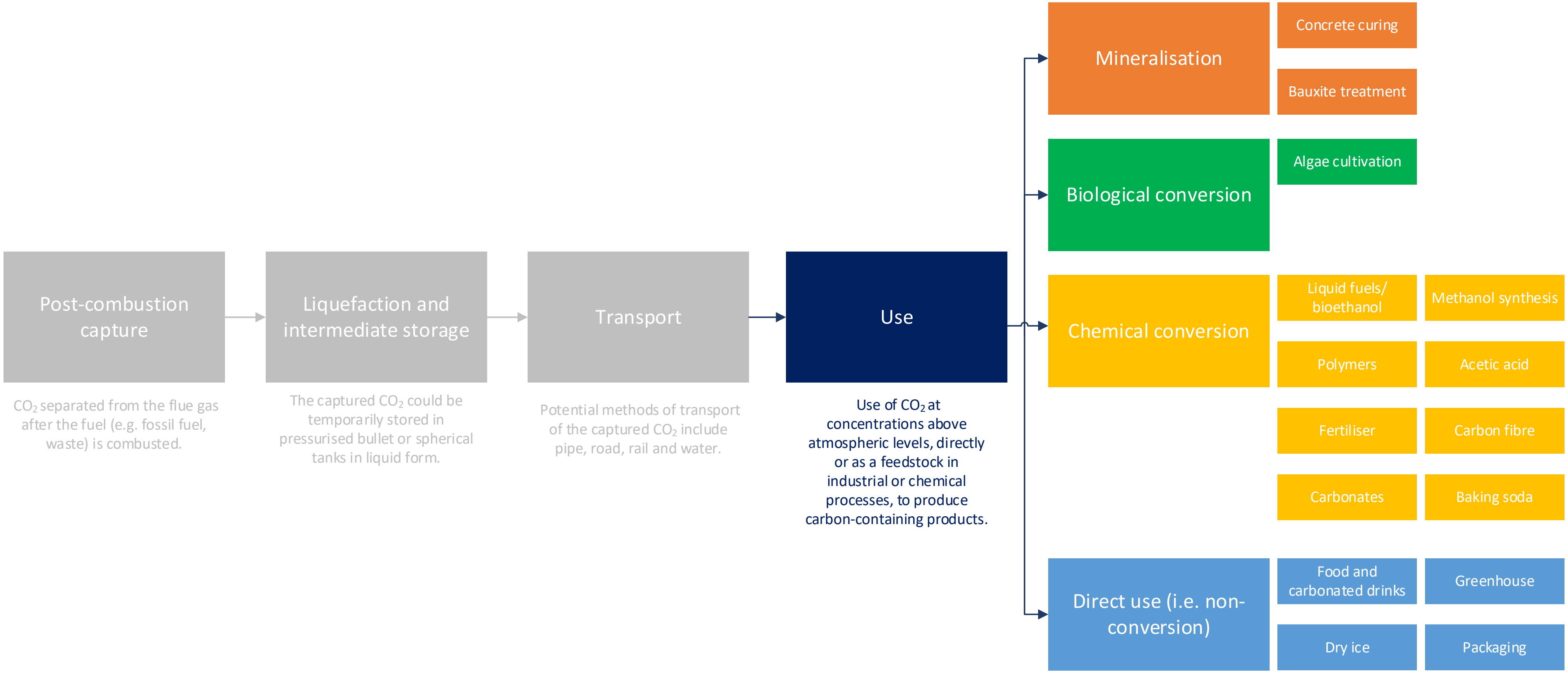

Figure 17: CCU options[66]

