Planetary Hydrogen

Westward OH2 GGR Project – Phase 1 Final Report

BEIS Contract - PLA202081

January 11, 2022

Table of Contents

Part I - Scientific and engineering foundations

The science and engineering underpinning Planetary Hydrogen's end-to-end SeaOH2 GGR process (Annex 1) is discussed in the following three chapters, covering;
1. carbon dioxide removal (CDR) by air-sea gas exchange as a result of ocean alkalinity enhancement (OAE) through magnesium hydroxide (MH) addition,
2. the electrochemical process to generate MH with low embodied carbon emissions,
3. the metallurgical process to recycle outputs and regenerate inputs to the electrochemical process.

1   Ocean alkalinity enhancement and carbon dioxide removal

By adding alkaline material (i.e. certain minerals or synthetic chemical bases) to surface seawater, OAE converts CO_2 to already-abundant seawater bicarbonate and carbonate ions in order to further increase the transfer of CO_2 from the air into the ocean.

The recent review "Greenhouse gas removal methods and their potential UK deployment", published for BEIS by Element Energy and the UK Centre for Ecology and Hydrology (BEIS 2021a), summarised OAE as follows;

Ocean alkalinity [enhancement] … seeks to raise the pH and thus the bicarbonate concentration of the ocean, by adding basic cations such as calcium and magnesium to sea-water. The fundamental science behind this concept is well established, and as this process would effectively counteract ocean acidification as a result of rising atmospheric CO_2 concentrations it could have co-benefits in offsetting ecological impacts on organisms with calcium carbonate shells or structures.

1.1   Carbon storage in the ocean

The ocean contains an estimated 39,000 billion tonnes of carbon (GtC), about 10 times greater that the terrestrial carbon inventory and around 50 times that of the atmosphere, and plays a critical role in mitigating climate change, having taken up about one third of fossil fuel CO_2 emissions since the start of the industrial era.

Atmospheric CO_2 is a very minor component of Earth's carbon inventory, primarily because of its reactivity with alkaline rocks (mineral weathering) and conversion to seawater bicarbonate and carbonate ions and eventually carbonate rocks – processes which occur naturally on geological timescales. The ocean will be the natural long-term sink of the majority of anthropogenic CO_2 emissions, on a 100,000 year timescale, as a result of this weathering process (Archer and others 2009).

Given the immense seawater carbon inventory and its continuing role as the primary natural sink for atmospheric CO_2, the ocean can play an important part in climate change mitigation if ocean alkalinization can be speeded up. Enhancing natural processes to accelerate CDR from the atmosphere and storage in the form of increased ocean alkalinity is one of a number of options that are being actively researched (Renforth and Henderson 2017).

1.2 Ocean alkalinity enhancement by hydroxide addition

The possibility of increasing carbon dioxide storage in the oceans by increasing ocean alkalinity was first suggested by Kheshgi (1995), the addition of hydroxide being one of a variety of methods that have since been proposed. CO_2 dissolved in seawater will readily react with excess hydroxyl bases (OH^-) to form bicarbonate ions (HCO_3^-), and to a lesser extent carbonate ions (CO_3^{2-}), reducing the partial pressure of CO_2 dissolved in seawater.

The equilibrium concentration of CO_2 in seawater is then restored by air-sea exchange, drawing down CO_2 to replace that converted to bicarbonate and carbonate ions, thus achieving the CDR objective while also raising local ocean pH and providing an antidote to ocean acidification. Further details of the air-sea gas exchange process and of the dissolution and settling of discharged hydroxide particles are given in Annex 2.

Low pH discharges to the sea originating from industrial or municipal activities, including waste water treatment, can cause the reverse process. In this case the increase in partial pressure of dissolved CO_2, arising from the transformation of bicarbonate back to dissolved CO_2 or due to a high biogenic CO_2 content in the discharge, can result in CO_2 emission to the atmosphere. Hydroxide addition to such a discharge can reduce its CO_2 partial pressure and thus prevent CO_2 release, which is equivalent to CDR due to the biological origin of the CO_2.

1.3 Environmental impact of magnesium hydroxide discharge to the sea

Magnesium hydroxide (MH) is of low toxicity to aquatic organisms. It is not classified as dangerous under the Classification, Labelling and Packaging (CLP) Regulation nor is it classified as persistent, bio-accumulative or toxic under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation.

The main UK environmental quality standard (EQS) applicable to the discharge is that for pH, with a 95 %ile maximum allowable concentration (MAC) of 8.5. Initial dilution studies performed during Phase 1 demonstrated that dilution to pH 8.5 from a discharge pH of 9.4 (the maximum possible for MH dissolved in seawater) can be achieved with a minimum of 5 m water depth above the discharge diffuser. This rapid initial dilution is confirmed by the results of the far-field discharge modelling study of the proposed pilot site, discussed below.

The discharge of undissolved hydroxide particles would cause turbidity downstream of the discharge point but the Environment Agency's default permit standard for suspended solids of 100 mg/L ($0.1 kg/m^3$) will not be exceeded for the planned hydroxide addition rates given the rapid tidal mixing at the proposed pilot location.

Planetary Hydrogen is currently supporting a research programme at Dalhousie University in Halifax, Nova Scotia which will assess the efficacy, impacts and benefits of adding hydroxide to seawater, including how it affects selected marine biota. Biological responses with coastal phytoplankton and with oyster larvae will be assessed in the lab as well as in field trials in the Bedford Basin and in a commercial oyster hatchery.

2   Electrochemical production of magnesium hydroxide

MH is a commodity chemical, approximately 1 million tonnes is produced globally each year with water treatment being the second largest market segment. For the purposes of ocean alkalinity, MH can be purchased from commodity providers and applied to the OAE process. Unfortunately, industrial MH production typically results in significant CO_2 emissions, which would reduce the net CDR efficiency. To address this challenge, Planetary Hydrogen is developing a proprietary process in which the acid (H_2SO_4) produced from electrolysis of $NaSO_4$ is used to extract magnesium salt from globally abundant magnesium silicate minerals and to convert this to MH, primarily in solid form, while reforming and recycling $NaSO_4$ for the system's electrolyte. Details of the electrochemical process can be found in (Rau and others 2018).

Optimising such a process to minimise cost and maximise CDR and environmental benefit is the primary, ongoing activity of Planetary Hydrogen, an essential initial step being to assess the efficacy and environmental benefit of MH addition to the ocean in the context of CO_2 removal and storage.

3   Metallurgical extraction of magnesium sulphate and production of magnesium hydroxide

The metallurgical component of the end-to-end SeaOH2 process is based on the well-established leaching/dissolution and precipitation steps (see Petersen 2016 for further details). Recovery of magnesium is the main objective of this process stage, but other metals present in the mineral feedstock, including aluminium, cobalt, iron, and nickel, are also recovered.

In the leaching/dissolution step, the mineral feedstock is irrigated with sulphuric acid, which reacts with mineral silicates to produce metal sulphates. The product stream from this step, known as the pregnant leach solution, then flows through a multistage precipitation process in which pH is progressively raised to precipitate Fe/Al, Ni/Co and finally Mg hydroxides. Following each precipitation stage, solid-liquid-separation is achieved using a combination of a thickening and filtration. Further details of the leaching and precipitation process are included in Annex 2.

Initial MH precipitation tests using relevant feedstocks indicate a hydroxide purity of 65% due to the formation of a double salt that adsorbs on the surface of the hydroxide product. In order to increase the purity of MH and make it suitable for direct ocean addition, future test-work will focus on the direct production of MH in the electrochemical cell. The development of a sodium free system will lead to a GEN2 pilot (see below) in which MH will be produced by the direct electrolysis of $MgSO_4$.

4   Life cycle analysis of CDR through the SeaOH2 process

The recent review "Greenhouse gas removal methods and their potential UK deployment", published for BEIS by Element Energy and the UK Centre for Ecology and Hydrology (BEIS 2021), summarised a number of challenges to the CDR effectiveness of OAE in general, notably;

- the generation of CO_2 in the production of synthetic alkalinity (e.g. calcination in the production of lime; chlor-alkali electrochemistry in the production of caustic soda)

- the cost and emissions penalty of the mining and milling of natural alkaline minerals such a mineral silicates
- the potential for CO_2 release as a result of carbonate precipitation in the ocean

The first two points relate to the lifecycle emissions of the solution, while the last relates to processes that may impact the efficiency of CDR once alkalinity is added to the ocean.

4.1   Life cycle analysis of the SeaOH2 process

A comprehensive assessment of the potential GHG emission reductions generated by the SeaOH2 process has been completed by OXIA Initiative Inc., using its methodology based on ISO 14064-2: 2019 - Greenhouse gases. The methodology includes development of a table of GHG sources, sinks and reservoirs (SSR table) relevant to the electrochemical hydrogen production process, and a consequence tree which defines the project boundary and the full magnitude of emissions attributable to the establishment and use of the project.

The assessment concluded that H_2 production using the SeaOH2 process will result in avoided emissions of 30 $kgCO_2/kgH_2$ produced, or 82% of the 36.5 $kgCO_2/kgH_2$ based on a theoretical assessment of the process (Rau GH, Willauer HD, and Ren ZJ 2018). The SSR table, consequence tree, and summary of the study results are appended in Annex 3.

During the metallurgical extraction, about 1 tonne of 95% CaO will be used in the iron and nickel precipitation circuits for each 13.8 tMH produced. CaO related emissions will depend on the energy source used in the production of CaO by calcination (i.e. fossil-fuel or renewable), and whether process CO_2 is captured and stored. The overall LCA will be updated following further development of the electrochemical and metallurgical processes.

The avoided emissions achieved for the GEN1 pilot, described below, will depend on the carbon intensity (CI) of the hydroxide supply. Most MH is currently produced through calcination, with a high energy requirements and CI due to CO_2 emissions in the calcination process, hence the need for low-carbon hydroxide production through the electrochemical and metallurgical process described above.

4.2   Marine processes impacting CDR efficiency

Simple stoichiometry indicates a removal of 2 mols of CO_2 per mol MH addition, although the partitioning of the increased dissolved inorganic carbon (DIC) between HCO_3^- and CO_3^{2-} will reduce this by around 20% at 20°C and pCO_{2SEA} ~400 ppm.

A range of other processes may further reduce efficiency, including biocalcification, which consumes carbonate alkalinity and releases CO_2, and photosynthesis, which converts DIC to organic carbon leading to eventual leakage via respiration. These effects are expected to be small relative to the existing DIC and A_T pools, and to the additional alkalinity added by the SeaOH2 process, but an efficiency factor of 90% factor has been adopted to reflect these potential losses, pending improved quantification. Given these uncertainties, an overall efficiency of 1 tCO_2 removed per tMH addition has been taken as the basis for engineering design.

