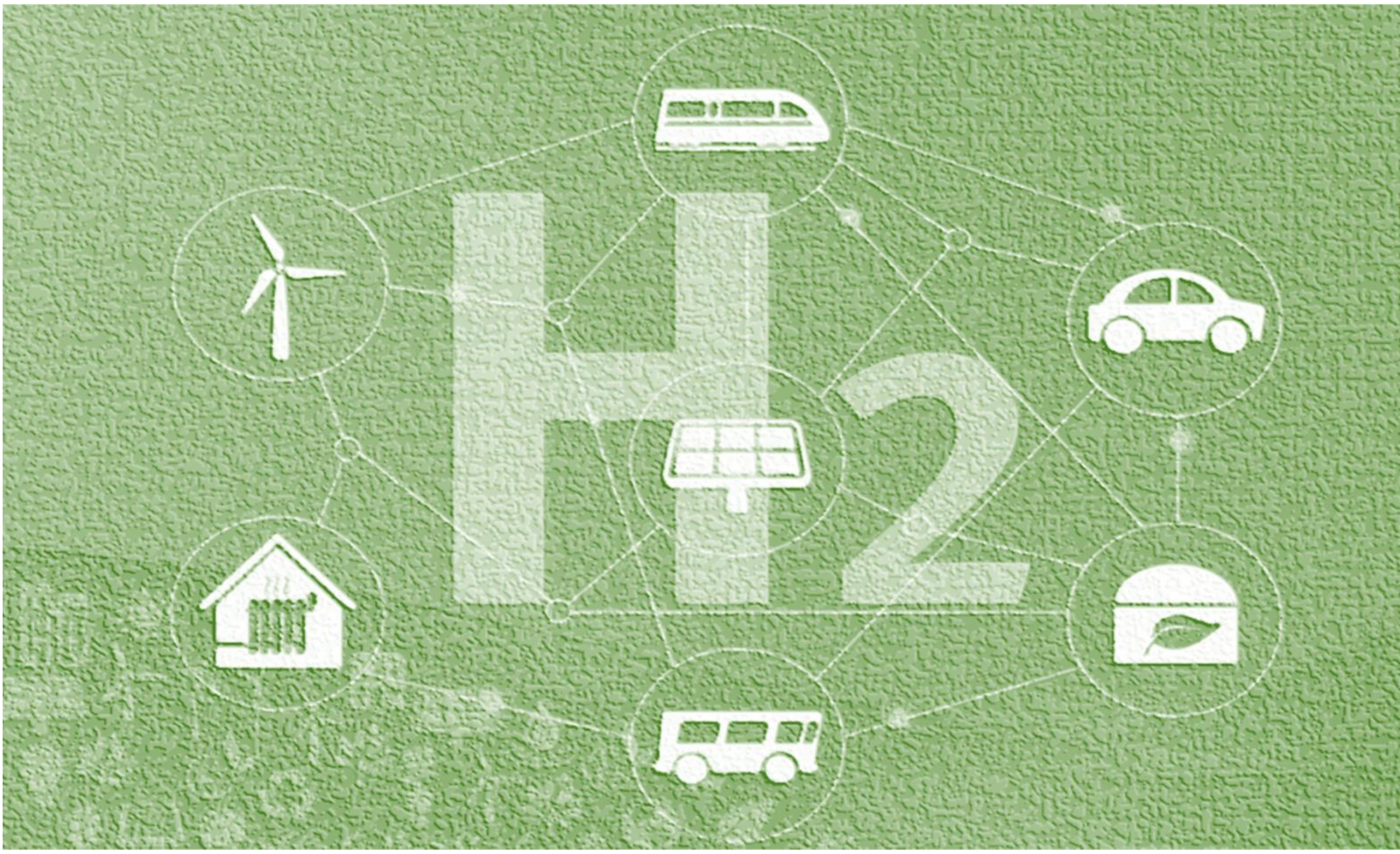

LOW CARBON HYDROGEN SUPPLY 2: STREAM 1 PHASE X

Tender Reference Number: TRN 5044/04/2021

100MW Green Hydrogen Hub
Feasibility Report

10th July 2022 Rev. No. 01

Report for

Department for Business, Energy & Industrial Strategy

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Document revisions

No.	Details	Date
01	Draft	22/06/2022
1A	Final	01/07/2022

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Executive Summary

This report provides a summary of the feasibility study undertaken and the results attained regarding the viability of a 100MW Green Hydrogen Hub, powered by low carbon renewable electricity and producing hydrogen through the process of electrolysis on the Marsh Barton industrial estate in Exeter.

The 100MW Green Hydrogen hub project aims to deliver a large-scale installation for the production of Green Hydrogen at low cost to be used in the South West region. The primary uses of grid injection and transport are aimed at improving the emissions experienced within the cities within the region, with Exeter city being the key focus of initial studies. The project also aims to demonstrate how the use of universal digital twins can help to identify areas of high energy usage within a region, track progress in decarbonisation and provide a user interface for people to fully understand the energy demands of a specific area. Emerald Green Power Ltd have worked in collaboration with the University of Exeter and City Science Corporation to complete the feasibility study, a precursor for the Phase 2 demonstration project.

The feasibility study used Emerald Green Power's OptoGem™, a techno-economic modelling software verified by the National Physical Laboratory, to assess the financial and technical viability of a 100MW Green Hydrogen hub powered by solar power. The study also developed initial demand mapping software used in the universal digital twins. Frameworks were identified for the optimisation algorithms, which will eventually dictate the most efficient downstream uses based on technical constraints and market conditions. Following initial large scale 100MW models, a 10MW electrolyser system paired with a 10MW solar array was used within the final feasibility study, capable of delivering 166.67kg of hydrogen per hour at peak capacity.

Following talks with Western Power Distribution, it was found that placing a 100MW hydrogen hub in a single location was not technically feasible due to the grid constraints of delivering such a quantity of electricity to a single point. As such the wider 100MW hub would now consist of multiple 5MW to 10MW feeder sites at various locations, primarily on sites where off grid renewables could be utilised. Due to this discovery the feasibility study focus switched to building multiple 5MW to 10MW sites creating a network of distributed and potentially decentralised hubs with an accumulated power of 100MW. By virtue of adopting a decentralised networked approach, growth can be managed more efficiently, and scalability is not as dependant on land or power availability.

It was found that a 10MW electrolyser directly coupled to a 10MW solar array would produce 197,350 kg of hydrogen annually, representing an electrolyser capacity factor of 13.5%. Over a project lifespan of 25 years, the cost of hydrogen assuming an electricity price of £50/MWh was found to be £5.55/kg to £6.67/kg, which accounted for differences in CAPEX costs which may be experienced.

To create the demand mapping digital twin, Blender software in conjunction with Google Earth 9 and Python scripting was used. This methodology was applied to the Matford Centre on Marsh Barton industrial estate to demonstrate the user interface for the viewing of the energy usage and overall carbon footprint of a building.

In order to solidify research findings and transition to the Phase 2 demonstration project, Emerald Green Power have formed partnerships with the National Farmers Union, Ixora Energy, Yeo Valley Farms, Muller, and Burt's Crisps, all of whom are eager to decarbonise their operations through onsite production of Green Hydrogen.

1. Introduction

EGP overview

Emerald Green Power has been created with the aim of designing and developing production and technology hubs to produce the Greenest hydrogen possible, matching the demands of an area with the amount of hydrogen produced through the use of universal digital twins. As a vector coupling technology company, EGP is designing novel methods of optimising renewable energy, creating innovative configurations of electrolysers to produce Green Hydrogen at a lower cost. To enable deep decarbonisation of the UK, EGP believes that Green Hydrogen hubs need to be created that can offset the energy demands of towns and cities in a region. With this in mind, EGP has conceptualised a 100MW Green Hydrogen hub supplying the South West region with hydrogen and reducing high emissions levels within key cities.

At present the vast majority of hydrogen is produced through the use of fossil fuels [1], either through Steam Methane Reformation, Oil Partial Oxidation or Coal Gasification. The 100MW Green Hydrogen hub project intends to demonstrate the viability for the production of low-cost hydrogen from electrolysis, with the electricity required being supplied primarily by solar, but also by wind turbines if this is an option on site. This method of hydrogen production supports the target of the UK Government to reach 10GW of low carbon hydrogen capacity by 2030 [2].

The project will supply the South West region with low carbon hydrogen, with the primary uses being injection into the natural gas grid and supplying Hydrogen Refuelling Stations as both the infrastructure develops and Hydrogen vehicle demand increases. Both of these use cases are important for the reduction of emissions on a large scale, but crucially within cities where the use of gas and fossil fuel powered vehicles can create dangerous levels of emissions and pollutants for residents.

The feasibility study undertaken was focussed largely on techno-economic modelling of the Green Hydrogen hub, but also considered the software which would be used to deliver a universal digital twin for the analysis of demand in specific buildings and regions. A full explanation of the feasibility study is detailed in Section 3.