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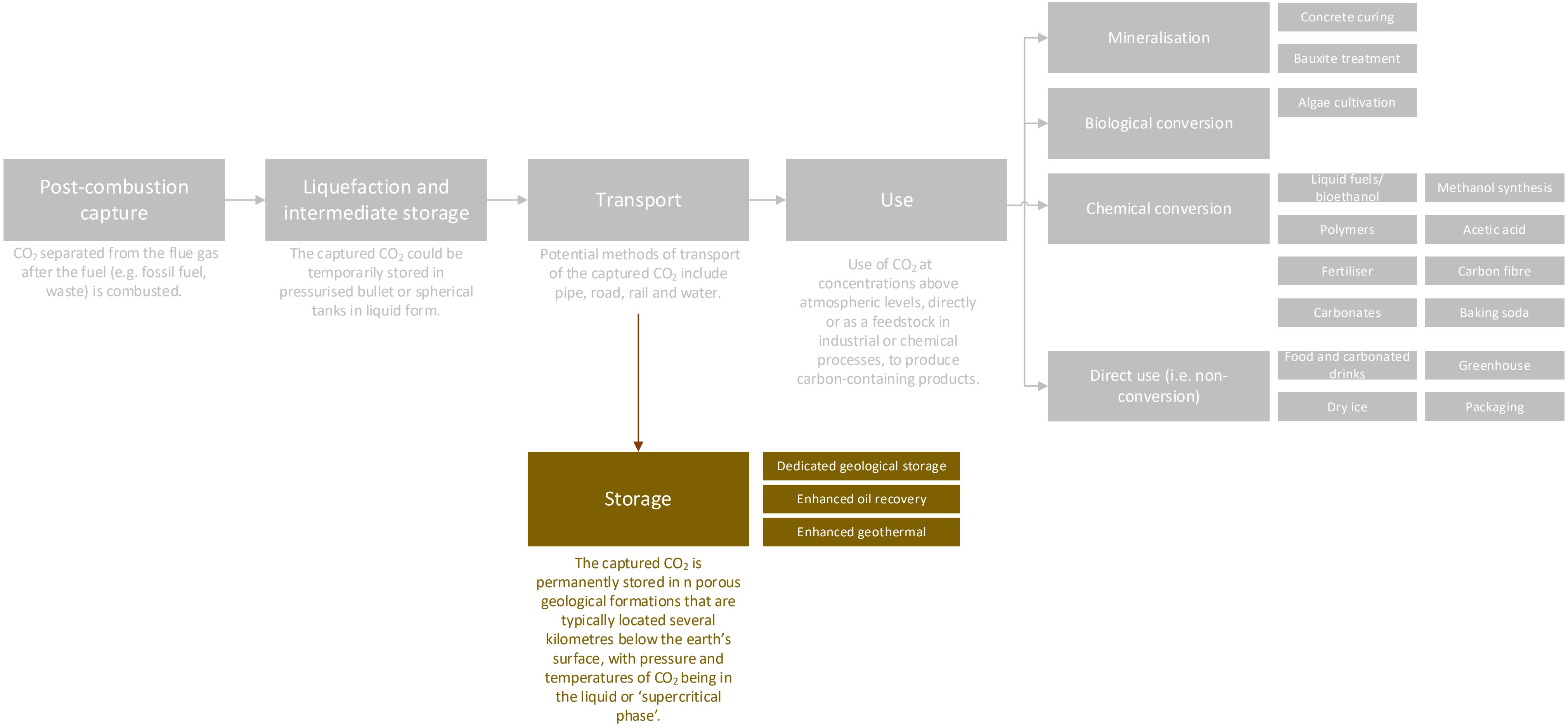
[66] Adapted from Global CCS Institute (2019), *Global Status of CCS*, Available at: https://www.globalccsinstitute.com/wp-content/uploads/2019/12/GCC_GLOBAL_STATUS_REPORT_2019.pdf (Accessed 30 April 2020).

7.3 CCS options

An overview of the main CCS options is given in Figure 18.



CO_2 separated from the flue gas after the fuel (e.g. fossil fuel, waste) is combusted.

The captured CO_2 could be temporarily stored in pressurised bullet or spherical tanks in liquid form.

Potential methods of transport of the captured CO_2 include pipe, road, rail and water.

Use of CO_2 at concentrations above atmospheric levels, directly or as a feedstock in industrial or chemical processes, to produce carbon-containing products.

The captured CO_2 is permanently stored in n porous geological formations that are typically located several kilometres below the earth's surface, with pressure and temperatures of CO_2 being in the liquid or 'supercritical phase'.

Figure 18: CCS options

7.4 CCUS qualitative assessment

Table 10 includes a list of potential CCU options for the ERF and a qualitative assessment against several factors, to provide an indicative overall rating of each option against its associated benefits and costs.

