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H2M – A Technology Enabling Cost Effective Industrial Fuel Switching for the UK

A Feasibility Report describing the benefits of Fuel Switching technology for the UK:

Prepared for: NZIP Industrial Fuel Switching Phase 1:

Feasibility Study 2022

Project Report Compiled by:

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Figure 1- Aerial Picture of Hillside Combined Renewable System

Executive Summary:

The UK’s net zero agenda alongside increasing prices of gas (including LPG) have accelerated the incentive to investigate the potential of using low carbon alternatives. The development of the hydrogen economy is central to the UK’s Hydrogen Strategy aiming for the deployment of 10GW of low carbon hydrogen production capacity by 2030. Internationally the IEAs sustainable development scenario envisages that Hydrogen production will increase significantly over the coming decades.

To produce low-carbon hydrogen various options are available including electrolysis powered via renewable energy or hydrocarbon steam reforming coupled with carbon capture and storage. A report published by BEIS reported that the costs of renewably sourced energy is significantly lower than CCGT + CCS post combustion Onshore wind levelized costs are £46/MWh where CCGT + CCS is £85/MWh. Recent European events, however has demonstrated that electricity prices for renewable based sources fluctuate with the cost of natural gas as gas fired power stations are currently used to stabilise the grid. By decoupling power generation from the electricity grid, the cost of power is based solely on the independent CAPEX and OPEX of the power generator, providing the cheapest form of energy to protcreate hydrogen. Of these options water electrolysis using curtailed and/or off-grid wind energy has been identified as the most economically effective means of producing green hydrogen in supporting the UK governments strategy in achieving net zero through decarbonisation and development of a hydrogen economy by 2050 [1] [2]. Research on CAPEX costs for electrolysers supports this, predicting electrolyser costs of $320/kW to $400/kW by 2030 for both Proton Exchange Membrane (PEM) and Alkaline water Electrolysers (AWE). Natural gas costs have recently doubled in price and future price fluctuations will undoubtedly occur; domestic hydrogen production avoids these price shocks providing security of supply. In rural areas such as Castlederg, located in the western-most part of UK and NI (see figure 8) where the electricity grid requires substantial upgrading to reduce curtailment of renewable electricity. An electrolyser can be used for grid arbitrage services when the local grid is congested providing an additional revenue stream and using otherwise wasted power until the required grid upgrades are carried out. The produced hydrogen can be stored and used in localised gas networks, transport applications or used in industry for subsequent power or heat generation.

Additional processing to heavier e-fuels can also facilitate the longer-term storage required for seasonal variations in production and this can be realised using chemical or biochemical pathways. Within agriculturally rich regions of the UK such as Northern Ireland (NI), there are clear synergies between green hydrogen and other forms of energy carriers such as biogas from Anaerobic Digestion (AD) enabling the H2M technology described in this report. The production of green hydrogen enhances the AD system and the co-produced oxygen can be used for other on-site activities including downstream processing, combustion, or water treatment.

In a rurally located agri-food industry, energy dense fuels are required for agricultural activities and the potential of producing these from agricultural wastes to replace currently used fossil fuels required this investigation. The test site used already produced biogas but the calorific value of this is too low to directly replace the current use of LPG. By upgrading the methane content of biogas would enable a straightforward retrofit solution to existing systems resulting in an onsite supply of gas which is insensitive to price shocks, more sustainable and contributes to the development of a circular agricultural economy. This project evaluated the feasibility of combining green hydrogen generation with biogas production from an AD plant using the process of biomethanisation to produce biogas comprised mainly as methane which could be readily used as an alternative to fossil LPG. This report describes how the feasibility of this was ascertained, providing onsite measured data which was subsequently analysed and used to validate the theoretical aspect of this study demonstrating the advantages of the H2M fuel switching technology. The results described in this report provide the impetus for the development of a physical demonstration system, which would stimulate its further deployment lowering the operational costs of similar projects and accelerate its uptake amongst similar industries throughout the UK.

Synopsis of feasibility findings

- Power to hydrogen can be effectively used to displace LPG when blended with biogas
- Hydrogen upgrading to heavier synfuels using biological processes is possible and while this would reduce gas storage volumes the process efficiency would be lowered.
- Waste rape cake from the agri-food business can be further processed using an Anaerobic Digestion (AD) unit converting a current agricultural waste to provide a low-carbon gas to supplement the hydrogen and enable 100% fuel switching within the process.
- A reduction of over 99% of the CO_2 emissions for the site (≈2,838 tonne per annum) would be achieved whilst NOx emissions are expected to be similar due to the unique combustion process employed which also provides a use for green oxygen.
- The site is ideally located to avail of planned electricity flex schemes whereby assets are used to increase or decrease loads on the network. Fuel cost savings of up to 6% were estimated.
- It was estimated that the cost of using a fuel comprised solely from hydrogen is prohibitive given current capital requirements, the combination of hydrogen and biogas is currently economically attractive and additionally provides significant system flexibility.
- Capital investment is required to enable a hydrogen demonstrator project due to the high price of key equipment. This cost is expected to reduce over time as the market develops.
- The proposed system design and unique location which is conducive for the process offers an opportunity to evaluate the combination of hydrogen and AD more broadly for deployment of energy fuel switching across the UK.
- H2M project consortium conducted several market consultations, with manufacturers, distribution network operators, distribution network owners, licensing, regulation departments, agricultural producers, community, and end users. Support has been received from the full supply chain (DSO – End user).

Contents

1 Fuel switching technology for the UK

The BEIS industrial fuel switching competition is looking for innovative projects that will help industries switch to lower carbon fuels. The H2M consortium proposes a novel solution which integrates renewable green hydrogen with biogas. The project aims to demonstrate that the decarbonisation of energy intense industries is possible while achieving security of energy supply and fuel cost reductions.

1.1 Introduction to H2M project

Hillside Combined Renewable Systems LTD (HCRS) is a company active within the renewable energy sector providing energy in the form of green electricity and heat to sister food production companies, Donegal Rapeseed Oil (DRSO) and Dontein which are geographically co-located. Dontein has an ambition to produce a net-zero protein for the vegan market and here the established production process typically uses significant quantities of steam and currently is reliant upon traditional hydrocarbon energy sources and combustion/boiler technology. Switching the fuel to a net-zero carbon alternative such as bioLPG, biogas or green hydrogen would allow the company to achieve its ambition. Of these options, biogas is currently the lowest cost, however it is expected that markets for biogas will expand over the short-medium term into areas such as transport (to avail of RTFOs) as well as wider gas grid decarbonisation. As such, a combination of green hydrogen and biogas is expected to dominate in the longer term. Accelerating this transition to low-carbon fuels however requires empirical evidence on the cost effectiveness and reliability of the approach which can only be realised where there is colocation of assets and access to suitable energy resources.

Here it is noted that the by-products of the food production process can be used as an Anaerobic Digestion (AD) feedstock. Supplementing the produced biogas with hydrogen (or e-fuels) could therefore bridge the gap and allow for the full displacement of fossil fuels within the process thereby meeting the UK's net-zero target as well as facilitating a closed loop circular economy. To realise this ambition, HCRS have proposed a novel fuel-switching solution (H2M) that alleviates Dontein's current reliance on hydrocarbons and aims to demonstrate a pathway for other similar industries to follow suit.

HCRS currently operates a 250kW wind turbine and a 500kW Anaerobic Digestion facility with power exported to the national grid. HCRS are in the process of commissioning a new 850kW off-grid wind turbine with the intention of expanding future generation capacity. It is this unit alongside increased AD capacity which is proposed to provide an alternative to LPG which is at present used to generate steam within the Dontein plant, a diagram of the proposed system is shown in figure 2.

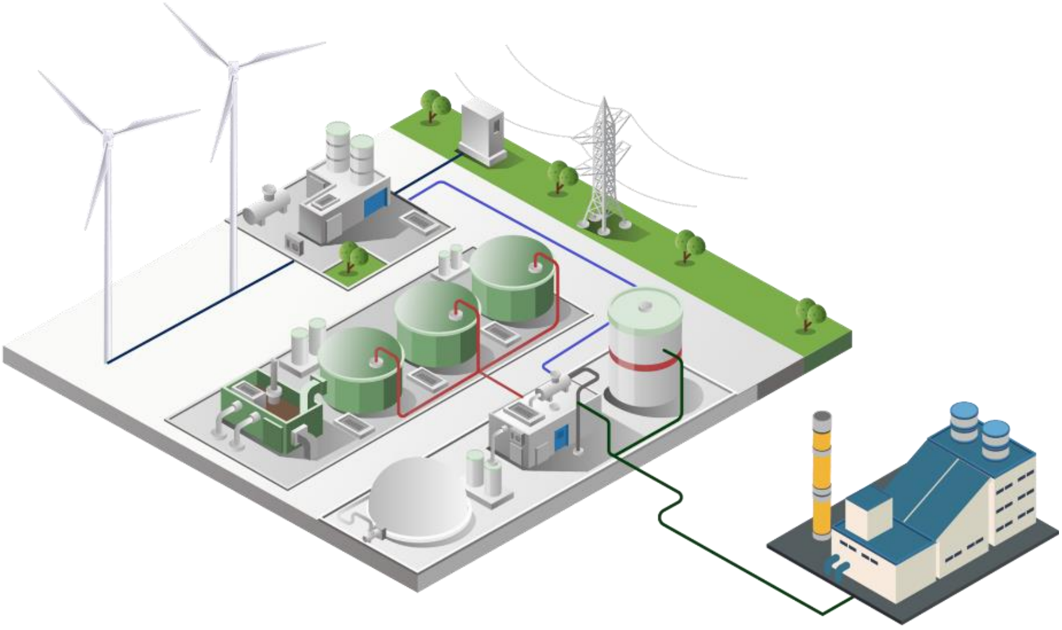


Figure 2 - Vector image of proposed site layout

For HCRS to facilitate Dontein's environmental ambitions it proposes the amalgamation of existing technologies and novel concepts to further reduce the reliance on traditional hydrocarbon fuel sources. Various options exist, for example, existing biogas facilities can be upgraded and enhanced with green hydrogen injection to produce biomethane in-situ. Green hydrogen is generated via the electrolysis of water using renewable energy as the power source, this requires the installation of an electrolyser. Alternatively, the green hydrogen can be used to directly enhance the output of methane by consuming carbon dioxide (CO_2) using secondary AD infrastructure or the hydrogen (H_2) can be blended with the gas to produce a gas mix for direct combustion. While many of these aspects have been shown to work at the laboratory/pilot scale they have not been tested at full commercial scale and hence this analysis was required to design a facility which could evaluate each of these options in a rural location platform with no connection to the gas network available to inform the wider agricultural community. The employed methodology used for determining this, is described in section 3.