Emerald Green Power worked in collaboration with the University of Exeter and City Science Corporation to substantiate our final conclusion and build the Phase 2 strategy leading to scalability.

The results from the feasibility study found that a 100MW hub in a single location is not feasible, however a group of sites up to 10MW constituting a wider 100MW hub was feasible both technically and economically. This report presents the rationale behind the project in Section 2, details the specific studies conducted in Section 3 and then presents the results found in Section 4. The scalability of the project is then described in Section 5, which highlights the current partnerships and ongoing grant applications that Emerald Green Power has with local businesses.

2. Project rationale

Emerald Green Power has partnered with the University of Exeter and City Science Corporation to explore the potential markets available for Green Hydrogen as a method of decarbonisation, and the strategies available to not only implement Green Hydrogen at a large scale but also to achieve new innovations within the energy sector. This section details the research and rationale behind Green Hydrogen development, and how specific innovative approaches can be taken.

2.1 Hydrogen market assessment

2.1.1 UK hydrogen market

The UK produces roughly 0.7 Mt of hydrogen each year, an overwhelming majority of which is used for industrial processes such as ammonia, methanol, and steel production [3]. At present the main processes used to produce hydrogen are Steam Methane Reforming (SMR), Oil Partial Oxidation and Coal gasification. These produce 49%, 29% and 18% of global hydrogen respectively, as shown in Figure 1 [1]. The issues with these production methods are a heavy reliance on fossil fuels. Within the production processes CO_2 is released as a by-product, and as such the production of hydrogen currently contributes towards greenhouse gas release. It is estimated that SMR releases between 8 and 12kg of CO_2 for each kilogram of hydrogen produced, whilst coal gasification is even higher at between 18 and 20kg.

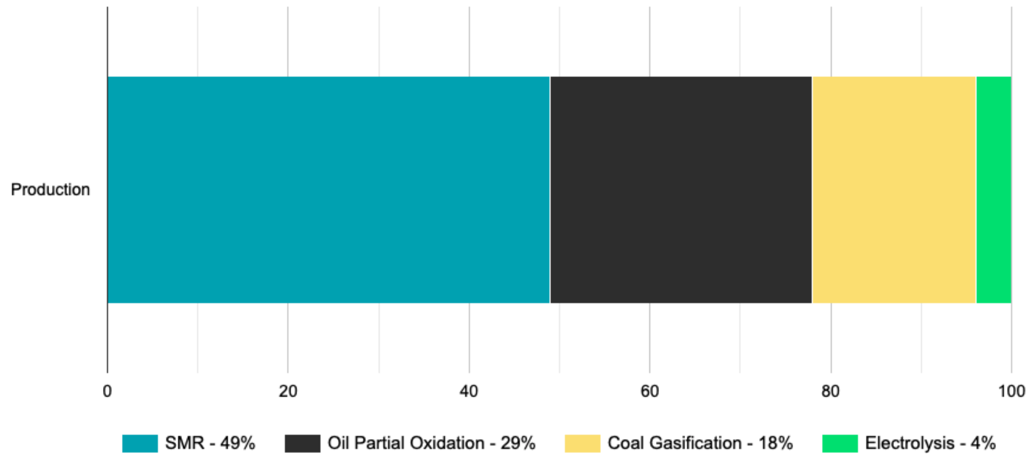

Figure 1 – Current hydrogen generation by process

Due to the high carbon footprint of production, the hydrogen market, as with the wider energy sector, is experiencing a significant change in mindset towards low carbon production methods. Low carbon hydrogen is widely identified using a colour system dependent on the production method used [4], as shown below;

- **Green hydrogen –** Produced through electrolysis of water, which splits the molecule into hydrogen and oxygen. Electricity is used to electrolyse the water, and as such can be sourced from 100% renewable energy sources
- **Blue hydrogen –** Applies the concept of Steam Methane Reforming, which splits natural gas molecules into hydrogen and carbon dioxide as a by-product. Therefore, this method relies on carbon capture and storage (CCS) to be considered low carbon
- **Pink hydrogen –** Electrolysis of water as in Green Hydrogen but powered by nuclear energy as opposed to renewable sources

It is important that low carbon production sources are developed further since an increase in hydrogen demand is being experienced due to the ability of hydrogen to decarbonise previously difficult to abate sectors such as heating and heavy goods transport. The UK Government recently doubled its ambition for low carbon from 5GW to 10GW by 2030 [2], illustrating the large emphasis being placed on the technologies and their use in a low carbon economy. An increase in demand for hydrogen without a change to low carbon sources would represent a significant increase in greenhouse gas emissions.

The challenges of low carbon hydrogen production are high capital investment (CAPEX) costs. This refers to the infrastructure which is required to generate hydrogen in a low carbon manner, carbon capture technology in the case of blue hydrogen and electrolysers in the case of green and pink hydrogen.

Emerald Green Power is working to address this through the development of Next Generation electrolysers which have a 25% lower capital expenditure than previous electrolysers, enabling low-cost production to occur through electrolysis.

2.1.2 Competitive analysis

Emerald Green Power has very few direct competitors who are creating hydrogen within a microgrid setup. A Truro based company, Soguard Hydrogen, is applying a similar technology but at a very different scale, not to the 100MW ambitions of EGP. Competition will be faced more in the future from companies purchasing electrolysers from manufacturers such as ITM Power, however the lead times on delivery are currently extremely long, and as such in the short-term competition is low. In theory there will be competition with electrical microgrid operators who generate electricity from sources such as solar and wind, however this is seen more as an opportunity for collaboration as opposed to competition. EGP intends to work with microgrid and renewable electricity generators to optimise the usage of the power generated, by applying hydrogen technology where curtailment occurs for example. EGP are in indirect competition with other companies developing low carbon methods of heating such as heat pumps, however the market for hydrogen is so large that this is not foreseen as being significant in terms of competition.

2.2 The South West region

During conceptual development of a 100MW Green Hydrogen hub it was important to have a clear purpose and reason behind the choice of location. Using data from the Office of National Statistics it was possible to identify the areas within the wider South West region which had the highest emissions and where the concentration of energy usage was highest. Figure 2 shows the total emissions per km^2 at a local authority level.

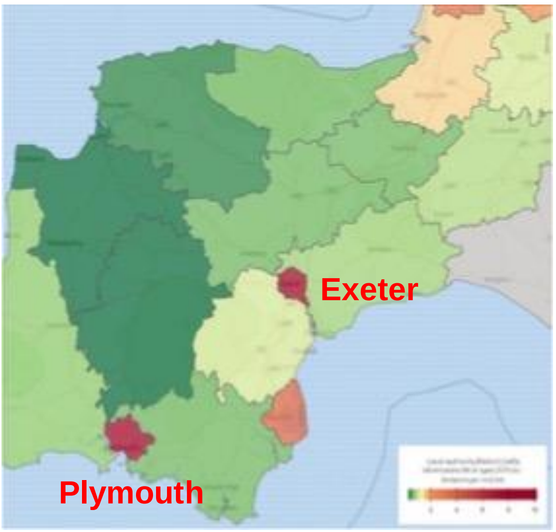

Figure 2 – South West emissions per km^2 at Local Authority level

It is clear that both Exeter and Plymouth have the greatest emissions, and usage of high carbon energy sources, within the South West region. This makes both cities prime targets for carbon reduction through the use of hydrogen. Due to relationships with the City Council and the company being based in the city, Exeter is the focus of initial studies.

2.2.1 Exeter city energy demand

Greenhouse gas emissions have been falling in Exeter since 2005, with the trend and source of emissions shown in Figure 3 [5]. It is clear that domestic emissions are the largest source of emissions within the city, with commercial and transport emissions being the next highest users with similar emissions respectively.

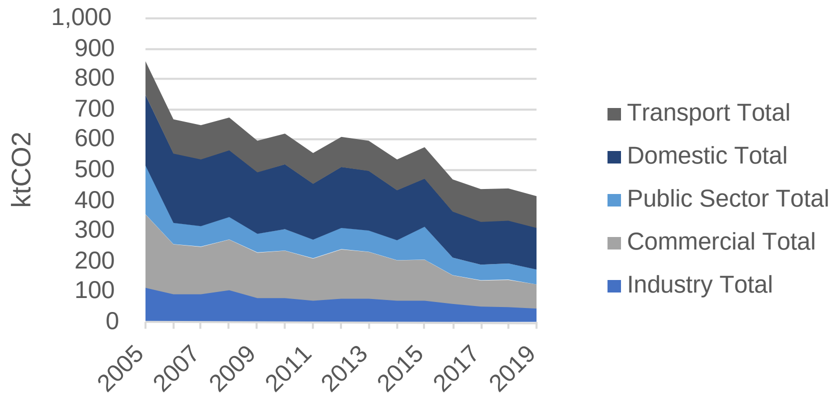

Figure 3 – Exeter emissions by source

Domestic and commercial emissions are experienced primarily through gas and electricity usage. Since hydrogen can directly replace gas usage, the gas usage within the city was explored further. A review of the current gas usage in Exeter, along with the resultant carbon emissions, are shown in Table 1. The CO2 emissions are calculated using Government conversion factors of 0.183 kgCO2/kWh of natural gas [6].

