The Case for On Premise Hydrogen Production in Data Centres for Greenhouse Gas Abatement Benefits

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Executive Summary

This paper sets out to review the potential for on-site production of low carbon hydrogen (hydrogen produced without associated carbon emissions) for use as an energy carrier in data centres (DCs).
The potential merit of such a system is the presence of energy storage and power generation in a conventional data centre and the possible synergies of converting these systems to hydrogen production to achieve carbon savings through carbon arbitrage.

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1. Introduction

This paper sets out to review the potential for on-site production of low-carbon hydrogen (hydrogen produced without associated carbon emissions) for use as an energy carrier in data centres (DCs).

The potential merit of such a system is the presence of energy storage and power generation in a conventional data centre and the possible synergies of converting these systems to hydrogen production to achieve carbon savings through carbon arbitrage;

This involves:

1. Consuming additional grid electricity to produce and store hydrogen at times of low grid carbon intensity.
2. Consuming stored on-site hydrogen to displace grid electricity at times of high carbon intensity.

This strategy offers carbon reductions in the absence of a reliable and continuous supply of green hydrogen which for medium to large hyperscale data centres (For example from 1MW up to 1GW) is not currently available within existing utility infrastructure or road transport capabilities.

To explore the possible merits or deficiencies of such a concept a mathematical model is proposed to consider the application of this concept to grid carbon variations in a series of different geographical locations. The model will use a notional data centre and a selection of applicable hydrogen technologies for hydrogen production, storage and power generation. The results will be used to assess potential merits or shortfalls and therefore analyse challenges and opportunities associated with this potential energy carrier technology.

Hydrogen as an Energy Store

The first thing to consider about hydrogen is that it can be utilised as a form of energy storage medium – similar to a battery. A typical hydrogen energy storage cycle is illustrated in Figure 1. With this in mind, the following section outlines the principles of energy storage to assist Variable Renewable Energy (VRE) and contribute to greater consumption of low-carbon renewable energy within data centres.

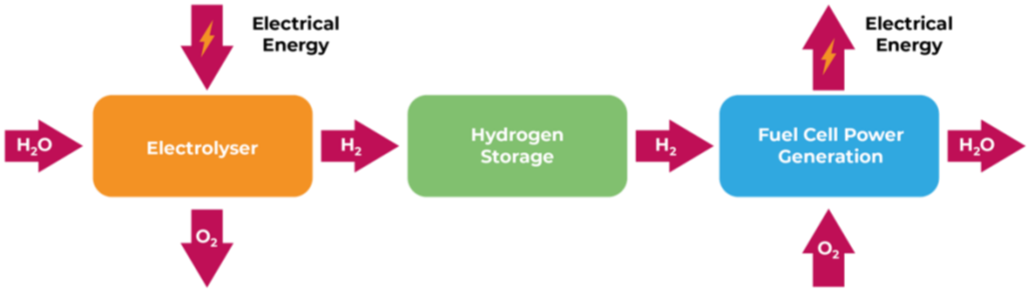


Figure 1.: Energy Cycle of Hydrogen Storage

Variable Renewable Energy & Energy Storage

To consider and discuss the use of energy storage as a component within a carbon reduction strategy it is necessary to consider the following phenomenon: VRE.

VRE is a renewable energy source that is not dispatchable due to its fluctuating nature, such as wind power and solar power, as opposed to a controllable renewable energy source, such as dammed hydroelectricity or biomass, or relatively constant sources, such as geothermal power.

Due to this variability and supply/demand imbalance, many national grids currently experience another phenomenon referred to as ‘curtailed VRE’. This is surplus renewable energy production which is effectively lost due to lack of simultaneous matching demand.

Energy storage technology is an increasingly critical component for the effective adoption of renewable energy. Energy storage plays the role of balancing supply and demand where the output of renewable energy is subject to weather and cannot be controlled to coincide with energy demand. Energy stored during times of high supply and low demand can be transported at times of low supply and high demand.

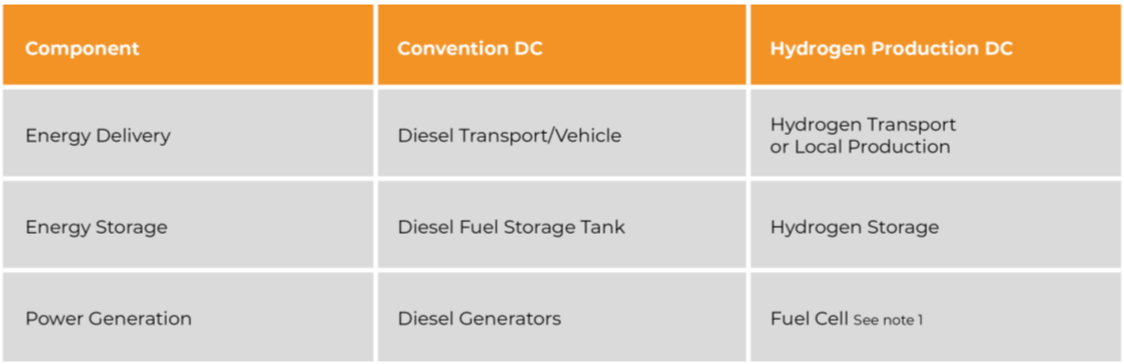
This means low carbon energy which is in surplus at certain times can be stored and discharged at alternative times of renewable energy deficit to achieve lower overall carbon emissions associated with energy consumption on the system.

Synergies For Energy Storage within Data Centres

Energy storage to manage VRE is typically considered at grid scale. However, data centre facilities comprise the following characteristics and elements which offer potential synergies with the objective of storage and increased consumption of VRE:

- High Electrical Energy Demand
- Energy Storage
- Power Generation
- Requirement to reduce operational Green House Gas Emissions

Figure 2 below illustrates the concept of this synergy in respect to the mapping of components between a typical conventional data centre facility and a data centre facility adopting hydrogen energy storage:



Component	Convention DC	Hydrogen Production DC
Energy Delivery	Diesel Transport/Vehicle	Hydrogen Transport or Local Production
Energy Storage	Diesel Fuel Storage Tank	Hydrogen Storage
Power Generation	Diesel Generators	Fuel Cell See note 1

Figure 2: Mapping of conventional DC facility components to Hydrogen energy storage cycle

Notes

1. Fuel Cells represent one leading technology for the conversion of storage hydrogen. A number of fuel cell types are available. An overview of a typical fuel cell technology is provided in the ‘Hydrogen Power Production’ section and fuller analysis of different fuel cell types is reviewed in the i$_3$ white paper titled: ‘Assessment and Application of Fuel Cells to Data Centres’.

In addition to fuel cells, it is also possible to extract electrical power from hydrogen by use of reciprocating engines. This technology will also be the topic of a separate GHG abatement white paper.

Standby or Prime

One aspect in this comparison which does not present an immediate synergy is the fact that the local power generation within a typical data centre is provided on a standby basis. (Considering data centres with access to relatively low carbon grid electricity).

The concept considered under an energy storage regime described in this paper requires continuous operation of power generation equipment using hydrogen energy during periods of high grid carbon intensity. At this time, the power generation is operated as the prime source of electricity and the grid reverts to a standby source.

During periods of low carbon intensity, this relationship reverses: the grid would change to the prime source of electricity and the power generation from hydrogen would revert to the standby source.

To take advantage of hydrogen production equipment to produce green energy there is also an economic necessity to maximise the utilisation of this equipment for the intended goal.

The principal purpose of the hydrogen production equipment is to operate as the prime source continuously for extended periods. A typical schematic showing this integration for a gas-supplied fuel cell technology in a prime application is shown below in Figure 3. This was first published within the i$_3$ Solutions *GHG Abatement Group paper: Assessment of Fuel Cells Application in Data Centres for Greenhouse Gas Abatement Benefits* and shows a fuel cell utilising natural gas. Under the premise of this paper, this hydrogen gas is proposed.

Within a VRE carbon reduction energy storage strategy, automated control of the switch between the two sources will be managed based on live grid carbon intensity data stream from the grid operator for the relevant grid region.

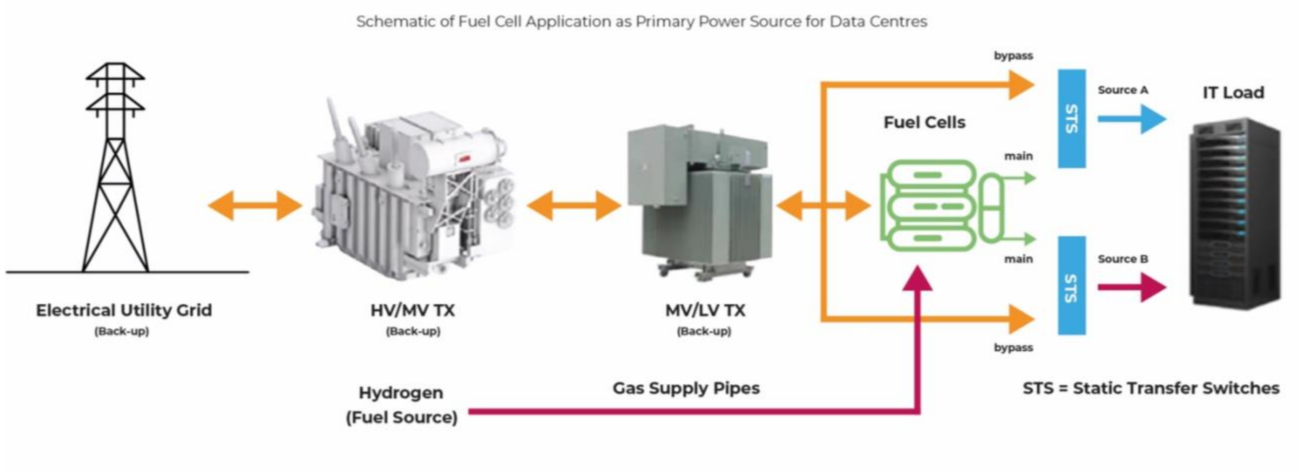


Figure 3: Schematic of Fuel Cell Application as Primary Power Source for Data Centres

Hydrogen Delivery or Local Production?

The long-term goal of the Hydrogen Economy's vision is large-scale production of zero-carbon, green hydrogen on a national and international scale. The progress of this vision is still in a nascent stage. However, the quantity and scale of such endeavours are accelerating rapidly at this moment in time. The hydrogen produced in this vision will require transportation to deliver the green fuel to data centres and other energy-consuming sites and purposes. Transport of hydrogen has a vast array of routes, technology options, states of storage and methods available for consideration. The options are also affected by strategy decisions regarding the geographical location of data centres and hydrogen production facilities with respect to the location of renewable energy sources and the location of demand for data centres.

An appraisal of these hydrogen transportation options and strategies will be the subject of a further white paper by the i_3 Solution Green House Gas Abatement Group.
The development of hydrogen delivery infrastructure is not available to continuously deliver hydrogen energy in the quantities necessary for prime electrical production in the first instance. For this reason, this first paper has chosen to appraise the possibility of local on-premises hydrogen production and power generation to achieve overall reduced carbon emissions by displacing consumption of electricity from times of high carbon intensity to times of low carbon intensity. In theory, carbon reduction could be achieved by the following steps:

- Increased consumption of grid variable renewable electricity at low carbon intensity
- Reduced consumption of fossil fuel electricity at high carbon intensity electricity
- Overall net reduction in greenhouse gas associated with data centre electricity consumption

To assess this value it is proposed to calculate this quantity by use of a mathematical model of a typical data centre provisioned with the potential hydrogen storage and power generation systems and typical grid carbon intensity patterns of a developed country. The potential for advantage that can be gained can be quantified in % and kg of carbon savings.

The development of this model is the primary focus of this paper in order to develop an understanding of the potential benefit of this approach. The details and method of the assessment are outlined in later sections of this paper.

2. Hydrogen Production

Colour Choices

In literal terms, hydrogen is colourless however a system of figurative colour coding has evolved to describe the source and/or process production. This is presented below.