The qualitative assessment is based on a RAG ‘traffic light’ system, where:

- An option is scored ‘Green’ against a factor if it is performing well against that factor relative to the alternative options (e.g. relatively low CAPEX).
- An option is scored ‘Amber’ against a factor if it is performing averagely against that factor relative to the alternative options (e.g. neither too high, neither relatively low CAPEX).
- An option is scored ‘Red’ against a factor if it is performing weakly against that factor relative to the alternative options (e.g. relatively high CAPEX).

Table 10: Qualitative assessment of CCUS options

No	Name	Description	Benefits	Challenges	CAPEX	Operational expenditure (OPEX)	CO_2 emissions reduction	Commercially available	Compatible with EfW
1	CO_2 mineralisation in construction materials	CO_2 mineral carbonation from flue gas. CO_2 chemically bound to calcium- or magnesium-containing minerals to form stable materials, which can be used to produce building and construction materials such as cement, paving stones and plasterboard.	● The chemistry involved in making carbonates based on calcium and magnesium is well known ● The conversion of CO_2, a low-energy molecule, into solid mineral carbonates is one of only a few thermodynamically favourable reactions involving CO_2 and can be accomplished at near-ambient temperatures ● Commercial plants already producing materials for the building industry in Europe and in North America ● CO_2 can be injected during the curing of concrete in traditional ready-mix or precast processes without major changes needed to the process or ingredients	● Energy intensive process ● Issues with transitioning from academic research based systems to commercial systems due to the reluctance of subsidy granting bodies and government agencies, who prefer better-known energy transition methods and CO_2 storage	🟩	🟨	🟩	🟥	🟩

No	Name	Description	Benefits	Challenges	CAPEX	Operational expenditure (OPEX)	CO_2 emissions reduction	Commercially available	Compatible with EfW
			• The CO_2 used in the carbonation process gets permanently sequestered in the end-products • The market for construction materials produced through mineral carbonation using waste CO_2 is expected to be grow by the growing demand for sustainable construction materials		🟩	🟨	🟩	🟥	🟩
2	CO_2 enhanced oil recovery (EOR)	Injection of high-pressure CO_2 from flue gas into oil reservoirs to enhance the extraction of oil and gas resources.	• EOR is the only industrial use of CO_2 that has reached a relatively large scale • EOR can recover up to 60% of the oil in a reservoir • When CO_2 is injected underground for EOR, around 90-95%, stays trapped in the geologic formation	• Debate around whether helping to extract more oil and gas can help tackle climate change • Oil field operators must consider the pressure of a depleted oil reservoir when evaluating its suitability, low pressured reservoirs may need to be re-pressurised by injecting water	🟨	🟨	🟨	🟩	🟩
3	Synthetic fuels from CO_2	Catalytic hydrogenation processes to convert CO_2 from flue gas into fuels, such as	• Synthetic fuels are renewable	• High temperatures and multi-component	🟥	🟨	🟨	🟨	🟩

No	**Name**	**Description**	**Benefits**	**Challenges**	**CAPEX**	**Operational expenditure (OPEX)**	**CO_2 emissions reduction**	**Commercially available**	**Compatible with EfW**
		synthetic gasoline, diesel and jet fuel.	• Existing vehicles do not need to be modified to start running on synthetic fuels	heterogenous catalyst required. • Requires sustainable source of cost-efficient hydrogen	🟥	🟨	🟨	🟨	🟩
4	CO_2 as a feedstock for polymers (polycarbonate polymers and polyols)	Manufacturing materials such as plastics by using CO_2 in the chemical supply chain.	• Renewable carbon feedstock • Important CO_2 co-polymers[67] can be synthesized by fixation of up to 50% of their mass with CO_2	• CO_2 is a relatively low energy and inert molecule and this is a major hurdle as it means that reactions involving CO_2 consume a lot of energy, and catalysts that overcome the low reactivity need to be used	🟨	🟥	🟩	🟨	🟩
5	Use of CO_2 in sodium bicarbonate production (see also case study in Section 8.4)	Reusing CO_2 by capturing it from the flue gases of the EfW facility and using it to produce sodium bicarbonate ($NaHCO_3$).	• System fully integrated into the EfW plant • Lower consumption of absorption liquids • Lower operational and transportation costs ($NaHCO_3$ is an expensive raw material)	• Only successfully implemented at a pilot plant in the Netherlands to date	🟥	🟩	🟨	🟨	🟩

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[67] A polymer made by reaction of two different monomers, with units of more than one kind.