Hydrogen production via electrolysis creates hydrogen and oxygen, in addition to hydrogen it was recognised that the co-produced oxygen could potentially displace nitrogen gas and increase the efficiency of the steam boilers used in the process, particularly when using biogas/hydrogen blends. Similarly other cost saving and efficiency measures can improve the techno-economics of the overall process. This includes the use of electrical energy flex schemes whereby the site can either generate or remove electricity from the grid to help stabilise the network at times of peak demand. Understanding the impact of these factors is therefore important when assessing the economic feasibility of the process. Electrolysis for green hydrogen production makes renewable energy power production more reliable as it is a storage vector, allowing use as required, benefitting both energy security and resilience of supply. The huge increase in the cost of natural gas during the winter period 2021 to 2022 has demonstrated the reliance on an unsecured energy source which is also required for many modern industrial processes. The largest cost factor in producing green hydrogen is the electrical energy required in splitting a water molecule into hydrogen and oxygen as described by equation 1 [3].

$$2H_2O \rightarrow 2H_2 + O_2 \qquad [1]$$

There are 2 electrolyser technologies mainly in commercial use for water electrolysis presently, Alkaline Water Electrolysis (AWE) and Polymer Electrolyte Membrane electrolysis (PEM). AWE electrolysis is the main technology in use presently due to its advantage of operating at a low temperature and requires inexpensive catalysts such as steel or nickel alloys for the electrodes. In a PEM electrolyser the electrodes require the use of expensive metal, using platinum as a catalyst for the cathode and Iridium Oxide for the anode (Miller et al., 2020). AWE uses potassium hydroxide (KOH) or sodium hydroxide (NaOH) at a concentration of 20–40 wt. % as the electrolyte, transferring hydroxyl ions (OH^-) from the cathode to the anode [5]. AWE was selected due to it cost advantage over PEM electrolysis. Overall HCRS have aimed to demonstrate the potential of H2M technology via a systems concept which will significantly and economically reduce the carbon emissions of an agri-food industry by allowing for a fuel-switch to a hydrogen rich biogas. Equipment design and integration were evaluated along with alternative uses for by-product gasses, identifying a technology mix which provides the required evidence to validate the approach. It is believed that the project can be readily replicated across the UK to reduce carbon emissions across many sectors particularly the agricultural sector which has been identified as particularly hard to decarbonise, thus contributing significantly to the UK's 5th carbon budget. The H2M project was developed to test and evaluate a strategy for low-cost hydrogen for an industrial fuel switching process which enhances the net energy output of existing anaerobic digestion infrastructure and where co-produced oxygen can further improve system efficiency. HCRS have partnered with QUB and Lagan MEICA. QUB are heavily involved in the theory and system balancing of the project, whereas Lagan MEICA are directly involved in the NI water project currently installing an electrolyser, giving insights on planning, construction and the engineering involved in implementing such technologies on an industrial scale.

1.2 System Concept

Figure 3 is a schematic outlining the overall H2M technology concept and its contribution towards the development of a more circular economy.

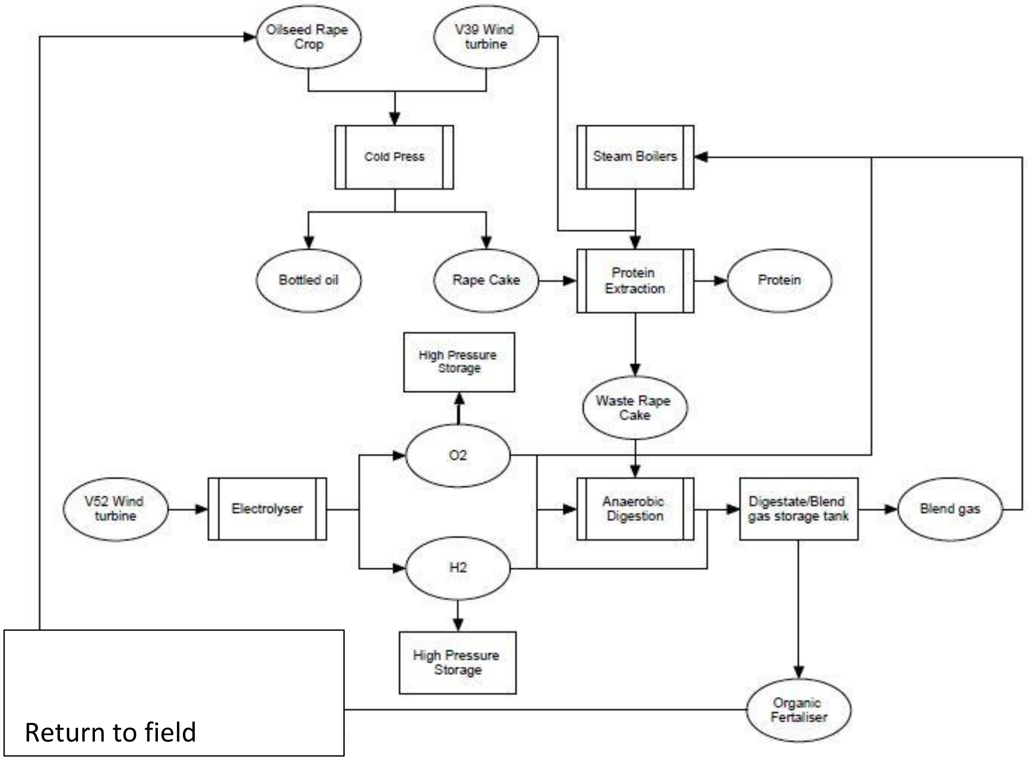


Figure 3 Schematic diagram of the proposed system

The H2M project also plans to support the wider decarbonisation of heat agenda by assisting regional networks in developing fuels for both on and off grid boilers using locally produced green/synthetic gas. That curtailed wind can contribute to circular energy economy, mitigating wastage of energy and enabling the production of high-quality grid injectable Green Hydrogen, reducing market price for rural industrial operations. Anaerobic digesters can operate using various biological feedstocks, allowing them to be flexible in nature. Many systems operate on high energy crops and farmyard manures, while others use commercial wastes and food manufacturing by-products. One of the project's goals is to demonstrate a circular economy approach and security of supply both in the feed and fuel switching aspect.

2 Background and current state of the art technologies literature review

The UK's biogas map shows that in June 2019 there were 76 operational AD facilities in Northern Ireland (NI), the majority of which (64) predominantly use agricultural feedstock, with the remaining 12 using municipal, commercial, and industrial waste as feedstock. Across the UK there is a total of 650 plants comprised of farm fed and waste fed units excluding waste water treatment sites [6].

Figure 4 - Map of Anaerobic digestion sites across the UK April 2022 [6]

This data demonstrates that number of AD plants per capita is higher in NI than other regions of the UK and suggests that NI is therefore a highly suitable region in which to test the proposed system.

While this feasibility investigates a specific site in NI which has unique attributes, making it particularly suited to evaluation of the fuel switching opportunity, it is recognised that every biogas plant across the UK could be potentially retrofitted and thereby benefit from implementing the system that the H2M consortium plans to demonstrate. It is also noted that strategically retrofitting existing sites close to constrained (electricity) grid sections would provide increased flexibility in the network as demonstrated later in this report. Similarly, the technology can be used as a method for power-2-X storage technology by using biological conversion methods which closely replicate the existing AD plant, thereby providing opportunities to boost renewable methane within the larger gas network. Within NI there are currently no direct gas to grid injection plants although there are plans to begin injection in 2023. At the same time the gas network in NI is limited with many of the existing facilities located in rural areas. Several facilities also have significant capacity to co-locate off-grid wind (and solar) energy assets. As such each can serve as locations for the production of green hydrogen. Recent work by the QUB team has demonstrated that 80% of Northern Irelands current gas demand could be met with biomethane derived from AD demonstrating the regional significance of the fuel [7]. This alongside the potential to operate an 80:20 gas mix (methane: hydrogen) suggests that hydrogen blending by combining biogas production with green hydrogen could significantly impact the wider regional transition to net-zero and serve as a demonstrator for how other similar regions in the UK and internationally that also suffer from grid constraints and lack of access to the gas supply network can use the approach. A desktop feasibility was conducted to estimate likely hydrogen concentrations and associated impacts on system performance. This analysis suggests that H_2 injection into anaerobic biogas reactors can lead to an initial negative impact. However, this is recovered when the H_2 consumption rate becomes equal to or greater than the hydrogen injection/consumption rate. Similarly, the analysis indicates that the addition of H_2 to the anaerobic reactor can result in an increase in pH, which would greatly affect the growth rates of acidogens and methanogens. In turn this suggests that H_2 injection should be considered alongside feedstock composition in order to help control conditions within the system. Significant increases in yield have been reported by previous research, for example, Okoro-Shekwaga et al [8]. identified that hydrogen addition improved the biomethane yield from 65% to 77.2% from food waste when using a gas mixture of 5%-H_2 and 95%-N_2. Their work also demonstrated a 12.1% increase in biomethane (from 417.6 to 468.3 NmL-CH_4/gVS_{added}) and a 38.9% reduction in CO_2 (from 227.1 to 138.7 NmL-CO_2/gVS_{added}). Similarly Luo and Angelodaki injected H_2 in volumes corresponding to the stoichiometric ratio of H_2:CO_2 for production of CH_4[9]. Due to mass transfer limitations the authors identified that methane production was around 58 % higher. Other groups evaluated the direct coupling of the two processes and here Tartzkovsky et al [10] investigated the electrolysis-enhanced AD of wastewater where they identified that methane production increased by 10–25%. Murphy et al. reviewed various biological hydrogen methanation systems amongst which was an analysis of the 'Electrochaea GmbH' full scale methanation plant in Copenhagen[11] (relevant to option (b))[12]. This plant is similar in scale to the proposed project in that it consisted of a commercial-scale 1MW capacity power-to-gas facility connected to both power and gas grids. It was reported that the system operated for 8 months using 42,193 Nm^3 biogas, 170 m^3 water and 708,215 kWh electricity to produce 129,290 Nm^3 hydrogen for methanation of ~16,000 Nm^3 CO_2 from the biogas and making available ~15,000 Nm^3 renewable methane and 85,000kWh heat. The system also operated at variable loads and was used intermittently. Of relevance to this feasibility is that the published data suggests that the power required per mass unit of H_2 is 60.85 kWh/kg and that 47.2 kWh was required per m^3 of produced methane. As such the net efficiency for electrical power to either H_2 or CH_4 fuels was 64.4% and 23.4% respectively based on the higher heating value of the fuel.

3 Methodology

The feasibility of developing the H2M project for deployment in the UK was carried out via an initial desktop analysis, detailed numerical modelling using computer software, and collection of real life data. The following information was collected; historical wind turbine performance, existing heat load demand patterns for the generation of steam, technical data of the components comprising the current system from an operational AD plant. This was to enable the feasibility of the proposed H2M technology to be objectively assessed and validate the theoretical modelling used.

3.1 Desktop feasibility

A desktop feasibility was conducted to estimate likely hydrogen concentrations and associated impacts on system performance. Three different options; a, b and c were considered as part of the fuel switching feasibility and shown schematically in figure 4.

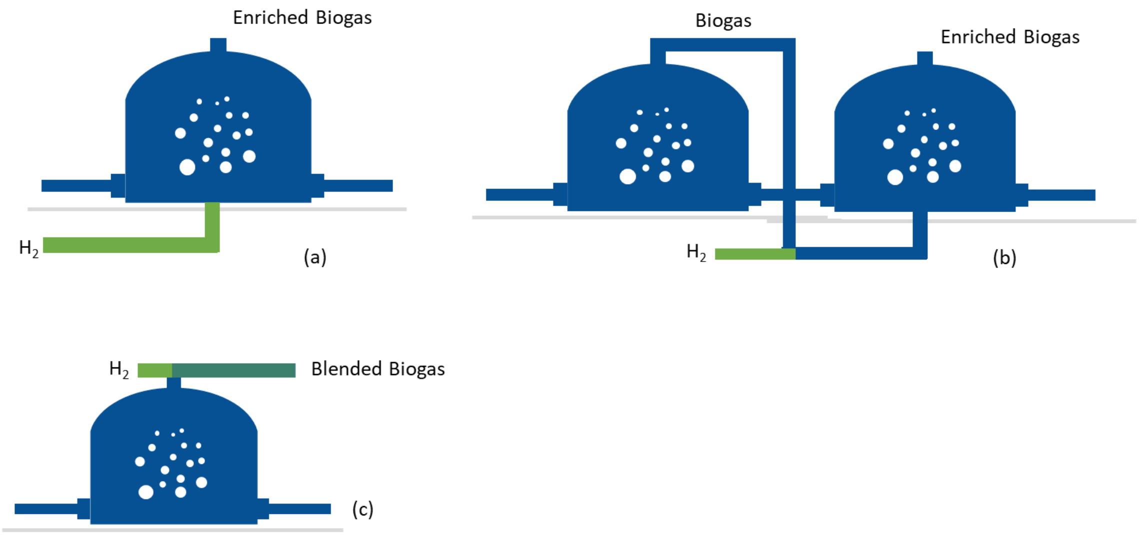


Figure 5 – Alternative versions of implementing hydrogen to AD

The first of these options (a) adds green hydrogen directly from the electrolyser to the AD unit where the microbiology of the system converts CO_2 within the biogas to methane. Option (b) differs slightly, the same microbiological processes occur but a secondary AD/reactor unit was used to optimise the environment for the reactions required for biomethanisation. Option (c) does not use biological conversion to upgrade biogas and alternatively the biogas is blended with hydrogen at some stage prior to combustion. Alternative versions and mixtures of these options are also available with the final layout dependent on the sensitivity of the AD units to hydrogen. This sensitivity can limit the concentrations used and as such options which blend (a) and/or (b) with (c) are likely. The proposed system will be set up so each option can be tested.