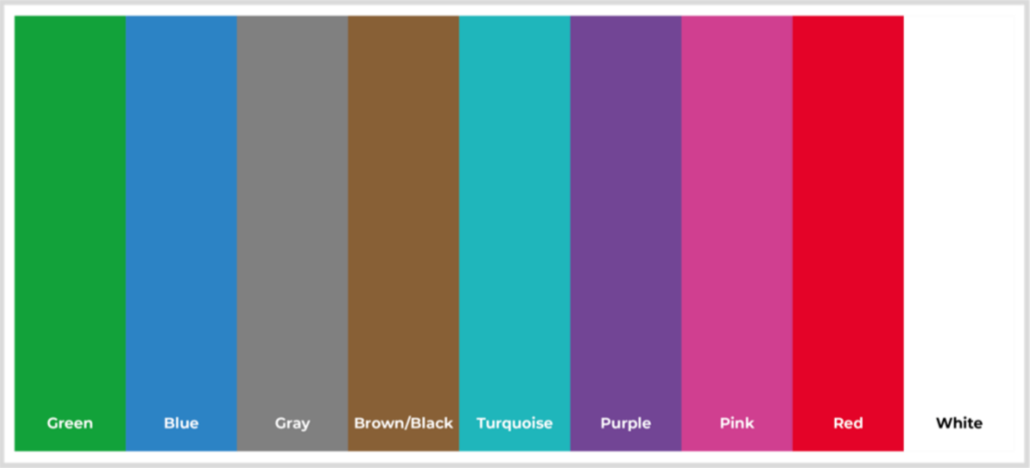


Figure 4: Hydrogen figurative colour coding

The figurative meaning of each colour has reached a recognised status and has been well defined by the following summary outlined by h2bulletin on their website (2):

- Green hydrogen is produced through the water electrolysis process by employing renewable electricity. The reason it is called green is that there is no CO2 emission during the production process. Water electrolysis is a process which uses electricity to decompose water into hydrogen gas and oxygen. The water required for this process is fresh water with as few contaminants as possible which would compromise the electrolysis process and efficiency. Sea water for example is not readily compatible with electrolysis.

- Blue hydrogen is sourced from fossil fuels. However, the CO2 is captured and stored underground (carbon sequestration). Companies are also trying to utilise the captured carbon called carbon capture, storage and utilisation (CCSU). Utilisation is not essential to qualify for blue hydrogen. As no CO2 is emitted, the blue hydrogen production process is categorised as carbon neutral.

- Grey hydrogen is produced from fossil fuel and commonly uses steam methane reforming (SMR) method. During this process, CO2 is produced and eventually released into the atmosphere.

- Black or brown hydrogen is produced from coal. The black and brown colours refer to the type of bituminous (black) and lignite (brown) coal. The gasification of coal is a method used to produce hydrogen.

- However, it is a very polluting process, and CO2 and carbon monoxide are produced as by-products and released into the atmosphere.
- Turquoise hydrogen can be extracted by using the thermal splitting of methane via methane pyrolysis. The process, though at the experimental stage, removes the carbon in a solid form instead of CO2 gas.

- Purple hydrogen is made through using nuclear power and heat through combined chemothermal electrolysis splitting of water.

- Pink hydrogen is generated through the electrolysis of water by using electricity from a nuclear power plant.

- Red hydrogen is produced through the high-temperature catalytic splitting of water using nuclear power thermal as an energy source.

- White hydrogen refers to naturally occurring hydrogen.

With the exception of 'Green', the hydrogen classifications above have several disadvantages, for example, reliance on fossil fuels and resulting carbon emissions or reliance on nuclear power and associated hazardous waste and other risks. White hydrogen does not incur these disadvantages. There have been some geological discoveries of natural hydrogen deposits in France recently which provide encouraging news of the potential for this hydrogen class. However, this class is not renewable and the extraction rate and distribution constraints from the relatively small number of available locations will place limits on application and availability.

The premise of this paper is reliant entirely on green production sources and methods which are outlined in the following section.

3. Green Hydrogen Production

Electrolytic splitting of water is the primary method considered in this paper for application in small-scale local production within data centres. However, it should be noted that there are other processes available such as the following:

- Thermochemical processes
- Biomass gasification
- Biomass-derived liquid reforming
- Solar thermochemical hydrogen
- Direct solar water splitting
- Photoelectrochemical (PEC)
- Photobiological
- Biological processes
- Microbial biomass conversion
- Photobiological. (Also, a form of direct solar as above)

The electrolysis of water considered in this paper and application is the process of splitting the water molecule into its constituent parts, hydrogen and oxygen. Whilst there are numerous nascent technologies currently at different stages of research and development, there are three main fuel cell technology types available on the market:

- Alkaline
- Solid oxide
- Proton exchange membrane (PEM)

The principles of the three technology types are outlined below:

Alkaline electrolysers

- Uses a liquid electrolyte solution such as potassium hydroxide (KOH) or sodium hydroxide (NAOH) and water.
- The hydrogen is produced in a “cell” which consists of an anode, cathode and membrane. The cells are typically assembled in series in a “cell stack” that produces more hydrogen and oxygen as the number of cells increases.
- When current is applied to the cell stack, the hydroxide ions (OH-) move through the electrolyte from the cathode to the anode of each cell, with hydrogen gas bubbles generated on the cathode side of the electrolyser and oxygen gas at the anode, as represented here.
- Low-cost technology
- Conventional alkaline electrolysis has an efficiency of about 70% (2) (3) (4)

Solid oxide electrolysers

- Use a solid oxide electrolyte, ceramic material such as zirconium dioxide
- Solid oxide electrolyser cells (SOEC) operate at temperatures which allow high-temperature electrolysis to occur, typically between 500 and 850 °C.
- When current and steam are both applied water is split, hydrogen is collected at the cathode where steam is introduced, and oxygen is conducted through the dense cathode to the anode side.
- The theoretical SOEC electrical efficiency is close to 100% while hydrogen production efficiency is around 90 %. (5)
- The disadvantage of high-temperature operation is the long start-up and response time.
- Relatively nascent level of technology maturity

PEM electrolysers

- PEM electrolysers use a proton exchange membrane which uses a solid polymer electrolyte.
- When current is applied to the cell stack, the water splits into hydrogen and oxygen and the hydrogen protons pass through the membrane to form H2 gas on the cathode side.
- Compact system design
- Average working efficiencies for PEM electrolysis are around 80%-90%. (6)
- High equipment cost

The further variants and alternatives of the above technologies use various catalysts, and alternative materials, additional sources of heat and energy to achieve advances in efficiency, reduced reliance on rare earth materials and lower capital costs. These are too numerous to fully outline and appraise within this paper which seeks to consider overall potential benefits for an onsite production to achieve a low carbon energy storage strategy which is primarily focused on what carbon reduction gains could be conceivably achieved as opposed to an appraisal of the wide range of varying technologies. For the purpose of this paper, a single technology is considered.

Due to the low-temperature operation and the established and commercialized status of the technology, alkaline electrolysis is the primary focus of this study. This offers a representative benchmark by which to make an overall appraisal of the concept.

PEM electrolysis has the advantage of compactness, low-temperature operation and the established and commercialized status of the technology. This does present PEM electrolysis as a viable option. However, this study has been completed based on the slightly lower efficiency and lower cost option of AFC.

Due to their relatively slow response time, SOEC electrolysers are not suitable for rapid responses to grid carbon intensity fluctuations and have not been considered for the basis of this VRE energy storage concept.

Both of these technologies have merits which can be applied to data centres in a range of strategies although alkaline electrolysis has been selected for the basis of the study for the above reasons.

4. Hydrogen Storage

The VRE energy storage regime studied in this paper requires a method for storage of generated hydrogen between periods of low grid carbon intensity when hydrogen would be produced on-site and periods of high grid carbon intensity when hydrogen would be consumed.

Hydrogen can be stored physically as either a gas or a liquid. Storage of hydrogen as a gas typically requires high-pressure tanks (350–700 bar [5,000–10,000 psi] tank pressure). Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one-atmosphere pressure is −252.8°C. Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption). (7)

The wide range of technologies for the storage of hydrogen are outlined below.
Physical based storage

- Compressed gas (ambient temperature and high pressure)
- Cryogenic liquid storage (between ambient and 4 bar pressure and very low temperatures)
- Cryo-compressed (very low ambient and very high temperatures)

Chemical & material-based storage.

- Adsorbent
- Liquid organic
- Interstitial hydride
- Complex hydride
- Chemical hydrogen (For example storage in combination with nitrogen in the form of ammonia)

For the purpose of this study, the simpler option of compressed gas has been selected. The lower complexity of this technology is more suited to a critical data centre in which downtime due to faults on numerous complex systems is not desirable.

This technology is mature although it has several disadvantages. As with all processes, there is an energy cost and so an inefficiency factor is required to account for the energy consumed undertaking the compression work. The efficiency of energy storage by compressed hydrogen gas is about 94% (8).

There is a further inefficiency due to material loss in this storage method. Despite the method using thick steel vessel walls hydrogen atoms are so extremely small that over time a portion of the stored high-pressure volume is lost due to atoms escaping through the vessel walls.

Compressed gas is also not the greatest option for storage density and as a result, the dimensions of a storage vessel for even a small or medium data centre is very large.

There is further work to be done appraising the optimal choice of storage technology. A review of hydrogen storage and transport options for use in data centres will be the subject of a further i₃ Solutions/EYP GHG white paper. However, for this preliminary appraisal, the option of compressed gas storage is applied, accounting for losses due to compression and gas escape of this technology.

5. Hydrogen Power Generation

Overview

Power production from stored hydrogen energy is dependent on the process of recombining hydrogen with oxygen to release energy. In its most simplistic form, this can be achieved by the combustion process. However, the use of fuel cells to achieve this energy extraction is more efficient and avoids other forms of local pollution associated with hydrogen combustion such as nitrogen oxide (formed due to the combination of any fuel with heat in the presence of air which includes both nitrogen and oxygen).

Principle of Fuel Cells

A fuel cell is an electrochemical cell that converts the chemical energy of a fuel combined with oxygen into electricity through an electrochemical reaction. Hydrogen fuel cells consist of an anode, a cathode, and an electrolyte that allows ions, positively charged hydrogen ions (protons), to move between the two sides of the fuel cell. At the anode, a catalyst causes the fuel to separate into ions (protons) and electrons. The ions move from the anode to the cathode through the electrolyte. At the same time, electrons flow through an external circuit, creating a flow of electricity. At the cathode, another catalyst causes ions, electrons, and oxygen to react, forming water and possibly other products including heat. (9) (10).