8 CCUS EfW case studies

8.1 Overview

An initial review of relevant CCUS projects has been undertaken and four CCUS case studies are given in the sub-sections below.

It is proposed that a more detailed review of available CCUS projects is undertaken to obtain more detailed information on capital investment costs and operational costs.

8.2 Fortum Klemetsrud Oslo, Norway

The Klemetsrud EfW facility[68,69], run a test program with Aker Solutions in 2016, to test carbon capture from the flue gas of the EfW process, using Aker Solutions 'Just Catch' modular carbon capture unit[70]. The pilot project lasted five months. It is estimated that the EfW facility releases 400,000 tonnes CO_2 in the flue gas. Currently, works are underway to establish at least one full-scale plant for carbon capture at Klemetsrud EfW by 2023 (see Figure 19 and Table 11).

Figure 19: Klemetsrud EfW facility (right: Aker Solutions test plant at Klemetsrud, left: Klemetsrud EfW front view)

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[68] COWI (2019), *Carbon Capture May Solve The Climate Crisis – But How Do We Get There?*, Available at: https://www.cowi.com/insights/carbon-capture-may-solve-the-climate-crisis-but-how-do-we-get-there; (Accessed 9 March 2020).

[69] Fortum (*no date*), *A full-scale carbon capture and storage (CCS) project initiated in Norway;* Available at: https://www.fortum.com/media/2018/11/full-scale-carbon-capture-and-storage-ccs-project-initiated-norway (Accessed 10 March 2020).

[70] Aker Solutions (2018), *Carbon Capture, Utilization and Storage (CCUS) Just Catch*, Available at: https://static1.squarespace.com/static/574c47228259b5de6737fbfe/t/5afd206303ce64542a64c5a5/1526538349706/6.+Graff+CCUS+in+Aker+Solutions.pdf (Accessed 17 April 2020).

Table 11: Fortum Oslo Varme project details

Year of commission	Waste throughput (tonnes/annum)	Footprint (m^2)	CAPEX and OPEX	Description of carbon capture technology and process	CO_2 capture capacity
Pilot: 2016 Planned commercial operation: 2023	566,000	EfW facility: 29,000 Aker Solutions pilot plant: approximately 1,614m^2 (including liquefaction, liquid CO_2 storage and CO_2 tanker loading station)	NOK11.8 billion (approx. EUR €1.05 billion) capital investment costs plus five-years operating costs EUR€3,000-€5,000/ tonne, which is 15-20 times higher than the EU Emissions Trading System (ETS) of approx. EUR€20/tonne of CO_2.	Fortum are establishing a full value chain for handling CO_2 based on a full-scale CCS using proven carbon capture technology. The CO_2e is removed from the cleaned flue gas using amine solution and heat. The CO_2e will be transported by ship from the carbon capture plant to an onshore facility on Norway's west coast for temporary storage. The CO_2e will then be transported via a pipeline to a subsea reservoir in the North Sea for storage in disused oil and gas reservoirs. Equinor, with its partners Shell and Total, are responsible for planning the storage facility.	90% (achieved by the 5-month test in 2016)

8.3 AVR Duiven, The Netherlands

The Dutch waste management company AVR, operates a commercial carbon capture plant, which captures CO_2 from the flue gases of an MSW EfW facility. The captured CO_2 is used in agriculture in Duiven in The Netherlands. This is the first plant of such a scale in the world, which was implemented after piloting an accurately simulated plant on a small scale on-site.

The carbon capture facility operates for around six months every year, to match the demand for the CO_2 in the crop growing season.

AVR started the first capture and supply of CO_2 to greenhouse horticulturists in 2019 (see Figure 20 and Table 12). The CO_2 capture installation at the site was completed in a little over a year with support from engineering firm TPI. The first 7,500 tonnes of CO_2 were captured and supplied to various buyers in the agricultural sector via business partner Air Liquide, who is responsible for CO_2 liquefaction.

Partners also include, Bilfinger Tebodin who were responsible for the conceptual engineering, and supported the basic engineering and the project execution phase.