3.2 Computer modelling

A full-scale simulation model of the system incorporating an AWE electrolyser was developed using the TRNSYS 18 software. TRNYSYS is a computer based, transient system simulation tool with its components based on empirically validated models used for to produce 100's of published research articles and was thus invaluable for investigating dynamic energy systems such as the H2M fuel switching project. To investigate the existing and proposed system in more detail, computer simulation software than can account for the transient nature of the different options; (Transient Systems Simulation Program) TRNSYS 18 was used. TRNSYS 18 was selected as it has been developed over the last 40 years and contains experimentally validated sub-routines of the components making up the existing and proposed systems enabling their performance when integrated to be estimated and the impacts of these to be quantified. Additionally, this software allows the addition of performance parameters to unique system components such as the wind turbine's power curve. To enable the likely quantity of green hydrogen and oxygen that could be generated annually.

3.3 Collection of relevant data from the site used in this feasibility study

Dontein currently uses LPG to power two boilers capable of generating 4000kg/hr of steam. The gas storage tanks have a combined capacity of 31,560 L, equivalent to 13.9 tonnes of LPG or approximately 6 days of capacity depending on system shutdowns and R&D works in the process. The waste stream from the Dontein process is the rape cake which has a very high energy value making it an ideal feed source for AD. Literature data suggests that waste Rape cake will create on average 620m^3 of biogas per tonne at 90% dry matter within the AD system [13].

Given that the production facility is designed to generate 14 tonnes of Rape meal/cake a day this equates to roughly 8,680m^3 of biogas. This value is in excess of the estimated 5,998m^3 of biogas is required per day (equivalent to 9.68 tonne of rape meal) to produce the blended gas suggesting that excess rape cake available. As such the balancing of the complete system is facilitated. The energy/load demand of the system over the course of a typical year can be matched to the expected output of a combined AD and hydrogen (from wind) facility. Here expected conversion factors can be applied to the electrolysis and process heat (steam) sections and used estimate the overall conversion efficiency (68% to H_2 and 80% to heat i.e. 54% overall). The variable wind (hydrogen equivalents) energy can be subsequently added to the baseload biogas to produce a net energy generation. The demand and generation profile of the site is shown in figure 6.

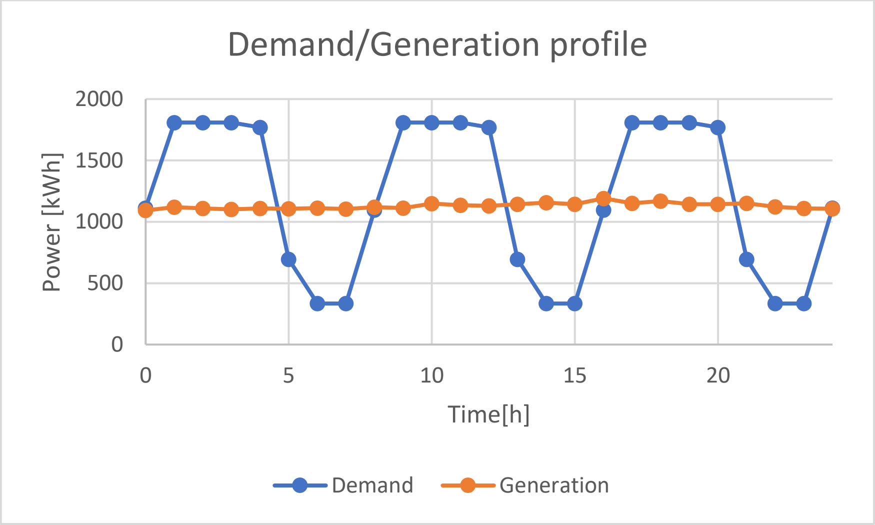


Figure 6 - Data collected showing demand/generation profile of site

The example of a low wind day presented in figure 6 shows the difference between the boiler demand and energy availability on site when matched to the annual demand. Here the differential between the two lines gives an indication of the level of on-site storage required. The ability to produce the lowest cost of hydrogen to support the fuel switching project is linked to the cost of electricity, particularly within systems which rely wholly or partially on a network connection. In this context it is important to evaluate the potential impacts and benefits which could emerge from wider system integration. Within NI, Northern Ireland Electricity Networks (NIE Networks) is the owner of the electricity transmission and distribution network and operator of the electricity distribution network and is responsible for the transport of electricity from the point of generation to over 895,000 customers including homes, businesses and farms. As the penetration of renewables increases, network constraints become more problematic and at present, the costs to reinforce the grid are passed to the developer which results in significant barriers for investment. As an alternative to grid reinforcement, it is possible to develop approaches whereby flexibility is added to the grid at peak times as shown in figure 7.

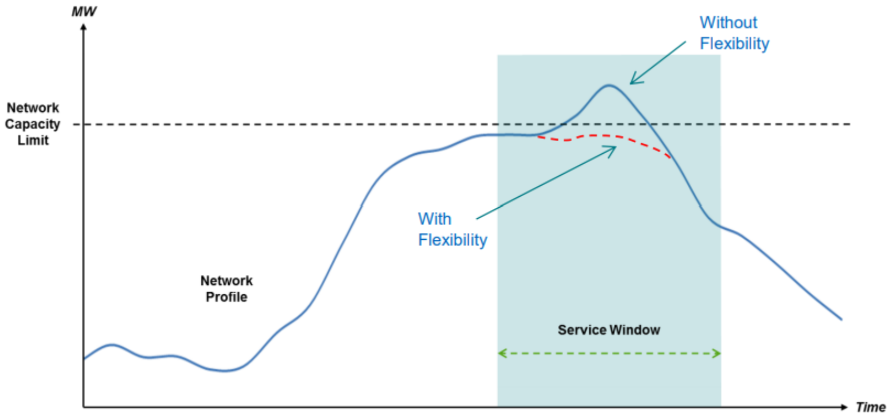
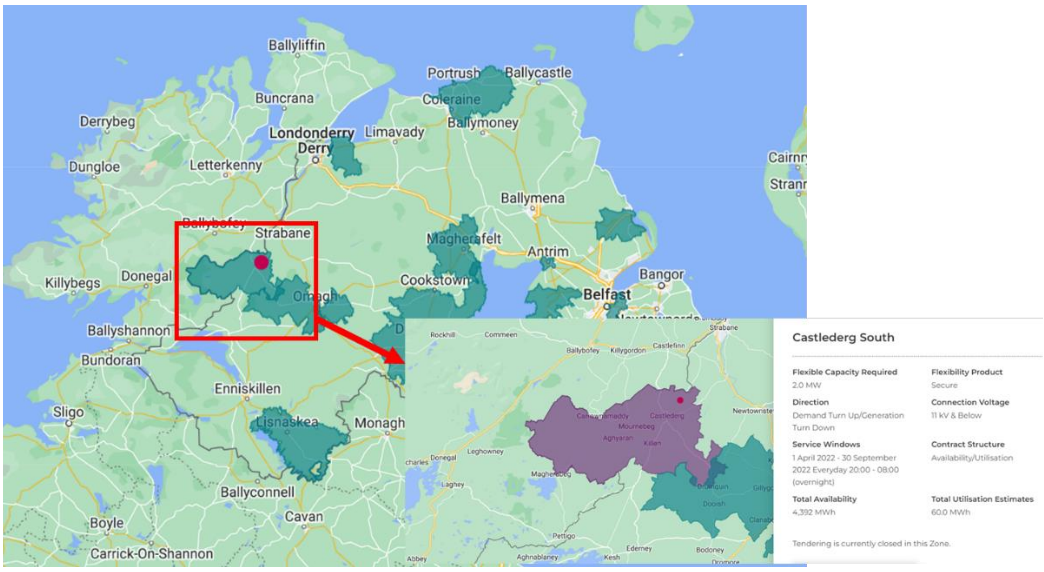


Figure 7 - Use of active power services

Figure 7 shows the flexibility services that can be provided supporting the evaluation of the impact of the recently launched FLEX innovation project by NIE. This aims to cost-effectively operate and maintain the NIE electricity network and maximise value for money for its customers. Here 'Flexibility Services' can be provided by any 'Flexible Asset' which can alter its consumption or generation pattern. Figure 8 shows the different regions within Northern Ireland that see grid network congestion during specific times and weather conditions and are the subject of the current NIE Flexibility project. Of the 17 zones identified by NIE Networks, only one requires a reduction in generation or an increase in demand – Castlederg South. As shown in figure 8 HCRS is located within the identified zone and hence the feasibility of operating as a FLEX asset was particularly relevant to achieving the project aims.



Castlederg South

Flexible Capacity Required
2.0 MW

Flexibility Product
Secure

Direction
Demand Turn Up/Generation Turn Down

Connection Voltage
11 kV & Below

Service Windows
1 April 2022 - 30 September 2022 Everyday 20:00 - 08:00 (overnight)

Contract Structure
Availability/Utilisation

Total Availability
4,392 MWh

Total Utilisation Estimates
60.0 MWh

Tendering is currently closed in this Zone.

Figure **8** - 17 Zones within Northern Ireland requiring Flex Service. HCRS location marked in red. Currently, HCRS have the capability to provide an 800kW swing for NIE consisting of a 400kW reduction in electricity export and a 400kW increase in electricity import on site and therefore was selected by NIE networks for a trial. This swing accounts for 40% of the required capacity for the zone. A trial was conducted during the period of this study, the success of which is demonstrated figure 9.

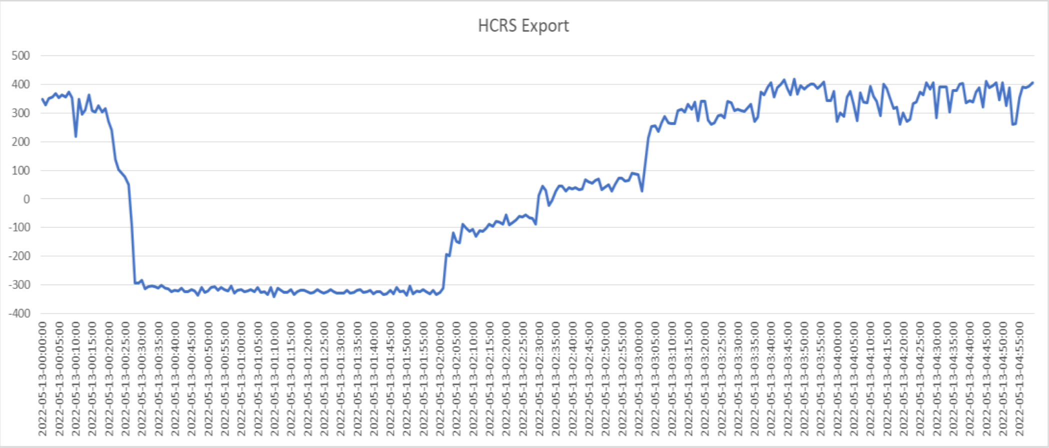


Figure 9 **- HCRS Electricity export trace during NIE Flex trials (13/05/2022)**

In September 2010, the Department of Economy set a target of 40% renewable electricity to be reached by 2020. Northern Ireland exceeded that target by producing 43.8% of its electricity from renewable resources within that year. However, in 2020 a total of 461 GWh was also lost due to curtailment of wind energy equivalent to 14.8% of the total wind energy generated from the 859 wind turbine sites in Northern Ireland[14]. Constraints occur due to several reasons including more wind generation than the localised carrying capacity of the network; or during outages for maintenance, upgrade works or faults and the figure below shows the monthly breakdown over 2020 [15].