Gas type	2020 consumption (MWh)	CO2 emissions (tonnes)
Non-domestic gas	380,967	69,717
Domestic gas	526,079	96,272
TOTAL	**907,046**	**165,989**

Table 1 – Exeter city gas consumption

With total emissions of 166ktCO2 per annum, gas emissions alone make up a large proportion of the 410ktCO2 total emissions within the city shown in Figure 3. This presents a large sector which could be positively impacted by the use of hydrogen injection into the gas grid.

2.2.2 Marsh Barton Industrial Estate

Businesses and industry combined are responsible for 21% of total greenhouse gas emissions in the UK [7], not including agricultural businesses which are responsible for 11% of total emissions. Industrial estates therefore form the initial phase of Emerald Green Power's decarbonisation strategy for any city. The targeting of these sites offers large benefits over other sectors, the key benefits given below;

- Businesses have decarbonisation targets to meet
- Roof shapes of the buildings allow for large solar deployment
- Often largely owned by the City Council

The main industrial estate in Exeter city is Marsh Barton, located across the river to the South of Exeter city centre. A building level energy demand model was deployed across the entire Marsh Barton industrial estate in order to gain an insight into the specific buildings with high energy usage along with an estimation of the total gas usage within the estate.

The building energy demand model uses a range of national, regional, and building level data sets to estimate the energy consumption of a building by end use and utility. The approach is scalable and can be applied across a far greater area. The model of Marsh Barton is shown in Figure 4, and indicates a number of high gas usage buildings in red. The largest individual consumer was estimated to use 615MWh each year, with a total annual gas consumption for the estate of 16.5GWh.

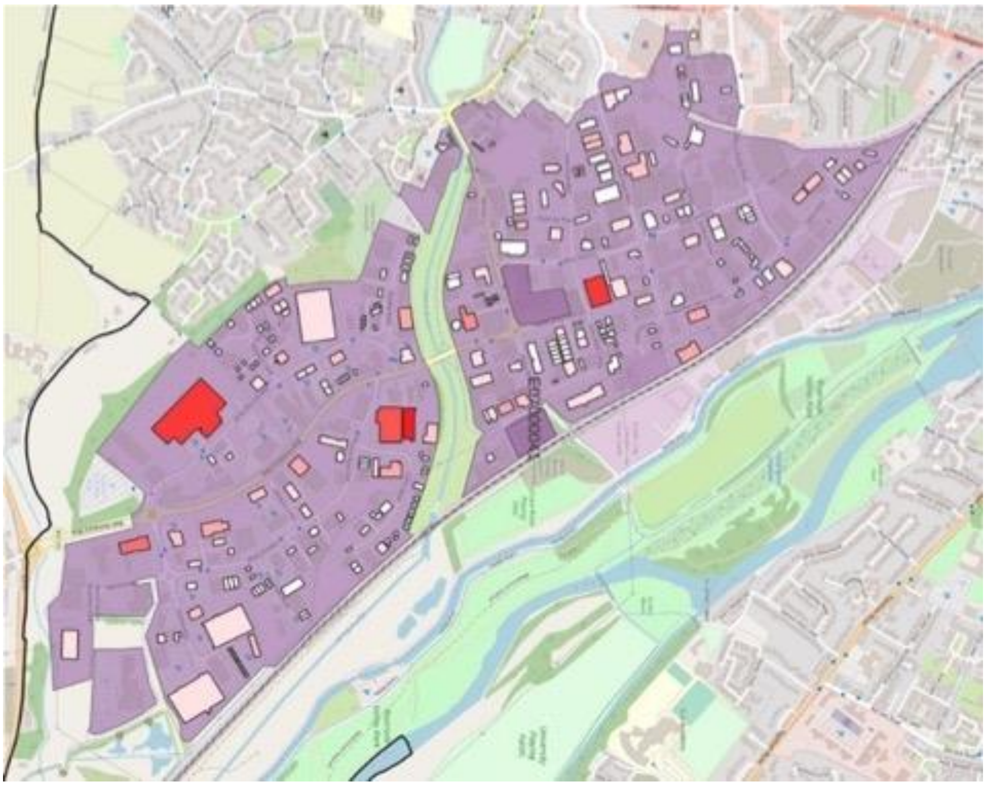

Figure 4 – Marsh Barton energy demand model output

As previously mentioned, one benefit of industrial estates as a focus is the nature of the buildings allowing for large amounts of solar panels to be deployed. An analysis was conducted of the solar potential for Marsh Barton using both aerial imagery and software to identify the roof area available for panels to be mounted. This area could then easily be converted into solar capacity using standard solar panels. The analysis found that the estate has the potential for 20MW of solar capacity on rooves without considering the potential for vertical solar on walls. This is a key benefit when deciding on where to place electrolysers since it allows for direct renewable to electrolyser coupling to occur.

2.2.3 Health impacts of air pollution

Whilst Emerald Green Power is committed to carbon reduction in all areas, the reduction of emissions within cities is a key focus of the company. The negative health effects of high emissions have been researched in depth and presented in Deliverable 6.3 Health Report. The report shows the clear importance of reducing emissions with regards to health.

Growing evidence suggests that environmentally relevant elevations in CO2 (<5,000 ppm) may pose direct risks for human health. Increasing atmospheric CO2 concentrations could make adverse exposures more frequent and prolonged through increases in indoor air concentrations and increased time spent indoors.

Particulate matter also can create both short term and long-term effects, with long term effects being experienced largely within the respiratory system [8].

Research has also found that mental health disorders such as anxiety and mild depression can be negatively affected by high levels of air pollution [9].

Hydrogen can play a significant role in the improvement of air quality, and as such the reduction in air pollution related physical and mental illness. In the short term, hydrogen injection into the natural gas grid, a maximum of 20% presently, can reduce carbon directly where people live since boilers will emit less carbon. In the longer term, both particulate matter and carbon emissions can be reduced through the use of hydrogen vehicles.

2.3 Innovative approach

Innovation is the key to addressing the issues identified in Section 2.2 through a 100MW Green Hydrogen hub. Emerald Green Power has developed innovative technology to enable more efficient operation and greater production from electrolysers, whilst building frameworks for digital twin modelling and researching potential future funding methods.

2.3.1 Self-healing stacks

As electrolysers evolve, reliability will feature as a key component to Green Hydrogen providers. The larger the stacks become, the more expensive the standby replacement units become. EGP are exploring concepts which allow large electrolyser to operate in conjunction with networks of smaller units. These will be deployed and configured in a pseudo self-healing operation, meaning that they can divert production between units to best match the available electricity through the use of Artificial Intelligence (AI) Controllers.

2.3.2 Decentralised and direct coupling

Localised and decentralised energy generation hubs are becoming an attractive alternative to grid scale centralised power distribution. Hubs allow for greater control of energy prices across the project lifespan, along with reduced transmission losses and infrastructure costs from grid connections. Electrolysers can be coupled directly to the renewable source, being supplied with power at a stable and known price across the length of the project, using all available power which may otherwise be curtailed by the grid at certain times. The direct coupling also allows electrolyser to connect in a DC-DC manner between a solar farm and the electrolyser, meaning power does not need to be transformed to AC before it can be used, thus reducing costs as no DC to AC inverters are required.

2.3.3 Metal hydride storage

Storage is a major cost in hydrogen infrastructure, with a key focus on safety. Storage of hydrogen as a gas typically requires high pressure tanks (350 –700 bar), whilst storage as a liquid requires cryogenic temperatures, since the boiling point of hydrogen at atmospheric pressure is −252.8°C.

Advancement in metal hydride storage will enable safety aspects and pressure restrictions to be overcome. Through work with partners at LSBU, EGP are developing a solution for low-cost metal hydride storage, which has been integrated into the 10MW plant design and will be built into Phase 2. The metal hydride solution is shown in Figure 5 with further technical information on metal hydride storage given in Deliverable 6.3.