The AVR Duiven project is an example of CO_2 substitution, whereby the project is contributing to enhanced plant growth through the addition of extra CO_2, while avoiding the use of natural CO_2 or natural gas for cultivation.

Figure 20: AVR Duiven CCUS facility (right image: overview of EfW facility with outline of carbon capture plant, left image: aerial view of carbon capture plant)

Table 12: AVR Duiven CCUS project details

Year of commission	Waste throughput (tonnes/annum)	Footprint (m^2)	CAPEX and OPEX	Description of carbon capture technology and process	CO_2 capture capacity
2019	Approximately 600,000	EfW facility: 21,000 On-site carbon capture facility: Approximately 2,000	*Not available*	The CO_2 is captured from the flue gas, purified and liquefied in storage tanks. The flue gas is conducted through a column containing the substance mono-ethanolamine. The amine molecules bind the CO_2 in the flue gas. Then, the CO_2-saturated amines are heated so that almost pure CO_2 is captured. Road tankers transport the liquid CO_2 to the greenhouse farming sector, where it is used for cultivation of plants such as vegetables and flowers.	85% of the CO_2 from one incineration line[71] 12 tonnes of CO_2/hour (or approx. 60,000-100,000 tonnes/annum)

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[71] From a discussion with AVR on 16 April 2020.

8.4 Twence Hengelo, The Netherlands

The Dutch waste management company, Twence, thermally treats MSW at their EfW facility in Hengelo, which produces approximately 600,000 tonnes CO$_2$/annum. Twence, in collaboration with the firm Procede, developed a system to capture CO$_2$ from the dry flue gas of one the EfW facility's incineration lines. Since 2014, the captured CO$_2$ is used to produce sodium bicarbonate (NaHCO$_3$), which acts as a scrubber of acid components in the flue gas[72,73].

Aker Solutions signed a deliver contract in 2019, for delivering a commercial carbon capture and liquefaction system for the EfW facility in Hengelo[74], (see Figure 21 and Table 13). The system used by Aker Solutions, called 'Just Catch', had been previously developed over a one-year operational test that they carried out on another EfW facility. It is a modular carbon capture system, designed around ease of installation and rapid deployment. The system will be commissioned in 2021.

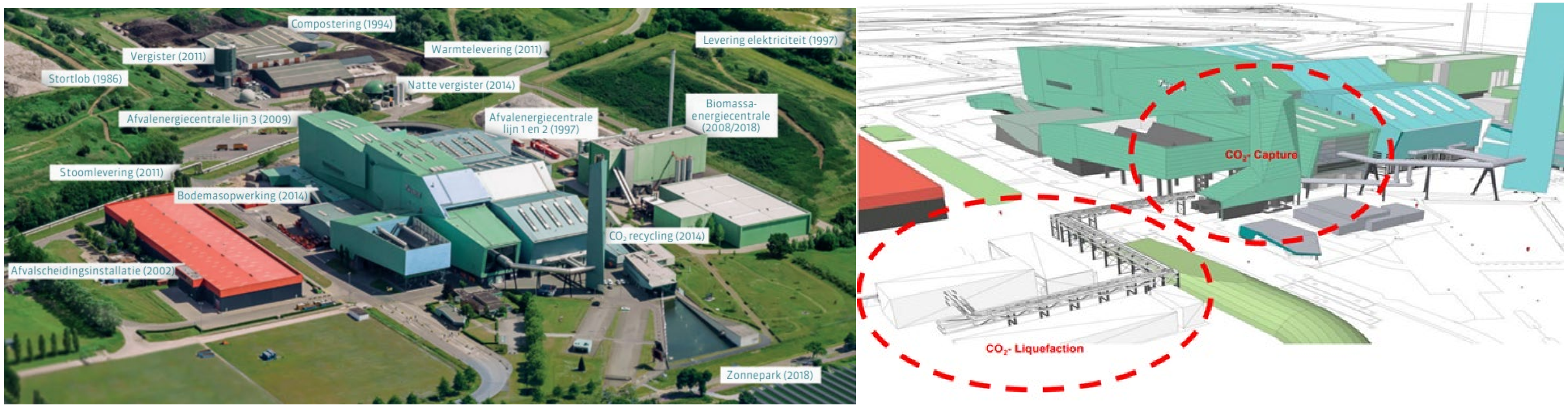

Figure 21: Twence, Hengelo EfW (left image: indicates NaHCO$_3$ facility, right image: indicates the carbon capture and liquefaction system)

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[72] Twence (*no date*), *CO$_2$/Sodium Bicarbonate Project,* Available at: https://www.twence.nl/dam/jcr:3245b1dc-65c1-406d-b7a2-e20bb62096a6/141215%20Factsheet%20CO2NBC%20UK.pdf (Accessed 11 March 2020).