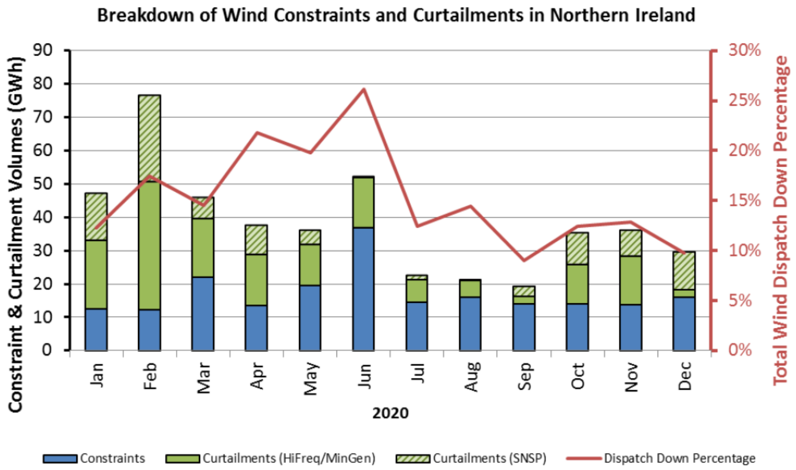


Figure 10 - Monthly breakdown of wind dispatch-down categories in Northern Ireland in 2020

For this feasibility study it is recognised that where general supply exceeds demand excess energy could be used to produce hydrogen. Similarly, the FLEX system would lead to a secondary requirement to reduce output from the AD CHP. As such the combination of lower cost electricity which can be directed to hydrogen production, and reduction in CHP output would yield an increase in overall gas storage. Based on this it was estimated that participation of the H2M project within the FLEX scheme would result in a 6% saving on the equivalent energy costs for the site over the year. It was estimated that if the 461 GWh of curtailed electricity was used to produce green hydrogen, approximately 8.1 million kg could have been generated when assuming generation of hydrogen at 57kWh/kg when using CPH2 membrane free electrolyser technology[16]. The quantity of actual hydrogen produced is dependent on the energy conversion efficiency which is also improving. During the course of this feasibility alternative electrolyser technologies were also evaluated including options for H2M to serve as a demonstrator for a new Petronas unit which boasts a lower requirement of 44kWh/kg of hydrogen[17]. Similarly, off-grid wind provides another potential source of hydrogen production. Between April 2020 and March 2021, 44.1 GWh of electricity was produced from off-grid generators in NI which has the potential to produce 773'684 kg of H_2 (@ 57kWh/kg).

4 Results

The results of the desktop feasibility study is shown in section 4.1 and 4.2 shows the results obtained via computer modelling.

4.1 Desktop feasibility results

The results generated from the simulation of the proposed design demonstrates its scalability. This scalable solution is flexible by design with a potential (assuming 10% penetration of industrial manufacturing operations) to be deployed to approximately 36,000 Industrial operations. In particular agricultural users with on-site generating capacity, and short/medium-term gas storage and power export capabilities could be used to help lower fuel costs in process plant as well as stabilise the electrical grid by implementing this Industrial Fuel switching application. The combustion of blended fuel is expected to result in lower CO2 and NOx emissions due to the lower fossil carbon content of the fuel and expected lower flame temperatures. To evaluate this, analysis was conducted by implementing the GRI- Mech 3.0 model within the Cantera package. This model uses the 53-species, 325-reaction natural gas combustion mechanism developed by Smith et al [18]. In this case a blend of a fuel gas along with air (at an 8% excess) is equilibrated to estimate the final gas temperature and NOx weight fraction.

For the case of Propane, a final temperature of 2208K was reached with a NOx mass fraction of 0.00354. This high value (≈5000 mg/kWh based on lower heating value) is due to the high temperatures and therefore flame control is needed by employing methods such as exhaust gas circulation or secondary air. Here it can be estimate that by controlling the combustion to, for example, 1200K would reduce the emissions to 41.5 mg/kWh.

For the hydrogen/biogas blend the feed is naturally diluted and hence a blend of 16% H_2, 46% CH_4 and 38% CO_2 by volume results in a lower flame temperature of 2046K and a NOx mass fraction of 0.00211 or ≈3238 mg/kWh based on the lower heating value of the fuel. As before equilibrating to a lower temperature of 1200 K would reduce the NOx mass fraction to 4.781e-05 or ≈73 mg/kWh. In this case the NOx is higher than that of propane. Additional calculations based on enriched air (22.4%), which would be available through the addition of oxygen from the electrolysis step, would increase the temperature to 2108 K and reduce the NOx production to 70 mg/kWh when controlling the combustion at 1200 K. This analysis suggests that the NOx emissions could increase within the boiler if operating at the same temperature and the higher air:fuel ratio. However, running the boiler on the hydrogen blend with a 2% excess of enriched air would lower the NOx emissions to 34 mg/kWh relative to 36 mg/kWh for propane. The net result of these calculations suggests that in terms of temperatures and boiler NOx emissions both fuels are expected to be similar to the current process and that boiler performance will not be impacted.

It is recognised that for optimal running, the boilers gas supply should maintain a consistent calorific value (CV) throughout the year. It is noted that biogas will stay relatively constant by maintaining a consistent feedstock. As above hydrogen production rates will be dependent on transient weather conditions thereby requiring a level of compressed storage and blending on-site. Within the proposed system a blending tank is employed to maintain a more consistent feed to the boiler. Due to the presence of hydrogen, it is noted that the CV of the biogas will decrease from 21.8 to 20.03 MJ/m^3 however the lower density of the gas means that the Wobbe number (which better reflects the energy delivered at the boiler) is very similar (21.98 vs 22.33). The value is however significantly different from propane (80.4) meaning that the nozzles will need to be replaced on the current system. At the same time the similarity between biogas and the blended gas values suggests that simply replacing nozzles to a biogas equivalent would be sufficient. Similarly, the sub 20% hydrogen concentration within the blended gas means that other safety devices, such as flame detection are sufficient.

According to the BEIS GHG green book data LPG has an (GEF) emission value of 0.21449 kgCO_2e/kWh. Similarly, biogas has a significantly lower emission value compared to LPG (0.00022 vs 0.21449 kg CO_2e/kWh) suggesting that switching to biogas alone would save over 99.9% of emissions. Interestingly the UK hydrogen strategy quotes the emission factor for Hydrogen produced from renewables at 0.1 gCO_2 e/MJ H_2 (LHV) which equates to 0.00036 kg CO_2e/kWh i.e. slightly larger than biogas. However, the difference is small and the CO_2 emission savings are still estimated to be 99.9%.

Given that the energy consumption for the Dontein's two fuel boilers has been forecasted to be 13.23 GWh per annum this translates to a reduction in CO_2 emissions from 2,838 tonnes to 3.2 tonnes.

From the demand/generation profile (figure 6) an estimation can be made on the volume of seasonal storage needed. This analysis has identified that gas storage is critical and the chosen H2M system has been designed to have an atmospheric storage capability of 4,825 m3, with an additional 5,719 m^3 available from an existing unit, giving a total gas storage capacity of 10,544 m^3. By utilising the existing assets associated with the AD infrastructure, a reduction in costs can be achieved however new gas storage is required which can be split across pure or blended gas streams. Hence multiple options exist for the use of the produced hydrogen. An evaluation of these suggested that the production of a blended gas stream utilising the new low-pressure tank as a buffer (see figure 3) would provide a relatively consistent feed to the boiler system allowing for cleaner operation. As such hydrogen would need to be stored on site to allow for seasonal variations in production. The quantity of hydrogen (Nm^3) required was calculated using the expected wind data and load profile over the course of the typical year with the results presented in figure 11.

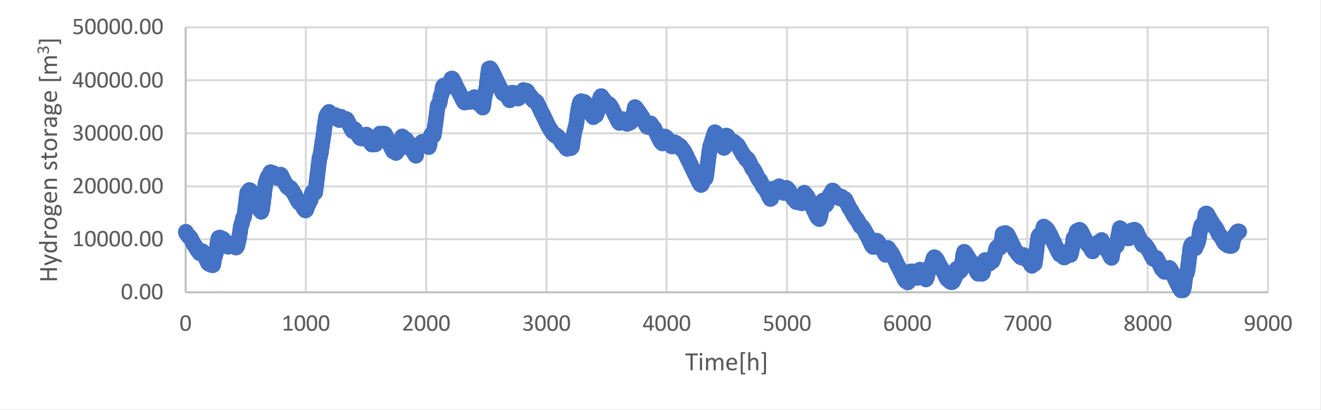


Figure 11 - Estimated requirement for on-site hydrogen storage capacity over the test year

Here the initial volume of hydrogen is set such that over the course of the year a hydrogen supply is always present. The demonstration project will adjust the quantity of hydrogen introduced into the AD, however it is estimated that a 5% hydrogen blend would be optimal. The existing digestate storage tank will act as the atmospheric pressure blending tank pre boilers. The blend again will be adjusted to investigate the optimal mix; however, the study has shown that a 16% hydrogen concentration would be ideal.

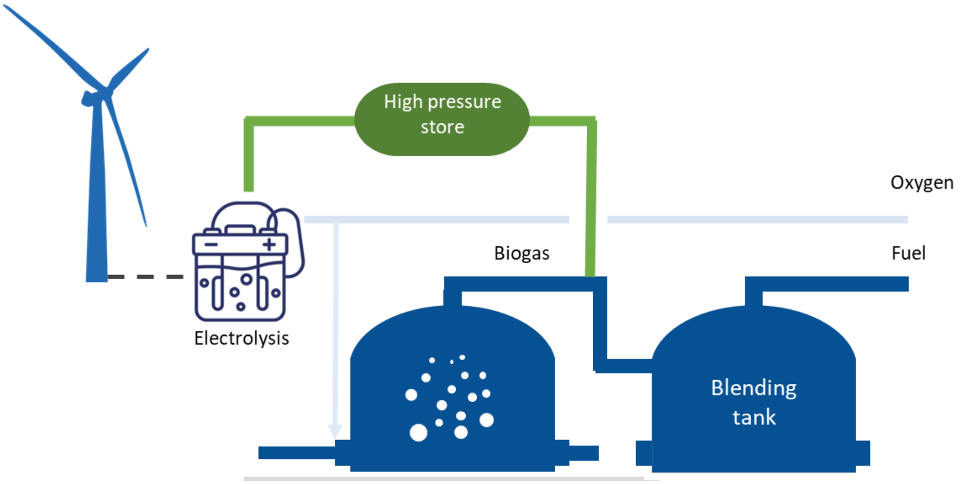


Figure 12 **- Use of high-pressure gas storage and gas blending.**

It is clear that significant volumes of hydrogen are produced over the earlier half of the year. Using this approach, the overall hydrogen concentration in the blended gas is estimated at 16% meaning that the boiler feed gas has a composition of 16% H_2, 46% CH_4 and 38% CO_2 on average.