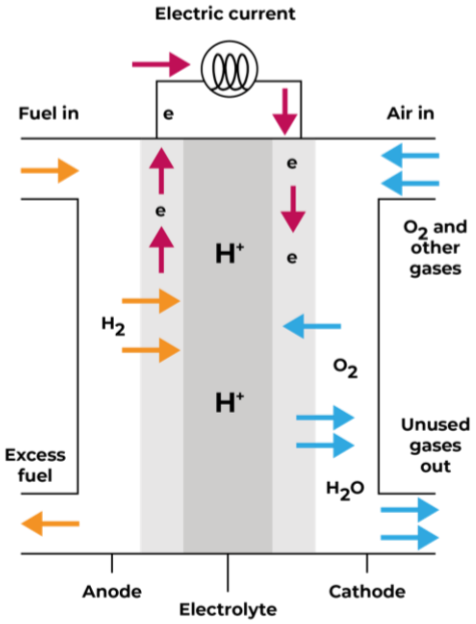
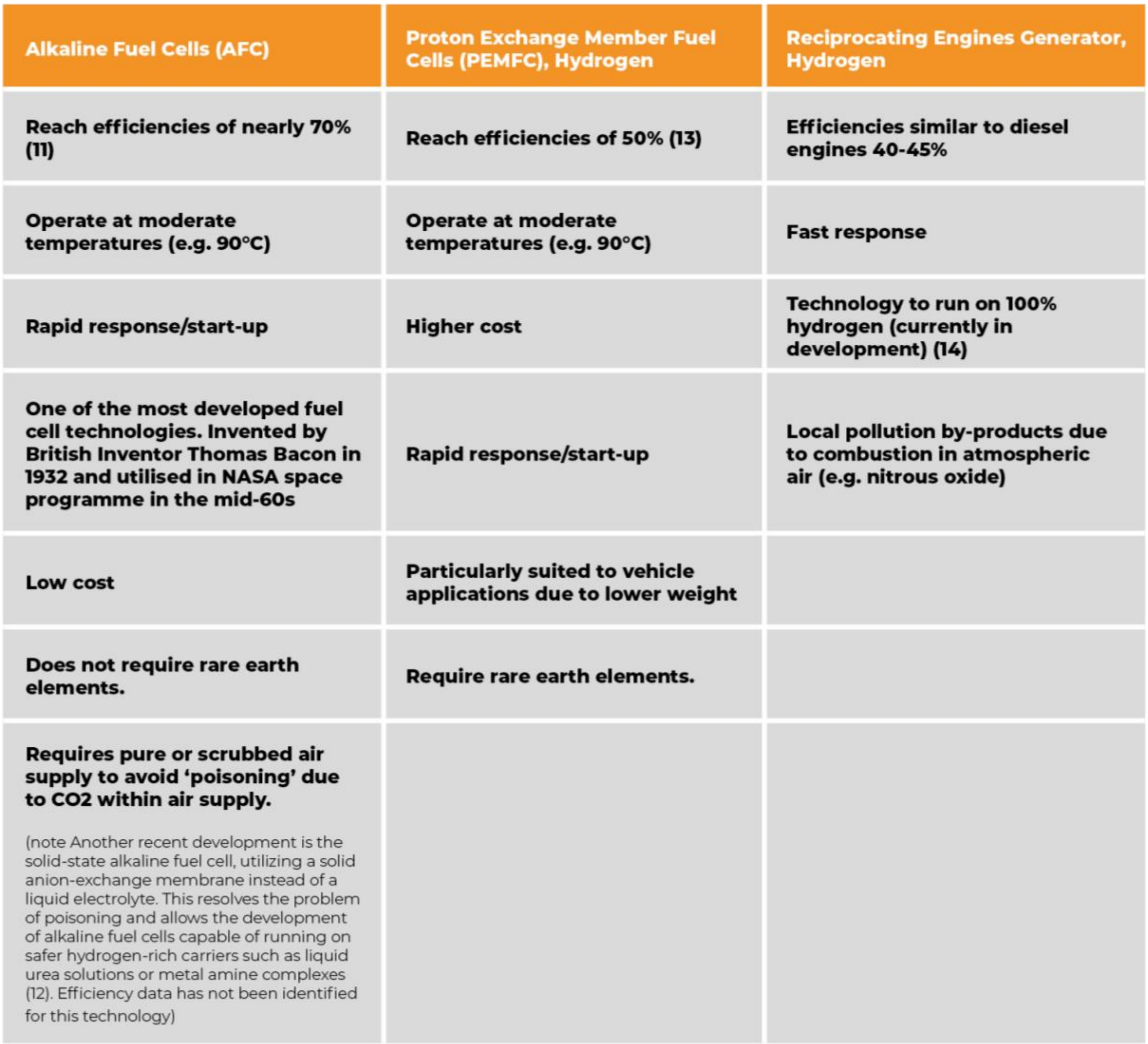


Figure 5 – Diagram outlining principle of fuel cell electricity generation

Available Technologies

The available technologies for fuel cells and reciprocating engines utilizing hydrogen fuel are outlined below:



Alkaline Fuel Cells (AFC)	Proton Exchange Member Fuel Cells (PEMFC), Hydrogen	Reciprocating Engines Generator, Hydrogen
Reach efficiencies of nearly 70% (11)	Reach efficiencies of 50% (13)	Efficiencies similar to diesel engines 40-45%
Operate at moderate temperatures (e.g. 90°C)	Operate at moderate temperatures (e.g. 90°C)	Fast response
Rapid response/start-up	Higher cost	Technology to run on 100% hydrogen (currently in development) (14)
One of the most developed fuel cell technologies. Invented by British Inventor Thomas Bacon in 1932 and utilised in NASA space programme in the mid-60s	Rapid response/start-up	Local pollution by-products due to combustion in atmospheric air (e.g. nitrous oxide)
Low cost	Particularly suited to vehicle applications due to lower weight	
Does not require rare earth elements.	Require rare earth elements.	
Requires pure or scrubbed air supply to avoid 'poisoning' due to CO2 within air supply. (note Another recent development is the solid-state alkaline fuel cell, utilizing a solid anion-exchange membrane instead of a liquid electrolyte. This resolves the problem of poisoning and allows the development of alkaline fuel cells capable of running on safer hydrogen-rich carriers such as liquid urea solutions or metal amine complexes (12). Efficiency data has not been identified for this technology)		

Figure 6 – Available technologies for fuel cells and reciprocating engines utilizing hydrogen fuel. Outline advantages and disadvantages

The following fuel cells which are not fed directly by hydrogen or require reformation of fossil fuels to provide hydrogen are listed below for information but not considered due to non-compatibility with the proposed concept.

- Direct methanol fuel Cells (DMFC) Methanol (15) (13)
- Phosphoric Acid Fuel Cells (PAFC), Natural Gas (15) (13)
- Molten Carbonate Fuel Cells (MCFC), Natural Gas (15) (13)
- Solid oxide fuel cells (SOFC), Natural Gas (15) (13)

6. Model Analysis

Overview

The method undertakes a calculation using historical data sets for grid carbon intensity. The calculation simulates the response of a hydrogen enabled notional data centre operated and controlled with the objective of offsetting grid power consumption using hydrogen energy storage and local power regeneration to reduce overall carbon emissions.

Different data sets are utilized for various locations (national or regional). This variety of locations provides an opportunity to compare and understand the outcome for different compositions, range and frequency of grid carbon intensity.

The selected technologies, discussed in the previous sections of this paper are adopted within the model and their characteristics such as process efficiency and losses are represented within the calculation. This includes the losses and efficiencies of the hydrogen production, storage and power generation systems including inefficiencies of water electrolyser, fuel cell, hydrogen compression system, and hydrogen gas losses associated with hydrogen storage.

Typical, nominal sizing characteristics are selected for the basis of a notional data centre and also reflected within the calculation model.

The model is created in Microsoft Excel and simulates the response of the hydrogen enabled data centre at each period of carbon intensity (half hourly data) with the following control philosophy described below and in the principle of a 'carbon arbitrage' model highlighted in figure 7 whereby grid electricity at high carbon intensity is traded for grid electricity at low carbon intensity:

- Hydrogen Production Mode: At periods of low carbon intensity, the data centre draws additional grid power in order to produce hydrogen via local electrolysers and store the hydrogen using compressed gas storage systems.
- Hydrogen Consumption Mode: At periods of high carbon intensity, the data centre avoids grid power consumption by switching to prime generation using hydrogen fuel cells and drawing from local hydrogen storage.
- At all times a minimum of 24 hours hydrogen fuel is conserved for standby resilience and the system fuel store fluctuates between 24- and 48-hours storage
- Hydrogen production and consumption mode set points are selected to achieve carbon reduction benefits.
- The set point selection to achieve this objective accounts for the round-trip efficiency of the hydrogen production, storage and discharge cycle and the range of carbon intensity for the location in each case.

Control set points are grid carbon intensity levels at which energy charge and discharge occur are calculated to determine maximum benefit accounting for the inefficiency of the full hydrogen energy storage cycle. For example, an overall energy cycle of 33% requires that a charge level carbon intensity 1 3rd lower than the discharge level before a carbon offsetting benefit is achieved. The round-trip efficiency for the system considered is 37%.

The model assumes that the site operation does not use carbon intensity forecasting and therefore has a fixed control set point for both charge and discharge throughout the year.

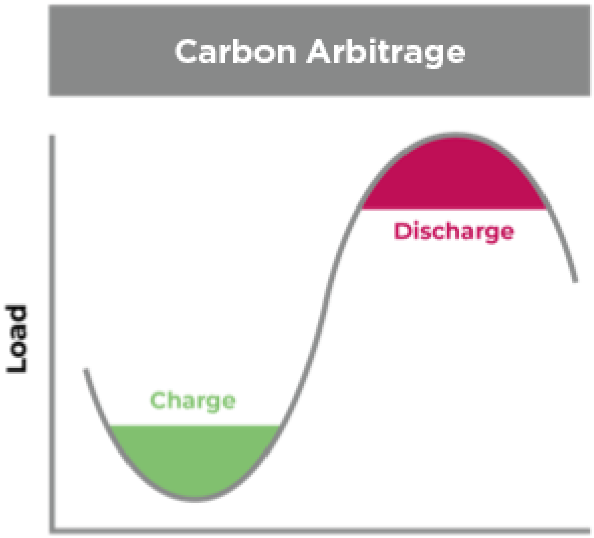


Figure 7: Principle of a 'carbon arbitrage' model whereby grid electricity at high carbon intensity is traded for grid electricity at low carbon intensity

7. Assumptions, Input Data and Parameters

The information, data and parameters utilized are listed below:

- Publicly available grid infrastructure hourly carbon intensity records for the year 2021 for each location. Sourced from respective national grid utility companies.
- Parameters of each selected hydrogen technology for the following energy cycle stages:
  - Hydrogen production.
  - Hydrogen storage.
  - Hydrogen power generation
- Parameters of a notional and typical data centre
- Carbon intensity 'charge' and 'discharge' control set points (calculated based on local carbon intensity average value and required range to achieve carbon reduction benefits).

The rationale, basis and values for key parameters are summarised in the following sections.

Grid Locations

The model has been applied to 4 different geographical regions with varying local grid carbon intensities due to variation and availability of composition of fossil fuel and renewable power production into the power grid regionally. Figure 8 lists the regions and source of carbon intensity to which the model has been applied:

Region	Time Period	Data Source
UK (nationally)	2021	National Grid Electricity System Operator (16)
UK (South East)	2021	National Grid Electricity System Operator (16)
Southern Scotland	2021	National Grid Electricity System Operator (16)
Ireland (All island)	2021	EIRGRID Smart Dashboard (17) (18)

Figure 8: Grid Carbon Intensity Data sets – Regions and Data Sources

Data has been selected as a recent and representative year for which complete data was available at the time of commencement of writing this paper.

Selected Hydrogen Technologies

The selected hydrogen energy cycle components are listed in Figure 9.

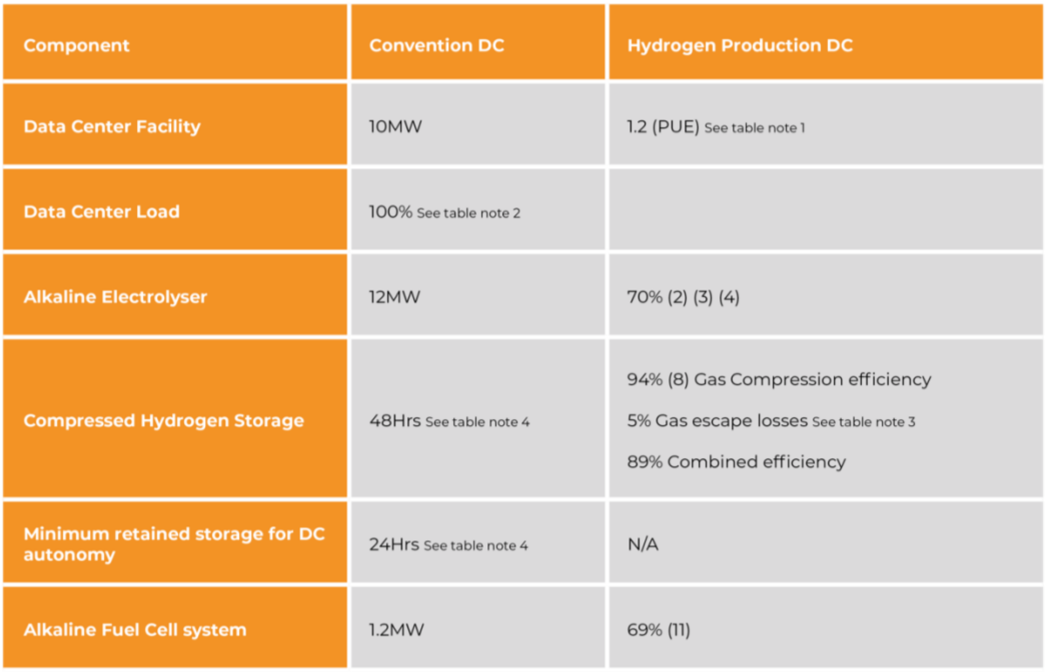
Component	Convention DC
Energy Production	Alkaline Electrolyser
Energy Storage	Compressed Vessel Storage
Power Generation	Alkaline Fuel Cell

Figure 9: Selected hydrogen technologies adopted within model

Notional Data Centre and System Parameters

For the purpose of the modelling, the typical data centre parameters and notional system capacities which have been selected are listed in Figure 10 in combination with the selected hydrogen energy generation, storage and power generation component parameters. System efficiencies are based on typical modern technology capabilities with reference to the information discussed earlier within the paper.