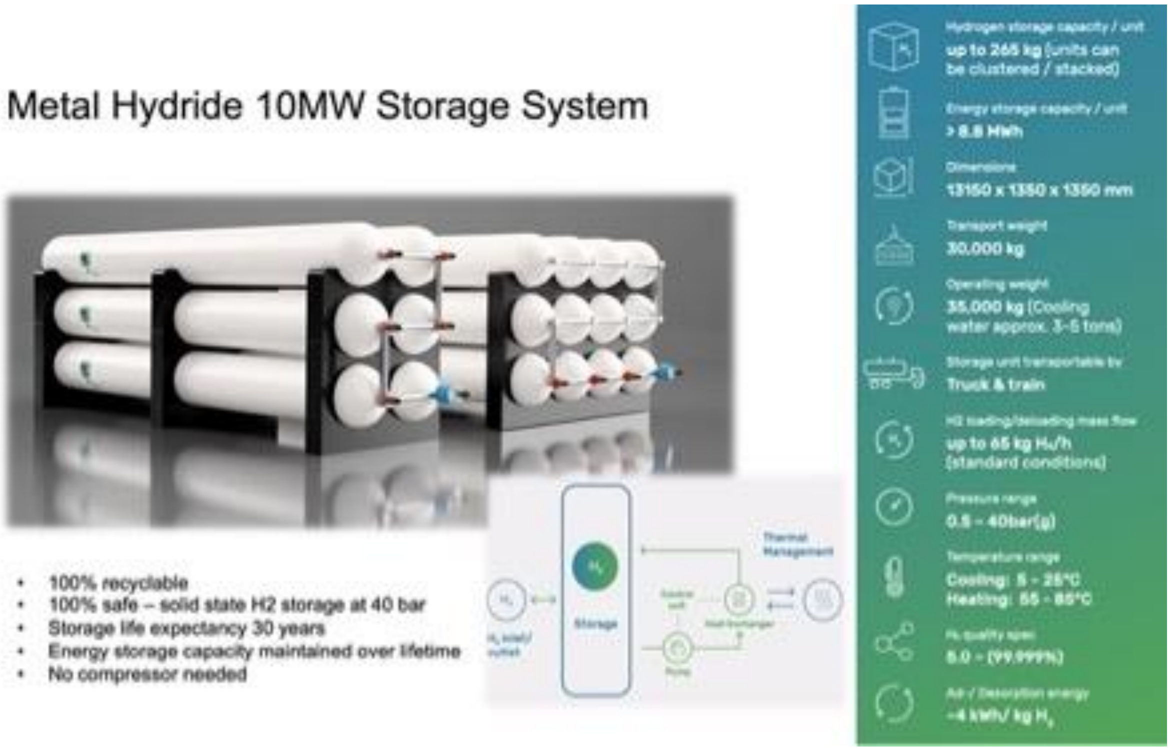

Figure 5 – Metal hydride storage solution

2.3.4 Digital twins

Emerald Green Power has developed trademarked software called TWINZ™, **T**actical **W**orkspace to **I**mplement **N**et **Z**ero. The software is split into two main sections, Romulus, and Remus. The Romulus software runs a simulation based digital twin, using sophisticated AI software to compile modules on asset mapping (primarily an industrial or domestic building), including gas and electricity usage data, and asset size to deliver the digital twin. The system generates carbon models which show the main influences along with average carbon emissions of the building user. The Remus software provides actual real-world data for the building and inputs this into the digital twin model, allowing the comparison between virtual and actual emissions.

Digital twins as an interactive tool are very useful since they enable an accurate perception to be made of a specific site or asset, along with tracking changes and being able to view disparities between expected and actual data visually.

2.3.5 Optimisation of delivery

Algorithms to optimise the planning of Green Hydrogen plants have been investigated, with the primary target of industrial estates. This requires the consideration of the full pipeline from renewable energy generation through electrolyser design and finally to the downstream uses of hydrogen. The downstream uses of hydrogen can play a very large role in determining what constitutes an efficiently operated production site. The development of decision-making algorithms which identify the best location for sale of hydrogen, along with the production amount required at any point in time, can enable profitability of a site to be maximised. The location of sites relative to the end user can also be included into the algorithm. Emerald Green Power is working with the University of Exeter to develop decision making algorithms to apply to the 100MW Green Hydrogen hub, which will enable the delivery of hydrogen to be optimised, which will change based on the desired outcome from the site at any point in time. These outcomes could be used to maximise profitability, maximise carbon reduction or minimise production costs, or a combination of all three.

2.3.6 Carbon trading

Carbon trading refers to the trading of 'credits' between companies who create high levels of carbon in their processes and companies which deliver carbon saving goods and services. The method through which credits will be traded is a Carbon Market such as the EU ETS [10], which is the first major Carbon Market aimed at reducing greenhouse gas emissions cost effectively.

It must be noted that carbon trading schemes are at an early developmental phase but have the possibility to deliver returns on capital expenditure for projects based around the amount of carbon that is being saved. As such, EGP has researched the feasibility of integrating a carbon trading-based interface into future projects, enabling them to be delivered at a lower cost or to reduce risk for outside investors.

3. Feasibility study

The key focus of the feasibility study was to identify whether it is possible to construct a 100MW Green Hydrogen hub near major cities in the UK. It became apparent very quickly following discussions with Western Power Distribution that the sheer amount of power required could not be delivered to a single location, making this option infeasible. The renewable capacity surrounding the Exeter area is also currently unable to fulfil the demand of a 100MW Green Hydrogen hub at a single location.

The solution to power constraints is to focus on a network of distributed hubs of up to 10MW per site, clustered closely together and all forming part of a regional 100MW hub. The specific locations will focus on sites at which a portion of the hydrogen can be used onsite, such as on farms with gas boilers, however this is not a requirement. The main considerations for a site are available renewable generation capacity and access for tube trailers to transport the hydrogen.

Therefore, the feasibility study detailed below is all based on a 10MW capacity site, which is characteristic of a site which would be present within the larger 100MW hub. The study is designed to address the objectives set out by Emerald Green Power at project conception.

3.1 Electrolyser system design

The specific electrolysers used were the Next Generation units from Emerald Green Power's sister company, HydroStar. The Next Generation units are 50kW in size but can be connected to scale the capacity to any requirement of size, in this case 10MW. The small capacity within each electrolyser unit is what allows the stacks to operate in a pseudo self-healing manner. Based on the power available as little as 50kW can be turned on or off as required, enabling as much power to be usefully consumed as possible.

The flexibility of the pseudo self-healing stack enables greater production of hydrogen, however it also requires greater design considerations due to the quantity of 50kW stacks that make up the system. As such a layout design is required for the site, covering the main aspects of;

- Arrangement of individual stacks
- Electrolyte and metal hydride storage proximity
- Workshop location and Autonomous Guided Vehicle paths
- An AI control centre

At the heart of the plant design was consideration of overall environmental impact, therefore recycled materials were used wherever possible, along with additions such as rainwater harvesting. The site layout drawing was shown both in terms of the footprint of the building but also as a 3D model overview. The two different views enable the design of the stacks themselves along with the surrounding area infrastructure to be visualised most effectively.

The next consideration was the location at which the feasibility study should be undertaken. As previously stated, the Marsh Barton industrial estate has the potential for 20 MW of solar generation on the rooves of buildings. The Matford Centre within the estate is a large purpose-built building for exhibitions and agricultural shows, which already has 1.5 MW of solar panels on the roof. This building specifically could not house the electrolyser system, however there is land available directly beside the Matford Centre on which an agricultural type building which would be used for electrolyser systems could be placed. An agricultural building of below 1000m2 is the most likely type of building to house an electrolyser due to the high available floor area and low planning restrictions (initial planning meeting with Exeter City Council conducted at site 07/2022). The location of the Matford Centre within the industrial estate makes it the perfect choice for running demonstration simulations. This is because it not only represents the most likely type of building within which electrolysers would be installed at the 10MW sites, but also enables study into the decarbonisation of industrial estates, one of EGP's key focusses.

3.2 Techno-economic modelling

To determine data regarding the technical outputs and economic potential of a 10MW system, Emerald Green Power's verified OptoGEM™ software was used. This allows EGP to match the power available from solar to the size of electrolyser in place so as to identify the expected annual production from the system. The Next Generation electrolysers modelled have an efficiency of 60kWh/kg of hydrogen. The software also enables the CAPEX and OPEX costs to be considered across the lifetime of the project so as to identify a cost per kilogram of hydrogen produced. The specific data required from the modelling were;

- Annual production of hydrogen
- Cost of hydrogen
- Resultant carbon savings (as a percentage of Exeter gas demand)
- Purity of hydrogen

For this techno-economic model, CAPEX prices for the electrolysers have been provided by EGP's sister company, HydroStar. Remaining infrastructure CAPEX costs have been taken from supplier quotes and academic papers to generate a realistic price range.

With this range in mind, high and low expected CAPEX costs have been simulated. This is paired with the use of varying electricity costs, generating a range between which the cost of hydrogen would be expected to fall. The use of these price ranges enables EGP to reduce the risks associated with price fluctuations in both the initial and operational costs. The lifetime of the project was assumed to be 25 years.

3.3 Digital twin demand mapping and optimisation of delivery

To assess the feasibility of using universal digital twins, a model was made of the Marsh Barton industrial estate, with the Matford Centre having a model developed into greater detail to illustrate data presentation. This process applied TwinZ™ software along with Blender software to generate the 3D modelling in tandem with Python commands to return the data required.