The HCRS storage system uses a flexible Biolene^{TM} [19] membrane over each anaerobic digester tank which consists of a 2mm thick Ethylene-propylene-diene (EPDM) polymer. EPDM elastomers have become a barrier material of significant commercial importance due to its superior resistance properties and are commonly used in AD systems. This allows the cover to stretch to 540% of its original size until it reaches its elastic limit and has a methane permeability of 500 cm^3 / (m^2*d*bar). Rutherford et. al. derived solubility and diffusivity parameters for a series of probe gases including helium, hydrogen, neon, argon, krypton, oxygen, nitrogen, carbon dioxide and methane for EPDM and reported the measured and predicted data [20]. This information was subsequently used to estimate the gas leakage rates from the system for the blended gas mixtures. Table 1 presents the diffusivity solubility parameters and estimated leakage rates for pure and expected blended gas. Within this it is noted that the permeation of pure methane can be increased to match the reported data by lowering the thickness of the membrane to 1.26 mm which would be realised during stretching.

Table 1 - Estimate of gas leakage rates. Leakage for pure gases determined using a thickness of 2mm whereas the blended gas uses 1.26 mm and blended gas concentrations at 1 atm pressure.

Gas	Diffusivity [cm^2/s[	Solubility [ccSTP/cc atm]	Leakage (pure) [cm^3 / (m^2*d*bar)]	Leakage (blend) [cm^3 / (m^2*d)]
H_2	8.00E-06	4.00E-02	1400.72	355.73
CO_2	3.60E-07	1.12	1764.90	1064.54
CH_4	2.30E-07	3.14E-01	316.12	230.82

Based on the above analysis hydrogen leakage rates of 144 L/day would be expected in each of the storage tanks suggesting that 105 m^3 of hydrogen would be lost per year or 0.025% of the expected annual production. Hence the leakage of hydrogen from the blended gas, which represents the maximum H_2 concentration as there is no biological conversion, is considered to be insignificant and therefore no changes to the materials of construction are expected to be required.

4.2 Computer modelling results

A system model of the Dontein plant was developed generating data at hourly time steps and validated by comparing current demand profiles with those predicted from the simulations, the results of this are shown in figure 13. Using a physical constraint for the wind turbine of 850kW a capacity factor of 24.8% was identified for the site over a test year (which compares favourably with measured values) this data was subsequently used to identify the size of an equivalent biogas plant (1.3MW equivalent raw biogas). Assuming a 35% electrical efficiency this equated to approximately 478 kW of equivalent electrical power and is therefore almost equivalent to a doubling of the existing plant capacity (499 kW) at HCRS. An energy model of the HCRS system as it currently is, with the 250kW wind turbine, steam boiler (fired using LPG) and the two CHP units (250kW and 249kW) was developed first to determine how accurately measured data could be simulated using TRNSYS. The quantity of hydrogen generated annually was then derived from the simulations for the present and proposed system by integrating an oversized Alkaline Water Electrolyser capacity (1.2MW) into the simulations. The oversizing was to account for participation in FLEX, enabling grid stability control and was carried out to estimate the quantity of hydrogen that could be generated and required for biomethanisation, allowing fuel switching from LPG to upgraded biogas with any excess production exported generating an additional revenue stream. Oxygen production rates were also recorded. While usually this is just vented to the atmosphere, the proposed fuel switching system will make use of this to maintain boiler operating temperature and help control emissions of NOx. The accuracy of the simulation was validated against the measured steam demand profile of the HCRS boiler which is currently fired using LPG and shown in figure 13.

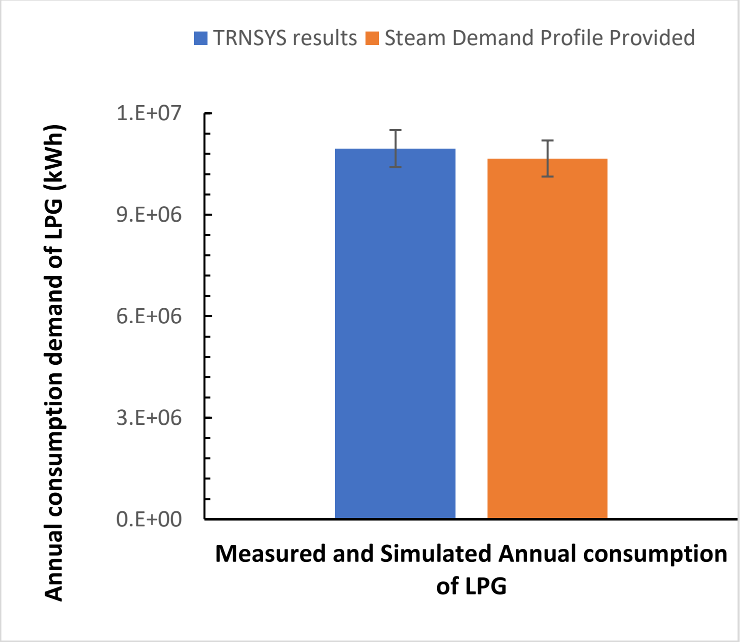


Figure 13 - Comparison of measured and simulated annual consumption of LPG for HCRS

As observed by the error bars in figure 13 measured and simulated values where within 5% validating the model used. Based on this, fuel switching to upgraded biogas would potentially save 10.6 to 10.9GWh of LPG per annum. An estimation of the energy generated from the existing 750kW system and with the addition of an 850kW wind turbine is shown in figure 14.

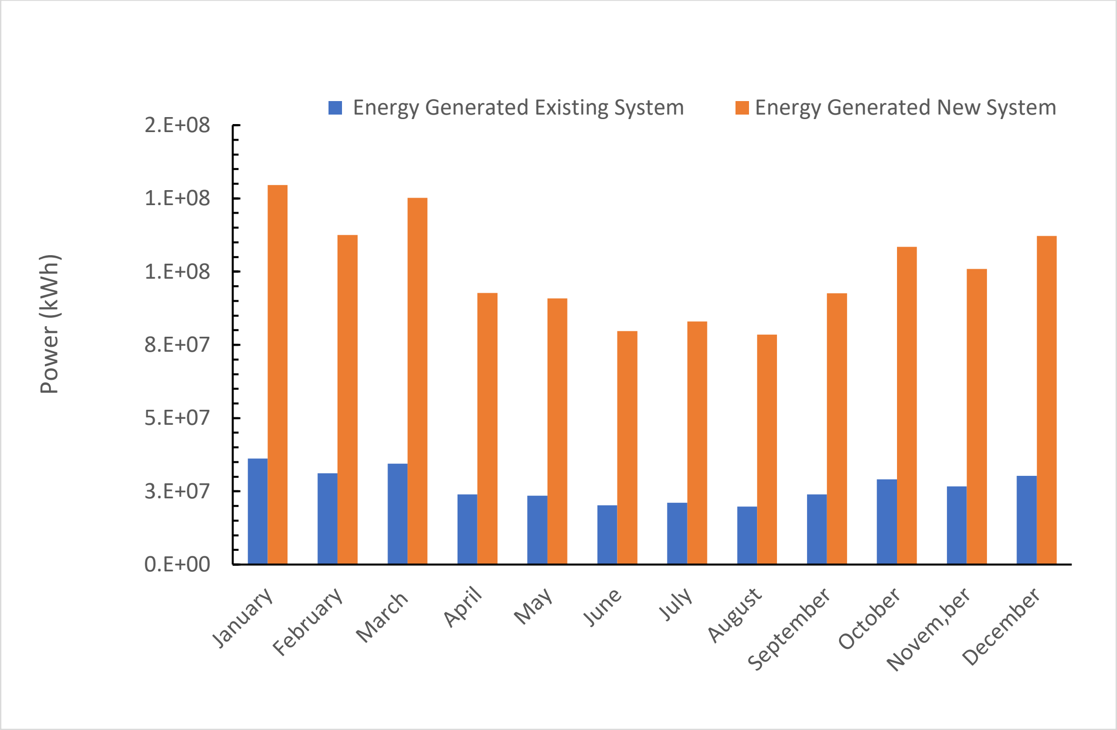


Figure 14 - Annual power generation from wind for existing and proposed system.

The addition of the 850kW wind turbine increases the installed electrical power generation capacity to 1.6MW. Using the same average metrological conditions, the volume of hydrogen and oxygen produced over the year at a pressure of 7 bar using the AWE are shown in figure 15.

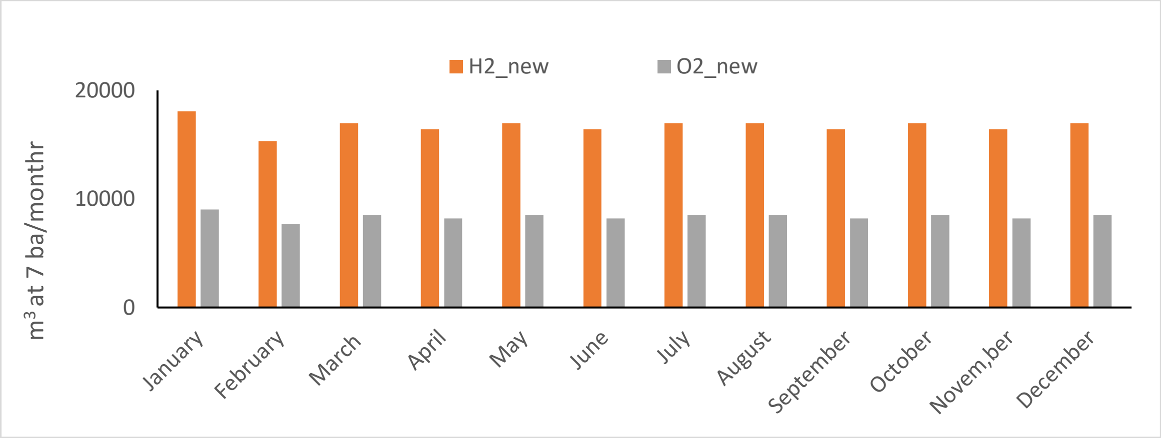


Figure 15 - Annual production profile of 1.2MW AWE

The system was evaluated for various scenarios including those which include the hydrogen storage compression energy provided from the onsite off-grid wind turbine as well as existing CHP plant. This data was then used to determine the impacts and more detailed design stages discussed in the analysis and conclusion sections.

5 Analysis

The analysis of the results obtained from the desktop feasibility study and computer modelling and their anticipated impacts are described in sections 5.1 to 5.3.

5.1 Desktop feasibility

This analysis found that H_2 injection into anaerobic biogas reactors can lead to an initial negative impact. However, this is recovered when the H_2 consumption rate becomes equal to or greater than the hydrogen injection/consumption rate. Similarly, the analysis indicates that the addition of H_2 to the anaerobic reactor can result in an increase in pH, which would greatly affect the growth rates of acidogens and methanogens. In turn this suggests that H_2 injection should be considered alongside feedstock composition in order to help control conditions within the system. The desktop study has validated that it is possible to utilise electrolysers to create hydrogen and biologically transform it to methane using existing AD plant in a process known as 'in situ' biomethanisation or power-to-gas generation. Here microbes in the digester use H_2 and CO_2 as feedstocks and thus the CH_4 content of the biogas produced can be increased up to 90%-99% instead of the usual 50%-60%. The analysis suggests that H_2 and bio-methane can work flexibly as complementary fuels, however it also confirms that enhanced controls would be needed to assure that the microbiology is not negatively affected. Similarly, it was noted that there are efficiency losses due to the microbiological conversion and hence the loss in delivered power would need to be balanced against the advantages of increased CH_4 concentrations e.g. energy density per unit volume ≈3.