Part II –Phase 1 findings and outcomes

5   Phase 1 studies

5.1   Phase 1 objectives

The main objectives of the Phase 1 project were;
- to develop analytical and numerical modelling tools to determine the rates and potential sites of alkalinity addition to seawater to effect CO_2 removal from the atmosphere and locally counter ocean acidification, while staying within UK-permitted discharge pH levels, and avoiding adverse chemical and biological effects.
- to develop an engineering design and costed project plan setting out how and where a pilot plant could be constructed to test the SeaOH2.

5.2   Initial discharge dilution study

An initial discharge dilution study was completed by HaskoningDHV UK in order to assess the water depth required at the discharge point to ensure a minimal mixing zone within which seawater pH might exceed the EQS upper limit (pH=8.5), for a range of tidal conditions.

The study, using industry standard correlations for initial dilution in moving and slack water conditions, confirmed that a minimum water depth of 5 m would be sufficient, and this was used as an additional site selection constraint.

5.3   Site investigation and selection

An investigation of potential coastal sites for the pilot plant was completed by HaskoningDHV UK, applying a ranked list of constraints including;

- Special Areas of Conservation (SAC) and Marine Conservation Zones (MCZ)
- Sites of Special Scientific interest (SSSI), Special Protected Areas (SPA) & other Ramsar sites
- Local and national nature reserves
- Bathing waters and blue flag beaches
- Dredging and anchorage areas
- Protected wrecks and other obstructions, including disposal/munitions grounds

The study identified 10 potential coastal locations on the UK south/south west coast, as shown in Annex 4. A full discussion of the investigation process and the shortlisted sites can be found in the HaskoningDHV study report (HaskoningDHV UK 2021a).

The study also identified and assessed existing outfall infrastructure, including the locations of 23 existing outfalls operated by three regional water companies (South West Water, Southern Water Services, and Wessex Water Services), and these sites were individually mapped to highlight the land- and marine-based constraints.

The water companies were contacted to initiate discussion on the possibility of hosting the pilot project, leading to the confirmation of the Hayle sewage treatment works (STW), operated by South West Water, as a preferred pilot site.

5.4   Permitting and consenting review

A review of consenting and permitting requirements relevant to the construction and operation of a pilot plant was completed by HaskoningDHV UK, a key objective being confirmation of relevant environmental quality standards (EQS) concerning the discharge of alkaline material in UK coastal waters, as well as other permitting considerations. The main findings for the construction and operating phases were as follows.

5.4.1   Construction phase requirements

For onshore construction work, planning permission from the Cornwall Council – Planning and Building Control department will be required for the installation of industrial plant although, in view of its fairly small footprint, the pilot plant would be considered a minor development.

In addition, if required for offshore monitoring, the installation of fixed buoys would require an application to the Marine Management Organisation (MMO) for a Marine Licence since this would involve a construction activity below mean high water springs (MHWS).

5.4.2   Operating phase requirements

Since the project achieves GGR through alkalinization of a marine discharge, applicable environmental quality standards (EQS) for such discharges will be complied with.

The EQS for pH specifies a maximum allowable "concentration" (MAC) with a 95 %ile value of 8.5. Initial dilution studies conducted during this phase have demonstrated that dilution from a discharge pH of 9.4 (the maximum possible for MH dissolved in seawater) can be achieved with a minimum of 5 m water depth above the discharge diffuser, well below the 25 m water depth at the Hayle STW outfall location, NW of Godrevy Point.

For a partially dissolved discharge, undissolved hydroxide particles would cause turbidity down-stream of the discharge point. However, the EA's default permit standard for suspended solids of 100 mg/L (0.1 kg/m^3) will not be exceeded at the MH dosing rates planned for the Phase 2 pilot. The target MH addition rate of 15 kg/h will add ~30 mg/L to the background total suspended solids (TSS) in the STW effluent at the minimum night time flow rate, or ~8 mg/L at the average daily flow rate.

The Hayle effluent is covered by an existing discharge permit, and the planned alkalinity addition will not breach any of the existing permit limits. An application to vary the existing permit limits is therefore not expected to be required.

5.5   Engineering studies

A conceptual design study for a dedicated seawater intake and outfall was completed by HaskoningDHV UK. This was required in order to provide a basis for the Phase 2 project in the event that it was not possible to identify a suitable existing discharge to which MH could be added.

A potential site for a stand-alone pilot plant was identified at Shoreham, and this was used as the basis for the design. Annex 5 shows the conceptual layout of the offshore systems. Further details can be found in reference HaskoningDHV UK, 2021b.

5.6 Far field discharge modelling study

Initial modelling studies of the behaviour of an alkalinity enhanced effluent discharge from the Hayle STW site have been conducted as part of the Phase 1 scope, following the modelling approach discussed in Annex 6. The results of the study include;

- confirmation that initial dilution of the discharge to achieve the environmental quality standard (EQS) of pH < 8.5 (95th %ile) will be rapidly achieved within a very small mixing zone downstream of the outfall diffusers,
- confirmation that addition of fully dissolved MH to the STW effluent leads to an increased air-sea drawdown of CO_2 in line with the planned MH addition rate,
- confirmation that the addition of undissolved MH further increases CDR and that at the modelled addition rates, seawater turbidity remains well below the EQS MAC of 100 mg/L.

The figures below show the modelled increases in air-sea CO_2 flux and seawater dissolved inorganic carbon (DIC) at the end of a 180 day simulation of MH addition at a rate corresponding to 1 t/d CO_2 removal, under winter condition.
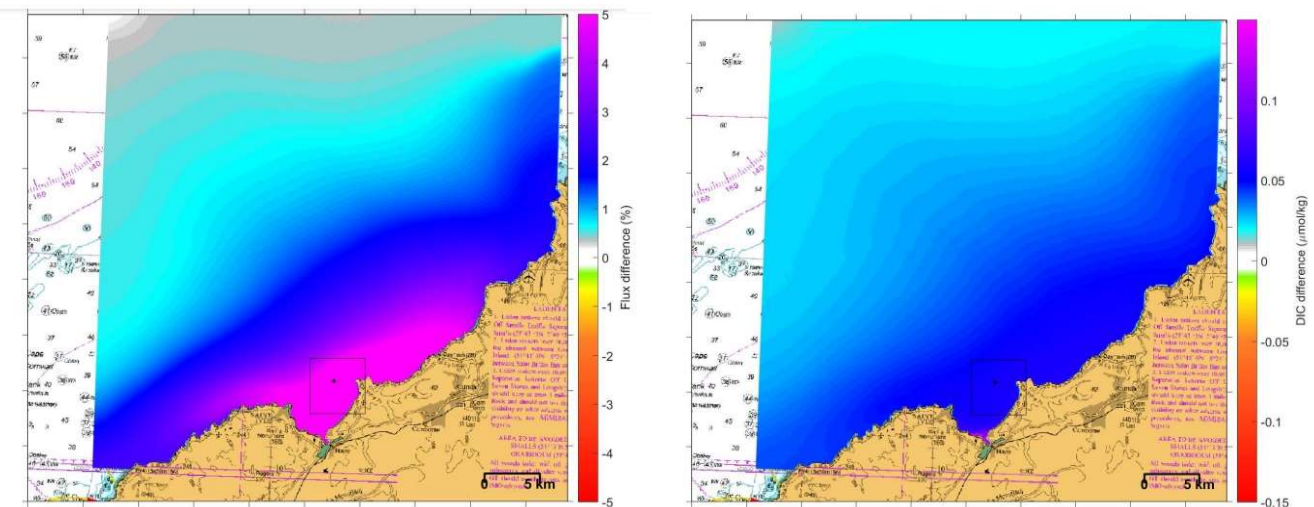
These results will guide the detailed design of the offshore monitoring program and the modelling work planned for Phase 2, as discussed below.

5.7 Hayle STW effluent analysis

A sample of the Hayle STW effluent was collected for full chemical analysis at the Plymouth Marine Laboratory to assess the effluent properties for use in the far field model. The analysis confirmed the high DIC (3341 μmol/L) and total alkalinity (2836 μmol/L) present in the effluent.

A titration with saturated MH solution was also performed which demonstrated the reduction in CO_2 partial pressure in the effluent with increasing alkalinity addition.

Part III –Pilot project development plan

6 Phase 2 project scope

As discussed in Part I, the end-to-end carbon-negative hydrogen production process comprises three sub-processes (Annex 1);

- CDR by air-sea gas exchange as a result of ocean alkalinity enhancement (OAE),
- electrochemical MH production with low embodied carbon emissions, and
- a metallurgical process recycling outputs and regenerating inputs to the electrochemical process.

The initial concept for the Phase 2 pilot included the electrochemical production of MH, starting from commercially available Na_2SO_4, as well as the demonstration of CDR via OAE. In parallel with the Phase 1 project, further development work has been undertaken to improve the efficiency of the electrochemical process and to integrate the metallurgical process. The results have led Planetary Hydrogen to pursue the development of an alternative, sodium-free electrochemical process which increases hydroxide purity. Preliminary results in testing this approach have been promising, but were not sufficiently advanced to provide the basis for initiating a FEED study for a Phase 2 pilot plant incorporating this revised process.

Planetary Hydrogen's technology development strategy, refined during the course of the Phase 1 work and discussed below, has identified a low risk, lower cost, scalable solution to achieve the Phase 2 100 t/yr CO_2 removal target, which will implement the first of the 3 sub-processes noted above (i.e. CDR via OAE), and forms the basis of the pilot project discussed below.

6.1 GEN1 SeaOH2 pilot concept

The GEN1 pilot project, proposed for implementation in Phase 2 of the GGR competition, aims to demonstrate verifiable CDR through OAE as a result of MH injection into the outfall from a sewage treatment works (STW). As such, the project aims to make a significant contribution to the development of detailed MRV protocols for CDR through ocean alkalinity enhancement, a key recommendation of HM Gov's recently published Monitoring, Reporting and Verification of Greenhouse Gas removals: Task and Finish Group Report (BEIS 2021b), while also achieving the BEIS GGR Lot 1 threshold of 100 tCO_2 removal per year.

The project will comprise two stages; commencing with monitoring on-site and in the sea around the STW outfall, in line with the MRV strategy discussed below. A proposal for the measurement and monitoring scope of work has been developed in collaboration with the Plymouth Marine Laboratory (PML). Offshore sampling and survey methods will be used to establish the seasonal background variability of seawater chemistry as a baseline against which the impact of the alkalinity addition will be measured. This stage is likely to last for 12 to 15 months, and during this period two hydroxide addition tests will be performed(currently planned for August 2022 and February 2023), once the summer and winter baselines have been established. Continuous onsite monitoring of the effluent discharge will also be undertaken at the STW.