To simulate a virtual environment for Marsh Barton in Blender, geolocation and time data was assigned to a chosen centre point of (0,0,0) representing the x, y and z axes. Time was controlled using the "Timeline" feature in Blender, with the units of either seconds, hours or days being selected at the start of the simulation. Once completed the simulation model added objects and features to the virtual location with real world geolocation data, using azimuth calculations and Python scripts to produce the required response. Time-varying data such as monthly utility bills, solar radiation or energy production and consumption could be added to the simulation as a final measure.

For the algorithms controlling the optimisation of delivery, frameworks were developed which showed the decision variables and process by which the algorithm would be optimised. Since full software development is a very lengthy process, the framework can act as a reference and plan for the development of specific sections of the algorithm. The objective functions were also identified.

4. Results

The results collected confirmed that a 10MW site operating within a larger 100MW Green Hydrogen hub is both technically and economically feasible. This section gives a detailed account of the results gained, showing cost estimates for the hydrogen production itself along with initial frameworks for the software involved.

4.1 Site identification and layout

As stated above, the Matford Centre in Marsh Barton was chosen since it already has solar panels installed on the roof and has ample space for the construction of an electrolyser housing building in the land adjacent. Both 2D layout and 3D visualisation models were made of the agricultural style building which would house the 50kW Next Generation electrolyser units, taking into consideration all of the bullet pointed objectives in Section 3.1. A 2D layout drawing is shown in Figure 6.

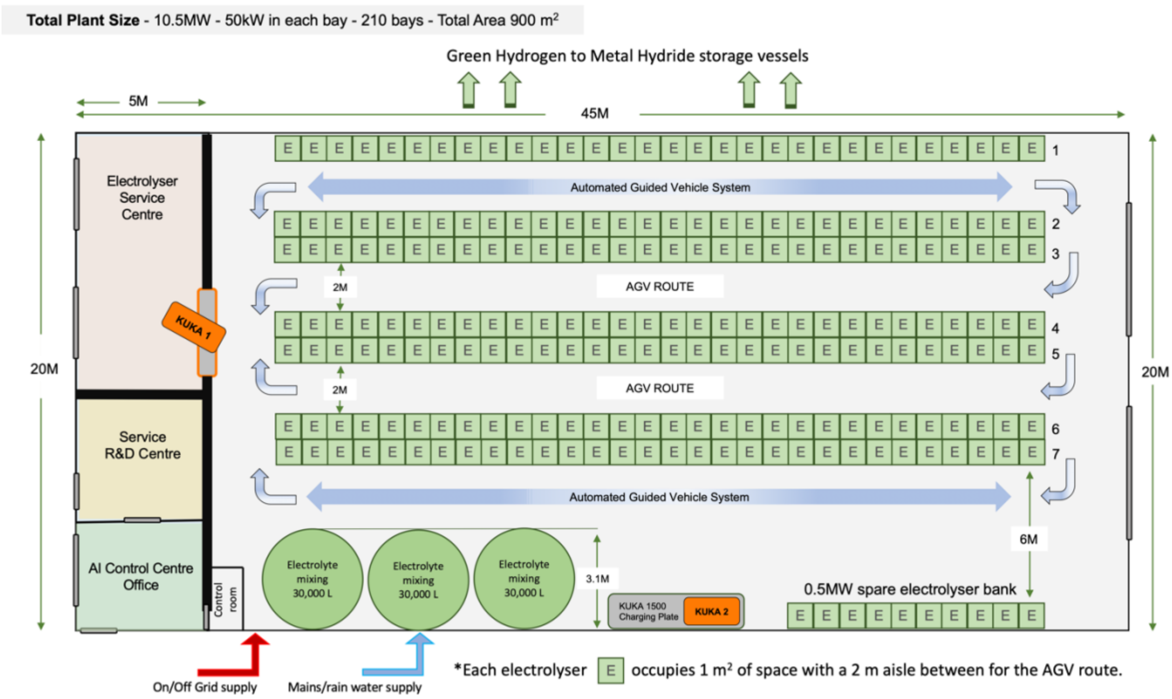

Figure 6 – Green Hydrogen production facility 2D layout drawing

Figure 6 shows the layout of the electrolysers in dedicated bays, each of which has an individual stack. The Automated Guided Vehicle routes allow for maintenance of specific stacks to occur automatically, taking the stack to the electrolyser service centre and being controlled through the use of AI. The AI control centre can be seen next to the R&D centre, separated from the electrolyser stacks and the service centre. The electrolyte is housed on the AGV route, meaning electrolyte can be delivered automatically where it is required.

A further 3D model of the site is shown in Figure 7. This gives a more realistic view of the type of building which would be used, including rainwater harvesting tanks and metal hydride storage tanks and their proximity to the electrolyser units. The rainwater harvesting tanks are sunk underground, whilst the metal hydride storage is overground. All roof space on the building will be covered with solar panels to maximise direct coupling of electricity generation to the electrolysers and aid in the powering of ancillary equipment.

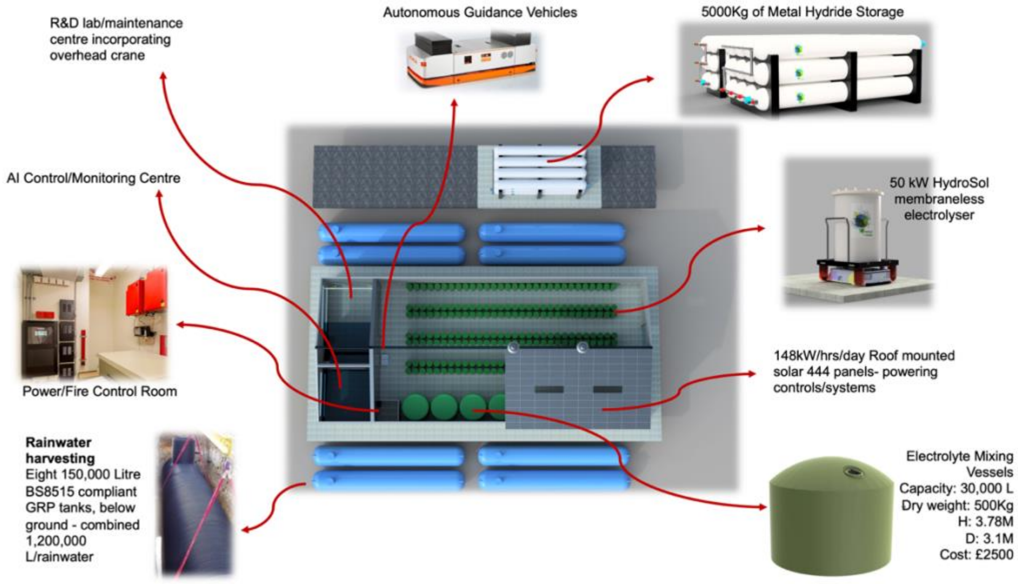

Figure 7 – Green Hydrogen production facility 3D concept drawing

4.2 Electrolyser system data

Through the use of EGP's OptoGEM™ software, the technical and economic data specified in Section 3.2 was calculated for the 10MW system. Since the location of the Matford Centre was known, solar data could be downloaded and input into the model so as to gain accurate power availability data for the simulation. The simulation found that 197,350 kilograms of hydrogen would be produced from a 10MW system supplied by solar electricity only. The hydrogen produced from the Next Generation electrolyser is at a purity level of 98%. This is sufficient for injection into the natural gas grid since the only other substance within the hydrogen is 2% oxygen from gas separation inside the electrolyser unit. A further reason that 98% purity is sufficient is that the metal hydride system indirectly purifies the hydrogen further simply because of the way the system functions. In metal hydride storage, the hydrogen chemically bonds with the metal in the storage tanks, but the oxygen does not chemically react and can therefore be released. When the hydrogen is needed, heat is applied to the metal hydride, resulting in a very high purity level. Details of this process are given in Deliverable 6.3.

In determining costs of production, a price range for electricity costs of £30/MWh to £100/MWh was used, representing the potentially different price levels at which a contract could be set for the use of the solar power available. As mentioned in Section 3.2, high and low CAPEX prices were also used, which simulated fluctuations which may be experienced in the costs of electrolysers, compressors, chillers, and hydrogen storage. The depreciation period used for the CAPEX costs was 25 years. The results are given in terms of cost per kilogram of hydrogen and are shown in Table 2.