5.2 Demonstration

The feasibility study seeks to further demonstrate that modular energy storage utilising curtailed wind energy is feasible. The demonstration project will adjust the quantity of hydrogen introduced into the AD, however it is estimated that a 5% hydrogen blend would be optimal. The existing digestate storage tank will act as the atmospheric pressure blending tank pre boilers. The blend again will be adjusted to investigate the optimal mix, however the study has shown that a 16% hydrogen concentration would be ideal (See desktop feasibility results). HCRS is in a unique position to demonstrate an IFS technique at the co-located agri-food business Dontein. The circular economy being implemented through this project enables cost effective, sustainable biogas production. It is estimated that current biogas price varies from £0.08/kWH – £0.13/kWH. Although it has been forecasted to drop below £0.07/kWH by 2050. Through a circular economy model H2M can price biogas at £0.05/kWH. This price is based on the CAPEX and OPEX (See appendices excel sheet 'project costings') of the AD system being implemented, showing substantial savings on the average EU cost.

With the adoption of off-grid wind and curtailed electricity provides substantial saving on renewable hydrogen production well below the national average. The cost of generating hydrogen from renewables is expected to be £0.112/kWh by 2025 using dedicated offshore wind. As the electrolyser market matures the CAPEX for producing renewable hydrogen will decrease. The UK hydrogen strategy foresees a 37% reduction in renewable hydrogen costs by 2050. When coupled with biogas from existing AD plants, a viable sustainable green fuel is formed capable of substituting carbon intense fossil fuels. Through the demonstration project the H2M consortium validated that a fuel switch is possible while reducing emissions by 99.9% and reducing fuel costs by 6% to the end user.

Combining biomethane with technologies to capture and recycle nutrients from the digestate that would otherwise be land spread can also help address nutrient loading and water quality problems. As a consequence, this would decrease environmental pollution from agriculture and assist in meeting the targets of the UK's 5th carbon budget and stimulate technology development. Again, it is recognised that other sustainable and advanced agricultural techniques such as aquaponics and vertical farming could be deployed/integrated in the process to utilise the waste nutrient and energy streams (e.g. waste heat, oxygen and CO_2) from the process to boost overall site productivity.

Nutrient management and impacts are important in terms of planning as is the deployment of additional renewable energy sources including wind [21]. For this project the site currently has an existing wind turbine and an Anaerobic Digestor system. A digester system with full planning, has been operating for a number of years and is regulated under a Waste Management Licence issued by the Northern Ireland Environment Agency (NIEA). A processing unit for the upgraded anaerobic digestate is currently with planning and awaiting receipt of approval - This system has been further upgraded with a recovery/recycle system which will deliver dried solids and ammonium sulphate liquid which can be used as fertiliser. This will virtually eliminate the ammonia emissions to air and greatly reduce the necessity for large field areas for land spreading.

From discussions with regulatory bodies and local councils, the H2M consortium discussed with all parties the scope of the project. The biggest cause for concern was the additional AD infrastructure and the effect of additional digestate on the surrounding environment. This has been addressed with the addition of a digestate dryer reducing ammonia emissions and allowing export of phosphates from the site. The increase in feedstock will remain below the waste intake limits permitted on the existing license. Another concern raised was the storage of gaseous elements such as oxygen and hydrogen on site. This will be addressed and will fall under section part 'A' of the PPC permit. This process takes roughly 6 months to complete which falls within the project scope.

The additional anaerobic digester modules will proceed through planning and will include an amendment to the Waste Management Licence while planning approval has also been obtained for the new wind turbine This plant is a new area of technology and only a handful of planning applications have been approved for schemes of this nature - with no specific planning policies for hydrogen energy schemes in place, it is essential to create a robust submission that tackles all potential issues upfront while highlighting its environmental credentials. Throughout this feasibility the NIEA have been consultees in all these planning applications. The time frame for planning is estimated to take 6-8 months, of which large portions of the workload has already been undertaken. Findings from in particular Lagan MEICA who have been developing the 1MW electrolyser unit for the NI water project has accelerated progress in this area. The integrated system (digesters and electrolyser) will be operated under a Part A, PPC Environmental Permit issued and regulated by the NIEA [22].

5.3 Support of H2M for accelerating government policy

The current UK energy storage models are not designed to accommodate long term capacity. The introduction of H2M project will provide fuel switching options for Off Grid and Flexible Capacity manufacturing sites, enhancing the reserve of fuel sources, by collaborating with Network operators, the H2M project can reduce reinforcement costs can be onto customers by balancing constrained capacity through H2M scalable models being deployed across Northern Ireland and the UK. Scaling the H2M project provides Network operators with greater visibility of what congestion looks like in the short to medium term timescale. The project will compliment NIE Networks FLEX Programme - Innovation project under price control project whereby locations seeking additional production generation can be managed without constraining the grid. Additional savings could be achieved through participation on this programme in collaboration with H2M modelling.

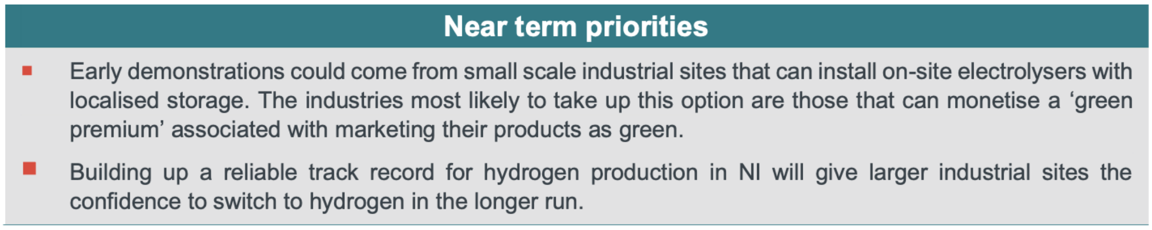
Recent discussions with the Network Operators indicated both Electricity and Grid operators were conducting a Biomethane whole system view and integration of FLEX system modelling. This gives grid operators more control of flexible load, managing and profiling inputs and outputs of fuel sources.

From consultations it is clear that the feasibility is in alignment with government strategies and has potential to provide a pathway to remove dependencies on government subsidies. The H2M has the Cross Departmental support and decarbonisation strategy alignments for Rural, Agricultural and Industrial Operators. DfE and DAERA have welcomed the feasibility and are fully supportive of a Phase Two demonstration project, to validate findings and economic profiling of this systems model.

During discussions with DAERA it was recognised that the H2M project aligns with DAERA Workstream 4 – DAERA -Farming for Carbon Policy Proposal 9: Potential development of biomethane and hydrogen circular economy initiatives.

The H2M project also aligns with DAERA policy FCM9 relating to the potential development of biomethane and hydrogen circular economy initiatives. This policy would involve the use of anaerobic digestion to generate biomethane for injection into the Northern Ireland gas grid and/or to produce hydrogen as a power source for the heavy goods transport sector using a combination of manures from livestock farms, waste streams from food processing and energy crops grown on land diverted from conventional agricultural uses. The use of biomethane compared to conventional natural gas produces less greenhouse gas emissions and therefore would potentially have medium to long term positive effects on the SEOs for both AQ and CF.

Table 2 - DfE Near Term Priorities published by Frontier Economics



Near term priorities
▪ Early demonstrations could come from small scale industrial sites that can install on-site electrolysers with localised storage. The industries most likely to take up this option are those that can monetise a 'green premium' associated with marketing their products as green.
▪ Building up a reliable track record for hydrogen production in NI will give larger industrial sites the confidence to switch to hydrogen in the longer run.

Below is a breakdown of the potential end users of the H2M system:

The system that has been evaluated and a baseline specific set of conditions has been identified for H2M integration, however these may expand if the H2M progresses to a Phase Two demonstrator. The current profile for a H2M participant is an agri-food business with an existing or planned AD facility, or and with existing renewables generation. Initially locations that are suitable for integrating are off-gas grid requiring LPG import and is in a constrained electrical or gas supply region. Sites participating in the FLEX asset scheme have also been identified as suitable H2M participants. The H2M project has been designed for areas that are not constrained and are connected to the grid, however priority for wider replicability is on off grid and constrained areas initially.

The H2M Project has potential to impact several industry sectors, depending on site assets and flexibility. Some of these industry sectors include, but not limited: Full support from Grid and Network Operators. The H2M project once deployed at scale will provide increased visibility at Network Level for Future scenario demand profiling. New markets could also be identified as a direct output. H2M consortium consulted with the leading Stakeholders in the Energy Market across the UK.

National Grid, Cadent Energy, NIE and SGN would like to see visibility of projected production capacity to forecasting and future modelling purposes. A Snapshot of the market potential (Scalability) is shown in figure 16 adapted from [23].

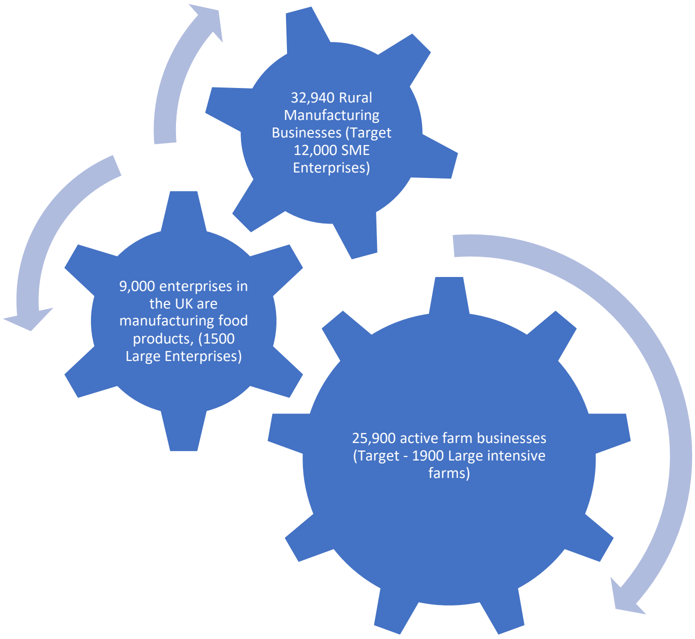


Figure 16 - A Snapshot of market potential (Scalability) [23]

There are 650 operational AD plants, once ROC payments have terminated, the owners of these plants could integrate the H2M model, generating savings and income, whilst removing the dependency on Government subsidies. To adopt the H2M system model, the following criteria has been identified (please note the eligibility criteria for integrating the H2M system may expand as during demonstration, depending on the systems flexibility as shown in figure 17.

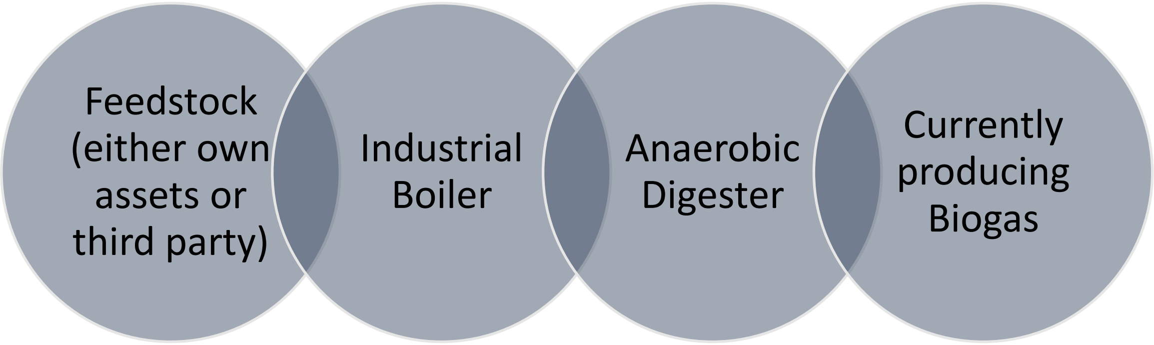


Figure 17 – Ideal requirements to implement the H2M model

Each of the industrial customers that currently use high volumes of LPG or fossil fuels will be considering fuel switching mechanisms to displace the surging price to operate their facilities. If costs are not reduced, manufacturers run the risk of losing market share as the price is offset to the customer. The H2M project is a gateway to providing longevity of operations whilst maintaining market share, through the production of Hydrogen as a fuel source on site. See figure 18 for further detail.