The measured background variability will be a key input to a 3D model of the discharge region, centred on the outfall NW of Godrevy Point. Modelling results will be used to optimise the design of the hydroxide addition tests (i.e. test duration, MH addition rate and schedule, etc.). The MH addition tests will be performed using a temporary chemical dosing system with the MH slurry transported to the site by road tanker.

In parallel with this monitoring and testing programme, the detailed design of a more permanent MH addition plant will be developed, based on industry standard equipment, similar chemical dosing systems being widely used in the water treatment industry. This plant will be designed to enable re-deployment at other potential sites. EPC contracting will also be completed during this first stage to establish a firm budget level cost and schedule for the plant construction.

A stagegate review will take place following the outcome of the second MH addition test and completion of EPC contracting, with the aim of confirming a final investment decision for the injection plant construction. Execution of the selected EPC contract will initiate the second stage of the project, with the detailed engineering, procurement, and construction activity expected to be completed within 5 months.

Following commissioning of the pilot facilities an extended period of operation and monitoring will be undertaken to demonstrate continuous, safe, and reliable operation with verifiable CDR at a minimum rate of 100 tCO$_2$/yr.

6.2 Selected site characteristics

The land- and marine-based constraints map for the Hayle water treatment works and discharge location is shown in Annex 7. The treatment works are located at South West Water, Sewage Treatment Works, St. Erth, Hayle, TR27 6LA.

No interaction with the current water treatment process is expected since the hydroxide addition point will be downstream of the treatment process and immediately upstream of the discharge pumping station.

7 Pilot project engineering design

The control of process pH through alkalinity dosing (typically with lime powder or slurry) is a standard practice in the water treatment industry, and many standard designs and off-the-shelf solutions are available. The requirements for a long operating lifetime and compliance with engineering standards for permanent installations would drive up the cost if applied to a pilot plant that will have a relatively short operating lifetime. The engineering design for the Phase 2 plant is therefore based on industry standard solutions with the aim of cost-effectively delivering the required functionality with a 10-year design life.

7.1 Basis of design

The main requirements that provide the design basis for the pilot plant are summarised in Table 7.1.

Item	Design basis	Units	Comments
CO_2 removal rate	100	tCO_2/yr	GGR Lot 1 threshold: gross removal rate
	1	tCO_2/d	Target gross removal rate
System uptime	80	%	
CDR efficiency	90	%	10% A_T loss to non-CDR processes
MH injection rate	15	kg/hr	Target MH addition rate for 100 tCO_2/y CDR
	58	kg/hr	Target MH addition rate for 1 tCO_2/d CDR
	100	kg/hr	Maximum design operating rate
MH particle size	3	μm	D50
	5	μm	D90
Effluent discharge	285	L/s	Average daily rate = 1.25 x Dry Weather Flow (DWF) of 228 L/s
	675	L/s	Full flow to treatment (FFT)
	120	L/s	Minimum night time flow
Design life	10	years	

Table 7.1 Summary of the main design basis parameters

The MH addition pilot plant consists of a 15,000 litre double skinned storage tank, together with dosing pump, instrumentation and control systems. The preliminary process flow, and piping and instrumentation diagrams are shown in Annexes 8 and 9. The system will add MH slurry directly to the final effluent from the STW, immediately upstream of the discharge pumping station, as shown in the general site layout (Annex 10).

7.2   Project operations philosophy

The plant operating philosophy is based on the requirements specified by South West Water's Technical Standard SWW TS 421 on pH Correction / Alkalinity Dosing Systems (South West Water 2020), to ensure that the routine operating and maintenance requirements of the pilot plant will follow the relevant requirements for industry standard pH control plants (e.g. lime slurry dosing plants), and will therefore be within the operating and maintenance capability of existing SWW staff at the pilot site.

The high level functional requirements to achieve this intent are as follows:

- Slurry to be used to avoid manual handling of bulk materials
- Storage tank sizing based on a minimum of ten days storage for MH addition at the GGR target rate of 100 tCO_2/yr
- Local control panel and automation (including automatic line flushing) to simplify slurry offloading operations, the control panel display to include storage tanks level indication,

dosing control signal, tank low and high level alarms, pump running / failed, and dosing system failed alarm
- The local control panel will be equipped with a human-machine interface (HMI) to allow operator adjustment of relevant settings. Adjustments to dosing profiles will be made via the local HMI panel or via remote telemetry.

7.3   Magnesium hydroxide supply

MH slurry will be mixed offsite and supplied to the dosing unit in bulk road tankers. Table 7.2 summarises the main characteristics of three commercially available MH products that could be utilised for slurry preparation.

Supplier	Product	D50 μm	D90 μm	MH %	CI	Price GBP/t	Notes
Martin Marietta	MagChem MH10	4	12	>98	TBC	~830	FCA Rotterdam (€ 975/t)
HEQI Brucite Mining	D50 3 Brucite	3		>90	Low	~980	Natural brucite powder; CIF Felixstowe (US$ 1349/t); FOB Dalian (US$ 699/t).
Chemisphere	ManMag H6	6	30	>99	Mid	1200	Delivered to site

Table 7.2 Main characteristics of commercially available MH products

For the synthetic MH products, trace metal content is an essential selection criterion, since these products typically contain a number of trace elements with tightly specified EQS limits. For the MH10 product, the most constraining of these are mercury, chromium and nickel, and the dosing limits resulting from the EQS maximum allowable quantities (EQS-MAC) are summarised in Table 7.3.

Trace element	MH10 assay (ppm)*	EQS-MAC (µg/L)	Max. trace element at given flow rate (µg/s)		Max. MH10 dose at given flow rate (kg/hr)	
			120 L/s	285 L/s	120 L/s	285 L/s
Mercury (Hg)	0.565	0.07	8.4	19.95	54	127
Chromium (Cr)	2.545	0.6	72	171	102	242
Nickel (Ni)	9.67	34.0	4080	9690	1519	3607

Table 7.3 MH10 dosing limits resulting from EQS-MAC for trace metals (Note: * maximum measured value during Q3/Q4 2020 assays)

Based on these assay results, EQS-MAC limits would not constrain the pilot plant operation when STW effluent is being discharged at the average daily rate, with an upper limit of ~50 kg/hr MH addition under minimum night-time flow conditions. These limits will be reconfirmed based on trace metal assay results for the final MH supply source.

8   Monitoring, reporting and verification strategy

The UK Net Zero Research and Innovation Framework (HM Government 2021) recognises the development of technology-specific MRV to enable robust carbon accounting and assignment of credits to support carbon markets as a key research and innovation challenge to be addressed by 2030, and as a prerequisite to commercial roll-out of GGR technologies. The framework specifically identifies the need to better understand;

• How much CO_2 has been removed from the atmosphere?
• When that removal has taken place?
• At what rate that removal will persist, and for how long?
• In what type of sink it has been stored?
• The characterisation and durability of that store.
• The point at which a given store reaches maximum stability / saturation.

In the case of OAE, the last four points are well understood (see Chapter 1), and the MRV challenge is in quantifying CO_2 drawdown from the atmosphere and locating this air-sea gas exchange in time and space.

MRV for OAE is a developing field. While there is strong science confirming the expected effect of the addition of reactive alkalinity to seawater, scale factors such as rapid dilution and a long air-sea gas exchange timescale will make direct measurement challenging. MRV protocols are likely to rely heavily on 3D ocean modelling tools, calibrated using site-specific survey and sampling programmes.

8.1   GEN1 pilot: MRV plan

The general monitoring and verification plan will be to measure seawater chemistry (pH, DIC and A_T) downstream from the point of alkalinity addition with the aim of assessing;

1) the elevation of seawater pH above background due to the addition of alkalinity
2) the elevation of DIC relative to background caused by either i) the retention of the excess biogenic CO_2 contained in the wastewater discharge that would have otherwise degassed to air or ii) the in-gassing of CO_2 from the atmosphere, and
3) the fate of the newly added or retained DIC.

The carbonate chemistry of coastal waters is very dynamic, with significant spatial and temporal variability due to seasonal cycling, varying fluvial export and nutrient delivery, microbial activity, and, in some regions, upwelling events (Kerr and others 2021). Detection of the pH and DIC impact of added alkalinity against this varying background will require an extended period of baseline monitoring prior to alkalinity addition.

The Phase 2 MRV plan will involve both onshore and offshore measurement and sampling. The offshore programme will involve monthly monitoring at two sites off Godrevy Point, directly at the STW outfall (S1) and an offset control station (S2). At these stations conductivity and temperature vs. depth profiles will be measured, and discrete water samples collected at multiple depths for nutrient and carbonate chemistry analysis (pH, DIC and A_T). Offshore

profiling and sampling will be supplemented by 3D surveys using autonomous underwater vehicles (AUVs or "gliders") between S1 and S2 in order to characterise the temperature, salinity and pH gradient away from the outfall.

Onshore monitoring will take place at the Hayle STW to measure the properties of the effluent upstream of the discharge point and to demonstrate drawdown of CO_2 from the effluent which would otherwise be expected to de-gas to the atmosphere after discharge at sea. Sensors in the sump where the effluent and MH will be mixed prior to discharge will provide continuous measurement of CO_2, pH, temperature and conductivity. Sensors will be calibrated prior to deployment and additionally by discrete water samples (collected monthly, and analysed in the laboratory, alongside sensor maintenance, data-download and battery changes).

A detailed 3D ocean model of the discharge area will be constructed, building on the experience gained in the Phase 1 far field modelling study. The model will couple FVCOM (Finite Volume Coastal Ocean Model) hydrodynamics (Qui and others, 2009) with ERSEM (European Regional Seas Ecosystem Model) biogeochemistry (Butenschoen and others, 2016). These widely used oceanographic research community tools will provide the opportunity to model a broad range of ecosystem aspects, should this be necessary.

A similar program, including offshore sampling, AUV and surface vehicle surveys, and modelling, is planned in conjunction with Planetary Hydrogen's Canadian pilot project in Nova Scotia, and will be undertaken by Dalhousie University. This pilot will involve a more constrained marine setting (Halifax harbour/Bedford Basin) and results from the two programs will be complementary in building the knowledge required to develop MRV protocols for OAE.

9   Project cost estimate

9.1   *Capital and operating cost estimate*

The total estimated cost of the proposed Phase 2 pilot project (FEL3, ±25%) is £1,824,200 (£2,146,300 incl. VAT), as itemised in Table 9.1. The full cost model is included in Annex 11, showing cost phasing through the 2022 to 2025 period.