The scale of the components tabled below for use in the assessment model are selected to consider the hypothetical value of a hydrogen energy storage system matched to the capacity and demand of the data centre. In practice the scale and cost of these components would be significant in relation to the physical scale of the notional 10MW data centre. However, for the purpose of this study and to assess the theoretical maximum benefit that could be achieved, this fully matched configuration is assessed as reference point from which value and opportunity can be considered.



Component	Convention DC	Hydrogen Production DC
Data Center Facility	10MW	1.2 (PUE) See table note 1
Data Center Load	100% See table note 2	
Alkaline Electrolyser	12MW	70% (2) (3) (4)
Compressed Hydrogen Storage	48Hrs See table note 4	94% (8) Gas Compression efficiency 5% Gas escape losses See table note 3 89% Combined efficiency
Minimum retained storage for DC autonomy	24Hrs See table note 4	N/A
Alkaline Fuel Cell system	1.2MW	69% (11)

Figure 10: Selected notional data centre and hydrogen technology parameters adopted within model

Notes

1 This is assumed to be constant throughout year. Whilst PUE typically reduces during winter periods due to improved efficiency due to low ambient temperature this characteristic is ignored for the purpose of simplification of the calculation model.

2. The model assumes that the data centre is under sustained continuous operation at 100% utilization throughout the year. Whilst utilization below 100% is more typical this value is set at an arbitrary level for the purpose of the model.
3. Estimated value
4. The fuel system storage is based on 24 hour baseline (retained at all times to provide this level of autonomy in the event of main failure) and an additional 24 hour energy storage which is utilized as grid energy storage and allowed to fluctuate in response to grid carbon intensity.

8. Model Results

The modelling results for each geographical region are presented in the following subsections of the paper. For each location and set of results the outcome is presented in two forms:

1. Graphical form showing:

- Time in months along the X Axis
- The fluctuation of grid carbon intensity across the whole year. The left-hand Y-axis shows the value of grid carbon intensity measured in gCO2/kWHr.
- The response of the data centre's hydrogen storage system. The right-hand Y-axis shows the value of hydrogen storage at each point in time measured in hours of data centre operation.
- Carbon intensity control set point at which hydrogen generation and surplus grid power consumption takes place via electrolyser. (i.e. sufficiently low grid carbon intensity)

- Carbon intensity control set point at which hydrogen consumption and power generation takes place via fuel cell. (i.e. sufficiently high grid carbon intensity)

2. Tabulated form showing:

Additional and Offset Energy

- Additional Energy Consumption for Hydrogen Production
- Annual grid energy consumed, in megawat hours (MWHrs), in order to generate/produce hydrogen locally within the facility.
- Offset energy consumption by hydrogen power generation.
- Annual grid energy, in MWHrs, avoided by virtue of local electricity production by consumption of locally stored hydrogen.

Net Energy Differences

- DC carbon grid energy consumption without hydrogen systems
- The total energy in MWHrs that would have been consumed by the DC in the absence of the hydrogen energy storage systems. Calculated for comparative purposes as a baseline against which to compare the total energy consumption of the DC with the hydrogen systems.
- DC carbon grid energy consumption with hydrogen systems
- The total energy consumption in MWHrs by the DC when applying the hydrogen production regime. Calculated for comparative purposes to compare against the baseline.
- Net additional grid energy consumption
- The additional difference in total grid energy consumed, in MWHrs, compared to the baseline, due to the operation of the hydrogen storage regime.
- % net additional grid energy consumption

The additional difference in total grid energy consumed, in percentage terms compared to the baseline, due to the operation of the hydrogen storage regime.

Net Carbon Emissions Differences

- DC carbon emissions without hydrogen systems
- The total carbon emissions, in tonnes of C02, that would have been consumed by the DC in the absence of the hydrogen energy storage. Calculated for comparative purposes as a baseline against which to compare the total carbon emissions of the DC with the hydrogen systems.
- DC carbon emissions with hydrogen systems
- The total carbon emissions, in tonnes of C02, caused by the DC when applying the hydrogen production regime. Calculated for comparative purposes to compare against the baseline.
- Carbon emission reduction
- The reduction in total grid energy consumed, in tonnes of C02, compared to the baseline, due to the operation of the hydrogen storage regime.
- Carbon emission reduction

- The reduction in total grid energy consumed, in percentage terms, compared to the baseline, due to the operation of the hydrogen storage regime.

UK (Nationally)

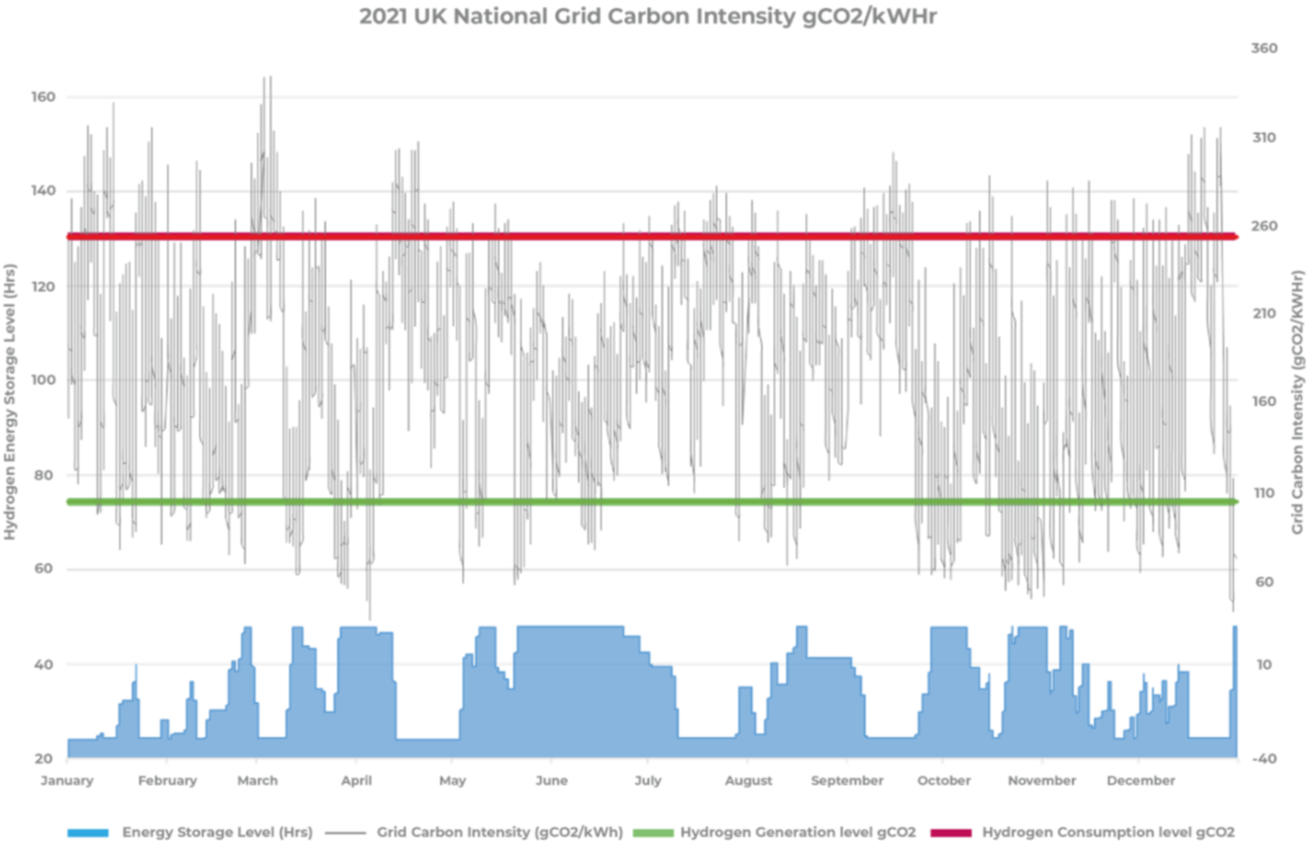
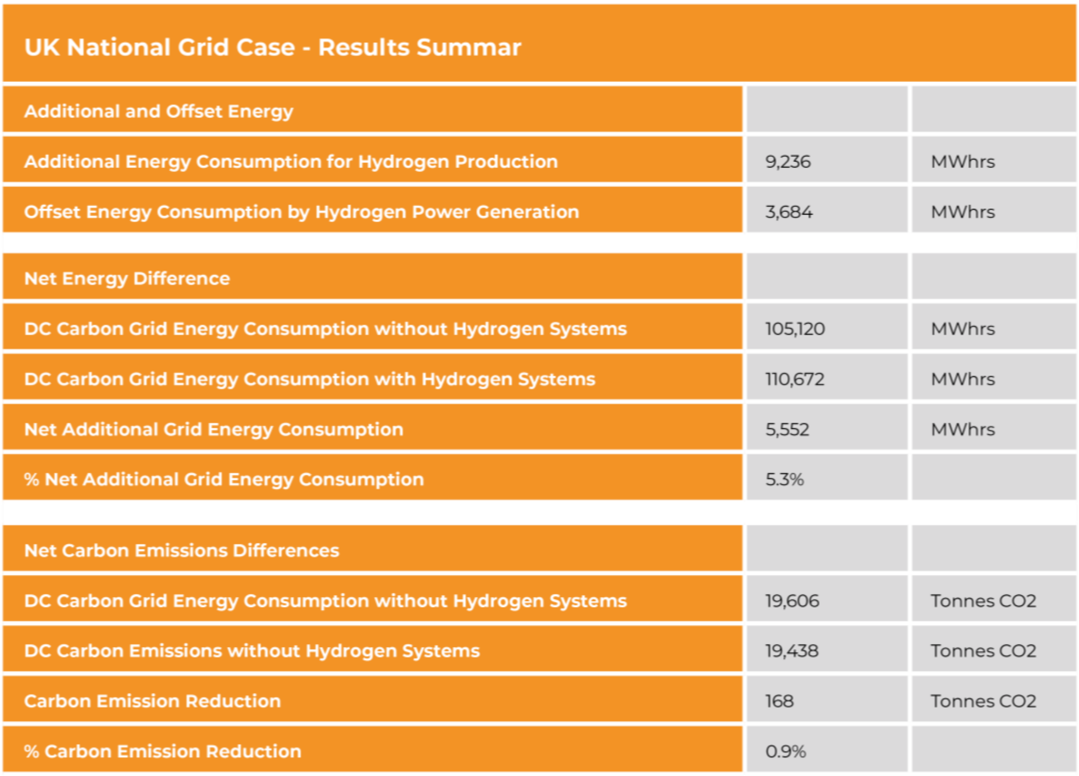


Figure 11: Simulated Results for Model of 10MW DC with Matched Hydrogen Production & Power Generation Facilities – 2021 UK National Grid Carbon Intensity