[73] Van de Ven, M. and Wielaard, J. (2018), *Analysing the Sodium bicarbonate production of Twence*, Available at: http://essay.utwente.nl/75645/1/Bachelor_assignment.pdf (Accessed 17 April 2020).

[74] Aker Solutions (2019), *Aker Solutions Signs Carbon Capture Contract with Twence in the Netherlands*. Available at: https://www.akersolutions.com/news/news-archive/2019/aker-solutions-signs-carbon-capture-contract-with-twence-in-the-netherlands/ (Accessed 10 March 2020).

Table 13: Twence, Hengelo CCUS project details

Year of commission	Waste throughput (tonnes/annum)	Footprint (m^2)	CAPEX and OPEX	Description of carbon capture technology and process	CO_2 capture capacity
$NaHCO_3$ production plant: 2014 CO_2 capture and liquefaction system: 2021	830,000	EfW facility: 60,000 $NaHCO_3$ production plant: approximately 1,600m^2 CO_2 capture and liquefaction system: *Not available*	*Not available*	Twence developed a process for reusing some of the captured CO_2 in the production of sodium bicarbonate ($NaHCO_3$). The produced $NaHCO_3$ is used in flue gas cleaning for the removal of acid components. The system is fully integrated into the EfW facility and produces approximately 8,000 tonnes/annum of $NaHCO_3$.	$NaHCO_3$ production: 2-3% of CO_2 in flue gas (i.e. 2,000 tonnes/annum) CO_2 capture and liquefaction system: 85-100% (i.e. 100,000 planned maximum design capacity)
				According to Aker Solutions, the use of standardised plant drawings, plant layout, containers and foundations greatly simplifies the engineering complexity and cost compared to a conventional capture project. The modular design enables flexible applications and offers cost savings relative to larger-scale manufacturing of carbon capture system components. Some of the capture system components are provided in standard shipping containers; a low-cost method of system delivery and packaging. Liquefied CO_2 is sold to customers by tanker for use in agricultural and industrial applications.	

8.5 Toshiba Saga City, Japan

Toshiba designed a carbon capture plant that operates at the Saga City EfW facility. The EfW facility emits approximately 220 tonnes CO_2/day.

The captured CO_2 is used to cultivate crops and create algae cultures in the local agriculture sector. It is a world-first application of carbon capture and waste treatment[75,76,77,78] (see Figure 22 and Table 14).

Figure 22: Toshiba Saga City EfW facility

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[75] Global CCS Institute (2019) *Waste-to-Energy: A pathway to carbon negative power generation*. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2019/10/Waste-to-Energy-Perspective_October-2019-5.pdf (Accessed 10 March 2020).

[76] Global CCS Institute (2019) *Saga City: The world's best kept secret (for now)* Available at: https://www.globalccsinstitute.com/news-media/insights/saga-city-the-worlds-best-kept-secret-for-now/ (Accessed 10 March 2020).

[77] Forbes (2016), *Why Stop at Carbon Capture Storage? Think CO_2 Utilization*, Available at: https://www.forbes.com/sites/jboyd/2016/08/18/why-stop-at-carbon-capture-storage-think-co2-utilization/ (Accessed 12 March 2020).

[78] Carbon Sequestration Leadership Forum (2018), Technical Summary of Bioenergy Carbon Capture and Storage (BECCS), Available at: https://www.cslforum.org/cslf/sites/default/files/documents/Publications/BECCS_Task_Force_Report_2018-04-04.pdf (Accessed 17 April 2020).