Cost of electricity (£/MWh)	Cost of hydrogen (£/kg)	
	Low CAPEX estimate	High CAPEX estimate
30	£4.35	£5.47
40	£4.95	£6.07
50	£5.55	£6.67
60	£6.15	£7.27
70	£6.75	£7.87
80	£7.35	£8.47
90	£7.95	£9.07
100	£8.55	£9.67

Table 2 – Hydrogen cost per kg at varying electricity prices

Using the results for production total, the carbon savings could be calculated and related to the natural gas demand of Exeter. Full calculations for the natural gas replacement carbon savings amount and car removal amount are given in Deliverable 6.3 Carbon Calculations. The total carbon savings for the 10MW system supplied by solar only focussed on in this feasibility study was 1,184 tonnes of CO2 per annum. The production total of 197,350kg when converted to kWh represents a 1.73% replacement of the non-domestic natural gas usage in Exeter, which in carbon reduction terms is the equivalent of removing 535 cars covering 10,000 miles per year from the roads.

The hydrogen production and carbon removal calculations are all representative of a 10MW production site. When these sites are considered as part of the 100MW Green Hydrogen hub, the totals increase by a factor of 10. Therefore, from a 100MW hub the expected annual output of hydrogen would be 1,973,500 per annum, replacing up to 17.3% of the non-domestic gas demand in Exeter and reducing CO2 by 11,840 tonnes annually.

All calculated data assumes that only solar power was used to generate Green Hydrogen. As such the electrolysers are only producing during hours of sunlight when solar is available, which means that there is a low-capacity factor for the electrolyser. As a hypothetical exercise a further analysis was taken which considered the future possibility of a Power Purchase Agreement (PPA) supplying low carbon renewable electricity to the electrolyser throughout the entire day, enabling the system to operate at as close to 100% capacity factor as possible whilst accounting for scheduled maintenance.

Assuming a 95% capacity factor which allows for both scheduled and unexpected maintenance, this form of operation found that from a 10MW system, 1,387,000 kilograms of hydrogen could be produced annually at a cost range of £3.50/kg to £3.70/kg, assuming an electricity cost of £50/MWh and the previously used High and Low CAPEX approach. This represented an annual reduction of CO2 of 8,321 tonnes and an equivalent of 3,758 cars being removed from the roads. In terms of percentage gas reduction, the amount of hydrogen produced converted to kWh would replace 12.1% of the non-domestic natural gas demand in Exeter. As with the solar only scenario all values would be increased by a factor of 10 when individual generation sites operate within a 100MW hub. In this case, when scaled to the 100MW size, a PPA based system would produce more than the non-domestic total for Exeter each year, with the surplus hydrogen available to tackle domestic gas usage also. The calculations natural gas replacement carbon savings and car removals for a PPA based system are also shown in Deliverable 6.3 Carbon Calculations.

4.3 Demand mapping

The digital twin methodology of using Blender software in conjunction with Python scripting was applied to the Marsh Barton industrial estate as a whole, and then the Matford Centre specifically. Figure 8 shows the Marsh Barton simulation model in Blender. Google Earth 9 data was also used within the model to source 3D data and imagery of the region, whilst RenderDoc software was used as a graphics debugger which enabled all data to be converted to a file type that could be imported to Blender.

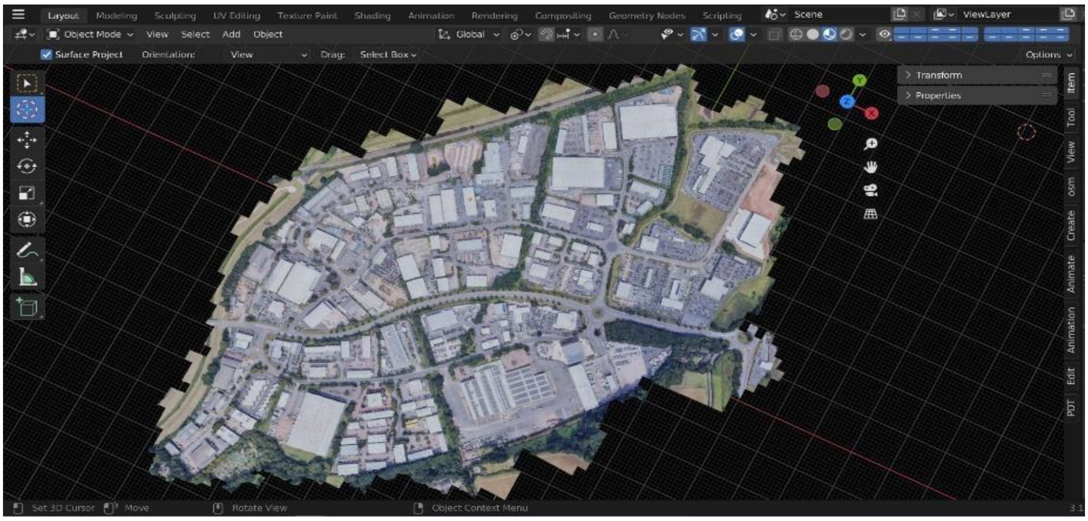

Figure 8 – Marsh Barton simulation model

The geolocation and time series principles described in Section 3.3 were applied to the Matford Centre within the wider Marsh Barton model. The Python script sorted data, and if it was relevant to the simulation model, added an information icon, an example of which is shown in Figure 9. The information icon was built using Blender's 3D modelling feature, and the process from scripting on the left-hand side of Figure 9 through to the material output on the right-hand side is shown.

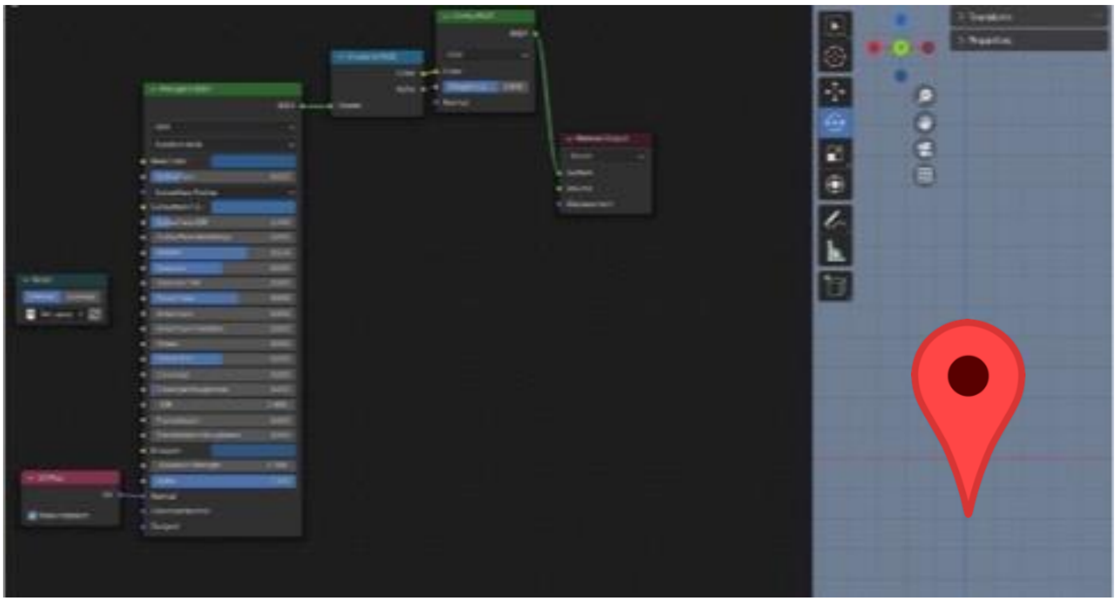

Figure 9 – Blender information icon and control system

To show individual building information, a Python update script is run. The script was written such that to view the building environmental information, the information icon can simply be selected. The icon triggers and Event Listener in the script, and an information pop-up title is displayed, as shown in Figure 10 of the Matford Centre below.

Figure 10 – Matford Centre in Blender with information icon

4.4 Optimisation of delivery

The optimisation fundamentals of decision variables and objective functions were identified, and a framework for the different algorithm models which would be required was developed. The framework gave an overall appreciation for the steps through which the optimisation would occur, showing which parts of the algorithm was dependent on others. The high-level framework is shown in Figure 11.