UK National Grid Case - Results Summar		
Additional and Offset Energy		
Additional Energy Consumption for Hydrogen Production	9,236	MWhrs
Offset Energy Consumption by Hydrogen Power Generation	3,684	MWhrs
Net Energy Difference		
DC Carbon Grid Energy Consumption without Hydrogen Systems	105,120	MWhrs
DC Carbon Grid Energy Consumption with Hydrogen Systems	110,672	MWhrs
Net Additional Grid Energy Consumption	5,552	MWhrs
% Net Additional Grid Energy Consumption	5.3%	
Net Carbon Emissions Differences		
DC Carbon Grid Energy Consumption without Hydrogen Systems	19,606	Tonnes CO2
DC Carbon Emissions without Hydrogen Systems	19,438	Tonnes CO2
Carbon Emission Reduction	168	Tonnes CO2
% Carbon Emission Reduction	0.9%	

Figure 12 - Simulated Summary Annual Results for Model of 10MW DC with Matched Hydrogen Production & Power Generation Facilities – 2021 UK National Grid Carbon Intensity

England (Southeast Region)

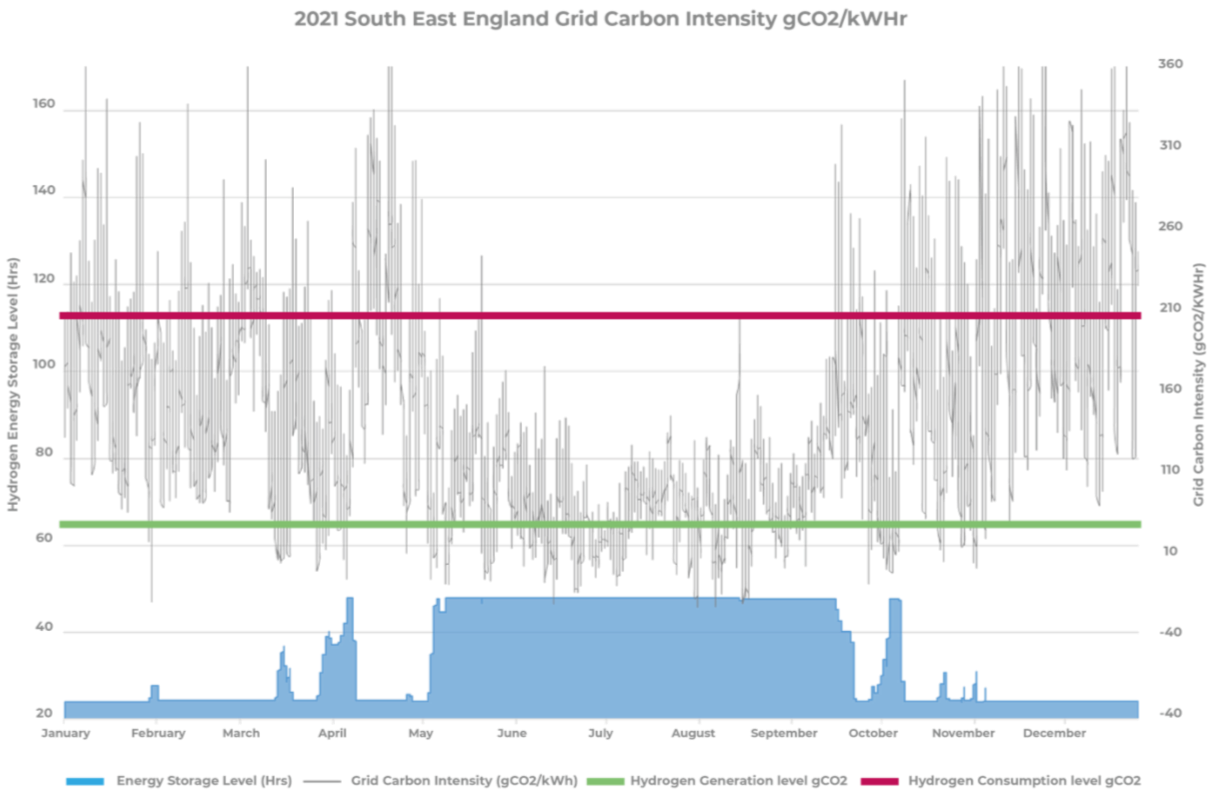


Figure 13: Simulated Results for Model of 10MW DC with Matched Hydrogen Production & Power Generation Facilities – 2021 England - Southeast Region Grid Carbon Intensity

England (Southeast Region) - Results Summar		
Additional and Offset Energy		
Additional Energy Consumption for Hydrogen Production	3,409	MWhrs
Offset Energy Consumption by Hydrogen Power Generation	1,464	MWhrs
Net Energy Difference		
DC Carbon Grid Energy Consumption without Hydrogen Systems	105,120	MWhrs
DC Carbon Grid Energy Consumption with Hydrogen Systems	107,065	MWhrs
Net Additional Grid Energy Consumption	1,945	MWhrs
% Net Additional Grid Energy Consumption	1.9%	
Net Carbon Emissions Differences		
DC Carbon Grid Energy Consumption without Hydrogen Systems	15,877	Tonnes CO2
DC Carbon Emissions without Hydrogen Systems	15,747	Tonnes CO2
Carbon Emission Reduction	130	Tonnes CO2
% Carbon Emission Reduction	0.8%	

Figure 14: Simulated Results for Model of 10MW DC with Matched Hydrogen Production & Power Generation Facilities – 2021 Scotland - Southern Region Grid Carbon Intensity

Scotland (Southern Region)

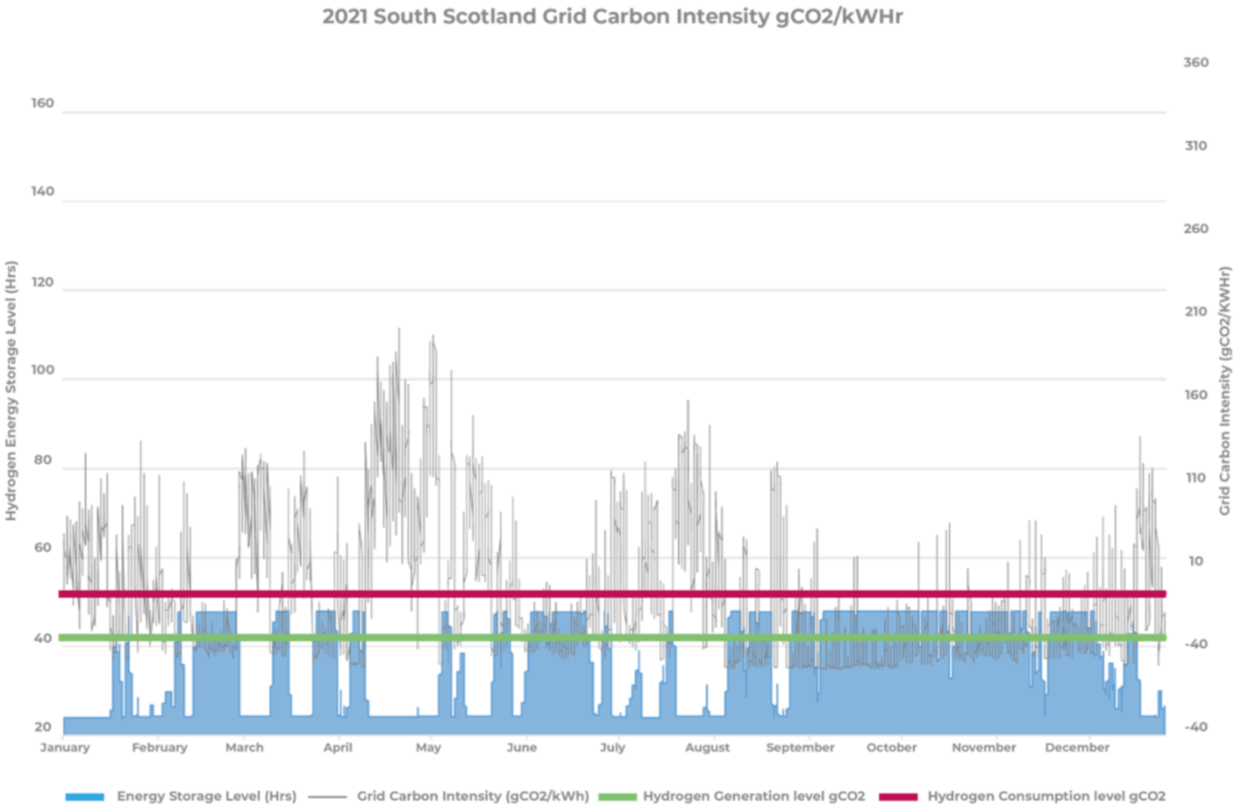
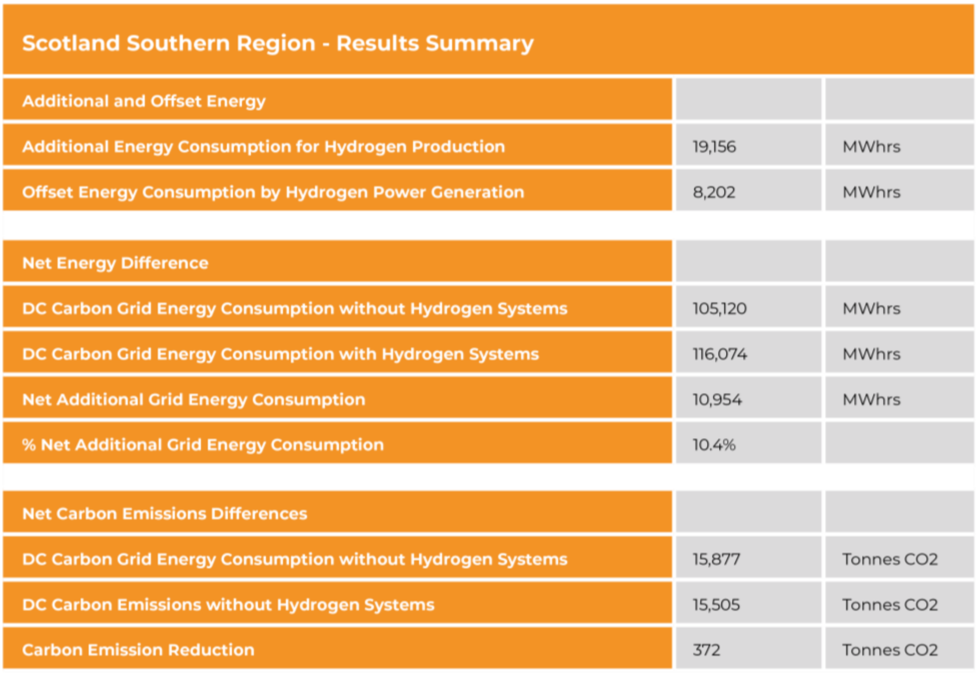


Figure 15 - Simulated Summary Annual Results for Model of 10MW DC with Matched Hydrogen Production & Power Generation Facilities – 2021 UK National Grid Carbon Intensity.