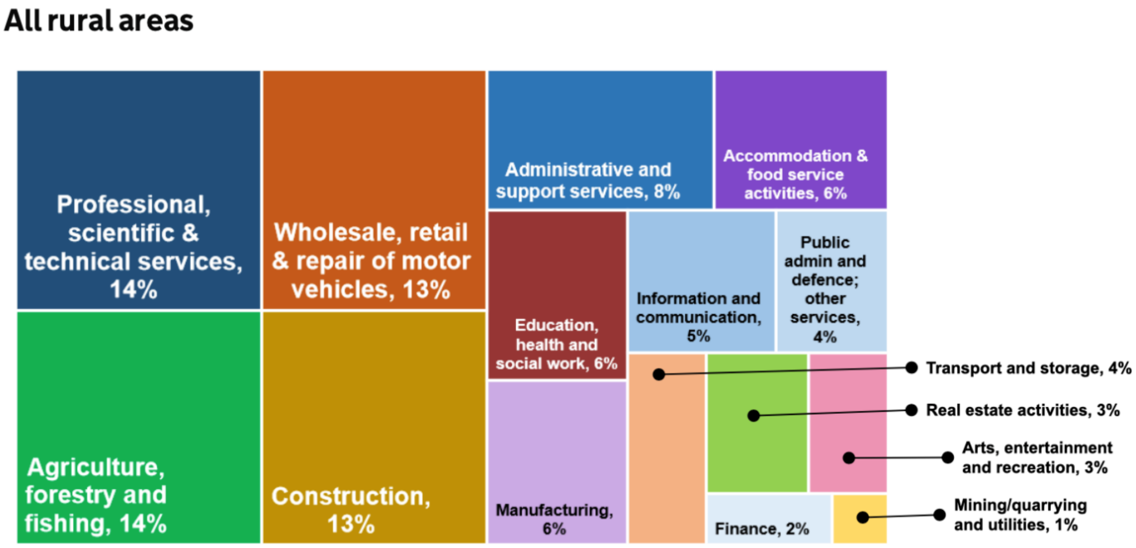


Figure 18 – Percentage of local unit registered businesses by industry, by rural-urban classification [23]

Due to the nature of the project, there will be price fluctuations on the cost of biogas and hydrogen production. While rolling out this system to the wider market post demonstration will potentially carry large capital savings, the feedstock used to create biogas varies from plant to plant hence individual economic assessments will be required. Hydrogen price will be dictated by the source of power to the electrolyser. The flexible system design will validate the application variables and system capacity.

This study projects potential fuel savings of £106k per year with a CAPEX + OPEX payback period of 10 Years. This saving is based on a daily expenditure of £4,531 on LPG. With the increasing pricing trend profile of fossil fuels and if the Electrolyser market matures, the payback will be reduced. The ROC Payments for AD sites was identified as a barrier to wider adaption of the H2M project, as the annual savings and payback period from H2M Project cannot sites that are beneficiaries of ROCs. However, H2M project has been identified as an exit strategy for ROC payments depending on site operations and capacity. If H2M progresses to Phase Two demonstration, the system flexibility could be examined further to determine how many existing ROC beneficiaries could transition to the H2M project model.

H2M project consortium conducted several market consultations, to determine the market acceptance, market barriers, scalability, and compatibility of the systems model. Market consultations were conducted with NI and UK Leading utility operators, Government bodies, associations, networks, and enterprises both SME and large entities. Twelve key stakeholders were identified as part of the market consultation exercise, this included public, private sector and charitable bodies. It was evident from the consultations; all the external stakeholders were fully supportive of the feasibility progressing to a phase two demonstration and written support was provided as evidence for the feasibility. During discussions, stakeholders did emphasis that cost would be the main driver of the wider replicability of the H2M project, and it was imperative the economic models stacked up to drive wider Government support. There were no technical concerns in relation to integration or operational capacity of the system.

The fact that the H2M project is replicable at SME level and is suitable for off grid locations was strongly welcomed by stakeholders, as it addresses the stigmas in the market that the production of hydrogen is only associated with large industrial players. Utility operators in NI and the UK also welcomed the H2M project at scale, as this can provide visibility of the industrial off grid generation capacity which would help assist utilities forecasting future demand profiles and flexibility capacity at grid level.

Through implementing the H2M project at scale, this can help drive market competition and drive down the cost of fuel consumption in NI and the UK and mitigate fuel poverty. By deploying a resilient fuel switching model like H2M Project, this can provide fuel security for multiple industrial operators, as well as deferring investment in grids.

The H2M project is in alignment with BEIS Fuel Switching Objectives, DAERA Green Growth Strategy and DfE 10x Economy" strategic vision, the Network Operators in NI and UK welcomes a bottom-up approach. Also leading Gas Operators in NI and UK see the merit for serving off grid sites and acknowledge the potential for demonstrating the solution.

The UK agricultural sector offers a unique opportunity for biomethane within a more circular economy, as an adoption-ready option to deliver early diesel replacement for tractors and HGVs. Incentivising adoption-ready technologies is important in reducing emissions now, whilst other technologies catch up. Also, on-site biomethane offers a route to the phasing out of the red diesel subsidy prior to 2030.

Consultations also took place with Farmers Unions who welcomed the H2M project, alongside the AD Bio Associations. The latest polls conducted NFU shows that 84% of farmers want net zero measures to be part of the new system that will reward farmers for environmentally friendly farming.

It is evident the UKs resources, feedstock knowledge and expertise provide the hallmarks for developing a world-leading clean hydrogen economy. The H2M project can improve UKs economy diversity and resilience. Currently the UK economy is heavily reliant on a few sectors, such as agriculture, construction, production, and services. By providing fuel switching pathways this will help sustain economic activities and global competitiveness through sustainable fuel supply

In addition to this, H2M will support a reduction on imported gas by exploiting our existing infrastructure to maximise our outputs of hydrogen gas, helping reduce the UK gas bill for the foreseeable future. H2M will be an enabler for investment signal effects, helping attract foreign direct investment and whilst improving infrastructure capabilities across the UK through replicating the H2M model. Additionally, H2M provides pathways for exploiting industrial land-based assets to make UK more resilient. If the project is demonstrated and scaled, this creates significant export opportunities for the UK as well as helping the UK meet private sector investment targets of £4bn

The UK is at the highest rate of inflation since the crash in 2008, with rising prices for Oil and Gas it is critical that companies consider alternative fuel sources to ensure security of supply. If H2M approach was to be replicated across the UK, this could provide a pathway to build a resilient industry that could potentially be fuel independent by 2035 reducing reliance on imported LNG. With the price of dairy and meat doubling in the last 12 months it is imperative fuel switching mechanisms particularly at rural levels are deployed, to enable energy and food security through sustainable fuel production. The H2M project could be a vector for offsetting this social cost, providing affordability and security of supply through reserve. Rather than offsetting the increasing fuel costs to the end user, manufacturers can change fuel sources to maintain price competitiveness and reduce the cost to end consumers through implementing H2M project that provides fuel security

Currently the low carbon sector in Northern Ireland employs more than 12,000 people in over 300 companies, some of these jobs could be sustained if H2M is deployed at scale**.** Post demonstration, the H2M project has the potential to directly support approximately 2,000 jobs [24]and create a hydrogen circular economy supply chain that could potentially be worth £150 million by 2030. According to the ONS, Low carbon and renewable energy economy, in 2020 there were 207,800 full-time equivalents (FTE). Again, these jobs could be sustained and H2M could enable growth in the LCREE market which hasn't changed much since 2014. Metal Industry, Contractors, manufacturers, and software monitoring companies all feed into the Hydrogen supply chain, jobs in these sectors could also be sustained through servicing new markets. Training and upskilling in alignment with the demonstrator will Fasttrack deployment and integration of the H2M Model, helping position the UK as a leader in the Production of affordable Hydrogen at SME level. In tandem with the H2M project, Academics and Councils across NI are working in cohesively to provide industry with the skillsets to integrate manage and distribute Hydrogen across multiple sectors and Industry. New skills generated from the H2M will be exchanged with a network of employment bodies, academic institutions and Industry.

90% of farm business operations use LPG fuel to power their sites, however with the rising cost of LPG, removal of the Red diesel subsidy and grid constraints, farm fuel diversification is taking place. Instability of global markets is reducing the security of supply for energy dense fuels. By exploiting multiple revenue streams this can further aid in balancing the markets in the presence of high renewable penetration. Wind curtailments between Scotland and England will cost consumers £1bn per year. To reduce the cost to consumers, H2M project will identify avenues to reduce the rate of curtailment through off-grid/curtailed energy modelling. UK farming is an integral part of the agri-food supply chain worth over £120 billion, maximising the full sustainable technical potential of biomethane would allow it to reach a 40% share of total gas demand in 2040. Options to tackle emissions from the remaining share could include H2M fuel switching model.

Hydrogen produced using sustainable feedstocks and low carbon processes would enable rapid emission reductions in the short to medium-term, through seamless integration with existing fossil fuel infrastructure and provide blended gas variables. At scale the H2M project has the potential to provide a fuel switching solution for 39% of the Agri food manufacturing sector across the UK. This is predominantly due to the scalable systems design and based on feedstock and AD infrastructure assets.

The H2M project is a bottom-up approach providing Network and System Operators greater visibility of the potential market for Hydrogen production across rural and flexible manufacturing processing sites.

The system model is adaptable for manufacturers looking to generate 1MW-5MW of Fuel source. With annual savings ranging from £106,000 up to £950,000 per annum, leveraging the dependency on network upgrades, fossil fuel and providing longevity of sustainable production and competitive pricing to export markets. The H2M model cannot compete with the existing subsidised AD ROC payments at Micro generation level, however modifications to system operations and new subsidy frameworks could be designed to make the market more resilient and less dependent on subsidies post 2040.

Accessing the grid is one of the big constraints faced by farmers and landowners looking to construct solar panels and wind turbines, with many not having overhead powerlines across their land and some not being able to connect due to the grid being at full capacity in their area. Having an electrolyser provides an outlet for excess power generation and an alternative more valuable option for off grid systems, the energy can be converted into another product which has green credentials and is saleable.

Feedback from several stakeholders indicated this systems model may have the capacity to replace ROC payments once the model was scaled. By removing the dependency on Government subsidies and deferring grid infrastructure cost through deployment of circular fuel switching models, this has this potential of making a significant contribution towards decarbonising the UK Industrial operations. DAERA has indicated the Ammonia and digestate management are key priorities for the Department. NIE and National Grid welcomes flexible technology, balancing distributed energy resources, and combining this all in together. By reverse engineering existing capacity map, the H2M Project will model more demand and more generation capacity across wider UK.

Gas Operators have indicated in the mainland UK current infrastructure is not capable of distributing 100% hydrogen. Pipelines are currently capable of supporting 20% hydrogen [25], although can handle natural gas and biomethane. The H2M project will demonstrate limits to blending hydrogen with the upgraded biomethane investigating the change of hydrogen concentration in the feed supply for the boilers. Our models suggest a 5% blend of hydrogen can be added to each AD with up to a 20% blend into the final gas storage tank. These figures will be modified during the demonstration project to explore the limits and the most efficient ways to utilise the hydrogen within the AD system.

The National Farmers Union (NFU) reported in 2019 that greenhouse gas (GHG) emissions from UK farms amounted to 45.4 million tonnes of carbon dioxide equivalent (CO_2e) in 2018 – about 10% of the country's total emissions. Farming activity covers some 43m acres (17.4m hectares) occupying around 71% of the UK landmass. As such, it constitutes a vital part of the UK's rural, agri-food and bioresource economies. DEFRA estimated that UK farming produced a total income of £4.1bn in 2020[26]. Some 219,000 UK agricultural holdings (66% of which are less than 50 ha) provide more than half (64%) of the nation's food. Many manufacturing plants are rurally located and therefore not connected to the mains gas network, these proposals are likely to affect the manufacturing industry quite significantly – not least operations that are currently using high-carbon fuels like oil, coal and diesel.