Cost element	Total cost (£)	Comment
MRV programme	806,000	Plymouth Marine Laboratory
MH addition tests	42,900	2022-2023
UK mineral study	80,000	Ultramafic resource commercialization
Pilot plant EPC	117,000	2023-2025, incl. decommissioning
Pilot plant operation	295,800	2024-2025
Manpower	482,500	incl. UK NI, overhead, travel & subsistence.
VAT	322,200	excl. non-UK payments
Total	**2,146,300**	

Table 9.1 Summary of the cost elements for the Phase 2 pilot project

In addition to the activities described above, provision has been included to conduct a study into the commercialization of ultramafic (magnesium rich) mineral resources in the UK, as discussed in Part IV below.

9.2   Cost savings compared with exclusive development contracts

As discussed above, development work on the electrochemical and metallurgical sub-processes continued alongside the studies completed under the BEIS Phase 1 contract. This work will be essential for the eventual commercial scale deployment of the SeaOH2 process, and will continue in parallel with the Phase 2 pilot project.

If the development work were to be executed under an exclusive contract, the contracting party would incur the full additional cost of this parallel work, estimated to be in the order of £5,800,000 (ca. CA$ 10,000,000) during the Phase 2 contract period from Q2 2022 to Q1 2025. The expected cost of the proposed Phase 2 work programme therefore represents a substantial saving compared to the cost that would be incurred under an exclusive arrangement.

10   Project schedule

A preliminary schedule for the pilot project is shown in Figure 10.1 and Annex 12.

Figure 10.1 Preliminary Gantt chart for the Phase 1 project
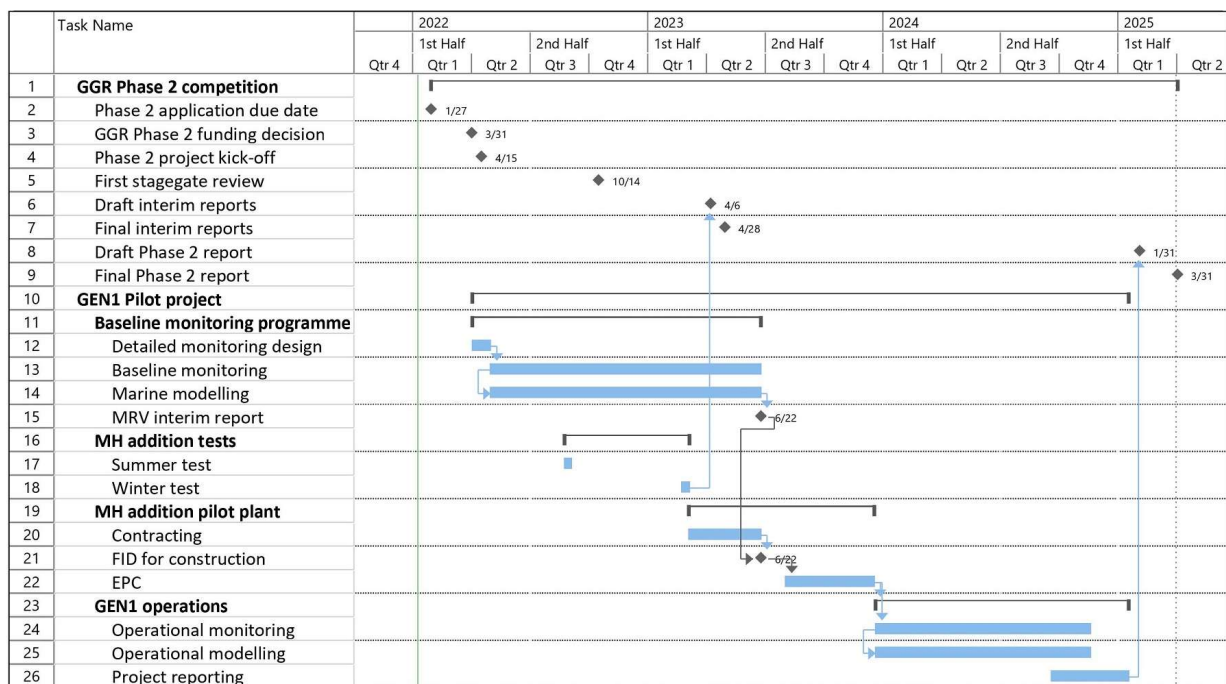
11   Risk and opportunity management plan

Risk management is the systematic identification, analysis, and control of events or hazards that have the potential to adversely affect the achievement of project objectives, while opportunity management is a similar systematic approach to realising the potential benefits from opportunities that improve project outcomes.

The main risk and opportunity management activities and outputs for the pilot project are summarised in Table 11.1.

Risk and opportunity management activity	Output/Deliverable
1) Risk and opportunity identification	Risk and opportunity lists
2) Assessment and classification of risks and opportunities in terms of likelihood and consequences	Risk and opportunity classification matrix
3) Define risk/opportunity ownership depending on classification level	Assignment of management responsibility for individual risks/opportunities
4) Determining the appropriate strategy for handling each risk (e.g. accept, transfer, avoid, mitigate.)	Risk strategy input to risk register
5) Develop, implement, and track mitigation steps to reduce each risk to an acceptable level.	Mitigation action plan, residual risk assessment
6) Develop, implement and track action plans to deliver the potential value from each opportunity.	Opportunity action plan, value delivery tracking

Table 11.1 Pilot project risk and opportunity management activities and outputs

Through this process, project risks will be systematically reduced to an acceptable residual level and value adding opportunities will be systematically pursued.

11.1 Risk register

A preliminary list of the principal risks that have been identified as having a potential impact during the execution and operating stages of the pilot project, and on subsequent deployment and scale-up is given in Table 11.2. A comprehensive risk register, including risk classification, mitigation actions, and residual risk classification will be developed at the start of Phase 2.

Risk category	Risk description
Technical	Unexpected impact on effluent or seawater chemistry High background seawater pH and DIC variability increases MRV uncertainty
Economic	Continued rapid growth in MH demand leads to increased OPEX
Commercial	Further site partnership opportunities do not materialize Magnesium rich mineral resources in the UK prove to be not commercially exploitable
Operational	Novelty of the process leads to additional permitting requirements
Social/Political	Policy support for carbon dioxide removals in the UK does not extend to ocean based methods

Table 11.2 Principal risks during the execution and operation of the pilot project

11.2 Opportunity register

Alongside these risks, a number of opportunities have been identified that will arise during Phase 2, the most significant of which are;

- Availability of a low-carbon MH source will increase CDR effectiveness
- Potential to duplicate the GEN1 pilot at other water treatments plants and other industrial waste water discharges

A comprehensive opportunity register, including opportunity classification and action plans to deliver the opportunity value will be developed at the start of Phase 2.

Part IV – Commercialization and business development plan

12   Commercialization and business development overview

12.1 Overview of commercialization plan

During 2021, the market for permanent voluntary carbon removals such as those that will be delivered by the SeaOH2 process has evolved rapidly. This growth in demand has allowed Planetary Hydrogen to evolve its product offering in order to rely more heavily on carbon dioxide removals as the core revenue model. This enables more flexibility in deployment and more rapid scale-up, leading to a revised 4-generation business development plan.

In the first generation (GEN1), which is the proposed GGR Phase 2 concept, PH plans to purchase MH in order to effect CDR through ocean alkalinity enhancement at the Hayle water treatment site. Existing MH sources typically have a high carbon footprint which will reduce the CDR effectiveness of the process. Accessing relatively low volumes of commercially available MH will also be expensive. It will, however, provide some CDR benefit and will prove out, at reasonable scale, the process of ocean capture and storage of atmospheric CO_2. Where contractual arrangements permit, further development work during this generation will be funded in part by voluntary carbon credit purchasers.

Beyond GEN1, PH's commercialisation plan focuses on licensing its negative emissions hydrogen technology to a variety of industries in the latter half of this decade, with nuclear power plants, wastewater treatment plants and NG fuelled power plants being specifically identified as potential hosts. Discussions with EDF and South West Water during Phase 1 have confirmed that deployment of PH's technology aligns with the innovation plans in these industries, providing support for the envisaged route to commercialisation.

There is also the potential for ongoing technology development to introduce additional pathways to commercialisation, and development work on the mineral leaching step has resulted in a commercial agreement with a nickel mining company that employs a similar mineral leaching process and where PH technology can add value to the process waste stream as well as reducing the overall carbon intensity of the mining operation.

13   GEN2 project outline

13.1 GEN2 project concept

MH is non-hazardous, so that carbon footprint and costs can be minimised by transporting hydroxide to distributed discharge sites from a large central production plant. In GEN2, in order

to reduce the environmental impact of mineral extraction, PH plans to locate a pilot electrochemical facility near an existing mine tailings pile. This facility will produce cheap, zero-carbon, high purity MH, replacing the first generation's purchased hydroxide. The facility will most likely vent hydrogen (unless there are on-site uses) but will produce revenue generating by-products such as nickel and cobalt.

The MH product will be distributed to a number of discharge sites where, due to its low carbon intensity, it will generate significant carbon credits, which will be sold to voluntary carbon purchasers to generate the primary revenue source.

13.2 Potential scale and location

The GEN2 pilot is expected to be sized for a CDR rate in the order of 1000 tCO$_2$/yr. As noted above, location of this plant adjacent to an existing mine tailings pile would be advantageous in terms of logistics and carbon footprint.

Suitable ultramafic mineral resources are not currently mined in the UK. Recent studies by the Energy Technologies Institute (ETI) have assessed the available data for a number of deposits that could potentially be exploited to produce chemical products as input to a variety of CDR technologies, including the current application. The total reactive rock resource was estimated to be 9.5 Gt, sufficient to capture 10% of UK emissions (2012 level) for a period of 100 years (ETI 2012). Development of these resources may be commercially viable when deployment reaches a 100 ktCO$_2$/yr scale (GEN3), by 2030. At the anticipated scale of the GEN2 pilot it is expected that MH will continue to be sourced from a 3rd party supplier.

Further investigation into the viability of exploiting these UK mineral resources has been included as part of the Phase 2 project scope.

13.3 Dependency on GEN1 and other ongoing work

The GEN1 pilot project aims to demonstrate the MRV activites that will be required to enable verification of CDR to the standard required by carbon removal credit purchasers in the voluntary carbon market. Parallel work on the metallurgical and electrochemical sub-processes will continue in parallel with the GEN1 pilot, but outside the scope that will be implemented in the Phase 2 project.