Scotland Southern Region - Results Summary		
Additional and Offset Energy		
Additional Energy Consumption for Hydrogen Production	19,156	MWhrs
Offset Energy Consumption by Hydrogen Power Generation	8,202	MWhrs
Net Energy Difference		
DC Carbon Grid Energy Consumption without Hydrogen Systems	105,120	MWhrs
DC Carbon Grid Energy Consumption with Hydrogen Systems	116,074	MWhrs
Net Additional Grid Energy Consumption	10,954	MWhrs
% Net Additional Grid Energy Consumption	10.4%	
Net Carbon Emissions Differences		
DC Carbon Grid Energy Consumption without Hydrogen Systems	15,877	Tonnes CO2
DC Carbon Emissions without Hydrogen Systems	15,505	Tonnes CO2
Carbon Emission Reduction	372	Tonnes CO2

Figure 16 - Simulated Summary Annual Results for Model of 10MW DC with Matched Hydrogen Production & Power Generation Facilities – 2021 Scotland - Southern Region Grid Carbon Intensity

Ireland (All-Island)

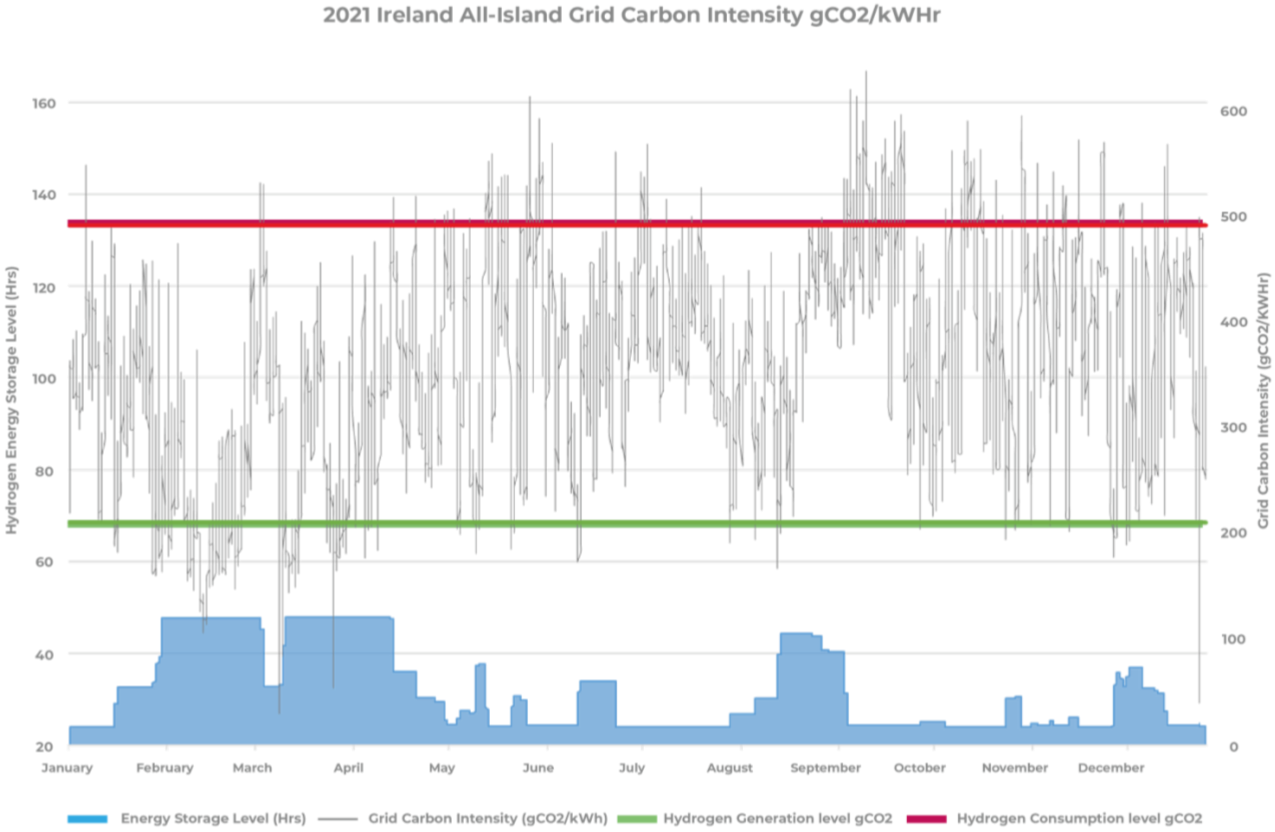
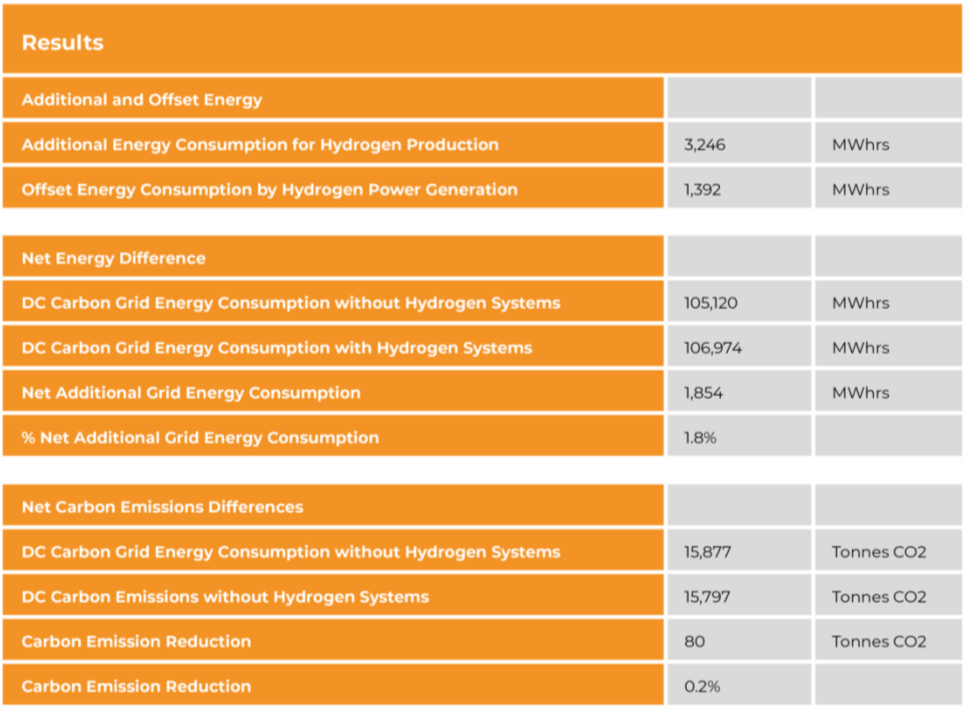


Figure 17: Simulated Results for Model of 10MW DC with Matched Hydrogen Production & Power Generation Facilities – 2021 Ireland – All-Island Region Grid Carbon Intensity



Results		
Additional and Offset Energy		
Additional Energy Consumption for Hydrogen Production	3,246	MWhrs
Offset Energy Consumption by Hydrogen Power Generation	1,392	MWhrs
Net Energy Difference		
DC Carbon Grid Energy Consumption without Hydrogen Systems	105,120	MWhrs
DC Carbon Grid Energy Consumption with Hydrogen Systems	106,974	MWhrs
Net Additional Grid Energy Consumption	1,854	MWhrs
% Net Additional Grid Energy Consumption	1.8%	
Net Carbon Emissions Differences		
DC Carbon Grid Energy Consumption without Hydrogen Systems	15,877	Tonnes CO2
DC Carbon Emissions without Hydrogen Systems	15,797	Tonnes CO2
Carbon Emission Reduction	80	Tonnes CO2
Carbon Emission Reduction	0.2%	

Figure 18: Simulated Summary Annual Results for Model of 10MW DC with Matched Hydrogen Production & Power Generation Facilities – 2021 Ireland – All-Island Region Grid Carbon Intensity

9. Results Analysis & Conclusion

Analysis & Discussion

The results show that carbon emissions saving can be achieved by employing on-site hydrogen production coupled with additional consumption of grid energy at times of low carbon intensity. However, the reductions achieved are very low.
Regions with generally lower carbon intensity offer more opportunity for gains due to the ability to produce relatively low carbon hydrogen. Whilst the offset grid energy is also generally at a less severe carbon intensity, the range of hydrogen generation and consumption control set points is much smaller. This allows a charge and discharge cycle to take place more frequently as smaller high frequency grid carbon intensity fluctuations can be exploited.

This is pattern and effect occur due to the round-trip efficiency of the hydrogen production and power generation cycle creating a requirement for a multiplying factor between hydrogen 'generation' levels and 'consumption' levels - represented by the green and red lines on the results graphs respectively. The round-trip efficiency of the modelled system is 43%. This essentially requires that the hydrogen 'production' takes place only when grid carbon intensity is at least 2.3* times greater than the grid carbon intensity level at which the hydrogen was generated.

$*Multiplying\ factor\ is\ effectively\ the\ reciprocal\ of\ the\ efficieny;\ \left(\frac{1}{0.43}\right) = 2.3$

The benefit of low carbon grid intensity is best demonstrated in the Southern Scotland region for which the hydrogen 'generation' grid carbon intensity level is as low as 19 gCO2/kWHr. Requiring a 'Consumption' grid carbon intensity control set point of approximately 45 gCO2/kWHr. The carbon intensity on the Scottish Southern grid frequently oscillates across this small range of 26 gCO2/kWHr offering regular opportunities for charging and discharging and trading between periods of low and high carbon intensity.

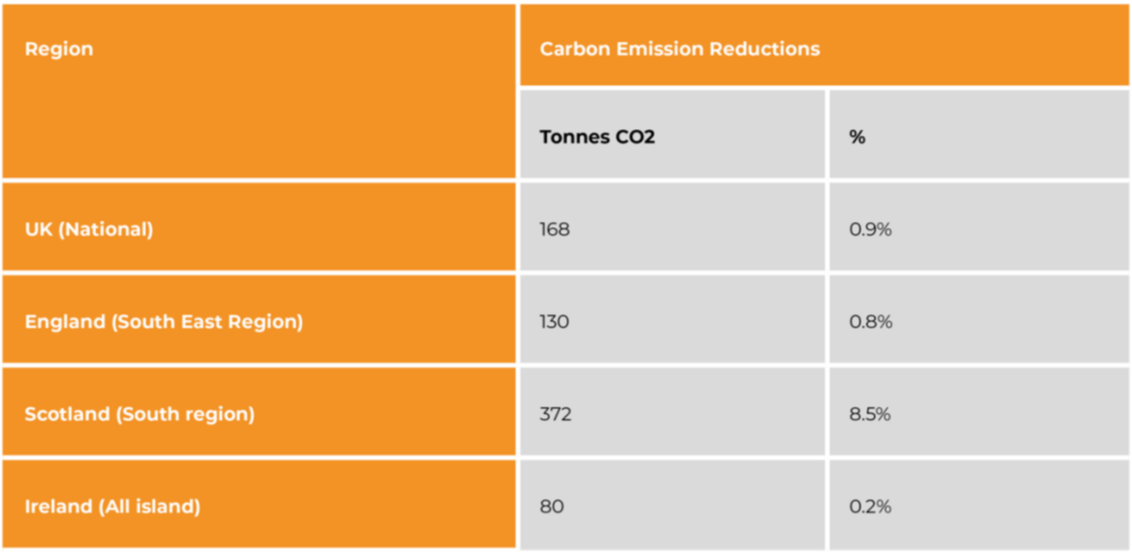
The high carbon intensity of the Irish (All-Island) grid is significantly higher on average. This results in a larger range between ‘generation’ and ‘consumption’ - 210 gCO2/kWHr and 190 gCO2/kWHr respectively - an absolute range of 280gCO2/kWHr. Whilst the grid in this region has a high degree of fluctuation it does not often exceed this wide range and so there are very few opportunities for beneficial carbon trading across the year.

This poor outcome can also be seen in the results for the south-east region of England. Whilst the grid intensity is lower in this region the required carbon intensity range between ‘generation’ and ‘consumption’ is between 86 gCO2/kWHr and 220 gCO2/kWHr respectively, resulting in an absolute range of 134 gCO2/kWHr. It can be seen, that through a significant proportion of the year, from June to September, there is below average grid carbon intensity and a modest variation in grid carbon intensity. However no advantage is gained from carbon intensity remaining below the hydrogen consumption level throughout this period. The hydrogen storage remains full and the system components unutilized throughout this period.

The UK national region represents a blended average of carbon intensities of all regions on the UK. For this reason, it offers an insufficient degree of variation due to the various conditions for grid renewables around the UK serving to offset each other and remove extremes from the data set.

The large-scale grid data is also an unrepresentative data set as it fails to recognize that should additional low carbon grid electricity be consumed due to a demand response strategy (such as that proposed in this paper) the source of the additional energy is much less likely to be consumed from the low carbon sources contributing to the low carbon factor. This is because of the geographical separation of the contributing power sources relative to the consumption location and limitation in the grid distribution infrastructure.