Table 14: Toshiba Saga City project summary

Year of commission	Waste throughput (tonnes/annum)	Footprint (m^2)	CAPEX and OPEX	Description of carbon capture technology and process	CO_2 capture capacity
Pilot: 2013 Commercial operation: 2016	40,000	EfW facility: 15,000 Carbon capture facility: Approximately 1,250	Estimated CAPEX GBP£11,770,000 (based on US$15,000,000)	Flue gases from the Saga EfW are conveyed to a low-temperature absorbent tower where a chemical absorbent (an alkaline amine solution) captures the CO_2. The solution is passed to a stripper tower and heated. This releases the CO_2 in a pure gaseous form. The absorbent is circulated back for recycling, while the CO_2 is stored as a pressurised gas. With the help of specialist contractors, Saga city constructed a pipeline connecting the stored CO_2 to nearby farmlands to cultivate algae and other suitable crops. Following the success of the test plant, the Toshiba-built carbon capture plant entered commercial operation in August 2016. The captured CO_2 is used by farmers for cultivation of algae at a neighbouring algae farm.	10 tonnes/day

9 Recommendations

9.1 General

Setting system boundaries at three different scales (i.e. NLWA, NLHPP and ERF) is important in order to calculate the embodied carbon of each of these three systems. This will allow the informed determination of the contribution of the ERF to the overall carbon footprint of NLHPP, and also more widely to NLWA as an organisation. This in turn, will help to inform any CO_2 emissions reduction targets for the ERF; ultimately informing the selection of the optimal carbon reduction interventions to achieve these targets.

9.2 Carbon offsetting

To provide more informed recommendations on the potential to proceed with carbon offsetting for the ERF, it is important to discuss and agree on several key areas including:

- **Carbon policy and targets**: Agreement on a carbon and climate change policy or statement of intent for carbon will help to guide what type of offset would be applicable or acceptable under the desired carbon target (e.g. if the project will be aiming for net zero or carbon neutral).
- **Standards**: Agreement on whether the project will be seeking certification under appropriate standards, such as PAS2060. If a standard/certification is pursued, this will also guide the requirement for carbon offsets as certain offset accreditations are recognised for certification and others are not.
- **NLWA corporate sustainability objectives**: It is important to align the carbon offset program with broader project or corporate objectives. For example, some organisations have an emphasis on local projects and community, while for others clean, renewable energy aligns better with their corporate goals. Establishing a clear picture of what is strategically important to NLWA will allow clearer recommendations of which carbon offsets align and if there are any offsets that would help satisfy broader objectives in addition to the carbon target.

In addition, potential risks associated with the carbon pricing and market availability for carbon credits need to be considered and explored further, as discussed in Section 5.4.

9.3 CCUS

Similar to the decision making on carbon offsetting, any decisions on investing in CCUS would need to be made following the establishment of a clearly defined climate change and carbon policy, objectives and targets, as described above. These objectives and targets would inform the decision on the quantity of CO_2 emissions to be captured on an annual basis.

An LCA would need to be undertaken to determine the level at which the proposed CCUS solution can offer positive environmental impacts and to conclude on the time required for it to achieve carbon payback.

A more detailed feasibility study would need to be carried out as a next step to determine a number of factors as outlined below.

The quantity of CO_2 to be captured annually will heavily influence several key technical decisions, namely:

- Overall size and footprint of the carbon capture plant;
- Size of intermediate storage facility in advance of CO_2 transport from site;
- Selection of CO_2 transport options to end user; and
- Selection of end user(s).

Once the targeted volume of CO_2 captured is determined, it is recommended that an assessment of the size of the necessary carbon capture plant is undertaken. This would include a review of the existing site layout to assess the space available and how the carbon capture plant interfaces with the planned ERF plant.

A more detailed understanding of the ERF will be necessary, to understand the interaction with the carbon capture plant, particularly the impact on the thermal efficiency and systems within the ERF. The composition of the flue gas from the ERF will need to be examined further, the selection of the carbon capture solvent and the requirements for any further treatment to condition the CO_2 for the identified end users.

One of the key decisions is to determine the potential end-users. A market study would need to be undertaken to understand the most commercially and technically viable end users of the CO_2 captured from the ERF, the quantity of CO_2 they can accommodate and the likely transport options for delivering the CO_2 to them. Linking up with potential industries operating within London and/or in proximity to the ERF would allow the creation of appropriate partnerships for using and/or storing the captured CO_2.

NLWA would need to undertake an assessment on the implications of adding a carbon capture plant to the existing consents, permits and approvals already in place for the ERF.