14 UK deployment potential – GEN3 and beyond

14.1 Scaling up deployment

In GEN3, plants at various mineral-rich locations will be scaled up, enabling large scale production of carbon-neutral MH, hydrogen and various by-product metals. Hydrogen will be used to reduce the carbon footprint of onsite operations using hydrogen powered vehicles. MH will be transported from the plant to various locations for ocean addition.

In GEN4, scale will be increased to the point where hydrogen produced exceeds onsite use. Hydrogen will be transported to appropriate offtakers in order to produce carbon-negative fuels. In addition the scale of MH production will exceed the scope of local discharge sites, and

novel ocean distribution methods will be required such as the use of ship's wakes for dilution and mixing, and the use of passive barges with ocean flow-through. The primary revenue model will be the sale of carbon-negative fuels on the low carbon fuels market under compliance carbon pricing schemes.

Experience to date during Phase 1 has reaffirmed the potential for rapid deployment and scale up of the SeaOH2 process, with megatonne scale CDR potential by the 2030s. A variety of partners have expressed interest in working with the process - including water treatment, nuclear generation and shipping companies, mine operators, renewable energy providers, and voluntary carbon purchasers.

14.2 Long term UK potential for ocean alkalinity enhancement

At SWW's Hayle treatment works, the average daily flow rate of 0.285 m^3/s would enable a CO_2 capture rate of 8 ktCO_2/yr while staying below the EA's 100 mg/L turbidity threshold (assuming 90% CDR effectiveness and an initial dilution factor of 10x.) Reported 2020 flow figures for the full SWW treatment network indicate a capture potential of some 95 ktCO_2/yr for this region alone. Across the UK, water treatment companies provide 15 Mm3/d of drinking water with a related discharge estimated to be 8.4 Mm3/d (based on SWWs reported performance of 56% disposal/supply). MH addition, based on similar assumptions, could deliver over 2 Mt/yr of CO_2 removal via these discharge volumes. This figure excludes the additional potential for alkalinization to prevent the release of CO_2 from such discharges.

As noted in section 1.2, MH addition to low pH, high DIC industrial discharges can also effect CDR by preventing CO_2 out-gassing from these discharges on reaching the sea. A recent assessment for the USA suggested potential removal of 88 Mt/yr of DIC from municipal water treatment discharges, avoiding the emission of around 320 MtCO_2/yr (Arabi and others, 2021). A similar opportunity exists in the UK, with a potential that could be in the tens of MtCO_2/yr range, although this remains to be quantified.

Nuclear cooling water discharge rates are typically several hundred times greater than the Hayle average discharge rate, (e.g. Sizewell C planned at > 100 m^3/s), so that a capture rate of several MtCO_2/yr seems achievable via alkalinity addition to the discharge from such a plant.

Ocean alkalinity enhancement using PH's SeaOH2 process, as well as other methods under development, can therefore make a very significant contribution to carbon dioxide removal in the UK.

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16 Annexes to the Report

Annex 1: High level block diagram of end-to-end SeaOH2 process

Annex 2: Details of air-sea gas exchange, dissolution and settling of magnesium hydroxide particles

Annex 3: LCA of the SeaOH2 hydrogen production processes

    3.1 Table of sources, sinks and reservoirs

    3.2 Consequence tree

    3.3 Summary of avoided emissions

Annex 4: Potential locations identified in the site investigation study

Annex 5: Conceptual layout of a dedicated intake and outfall system

Annex 6: Far field discharge modelling study summary

Annex 7: Constraints map for Hayle water treatment works and outfall location

Annex 8: Preliminary process flow diagram of the Phase 2 pilot plant

Annex 9: Preliminary piping and instrumentation diagram of the Phase 2 pilot plant
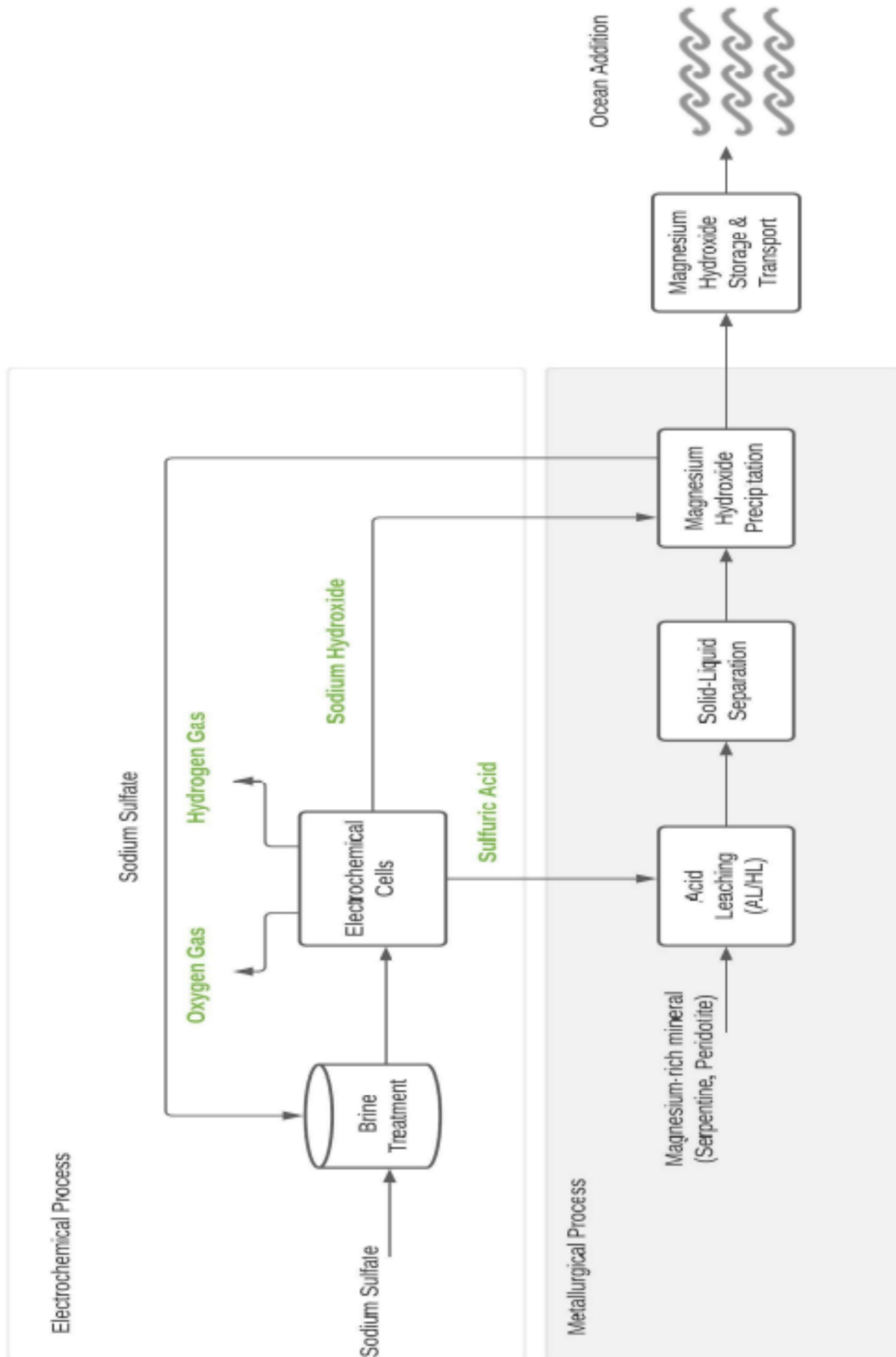
Annex 10: Hayle STW general site layout and Phase 2 pilot plant location

Annex 11: Phase 2 cost model

Annex 12: Preliminary Phase 2 pilot project schedule (Gantt chart)

Annex 13: Acronyms and glossary

Annex 1: High level process block diagram of end-to-end SeaOH2 process

Annex 2: Details of air-sea gas exchange, dissolution and settling of magnesium hydroxide particles

Air-sea gas exchange

Air-sea CO_2 flux is determined by the partial pressure difference, according to;

Flux = CO_2 solubility (pCO_{2AIR} - pCO_{2SEA}) k_v

where k_v is the wind-speed dependent gas exchange velocity and pCO_{2AIR} is currently ~414 µatms. Details of the process can be found in Jacobs, Kohsiek, and Oost (1999). The simplified expression given for CO_2 flux (F) determined by Wanninkhof (2014) has been used in the Phase 1 modelling study;

$$F = 7.7 \times 10^{-4} <U_{10}^2> \Delta pCO_2$$

where F has units of $mol/m^2/yr$, $<U_{10}^2>$ is the mean value of the square of the wind speed at 10 m height $(m/s)^2$, and ΔpCO_2, the CO_2 partial pressure difference, is in µatm.

Dissolution and settling of magnesium hydroxide particles

The dissolution rate of $Mg(OH)_2$ at 25°C as a function of pH has been investigated by Pokrovsky and Schott (2004) and the experimental rates are given by the polynomial fit;

$$Log_{10} (R) = -7.6435 + 0.7046(pH) - 0.2495(pH)^2 + 0.0309(pH)^3 - 0.0014(pH)^4$$

where R has units $mols/m^2/s$, and m^2 refers to the total $Mg(OH)_2$ particle surface area. In ambient seawater at pH ~ 8, $Log_{10}(R)$ = -7.8.

The terminal velocity (v) of a spherical particle sinking in a fluid is given by the Stokes equation;

$$v = 2\Delta\rho g r^2/9\mu$$

where $\Delta\rho$ is the density difference between the particle and the fluid (kg/m^3), g is the acceleration due to gravity (m/s^2), r is the particle radius (m), and μ is the kinematic viscosity of the fluid $(N.s/m^2)$. Since both the dissolution rate and sinking velocity are proportional to r^2 it is straightforward to determine the distance over which a particle of a given size will sink before fully dissolving, as shown in Table A9.1.

Settling depth to dissolution z_0 (m)	1	5	10	25
Critical particle mass M_0 (kg)	4.22×10^{-14}	2.11×10^{-13}	4.22×10^{-13}	1.05×10^{-12}
Critical particle diameter D_0 (µm)	3.25	5.56	7.00	9.50

Table A9.1 Particle masses and diameters versus sinking depth to dissolution.

Since MH has a laminar crystal structure, particles will tend to be plate like rather than spherical and sinking velocity will tend to be overestimated by Eq. 9. However the terminal velocity correction factor is likely to be <2 (Bagheri and Bonadonna 2016, Figure 10) so that D_0 would increase by at most ~25%.