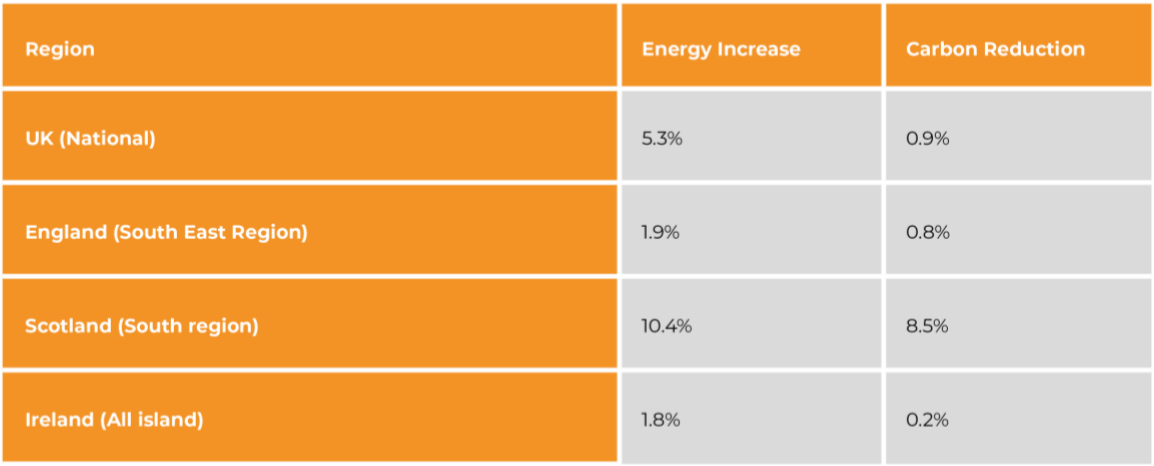
The results for all regions are summarised below:



Region	**Carbon Emission Reductions**	
	Tonnes CO2	**%**
UK (National)	168	0.9%
England (South East Region)	130	0.8%
Scotland (South region)	372	8.5%
Ireland (All island)	80	0.2%

Figure 19: Carbon Emissions Reduction by Region

Another aspect demonstrated in the results is the expected additional net power consumption required to operate the regime by which hydrogen energy is created and stored within the energy storage cycle. The increased energy consumption for each region is tabulated against carbon reduction achieved below:



Region	Energy Increase	Carbon Reduction
UK (National)	5.3%	0.9%
England (South East Region)	1.9%	0.8%
Scotland (South region)	10.4%	8.5%
Ireland (All island)	1.8%	0.2%

Figure 20: Additional Energy consumption against carbon emissions reduction by region

10. Results Summary

The following conclusions can be drawn from this analysis:

- Low carbon reductions can only be achieved by use of on-site hydrogen production in DCs
- The carbon reductions achievable in areas of high average grid carbon intensity and relatively low variation in grid carbon intensity are very poor - less than 1%.
- In regions with low carbon intensity and relatively wide and frequent fluctuations in grid carbon intensity modest carbon emission reductions can be achieved.
- The best value demonstrated within the data sets analysed, is the southern Scotland region which is shown to achieve an 8.5% carbon emission reduction of 372 tonnes of CO2. Equivalent to 660 flight trips between London and New York or 744 hours of carbon free operation of the 10MW DC.
- This quantity of carbon emissions it is unlikely to justify the cost of the system's electrolysers, hydrogen compression and storage, fuel cell installation and additional energy costs over and above the cost of a conventional DC standby power installation, particularly at this scale in comparison to the cost of other carbon reduction concepts (With respect to the carbon that could be saved with this expenditure elsewhere).

11. Challenges & Opportunities

There are a number of shortfalls inherent in the systems conceived for on-premises hydrogen production in data centres. These are demonstrated in the simulation results and analysis. These shortfalls are identified and discussed under the following subheadings with the objective of considering how best to overcome these shortfalls or reconsider the concept for combining data centres with on premises green hydrogen production.

The challenges and opportunities are considered under the following key subject areas:

- Utilization
- Round-trip efficiency
- Cost & scale
- Operational risks

12. Utilization

Utilization Challenge

All modelled scenarios demonstrated a low number of hours of system and equipment operation. This is a significant shortfall as it indicates that poor value is obtained from the system. Put in context the utilization factor is an improvement over conventional standby generator systems which are very rarely called into useful action outside of routine testing hours. However, the low utilization of the electrolyser and fuel cell equipment indicates that this technology is not being applied in the most productive way.

The electrolysers' operation is curtailed by the following features of the concept:

- Hydrogen storage – once storage reaches capacity electrolysers have to stop operating.
- Range of grid carbon intensity values – electrolyser is only useful to operate when grid carbon intensity is a certain factor below average and peak levels. The round-trip efficiency of the system creates the need for a wide range of carbon intensity required to offer carbon gains in the carbon arbitrage process.
- Fixed and rigid control set points – The fixed control set point regime adopted into the models in this paper misses an opportunity to make significant gains associated with certain fluctuations in carbon intensity. It can be seen from the grid carbon graphs in several locations that certain fluctuations, with sufficient range for carbon saving do exist, and these are missed by the fixed set points in the models. These wide range fluctuations are missed because they occur at levels which are offset from annual average patterns

Utilization Opportunities

Hydrogen Storage

The obvious solution is to simply increase the storage capacity. For example; doubling the total storage capacity from 48Hours to 96hours, on the South Scotland model, would result in an increased carbon reduction of 14.4% /627 tonnes CO2 up from 8.5%/372 tonnes CO2.

However, this is a significant spatial and cost increase of an installation which is already significant in scale and cost.

Alternatively, the fraction of the system which is reserved for standby autonomy in the event of mains failure could be reduced and reallocated for use in the hydrogen energy cycle. For example, the base storage could be reduced from 24 to 12 hours and the volume available for energy storage cycling would increase to 36 Hours. Whilst the system would not be reduced to 12 hours standby autonomy throughout the year it would clearly have the disadvantage of increasing the risk that available autonomy is exceeded if a utility failure were to occur coincident with a low point in the hydrogen storage cycle for the site.

Import/export

A solution which has been discounted in the premise of this paper, due to available infrastructure at the necessary volumes, is the importing of hydrogen to site via a means of transport. The transportation of hydrogen for use in DCs is the subject of a future paper. The above consideration does open the possibility to consider smaller manageable hydrogen deliveries when coupled with an onsite production regime. The concept that presents itself is that of supplementing low storage levels by delivery of green hydrogen during periods of extended high grid carbon intensity when storage levels are low, for example when storage levels dip below the required 24hour autonomy level. These deliveries could be more manageable in scale and scheduled to align with these periods of time. This hybrid regime would allow increased utilization of the system's fuel cells and if the delivered hydrogen is green, it would bring about clear carbon emissions reductions.

Another solution is to increase hours of hydrogen production and electrolyser utilization, which does not incur the penalty of increased storage or autonomy risk, is to export hydrogen gas for use off-site. This presents an opportunity to offer low carbon hydrogen to other users within the local economy and create a revenue stream for the facility in addition to achieving further carbon reductions.

Location

The optimal solution to maximise electrolyser utilization for green hydrogen production is to site the installation in the geographical location of renewable power generation, with ample hydrogen storage capacity and ability to export surplus hydrogen. In this way every available hour of surplus renewable energy production can be exploited using electrolyser plant operation.

This opportunity leads to the broader view that the ideal location for a data centre is in close proximity to renewable power generation infrastructure. This would afford the DC the potential opportunity to use hydrogen as a prime energy source with continuous availability to large scale hydrogen production and storage and access to the grid connection for back-up secondary power.

The optimal geographical location for on-premises hydrogen production is the location where the grid offers low and relatively wide range of grid intensity. The data set for the South of Scotland provides a good example of this. However, there may be opportunities to seek and identify regions in a wider global search which could offer greater characteristics more suited to this system concept.

Carbon Exchange Control

More intelligent or predictive control regimes may harvest more opportunities available from a further range of variations which exist in grid carbon intensity. There is an opportunity to use carbon forecasting technique to gain more advantage from the range of carbon intensity. 96 hour forecast data of carbon intensity is publicly available. This may offer some advanced decision making to optimize carbon intensity advantages. For example if the following 4 days are projecting lower carbon intensity and storage levels are approaching maximum levels hydrogen production could be held off to await the low carbon opportunity.
Greater opportunities exist for forecasting information through the use of AI.

This approach uses machine learning and optimization algorithms to make intelligent, data-driven decisions to identify the most cost-effective times for hydrogen generation and storage. One such study adopts real-time usage of artificial intelligence (AI) software to optimize hydrogen production and storage at the European Marine Energy Centre (EMEC) in Orkney (19).

Round Trip Efficiency

As has been analysed within the results summary, the energy cycle regime is limited by the round trip efficiency which creates a requirement for wide range between the carbon intensity levels at which hydrogen generation and consumption can take place beneficially. This limits the possibilities for the system to be applied where the grid carbon intensity variation does not sufficiently offer the required range.
A high round trip efficiency is also to the detriment of the carbon value gained form each unit of hydrogen produced. The carbon intensity of the hydrogen produced is a product of the two following parameters:

- Grid carbon intensity at the point of production
- Inefficiency of the round trip cycle.

Round Trip Efficiency - Opportunity

Certain technologies available for each stage in the hydrogen energy cycle are currently mature and unlikely to undergo significant improvements in efficiency. However due to the high level of interest in hydrogen as an energy carrier in the drive to achieve net zero carbon across all industries, there is a great deal of

technological advancement in new or novel variations on existing technology for hydrogen production, hydrogen storage and hydrogen power generation.
It is predicted that PEM electrolyser technology which currently achieves circa 50% (13) will increase and whilst those predictions vary there is anecdotal evidence suggesting much high efficiency will be achieved. For example, a recent report of a record breaking 95% efficiency in 2022 from the manufacturer Hysata (20).

There are also technologies available which have not been considered within this paper which utilise waste heat as an additional energy input into the hydrogen production process. For example, high temperature electrolysis. Whilst the efficiency improvement is comparable with the alkaline electrolysers the fact that there is a significant quantity of waste heat from conventional data centres presents the possibility that additional hydrogen production can be achieved at zero or close to zero additional energy cost. The opportunities for this system require further investigation. High temperature electrolysis is likely to require conversion of low-grade waste heat (typically created within data centres) to high grade temperature via additional processes. Thus improvements in the near future will increase the range of sites at which hydrogen production can be considered and increase the carbon reduction gains for a given system size. Therefore, this will also contribute to cost efficiency.

Cost & Scale

The capital cost of the systems described within the models in this paper is significantly greater than those of a conventional diesel generator backed data centre.

The scale, in volume and area, to accommodate the very large hydrogen storage vessels, gas compression and treatment systems, electrolyser plant and fuel cell plant is significantly greater than that of a conventional diesel generator backed data centre. Land with access to sufficient grid power capacity and proximity to areas of demand for data centre services and connectivity is at a premium and therefore this increased spatial requirement incurs further significant costs associated with the system concepts discussed in this paper.

Whilst the costs analysis of such a system is not analysed in detail one of the most notable features of system considered in this paper is the sheer volume size of the stored gas. Whilst hydrogen has an impressive energy density by mass the energy density by volume is relatively low due to the gas's low density. Even at very high storage pressures the vessels size are in the order of magnitude which would require land area 4 to 5 times that of an equivalent conventional data centre.

Hydrogen gas has a higher risk profile than diesel fuel due to explosion risk and ability of the gas's small atoms to escape as discussed on the report sub section Operational Risks. The cost of safely storing this gas will be reflected in the higher cost of these storage systems. There will be a higher standard and requirement for operation of a facility using large volumes of hydrogen gas in order to ensure safety. The low utilization of equipment discussed above also contributes to a low level of value offered by the concept's systems.

Whilst it may be predicted that future legislation may soon require data centre development to incur greater costs necessary to drive down carbon emissions associated with this service provision in society, it will remain necessary to seek the most cost-effective solutions to achieve this outcome. If these challenges are not met and addressed then this concept is unlikely to play a role in this objective.