Figure 11 – Optimisation of delivery algorithm framework

The optimisation was split into two different modes of "Design" and "Operation", with design mode optimising the actual plant which would be most effective at a given location and operational mode optimising how that plant would be run during its lifetime. With these modes in mind, the objective functions were identified;

- **Cost**
  - **Design mode** – Construction and procurement costs for the renewable energy generation components, electrolyser, and distribution infrastructure. May be costed in a number of planning horizons, and Net Present Value used as a metric
  - **Operational mode** – Costs associated with running the electrolyser including provision of water, distribution costs, additional energy used above renewable generation components

- **Benefit**
  - **Revenue Generated** – Potential daily revenue will depend on the renewable energy available along with the market conditions for resale and the specific end use of the hydrogen (grid injection, transport etc)
  - **CO2 saved** – The end use of the hydrogen and daily quantity generated will determine the specific carbon savings experienced
  - **Emissions saved** – Similar to carbon savings but applied to other emissions such as Sulphur Dioxide or Particulate Matter, and crucially the location that the emissions are reduced in such as densely populated areas

Following the objective functions, the decision variables were identified, and split between the design and operational modes as before;

- **Design mode decision variables**
  - **Solar PV installation** – Determining which buildings receive panels, the number and orientation of panels, and any other components relating to solar
  - **Power distribution** – Infrastructure required to move power from the solar array to the electrolyser or grid
  - **Electrolyser components** – Location, sizing, and balance of plant infrastructure
  - **Additional infrastructure** – Including water provisions and tube trailer facilities
  - **Storage** – Multiple storage types, such as battery for power, water tanks for rainwater harvesting or metal hydride hydrogen storage

- **Operational mode decision variables**
  - **Power generation** – Determining whether to sell PV generated as electricity directly to grid or to create hydrogen
  - **Electrolyser** – Determination of the quantity of hydrogen to produce given available renewable power and downstream demand
  - **Hydrogen storage and sale** – Determining whether to sell or store the hydrogen based on the market value and available storage
  - **Downstream use** – Using the amount of hydrogen available for sale to determine the most efficient downstream use case

5. Scalability

The knowledge gained from the feasibility studies undertaken will inform decision making within Emerald Green Power both in terms of Phase 2 but also for the wider business in the projects that are being operated with clients. This section details the strategies by which scalability will be applied to the Hydrogen Hub creation.

5.1 Phase 2 development and key steps to commercialisation

Using the knowledge gained from the feasibility study, the key developments focussed on in Phase 2 are constructing a 2MW demonstrator project at the Matford Centre in Marsh Barton. Whilst the project will fundamentally demonstrate the delivery of Green Hydrogen to decarbonise the Marsh Barton industrial estate, it will also operate as a living lab, through which knowledge can be shared with regional businesses, Exeter City Council and the local community as a whole. The Matford Centre is a particularly useful location to share the technology with farmers and agricultural businesses, since there is a farmers livestock meet every week at the Centre. This will enable the viewing of technology without the need for farmers to take time out of their schedules.

The 2MW demonstrator project also acts as a testing platform for all the infrastructure present in an electrolyser system, along with the development and refinement of control systems. Key milestones within this next project are achieving gas interface for hydrogen directly into either the mains, into metal hydride storage, and integrating the Q-Drive™ (EGP's AI controller) control system algorithms. A full breakdown of the tasks and milestones, along with the timelines associated is shown in the Gantt chart in Appendix 1. The development of control and hydrogen integration systems are imperative to scalability, since the knowledge gained can be applied very easily from 2MW to the 10MW hubs, the ultimate goal. This reduces the risks of operational inefficiency and unexpected costs arising since a number of challenges will already have been identified within the demonstrator hub.

5.2 Routes to market – M5 distributed production and delivery

Emerald Green Power has received significant private investment to work on our distribution strategy, which focusses on developing the 10MW hubs referred to in the feasibility study at strategic locations close to and spread out along the M5 motorway. These will constitute the sites which make up the wider 100MW Green Hydrogen hub and will assist in the decarbonisation of local cities and towns through grid injection. Details of the key partnerships representing routes to market are explored in the following sections.

5.2.1 Anaerobic Digestion – Ixora Energy

EGP has partnered with Ixora Energy, an Anaerobic Digestion company, to explore different strategies which can be implemented on their site to utilise Green Hydrogen. The first area of focus is the potential for hydrogen injection into the Anaerobic Digestion units to optimise CH_4 production and effectively reduce CO_2 emissions by 10%. The second strategy at the site is to use the existing connection to the natural gas grid on site to inject Green Hydrogen directly into the grid. From this location gas flows directly into Exeter city, and as such would result in a reduction in emissions within the city itself.

The final and most innovative approach is the potential for the optimisation of an Anaerobic Digestion plant to create Green Hydrogen as opposed to Methane, by stopping the digestion process at a specific point through novel and patentable technology, currently in progress.

5.2.2 National Farmers Union EnZero

Working with the National Farmers Union, Emerald Green Power are addressing problems faced by farmers who have the land available for large scale solar installations but are not able to couple onto the electricity grid, due to either infrastructure constraints or connection funding constraints. Even if farmers could connect, they would often experience curtailment, up to 50% in many regions, making the operation unprofitable. The solution is to generate hydrogen on their land as standalone hydrogen hub, as explored in the feasibility study. Solar could be placed on less productive fields and fed through direct coupling to the DC electrolysers. The hydrogen produced can help to stabilise the spiralling energy costs being experienced by farmers whilst allowing them to reduce their carbon emissions. Remaining hydrogen could be either fed into the gas main or transported to hydrogen refuelling stations for transport use.

Further work with the NFU will focus on turning Green Hydrogen into Green Ammonia for use as a fertiliser. This would also represent a reduction in CO2 emissions compared to current ammonia production methods, whilst again stabilising a key farming overhead.

5.2.3 High gas demand businesses

Many businesses have high gas demands, used to power boilers, fryers, or other industrial equipment. Emerald Green Power are building digital twins for Yeo Valley Farms (organic food produce), Muller (yoghurt production) and Burt’s Crisps (potato chips), so as to better understand their energy demands and to prove to investors that projects such as these are both financially responsible and profitable. Each of the chosen sites has the potential to produce at least 10MW of renewable power, and as such fit very well into the wider M5 strategy. These projects also offer the potential for companies to offer Net Zero food products, since all energy onsite can be met by a mixture of renewable power being fed directly to site electrical demand, or Green Hydrogen being produced for the gas demand.

5.3 Barriers and risks

There are few significant barriers for standard Green Hydrogen production since the electrolyser units have a technology readiness level of TRL 9, and are proven, however the risks are faced more in terms of long lead times for equipment. To mitigate this risk, system design and procurement activities must happen as quickly as possible within a project.

Risks are experienced in the use of metal hydride storage since the effective containment of hydrogen is of utmost importance. Therefore, safety elements are the most important consideration within the installation and operation of storage methods.

Modelling and the generation of digital twins have very few risks if any at all. However, barriers are faced in terms of lack of data available, through either the data not existing in the required format or businesses being slow to comply with data requests. Some of these data barriers are reduced in the Marsh Barton industrial estate because Exeter City Council owns many of the buildings. As such the only real risk is the time taken to build the models for any given location.

5.4 Job creation

It is estimated that each 10MW of Green Hydrogen hub will create 10 jobs, through the construction, ongoing operation, and planning of sites. When scaled to the larger 100MW hub this results in 100 jobs being created.

Emerald Green Power as a business is in a very rapid business growth phase. The company has gone from 4 employees to over 20 in less than one year, being driven by strong relationships with clients and universities across the country.

A whole supply chain will be used for the procurement of the total system infrastructure components of electrolysers, compressors, hydrogen storage and balance of plant, creating indirect jobs in multiple industries. Emerald Green Power is facilitating discussions between the UK DIT and global suppliers who will potentially build manufacturing and assembly plants in the UK, creating further employment opportunities.

6. Conclusions

The feasibility study generated very useful data for Emerald Green Power, finding initially that a system of 100MW in size in one location was not feasible, but that multiple 5MW to 10MW sites operating as part of a wider Green Hydrogen hub were both technically and economically feasible. The cost of hydrogen was found to be between £5.55/kg and £6.67/kg at an electricity cost of £50/MWh, with a potential reduction in annual CO2 emissions of 1,184 tonnes from each 10MW site. This would represent a 1.73% reduction in non-domestic natural gas usage in Exeter city, increasing to 17.3% when scaled to the wider 100MW hub. A reduction of gas usage of this magnitude would reduce emissions within the city where the majority of people are based, and as such has the potential to improve public health and reduce the negative effects of emissions.

Initial demand mapping interfaces were developed, which showed that the process of mapping buildings through the use of Blender software with Python scripting could be applied and scaled to large locations. A framework for delivery optimisation identified the different components which would be present in the algorithm along with the objective functions and decision variables present in both Design and Operational mode.

With regards to scalability, Emerald Green Power has a strong plan in place for Phase 2 demonstration development, encompassing key elements of control systems and hydrogen interfaces. We will continue to work with the University of Exeter and City Science to develop improved carbon reporting methods, building energy management mapping and optimisation data interfaces.

Significant end uses have been identified, both in terms of hydrogen injection into the natural gas grid, but also in terms of decarbonisation of farms and high gas usage businesses such as Yeo Valley Farms and Burt’s Crisps. Emerald Green Power is working with clients to apply for Government grants, whilst building digital twins of site energy usage so as to decarbonise production and create the first 10MW sites within the larger 100MW Green Hydrogen hub.