Mineral leaching/dissolution

In the leaching/dissolution step, the mineral feedstock is irrigated with 7-10% sulfuric acid (H_2SO_4) resulting in the following reactions:

$$Mg_3Si_2O_5(OH)_4 + 3H_2SO_4 \rightarrow 3MgSO_4 + 2SiO_2 + 5H_2O$$

$$MiO + H_2SO_4 \rightarrow MSO_4 + H_2O$$
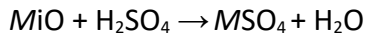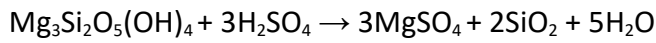
where M is a divalent metal such as Ni, Co, Fe(II) or Ca, and

$$\mathbb{M}_2O_3 + 3H_2SO_4 \rightarrow \mathbb{M}_2(SO_4)_3 + 3H_2O$$

where $\mathbb{M}$ is a trivalent metal such as Fe(III) or Al. Magnesium recovery is here represented by chrysotile dissolution, although other magnesium rich minerals such as olivine or serpentine can also be used.

Metal hydroxide precipitation

The product stream from the leaching/dissolution step, known as the pregnant leach solution (PLS), then flows through a multi-stage pH-controlled oxidative precipitation process. Firstly, pH is raised to 4 by the addition of slaked lime ($Ca(OH)_2$) resulting in the precipitation of Fe(III) and Al;

$$Fe_2(SO_4)_3 + 3Ca(OH)_2 + 6H_2O \rightarrow 2Fe(OH)_3 + 3CaSO_4.2H_2O_{(s)}$$

$$Al_2(SO_4)_3 + 6H_2O + 3Ca(OH)_2 \rightarrow 3CaSO_4.2H_2O_{(s)} + 2Al(OH)_3$$
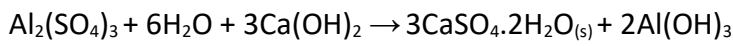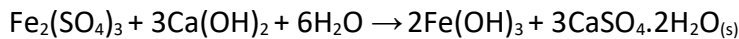
Oxygen may be added at this stage if required, for example from the PH electrochemical process, to re-oxidize any Fe(II) in the PLS to insoluble Fe(III);
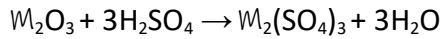
$$4FeSO_4 + O_2 + 10H_2O + 4Ca(OH)_2 \rightarrow 4Fe(OH)_3 + 4CaSO_4.2H_2O_{(s)}$$

$$Fe(OH)_3 \rightarrow FeOOH + H_2O$$
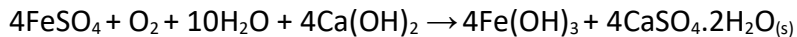
Further lime addition raises the pH to 7, initiating the precipitation of Ni and Co as a Ni-Co mixed hydroxide product (MHP);

$$MSO_4 + 2H_2O + Ca(OH)_2 \rightarrow CaSO_4.2H_2O_{(s)} + M(OH)_2$$
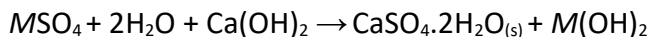
where M = Ni or Co. Finally the pH is raised to 10 by the addition of a 7-10% NaOH solution from the PH electrochemical cell, resulting in near complete magnesium precipitation;

$$MgSO_4 + 2NaOH \rightarrow Na_2SO_4 + Mg(OH)_2$$
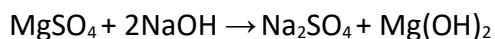
It is envisaged that the goethite (FeOOH) and any unreacted $Ca(OH)_2$ from the iron precipitation circuit will be used for land-based carbon capture, while the Ni/Co MHP will be sold to offtake metal refiners.

Annex 3.1: Table of sources, sinks and reservoirs

SSR TABLE				
SSR	DESCRIPTION	Included / Excluded	Controlled / Related / Affected	JUSTIFICATION OF EXCLUSION
SOLUTION				
Electricity consumption: indirect emissions	Indirect emissions from electricity generation.	Included	Related	-
Electrolyser and storage tank manufacturing: indirect emissions	Emissions from raw materials production, energy requirements for manufacture and assembly of parts, the system's transport from manufacturing site to operation site.	Included	Related	-
Hyrogen transportation: direct and indirect emissions	Emissions from diesel combustion, dibenzyltoluene consumption, hydrogenation and dehydrogenation.	Included	Related	·
Hydrogen usage: direct emissions	Emissions from the use stage of hydrogen.	Excluded	Related	Equivalent to the baseline scenario and negligible.
Sulfuric acid usage and end of life	Emissions from sulfuric acid usage and end of life.	Excluded	Related	Emissions from sulfuric acid usage and end of life are considered to be negligible compared to emissions from sulfuric acid production, which are avoided by the solution.
Carbon capture and storage	Atmospheric CO2 captured and stored by hydroxide.	Included	Related	-
Sodium sulphate transporation: direct and indirect emissions	Emissions from diesel combustion and upstream processes.	Included	Related	-
BASELINE SCENARIO				
Hydrogen production: direct and indirect emissions	Emissions from construction and decommissioning of the hydrogen plant, natural gas production and transportation, electricity generation, H2 plant operations, and fugitive and avoided emissions.	Included	Related	-
Hydrogen usage: direct emissions	Emissions from the use stage of hydrogen.	Excluded	Related	Equivalent to the solution and negligible.

Annex 3.2: Consequence tree
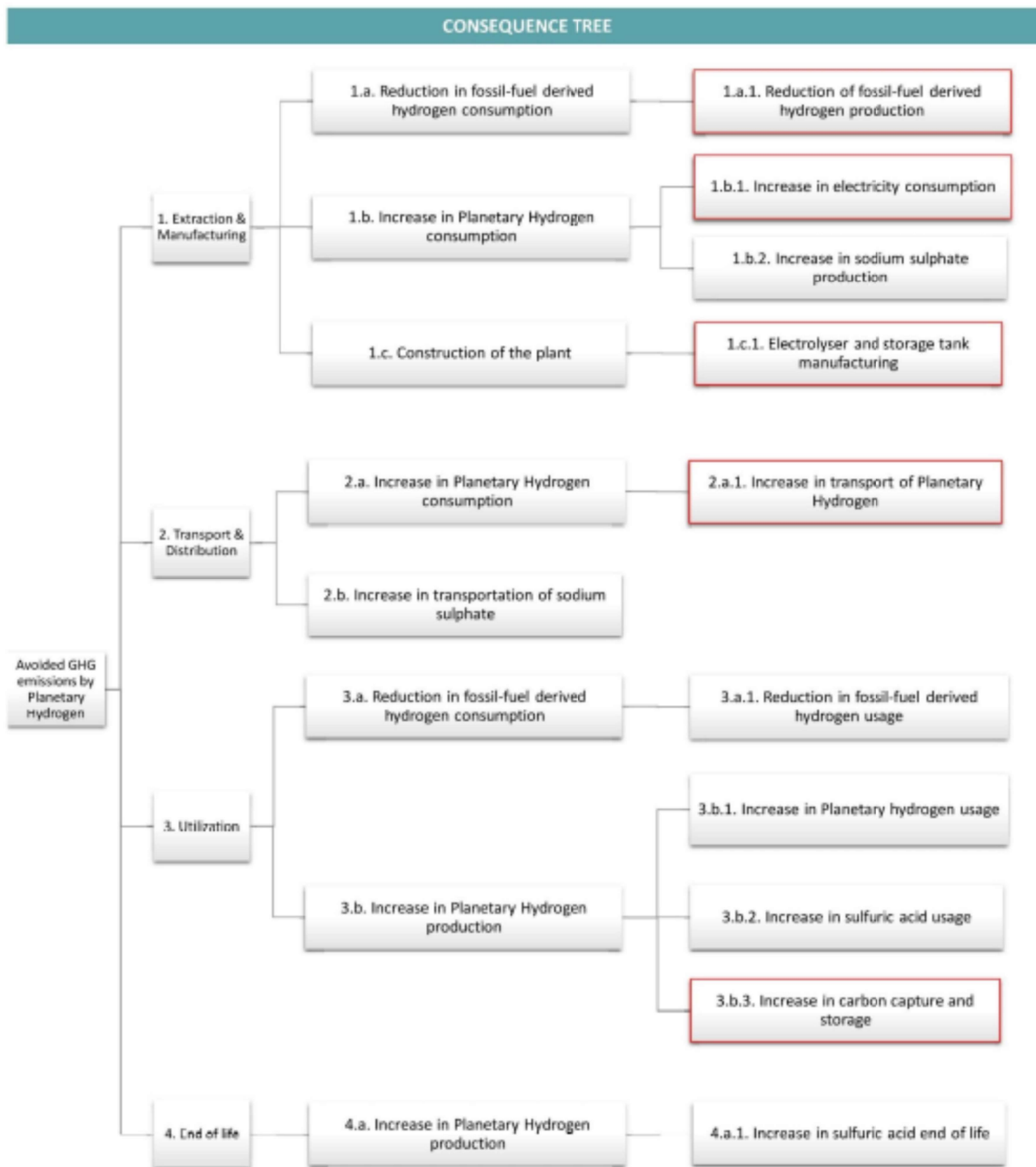
Annex 3.3: Summary of avoided emissions