Cost & Scale - Opportunity

Storage Size

Opportunities to reduce the size and cost of hydrogen storage lay in the available technologies alternative to the compressed gas systems selected in this study. These are listed below as identified in the review of available technologies earlier in this paper:

- Physical-based storage.
    - Cryogenic liquid storage (between ambient and 4 bar pressure and very low temperatures)
    - Cryo-compressed (very low ambient and very high temperatures)
- Chemical & material-based storage.
    - Adsorbent
    - Liquid organic
    - Interstitial hydride
    - Complex hydride
    - Chemical hydrogen (For example storage in combination with nitrogen in the form of Ammonia)

A number of the above technologies have different characteristics in respect to energy density by volume and may offer superior spatial benefits. These technologies may also offer superior efficiencies in terms of storage conversions and rate of energy loss over prolonged storage periods.

Storage size may also be mitigated under a hybrid concept combining storage with an import/export strategy as discussed above in respect to the opportunities to improve system utilization. The ability to rely on hydrogen fuel delivery on a regular basis would also serve to reduce the scale of required on-site storage capacity.

It is the intention of the i$_3$ Solutions/EYP Green House Gas Abatement group to release a future paper focusing specifically on transport and delivery strategy for use of hydrogen in data centres. This paper will review the available storage and transport possibilities in greater detail.

Other hybrid concepts combining the new system on a smaller scale in combination with a conventional diesel backup system may offer a gateway solution to commence incorporation of hydrogen production and may even offer better value in terms of carbon per unit of additional expenditure.

Location considerations discussed under utilization opportunities also apply to solutions for scale and cost. Siting of DCs close to central green hydrogen production sites offers greater access to delivered hydrogen. Siting DCs directly adjacent or within central hydrogen production facilities offers the ability to share storage systems and therefore share costs or and benefit of these required storage facilities.

A great deal of improvement is underway with respect to the cost of fuel cell and electrolyser technology. The increased availability and use of this equipment as a wide range of industries adopt hydrogen is driving down costs.

One of the key metrics discussed in associated with electrolyser equipment is utilization. The commercial value of this equipment is determined by hours of hydrogen production. Therefore, the opportunities to improve utilization will also contribute to value.

In addition to revenue streams associated with surplus hydrogen production there is also the potential for co-production. Oxygen gas (a highly valuable gas in medical applications and other industries) is a by-product of splitting water to form hydrogen. Although not a conventional service offered by data centres, capture and sale of this gas would serve to offset system capital and operational costs.

Operational Risks

Operational Risk – Challenge

The risks associated with hydrogen use and storage are greater in comparison to conventional power generation fuels. Hydrogen is highly flammable. It has an ignition range approximately seven times wider than natural gas for example. The gas is more prone to leakage due to the small size of the gas atoms.

Whilst the storage and management of this gas and other similar explosive gases is well understood and standards and practices for effectively mitigating explosion risks are well established, the fact that the use of green hydrogen is growing and undergoing innovation and development including new applications does present increased risks.

These risks would be presented during construction, testing and operation of a data centre utilising hydrogen energy. Effective mitigation of these risks would require increased capital and operational costs and sufficient separation space.

Operational Risk – Opportunity

The technologies and practices to effectively mitigate the risks associated with hydrogen gas storage are available. In the case of compressed gas storage and management it is anticipated that these practices would include the following:

- Locating storage vessels at higher pressures below ground to protect from impact and provide reinforcement of storage structure.
- Locating vessel above ground where suitable for pressure involved
- Locating storage away from structures and personnel
- Pressure relief management
- Automatic power and production cut off controls.
- Continuous ventilation and emergency ventilation arrangements
- Continuous detection (gas detection systems) and pressure monitoring
- Secondary and tertiary leakage containment systems
- Fire detection and suppression systems
- Installation designed, constructed, tested, and operated in accordance with recognised standards and practices and by qualified and trained personnel.

13.Conclusion

This paper has set out to review the potential for on-site production of low carbon hydrogen for use as an energy carrier in data centres.

The potential merit of such a system is the presence of energy storage and power generation in a conventional data centre and the possible synergies of converting these systems to hydrogen production to achieve carbon savings through carbon arbitrage; This involves:

1. Consuming additional grid electricity to produce and store hydrogen at times of low grid carbon intensity.
2. Consuming stored on-site hydrogen to displace grid electricity at times of high carbon intensity.

This strategy offers carbon reductions in the absence of a reliable and continuous supply of green hydrogen at the volumes necessary to continuously supply a modern medium, large data centre facility.

To explore the possible merits or deficiencies of such a concept a mathematical model has been created to consider application of this concept to grid carbon variations in a series of different geographical locations. The model has used a notional data centre and a selection of applicable hydrogen technologies for hydrogen production, storage and power generation.
The model has reached the following findings:

- Only low carbon reductions can be achieved by use of on-site hydrogen production in DCs
- The carbon reductions achievable in areas of high average grid carbon intensity and relatively low variation in grid carbon intensity are very poor. Less than 1%
- In regions with low carbon intensity and relatively wide and frequent fluctuations in grid carbon intensity modest carbon emission reductions can be achieved.
- The best value demonstrated within the data sets analysed, is the South Scotland Region which is shown to achieve an 8.5% carbon emission reduction of 372 Tonnes of CO2. Equivalent to 660 Flight trips between London and New York or 744 hours of carbon-free operation of the 10MW DC.
- This quantity of carbon emissions it is unlikely to justify the cost of the system's electrolysers, hydrogen compression and storage, fuel cell installation and additional energy costs over and above the cost of a conventional DC standby power installation. Particularly at this scale in comparison to the cost of other carbon reduction concepts. (With respect to the carbon that could be saved with this expenditure elsewhere)

In summary, it can be concluded that the merits of full-scale on-site hydrogen production range from low to medium depending on location. In all locations the carbon reductions do not indicate value in comparison to the scale and cost of the system. Further advantages or gains are needed to achieve value commercially and in respect to alternative carbon reduction solutions.

A review of challenges and opportunities indicates that there are a range of opportunities to incrementally improve the potential value:

1. Alternative hydrogen storage – higher density in order to achieve greater spatial efficiency.
2. Intelligent carbon intensity control and forecasting – greater carbon reduction
3. Further round-trip efficiency improvements of new hydrogen technologies – greater carbon reductions and reduced costs

More significantly the study has highlighted several opportunities and areas for further consideration:

1. To achieve major carbon reductions in data centres the infrastructure to deliver a continuous supply of green hydrogen is needed.
2. Hybrid on-site hydrogen production may offer a stepping stone opportunity on the hydrogen road map – in combination with hydrogen import-export. This may also offer better value on smaller-scale systems in combination with conventional DC power technology.
3. Combined campuses including central utility infrastructure for green hydrogen production with data centre facilities may offer a solution where shared cost and benefits of energy storage if available.

It is the intention of the i$_3$ Solutions/EYP GHG, Green House Gas Abatement Group to further investigate these considerations – in particular the possibility of large-scale green hydrogen storage and transport.

The ability to deliver zero-carbon energy to data centre facilities in the future is considered essential to reduce global carbon emissions. Hydrogen remains an energy carrier of great interest in this goal. Both the location of data centres and transport infrastructure associated with green hydrogen production will be pivotal. Taking advantage of this potential zero-carbon energy carrier is of critical interest to data centre development.

14. References

1. **Wee, Lee Seng.** *Assessment of Fuel Cells Application in Data Centres for Greenhouse Gas Abatement Benefits.* s.l. : i3 Solutiuons and EYP GHG Abatment Group, 2023.

2. *Alkaline Water Electrolysis Powered by Renewable Energy: A Review.* **Brauns, Jorn and Turek, Thomas.** s.l. : MDPI & Institute of Chemical and Electrochemical Process Engineering, Clausthal University of Technology.

3. *A comprehensive review on PEM water electrolysis.* **Carmo, Marcelo, et al.** s.l. : Science Direct, International Journal of Hydrogen, 2012.

4. *Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review.* **Buttler, Alexander and Spliethoff, Hartmut.** s.l. : Science Direct, Renewable and Sustainable Energy Reviews, 2017.

5. **Trimis, Prof. Dr.-Ing. Dimosthenis.** http://www.helmeth.eu/index.php. [Online] Helmeth, 19 08 2023. [Cited: 19 08 2023.] http://www.helmeth.eu/index.php/technologies/high-temperature-electrolysis-cell-soec.

6. *Hydrogen production by PEM water electrolysis – A review.* **Kumar, S. Shiva and Himabindu, V.** 3, s.l. : Science Direct, 2019, Materials Science for Energy Technologies, Vol. 2.

7. **Energy, US Department of.** Hydrogen Storage. *Office of ENERGY EFFICIENCY & RENEWABLE ENERGY.* [Online] https://www.energy.gov/eere/fuelcells/hydrogen-storage#:~:text=Hydrogen%20can%20be%20stored%20physically,pressure%20is%20%E2%88%92252.8%C2%B0C..

8. **Leung, MKH, et al.** *Feasibility study of renewable hydrogen in Hong Kong.* s.l. : The University of Hong Kong Library, 2004.

9. **Energy and US Department of.** Fuel Cells. *Office of ENERGY EFFICIENCY & RENEWABLE ENERGY.* [Online] 2023. https://www.energy.gov/eere/fuelcells/fuel-cells#:~:text=A%20fuel%2C%20such%20as%20hydrogen,creating%20a%20flow%20of%20electricity..

10. **Wikipedia.** Fuel Cell. [Online] 2023. https://en.wikipedia.org/wiki/Fuel_cell.

11. *Solar Energy Engineering (Second Edition), Chapter 7 - Industrial Process Heat, Chemistry Applications, and Solar Dryers.* **Kalogirou, Soteris A.** 2nd, s.l. : Academic Press.

12. **Wikipedia, - Contributors.** Alkaline fuel cell. *Wikipedia.* [Online] March 2023. https://en.wikipedia.org/wiki/Alkaline_fuel_cell.

13. *Emerging electrochemical energy conversion and storage technologies.* **Sukhvinder P. S. Badwal, et al.** s.l. : Frontiers in Chemistry, 2014.

14. **Wartsila Corporation.** Wärtsilä launches major test programme towards carbon-free solutions with hydrogen and ammonia. *www.wartsila.com/media/news.* [Online] https://www.wartsila.com/media/news/14-07-2021-wartsila-launches-major-test-programme-towards-carbon-free-solutions-with-hydrogen-and-ammonia-2953362.

15. **Energy, Department of.** Types of Fuel Cells. *Office of Energy Efficiency & Renewables Energy.* [Online] https://www.energy.gov/eere/fuelcells/types-fuel-cells.

16. **National Grid ESO.** data-groups/carbon-intensity1. *Data.National Grid ESO.* [Online] 2023. https://data.nationalgrideso.com/data-groups/carbon-intensity1.

17. **EirGrid Group.** Smart Grid Dashboard. *Smart Grid Dashboard.* [Online] 2023. https://smartgriddashboard.com/#.

18. CO_2 intensity (gCO_2/kWh) of the all-island electricity grid. 01.01.2021. 15 minutes interval data. [compl.] Head of Market Operations Viotas Jon Sedgwick.

19. **EMEC, The European Marine Energy Centre Ltd.** PRESS RELEASE: H2GO POWER TO TRIAL AI HYDROGEN OPTIMISATION SYSTEM AT EMEC. *The European Marine Energy Centre Ltd.* [Online] 2022. https://www.emec.org.uk/h2go-power-to-trial-ai-at-emec/.

20. **E GÜLZOW, M SCHULZE.** 3 - Alkaline fuel cells. *Materials for Fuel Cells.* s.l. : Science Direct.

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Joe joined i_3 Solutions with over 15 years' management and delivery experience spanning critical facility modernisation and £1bn+ construction projects. Joe has worked on some of the largest scale data centre deployments in Europe.

His mechanical engineering expertise and wealth of knowledge within the construction industry is the foundation of an approach that combines strategic thinking with practical solution focused outcomes. Joe leads the design production of mechanical services across various i_3 projects. A key strength is his ability to consider every aspect of client requirements, from cost to buildability.

Contact Us

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