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Appendix 1 – Gantt Chart for 2MW Demonstrator project (Phase 2)

x

Application: Emerald Green Power | WP Role Key: Lead - ✓ (red) | Secondary input - ✓

Work Packages and Tasks - The tasks can also be viewed as project deliverables.	I. Gordon	G. Nicholson	D. Bridglalsingh	J. White	C. Newbold	A. Uphadya	EGP Eng Team 1	EGP Eng Team 2	EGP Eng Team 3	City Science	University of Exeter	Q1 (M1 M2 M3) Q2 (M4 M5 M6) Q3 (M7 M8 M9) Q4 (M10 M11 M12) Q5 (M13 M14 M15) Q6 (M16 M17 M18)
WP 1 - PROJECT MANAGEMENT & REPORTING	✓ (lead)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
T1.1 Establish baseline Project Management Plan (PMP)												
T1.2 Risk Management												
T1.3 Reporting and Documentation												
WP 10 - EXPLOITATION & DISSEMINATION	✓ (lead)	✓	✓	x	x	x	x	x	x	x	x	
T10.1 Exploitation Management incl. IP management												
T10.2 Dissemination activiities												
T10.3 Recyclability and end of life study												
T10.4 Economic Assessment												
Milestone 1a,b,c: Interim Reports reviewed												MS1a MS1b MS1c
Milestone 2: Exploitation and Dissemination activities completed												MS2a MS2b MS2c
WP 2 - 100MW systems emulation	✓ (lead)	✓	✓	x	✓	✓	✓	✓	✓	x	x	
T2.1 Design a fully operational 100MW Green Hydrogen hub with AI control systems												
T2.2 Physical Green Hydrogen production systems layout and full architecture												
T2.3 Internal components of Green Hydrogen hub systems and design												
T2.4 Universal digital twin - Emulator and simulator - Local and regional demand simulated												
T2.5 Universal digital twin - Emulator and simulator - Hydrogen hub modelled												
T2.6 Universal digital twin - Estimator and simulator - Green H2 requirements, building ID and data												
Milestone 3: 100MW system designed												MS3
Milestone 4: Universal Digital Twins developed												MS4
WP 3 - 2MW of electrolyser installations	✓	✓ (lead)	x	x	✓	x	✓	✓	✓	x	x	
T3.1 Order electrolyser units												
T3.2 Module designs for the electrolyser setup												
T3.3 Experimental design and operational schedules												
T3.4 Installation of electrolysers												
T3.5 Testing and verification of data												
T3.6 Reporting of results												
Milestone 5: Designs and purchases completed												MS5
Milestone 6: Electrolyser systems installed and testing completed												MS6
WP 4 - Self healing stack systems	x	✓	✓ (lead)	x	✓	✓	✓	✓	✓	x	x	
T4.1 Design the self healing stack												
T4.2 Experimenal design and operational schedules												
T4.3 Build test rig, including power electronics infrastructure												
T4.4 Test and gather data												
T4.5 Reporting of results												
Milestone 7: Self healing stack designed												MS7
Milestone 8: Testing rig constructed and tested												MS8
WP 5 - Virtual gigafactory	✓	✓ (lead)	x	x	✓	✓	✓	✓	x	x	x	
T5.1 Develop concepts, approaches, methodology and contracts												
T5.2 Work with South West Manufacturing Association regarding local manufacture												
Milestone 9: Meetings with South West Manufacturing Association underway												MS9
WP 6 - Control system - Q Drive	x	✓ (lead)	x	x	✓	✓	✓	✓	✓	x	x	
T6.1 Demonstrate AI components of the control and monitoring systems using Raspberry Pi												
T6.1.1 Set up test modules												
T6.1.2 Design experiments and initial algorithm												
T6.1.3 Intelligent testing of modules												
T6.2 Environmental intelligence AI algorithm and data management												
T6.2.1 Background research for patents												
T6.2.2 Design algorithms and experiments												
T6.2.3 Intelligent testing of modules												
Milestone 10: Control system experiments underway												MS10
Milestone 11: Algorithm for environmental intelligence developed												MS11
WP 7 - Energy vector coupling and interfaces	x	✓ (lead)	x	x	✓	✓	✓	✓	✓	x	x	
T7.1 Build and demonstrate AI energy interface components for vector system												
T7.2 Grid availability based green hydrogen research, development and experimentation												
T7.3 Curtailment green hydrogen experiments as secondary vector												
T7.4 Direct coupling of 5MW solar farm to green hydrogen production												
T7.5 Multiple vector applications on a 5MW solar farm to green hydrogen production												
T7.6 Research and development of solar system during the day and nuclear power overnight												
T7.7 Grid analysis and components												
Milestone 12: AI energy interface built												MS12
Milestone 13: All different coupling scenarios tested												MS13
WP 8 - Gas interface and demand side modelling	x	✓	✓ (lead)	x	✓	✓	✓	✓	✓	x	x	
T8.1 Design gas interface components where green hydrogen can be injected directly to source												
T8.2 Identify potential site for green hydrogen injection												
T8.3 Consultation with Wales and West on hydrogen injection system for Exeter												
Milestone 14: Gas interface for hydrogen injection developed												MS14
Milestone 15: Potential site for example project identified												MS15
WP 9 - Carbon credits and measurement systems	x	✓	✓	✓ (lead)	x	✓	✓	✓	x	x	x	
T9.1 Carbon credits and measurement hardware and software development												
T9.2 Air quality and emissions module for Universal Digital Twin												
T9.3 Development of health module tied to city emissions for Universal Digital Twin												
Milestone 16: Air quality and health modules developed												MS16
PARTNER 1 - City Science - Detailed green hydrogen demand modelling	x	✓	x	✓	x	x	x	x	x	✓ (lead)	x	
CS 1.1 Mapping data sources and calculations												
CS 1.2 Carbon data sources and calculations												
CS 1.3 Carbon credit modelling and verification system with EGP												
CS 1.4 Verification and reoprting components												
Milestone 1: Mapping and carbon data sources and calculations completed												
Milestone 2: Carbon credit modelling system verified												
PARTNER 2 - University of Exeter - Net Zero priorities and scheduling system for the South West	x	✓	x	x	x	x	x	x	x	x	✓ (lead)	
UOE 1.1 Main digital twin architecture with EGP												
UOE 1.2 Platform, components, software, graphics, data layers and interfaces developed												
UOE 1.3 Algorithms and data management systems built												
UOE 1.4 Simulator and software design management												
Milestone 1: All components of digital twin model designed												
Milestone 2: Algorithms and simulator developed												

Cost	I. Gordon	G. Nicholson	D. Bridglalsingh	J. White	C. Newbold	A. Uphadya	EGP Eng Team 1	EGP Eng Team 2	EGP Eng Team 3	City Science	University of Exeter	Totals
WP 1	£47,000	£10,000	£10,000	£7,000	£6,000	£6,000	£3,000	£3,000	£3,000	£0	£0	£95,000
	WP1 - Total Personnel Costs - £95,000											
WP 10	£55,000	£17,000	£13,000	£0	£0	£0	£0	£0	£0	£0	£0	£85,000
	WP10 - Total Personnel Costs - £85,000											
WP 2	£60,000	£40,000	£40,000	£0	£35,000	£30,000	£70,000	£65,000	£60,000	£0	£0	£400,000
	WP2 - Total Personnel Costs - £400,000											
WP 3	£8,000	£13,000	£0	£0	£8,000	£0	£17,000	£17,000	£17,000	£0	£0	£80,000
	WP3 - Total Personnel Costs - £80,000											
WP 4	£0	£12,000	£20,000	£0	£10,000	£10,000	£23,000	£23,000	£22,000	£0	£0	£120,000
	WP4 - Total Personnel Costs -£120,000											
WP 5	£10,000	£15,000	£0	£0	£7,500	£7,500	£20,000	£20,000	£0	£0	£0	£80,000
	WP5 - Total Personnel Costs - £80,000											
WP 6	£0	£40,000	£0	£0	£20,000	£15,000	£55,000	£55,000	£55,000	£0	£0	£240,000
	WP6 - Total Personnel Costs - £240,000											
WP 7	£0	£60,000	£0	£0	£50,000	£40,000	£50,000	£50,000	£50,000	£0	£0	£300,000
	WP7 - Total Personnel Costs - £300,000											
WP 8	£0	£8,000	£20,000	£0	£8,000	£8,000	£12,000	£12,000	£12,000	£0	£0	£80,000
	WP8 - Total Personnel Costs - £80,000											
WP 9	£0	£45,000	£70,000	£100,000	£0	£25,000	£50,000	£50,000	£0	£0	£0	£340,000
	WP9 - Total Personnel Costs - £340,000											
PARTNER 1	£0	£0	£0	£0	£0	£0	£0	£0	£0	£200,000	£0	£200,000
	CS - Costs - £200,000											
PARTNER 2	£0	£0	£0	£0	£0	£0	£0	£0	£0	£0	£200,000	£200,000
	UOE - Costs - £200,000											
											TOTAL	£2,220,000

NOTE - Gantt Chart is prepared in principle, when the project is won we will be building individual Gantt charts for each work package and reapportion the costs more accurately