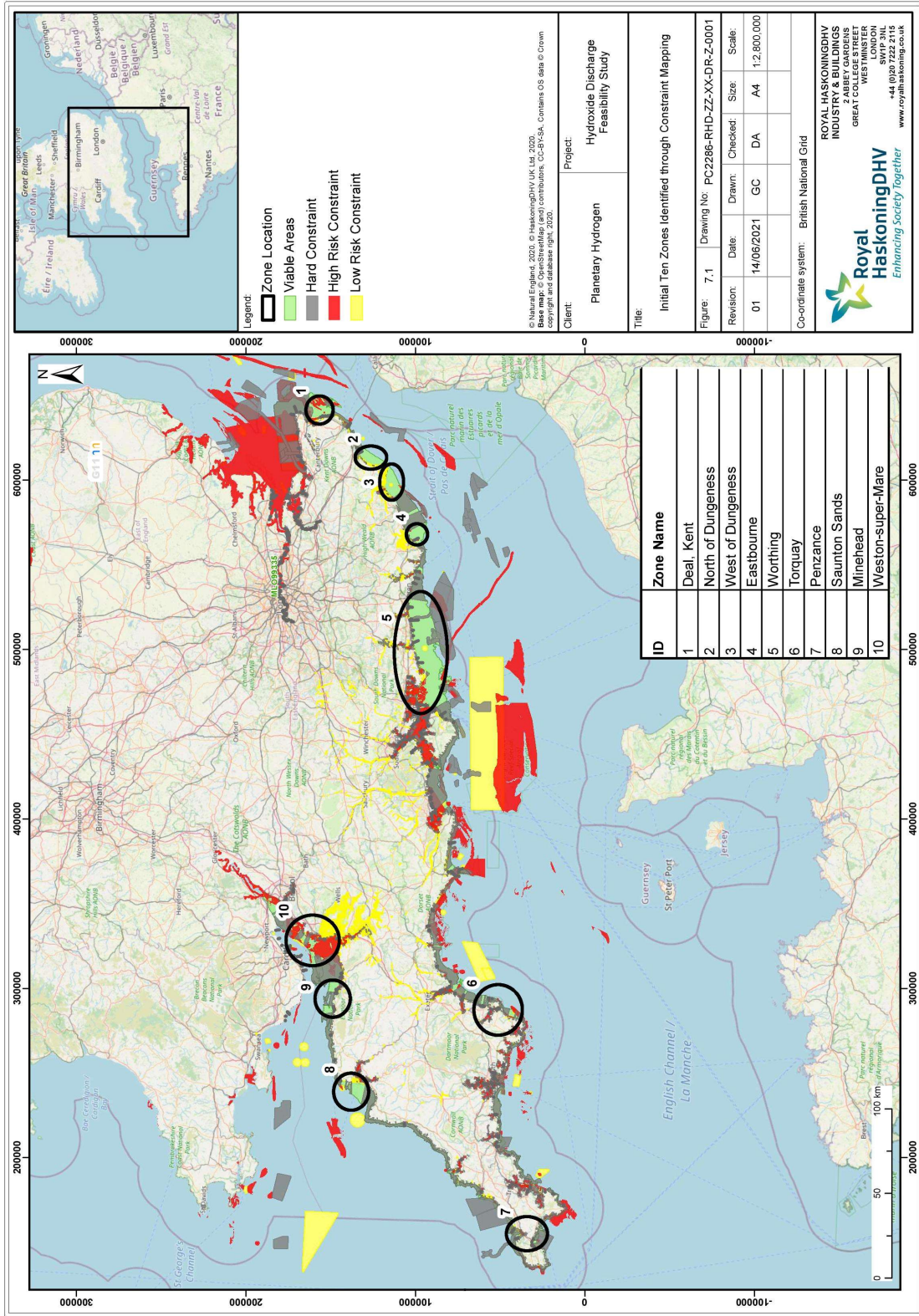| SSR TABLE				
SSR	**DESCRIPTION**	**Included / Excluded**	**Controlled / Related / Affected**	**JUSTIFICATION OF EXCLUSION**
SOLUTION				
Electricity consumption: indirect emissions	Indirect emissions from electricity generation.	Included	Related	-
Electrolyser and storage tank manufacturing: indirect emissions	Emissions from raw materials production, energy requirements for manufacture and assembly of parts, the system's transport from manufacturing site to operation site.	Included	Related	-
Hyrogen transportation: direct and indirect emissions	Emissions from diesel combustion, dibenzyltoluene consumption, hydrogenation and dehydrogenation.	Included	Related	-
Hydrogen usage: direct emissions	Emissions from the use stage of hydrogen.	Excluded	Related	Equivalent to the baseline scenario and negligible.
Sulfuric acid usage and end of life	Emissions from sulfuric acid usage and end of life.	Excluded	Related	Emissions from sulfuric acid usage and end of life are considered to be negligible compared to emissions from sulfuric acid production, which are avoided by the solution.
Carbon capture and storage	Atmospheric CO_2 captured and stored by hydroxide.	Included	Related	-
Sodium sulphate transporation: direct and indirect emissions	Emissions from diesel combustion and upstream processes.	Included	Related	-
BASELINE SCENARIO				
Hydrogen production: direct and indirect emissions	Emissions from construction and decommissioning of the hydrogen plant, natural gas production and transportation, electricity generation, H2 plant operations, and fugitive and avoided emissions.	Included	Related	-
Hydrogen usage: direct emissions	Emissions from the use stage of hydrogen.	Excluded	Related	Equivalent to the solution and negligible.

Annex 4: Potential locations identified in the site investigation study

Legend:
- Zone Location
- Viable Areas
- Hard Constraint
- High Risk Constraint
- Low Risk Constraint

ID	Zone Name
1	Deal, Kent
2	North of Dungeness
3	West of Dungeness
4	Eastbourne
5	Worthing
6	Torquay
7	Penzance
8	Saunton Sands
9	Minehead
10	Weston-super-Mare

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Base map: © OpenStreetMap (and) contributors, CC-BY-SA. Contains OS data © Crown copyright and database right, 2020.

Client: Planetary Hydrogen

Project: Hydroxide Discharge Feasibility Study

Title: Initial Ten Zones Identified through Constraint Mapping

Figure: 7.1	Drawing No: PC2286-RHD-ZZ-XX-DR-Z-0001			Scale:
Revision: 01	Date: 14/06/2021	Drawn: GC	Checked: DA	Size: A4	1:2,800,000

Co-ordinate system: British National Grid

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Annex 5: Conceptual layout of a dedicated intake and outfall system

Annex 6: Far field discharge modelling study summary

A numerical modelling study has been completed to assess the marine impact of MH addition for two limiting cases:
- a fully dissolved case where the effluent discharge is fully saturated with $Mg(OH)_2$, representing the most immediate and highest possible impact on seawater pH; and
- a partially dissolved case where the discharge is also loaded with micron-scale MH particles, representing the maximum impact on seawater turbidity, with a pH perturbation moderated by gradual dissolution.

In both cases the reduction in the partial pressure of CO_2 dissolved in seawater is determined, followed by a calculation of the drawdown of CO_2 from the atmosphere via air-sea gas exchange, restoring the CO_2 partial pressure equilibrium, to determine the quantity of CO_2 removed and sequestered from the atmosphere.

The Delft3D software suite developed and maintained by Deltares is internationally recognised and has been widely applied for discharge permit applications both in the UK and overseas. This suite largely includes the necessary modules to address these modelling requirements, including a hydrodynamic module (D-FLOW) for simulating the ambient flow conditions and a water quality module (D-WAQ) for simulating the effect of the discharge on the marine environment. An additional calculation library has been developed as part of this study to incorporate MH particle dissolution and tracking, the impact of alkalinity addition on seawater carbonate chemistry, and the calculation of air-sea gas flux.

In addition, near-field dispersion modelling has been undertaken using the industry standard CORMIX software to simulate the initial dispersion of the discharge from the diffuser, in order to determine how the discharge should be represented in the Delft3D software, which models the mid- to far-field dispersion.

The hydrodynamic model domain extends from Lands End to the southwest (approximately 35 km from the discharge location), to Holywell Bay to the northeast (approximately 27 km from the discharge location) and around 30 km in an offshore direction (Figure A6.1). The model domain is defined by a single curvilinear grid with a variable horizontal resolution. The resolution varies from 60 m by 60 m at the outfall to 120 m x 180 m at the offshore boundaries. The hydrodynamic model was calibrated over a full spring-neap cycle against available tidal level and tidal stream velocity data, and was found to perform well using widely accepted metrics for marine model performance assessment.

The Atlantic-European North West Shelf Ocean Physics Analysis and Forecast model indicates that the study area is well mixed, with little vertical stratification (O'Dea and others 2012), and CORMIX analysis also demonstrated that the discharge will be full mixed within the water column during intertidal periods of high velocity. It was therefore considered appropriate to model the hydrodynamics in 2D, enabling a higher spatial and temporal resolution to be achieved, without resulting in prohibitively long simulation times or large output files.
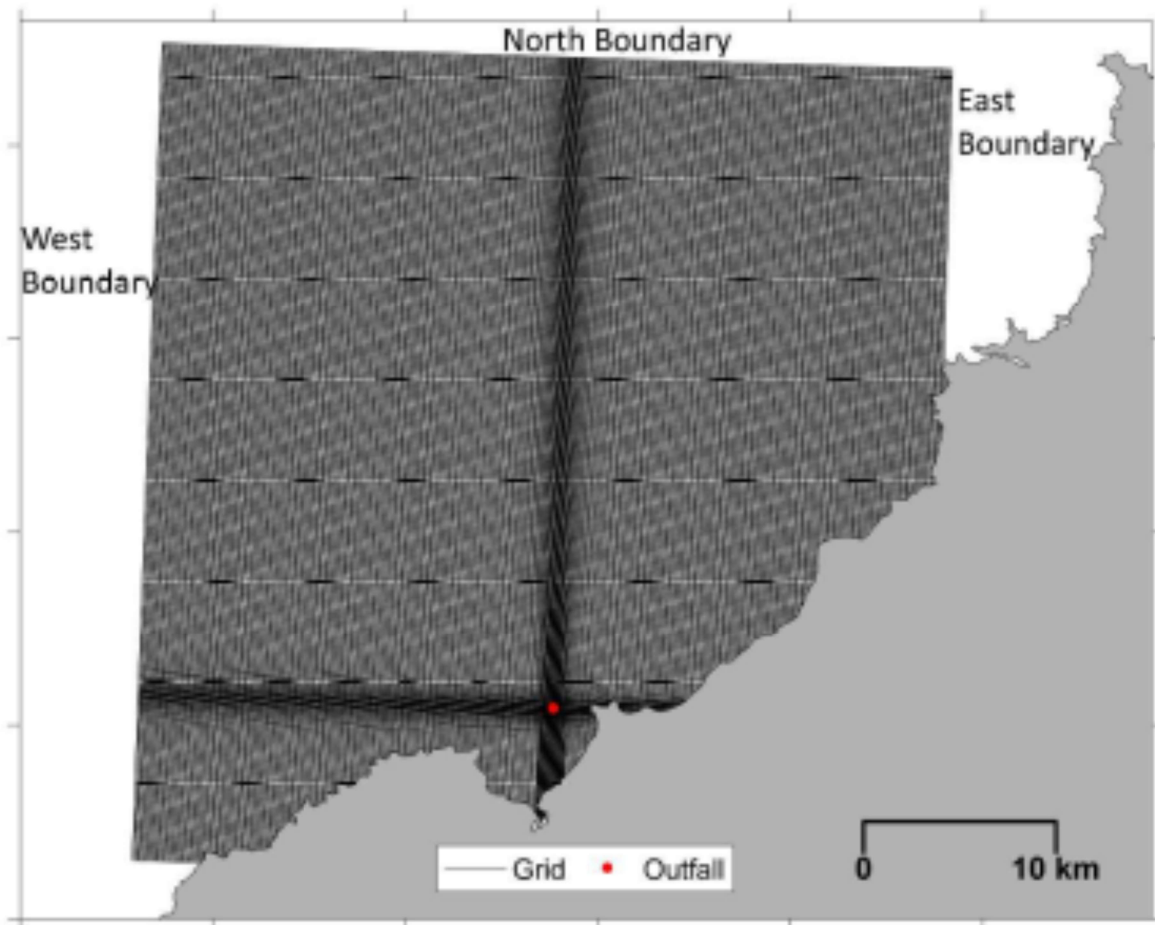
Figure A6.1 Hydrodynamic model extent and grid geometry

Model runs to assess the impact of MH addition were run under winter and summer conditions for seawater chemistry (T, DIC, A_T) and wind speed – a key determinant of the air-sea flux (see Annex 2). The effluent chemistry was confirmed by sampling and analysis at Plymouth Marine Laboratory. A background run without the effluent or MH addition confirmed that the model was correctly assessing ambient air-sea CO_2 exchange for the specified winter and summer initial conditions. Runs with the effluent discharge and with MH addition were made to assess the impact on CO_2 removal (see Port and Coastal Solutions 2022 for further details.)

For the MH addition assessment, runs were made for dissolved MH only and for partially dissolved cases in which both dissolved MH and particulate MH are added. In the fully dissolved case an MH addition rate of 158 kg/day saturates the daily average effluent discharge, while in the partially dissolved "low dosing" case, equivalent to 100 tCO₂/yr, 112 kg/day was added in particulate form, increasing to 842 kg/day for a "high dosing" case equivalent to 1 tCO₂/day.

	Flux (tonnes per 6 months)		Change in Flux Relative to Existing			
			Winter		Summer	
	Winter	Summer	Tonnes/6 months	%	Tonnes/6 months	%
Existing Discharge	20,555	52,577	-	-	-	-
Fully Dissolved MH addition	20,576	52,587	21	0.10	10	0.02
Addition of Low Dose MH	20,588	52,592	33	0.16	15	0.03
Addition of High Dose MH	20,665	52,625	110	0.54	48	0.09

Table A6.1 Air-sea CO_2 flux for the modelled MH addition cases

Table A6.1 summarises the air-sea flux results. Background air to sea CO_2 flux over the model area of 20.6 and 52.6 $ktCO_2$ during 6 months at winter and summer conditions respectively, results from the initial seawater pCO_2 being below atmospheric and from a small incremental impact from the effluent chemistry.

Summing the winter and summer values, MH addition resulted in a 48 tCO_2 flux increase in the low dosing case (100 tCO_2/yr equivalent), and 158 tCO_2 in the high dosing case (1 t CO_2/d equivalent). These values do not reach the full 100 and 365 tCO_2 equivalent levels as a result of advective transport of dissolved and particulate MH outside the model domain (ca. 17% of added MH in the (high dose, winter case), and because MH added towards the end of the 180 day period has progressively less time to dissolve and contribute to CO_2 flux.

The study successfully delivered a numerical modelling tool that can be used to determine the CDR impact of alkalinity addition to seawater at the Hayle site, and confirmed compliance with permitted discharge levels for pH and turbidity for the planned Phase 2 pilot.

Annex 7: Constraints map for Hayle water treatment works and outfall location

Annex 8: Preliminary process flow diagram of the Phase 2 pilot plant

MH SLURRY 40% W/W
TO: FINAL EFFLUENT DISCHARGE

HE-001

P-001

AG-001

V-001
MH SLURRY STORAGE TANK

MH SLURRY 40% W/W
FROM: TANKER DISCHARGE

WATER PURGE
FROM: MAIN SUPPLY

PRELIMINARY
NOT FOR CONSTRUCTION

INTERMITTENT OR BATCH FLOW

NOTES : 1. TANKER DISCHARGE RATE OF 30 M³/HR ASUMED
2. PURGE WATER RATE SUFFICIENT TO PURGE HEADERS IN UNDER 1 MINUTE

	Description	1	2	3
	Stream Number	MH SLURRY LOADING FROM ROAD TANKER	MH SLURRY ADDITION TO FINAL EFFLUENT	
Flow	kg/h	5 (MIN)	5 (MIN)	5 (MIN)
Temperature	°C	100	100	100
Pressure	kPa (g)	18.000	150.0	NOTE 2
H₂O (aq)	kg/h	0.108	0.0009	
Mg(OH)₂ (aq)	kg/h	12.000	100.0	
Mg(OH)₂ (s)	kg/h			

MH SLURRY STORAGE TANK
V-001

MH SLURRY AGITATOR
AG-001

MH SLURRY TRANSFER PUMP
P-001

RECIRCULATION HEATER
HE-001

Rev	Revision Description	Date
A	ISSUED FOR INFORMATION	DEC 2021

DRAWING REVISION

PLANETARY HYDROGEN
100 tCO₂/YR GEN1 CDR PILOT PLANT
PROCESS FLOW DIAGRAM
MAGNESIUM HYDROXIDE STORAGE AND ADDITION

N.T.S.
Date DEC 2021 SR
Date DEC 2021 SR
Date DEC 2021 BX

PFD-001
PH-L0K001

REFERENCE DRAWINGS

Annex 9: Preliminary piping and instrumentation diagram of the Phase 2 pilot plant

Annex 10: Hayle STW general site layout and Phase 2 pilot plant location

Annex 11: Phase 2 project cost model

OPEX

OPEX	2022			2023				2024				2025	Total
	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	
MRV													
PML monitoring costs	49.9	74.8	74.8	74.8	74.8	24.9	0.0	53.6	53.6	53.6	53.6	0.0	**588.5**
PML modelling costs	24.2	36.3	36.3	36.3	12.1	0.0	0.0	18.1	18.1	18.1	18.1	0.0	**217.5**
VAT	14.8	22.2	22.2	22.2	17.4	5.0	0.0	14.3	14.3	14.3	14.3	0.0	**161.2**
Project operations													
MH slurry supply		9.0	0.0	9.0	0.0	0.0	0.0	68.4	68.4	68.4	68.4	0.0	**291.8**
Test plant rental		6.8	5.3	5.3	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**18.9**
Plant maintenance				3.0	0.0	0.0	0.0	2.5	2.5	2.5	2.5	0.0	**10.0**
Site services		3.0	0.0	3.0	0.0	0.0	0.0	3.0	3.0	3.0	3.0	0.0	**18.0**
VAT		3.8	1.1	3.5	0.3	0.0	0.0	14.8	14.8	14.8	14.8	0.0	**67.7**
UK mineral resources													
Commercialization study			20.0	30.0	30.0								**80.0**
VAT			4.0	6.0	6.0								**16.0**
Project staff													
Project Manager (UK)	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	**101.0**
Project Coordinator (UK)	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	**132.9**
Project Administrator (CA)	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	**66.0**
Scientific oversight (US)	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	**127.8**
Overhead	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	**42.8**
Travel and subsistence (UK)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	**12.0**
VAT	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	**53.9**
OPEX total	**133.6**	**200.6**	**208.3**	**234.7**	**186.9**	**74.6**	**44.7**	**219.5**	**219.5**	**219.5**	**219.5**	**44.7**	**2005.9**
												excl VAT	**1707.2**

CAPEX

CAPEX	2022			2023				2024				2025	Total
	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	
Plant design and construction						26.3	48.8						**75.0**
Installation							18.8						**18.8**
On site spare parts							4.5						**4.5**
Decommissioning												18.8	**18.8**
VAT						5.3	14.4					3.8	**23.4**
CAPEX total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**31.5**	**86.4**	**0.0**	**0.0**	**0.0**	**0.0**	**22.5**	**140.4**
												excl VAT	**117.0**

inc VAT	**2146.3**
excl VAT	**1824.2**

Annex 12: Preliminary Phase 2 pilot project schedule (Gantt chart)

Annex 13: Acronyms and glossary

AUV: Autonomous underwater vehicle.

CDR: Carbon dioxide removal, methods to mitigate climate change by the removal of CO_2 from the atmosphere.

CI: Carbon intensity, a measure of the carbon embodied in a product.

DIC: Dissolved inorganic carbon (DIC), the sum of the aqueous species of inorganic carbon in a solution.

EA: Environmental agency.

EPC: Engineering, procurement and construction.

EQS: Environmental quality standard.

FEED: Front-end engineering design.

GGR: Greenhouse gas removal, methods to mitigate climate change by the removal of CO_2, CH_4, and other greenhouse gases from the atmosphere.

LCA: Life cycle analysis.

MAC: Maximum allowable concentration.

MH: Magnesium Hydroxide (MH), the inorganic compound with chemical formula $Mg(OH)_2$.

MRV: Measurement, reporting, and verification, the process by which greenhouse gas removals are monitored and quantified as the basis for the issue of carbon removal credits.

OAE: Ocean alkalinity enhancement, carbon dioxide removal by the addition of alkalinity to the ocean.

PML: Plymouth Marine Laboratory.

STW: Sewage treatment works.

SWW: South West Water, regional water company supplying Devon and Cornwall and areas of Dorset and Somerset.

TSS: Total suspended solids.

Alkalinity: The capacity of a solution to neutralize acids. In seawater the main contributors to total alkalinity are bicarbonate, carbonate, borate and hydroxyl anions.

Bicarbonate: in seawater refers to the bicarbonate ion (HCO_3^-).

Biocalcification: biological processes, such as shell formation, that cause the precipitation of calcium carbonate from seawater.

Brucite: a naturally occurring mineral form of magnesium hydroxide, in the form of tabular, foliated crystals.

Carbonate: in seawater refers to the carbonate ion (CO_3^{2-}).

Effluent: liquid waste discharged into a river or the sea.

Electrochemical process: a process in which chemical changes are induced in a solution by application of an electric field, with electrons being transferred between reactants via an external circuit.

Hydroxide: a diatomic anion with chemical formula OH^-, consisting of oxygen and hydrogen atoms held together by a single covalent bond, and carrying a negative electric charge.

Metallurgy: the study of the physical and chemical behavior of metals, and the engineering of metal products.

Mineral leaching/ dissolution: a chemical process in mining for extracting minerals from ore.

Mineral weathering: the natural process by which alkalinity is extracted from surface rocks by carbonic acid in rainwater and stored as DIC in the ocean.

Ocean acidification: the decline in ocean pH resulting from the uptake of anthropogenic carbon dioxide from the atmosphere.

Outfall: the place where a river, drain, or sewer empties into the sea, a river, or a lake.

SeaOH2: the patented Planetary Hydrogen Ocean Air Capture (OAC) technology using renewable electricity to produce hydrogen via electrolysis.

Turbidity: the cloudiness of a fluid caused by large numbers of individual particles that are generally invisible to the naked eye, analogous to the presence of smoke in air.