The H2M developed an energy systems model that has the capacity to satisfy initially, the high-quality energy demands of small-scale food producers in rural areas with high environmental and landscape value and accurately identify a compact modular system dedicated to family farming to reduce external inputs and waste assisting the development of a more circular economy. If the H2M project progresses to Phase Two demonstration, the system flexibility and adaptability could be further expanded to service a wider network of industrial operations, both on and off grid.

H2M has identified a pathway to fuel independence, self-sufficiency (in off-grid vision) and capacity to generate hydrogen at small scale, providing a bottom-up approach that is scalable and provides system balancing for utilities.

6 Proposals for phase 2 activities

The feasibility analysis described in this report suggests that a hydrogen/biogas blend gas can be produced using a combination of wind and by-product rape meal cake. The combination of the two energy streams with on-site storage allows for the creation of a closed loop circular economy and a net zero product at the Dontein site. Oversupply of both hydrogen and biogas is also likely given the predicted outputs and other energy saving methods (e.g., FLEX schemes). This then allows for the system to provide additional low carbon fuels to facilitate transport and other services to the site. These services were beyond the scope of the feasibility study but further demonstrate how the proposed system could potentially serve as a wider demonstration site to inform the UK community. Delivering green hydrogen at low cost is essential for providing replacement fuels that are comparative or lower cost than fossil alternatives. The cost of the hydrogen system was evaluated using existing experience of the CPH2 electrolyser unit which combines a membrane free stack with cryogenic separation to produce a robust and low ownership cost system. Lagan MEICA developed this experience from the initial studies carried out on a 10 kW CPH2 unit which subsequently informed the design of a £5m investment for a 1 MW demonstrator unit currently being integrated into a Northern Ireland Water wastewater treatment plant (due October 2022). Work at the site is ongoing to optimise system integration into grid services to enable both access to inexpensive night-time electricity and also DS3 services (an alternative to flex) where payment is received for switching off grid power for short times at times of high electricity demand. The similarities between the system at NI Water and the H2M project present an opportunity to evaluate the capital costs for the H2M project to better inform the economics.

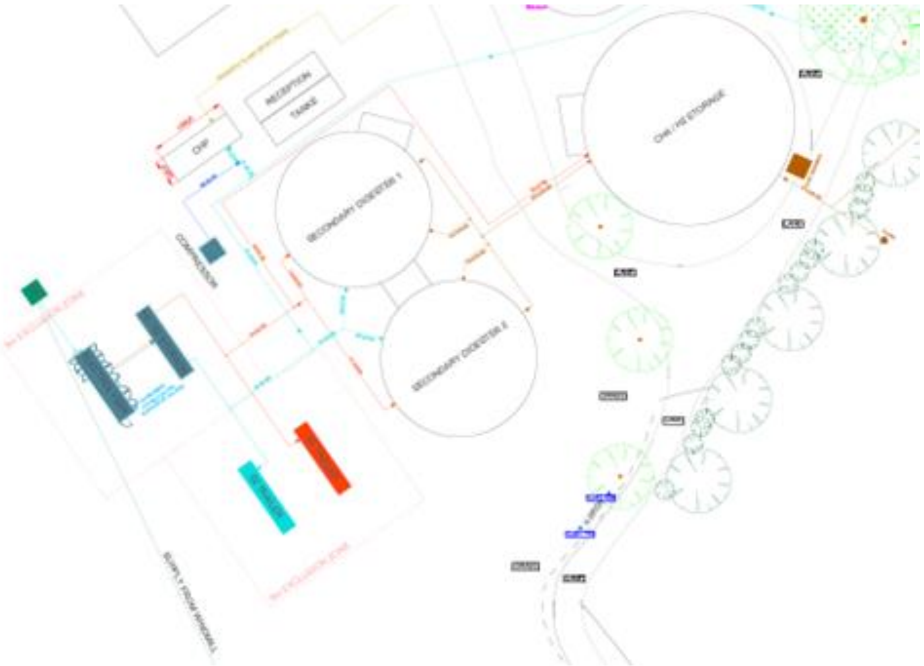


Figure 19 - H2M planned proposal layout

Figure 19 shows the basic layout of the site. The demonstration project will require a separate AD to run experimental tests under a controlled setting. By implementing this system to the existing AD would cause a risk to HCRS's main income stream and provide difficulties when carrying out experiments that could potentially affect the bacteria within the AD. As stated in section 2 of this report implementing hydrogen to the AD environment can initially cause negative impacts to the ecosystem. The lack of commercial scale systems brings an inherent risk to implementing such a system to existing AD infrastructure, this project can reduce those risks for future commercialisation. Additionally, by running an 'off-grid' model the parameters of the system can be changed to find optimal running conditions and provide real time data for other industries to follow suit. A more detailed process flow of the proposed system was developed and used to determine the capital cost for the project, this is shown in figure 20.

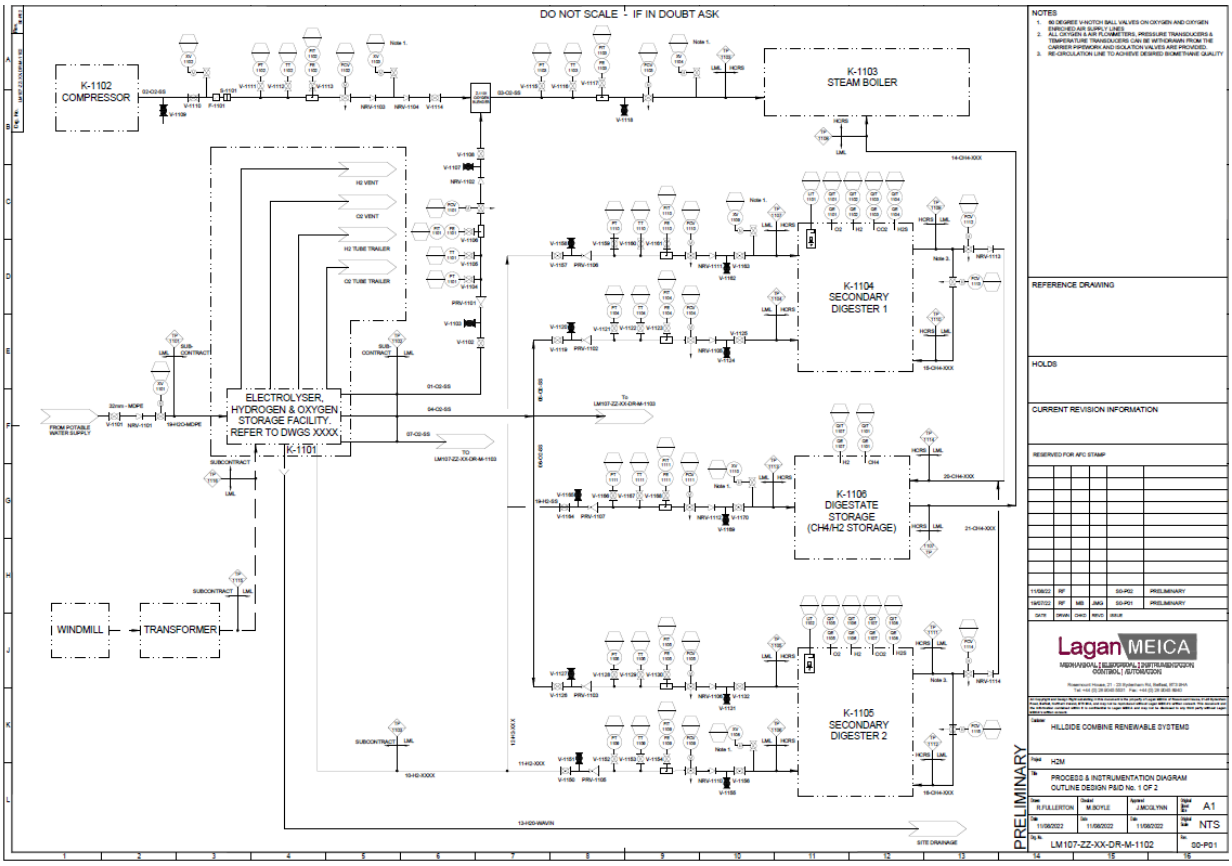


Figure 20 - P&ID of the proposed H2M Project

The outputs of this were subsequently used to estimate costs and savings as summarised in table 3.

Table 3 - H2M Projected Fuel Costs and Potential Savings

Factor	Assumption	Rationale
Thermal Energy Consumption	13,230,000 kWh/ Year	Based on Dontein's steam load consumption.
Cost of LPG/day	~£4,531[27]	Based on the price of LPG on June 2022
LPG Carbon Content	0.21449kg CO_2e/kWh, 2,837,703kg CO_2e per Year	Based on BEIS GHG reporting data
Carbon Price	€87.07 per Ton	Based on the European Carbon credit market on the (June 2022) [28] .
Biogas Price	£0.28/nm^3	Based on the CAPEX (AD infrastructure + pipe work to boilers) and OPEX (Wages and maintenance contracts on AD equipment) Figures based on a 10-year payback period.
H2 Price	£1.49/nm^3	Based on the CAPEX (Electrolyser, Compressors and high-pressure storage systems) and OPEX (Wages and maintenance contracts for compressors and electrolyser) 11.5p/kWh has also been factored in to give a return over a 10-year period.
Biogas Hydrogen blend Carbon Cost	~3,200kg CO_2e per year	Based on BEIS GHG reporting data. Amount of CO_2 emitted if the fuel switch was entirely swapped with a biogas/H_2 blend.
Biogas/H2 blend price /Day	~£4,241	16% H2 84% Biogas
Savings from IFS	~£290/day	
CAPEX Cost **OPEX Cost**	£5,625,000 CAPEX £6,456,056 OPEX	Based of a 16% H2, 84% Biogas blend over a 10-year period

*CAPEX + OPEX costs based on manufacturer prices as of July 2022

It is noted that phase 2 will focus on providing the most cost-effective fuel mixture to enable a fuel switch through the balancing of the two technologies. H2M will investigate the limitations of hydrogen within the AD system. The mix of gas selected will alter the end fuel supply cost.

The H2M project consortium aim to complete this project by Q1 2025. The overall project schedule consists of engineering, civil works, procurement, contract negotiation, commissioning, and performance validation. The H2M project team are aware of the lead times for the procurement of electrolyser technology and have factored this into the project timeline, with contingency plans in place to keep within the project timelines. The project consortium consortia will work with Original Equipment Manufacturer (OEM) suppliers, Engineering, Procurement, and construction (EPC) contractors, financing partners, and planning professionals, alongside public bodies to prepare for the installation of the electrolyser on site.

The Phase two project will commence March 2023 and will be completed by Q1 2025 in alignment with the Industrial Fuel Switching programmes timelines

Table 2 Proposed Work packages

	Task
1	NPD Plan/Project Management
2	Civil works
3	Mechanical & Electrical
4	Control and Automation
5	Instrumentation and Control Validation
6	Infrastructure commissioning
7	Testing & Academic Validation
8	System flexibility
9	Techno-economic and environmental assessment
10	Market Adaption
11	Exploitable Results
12	Commercialisation

There will be ongoing consultations with public bodies, Licensing, Environmental, H&S Executive, Planning departments and Hydrogen Division within Department for Economy NI. Knowledge exchange will be an ongoing activity and output from the Phase two project and findings from each work package will be disseminated with: Technical Advisory's, Industry Groups and affiliate Networks and associations.

The anticipated outputs are listed below

- Provide a roadmap for producing Hydrogen at SME level
- Deferred wind curtailment costs – Consumer savings and optimised configurations
- Development of a validated AD model using the measured outputs
- Potential for development of District Heating and Centralised distribution of Hydrogen as a fuel source
- Leverage constrained areas of the Grid, through reserve load
- Increase production of high-quality grid injectable Green Hydrogen
- Provide fuel security for Off Grid and Rural Manufacturers
- Provide additional Flex Capacity for Network Operators (Subject to volume of Hydrogen)
- Visibility of Off grid capacity capabilities (Flex Reserve)
- Enable the product of high-quality grid injectable Green Hydrogen at SME level
- Improve the performance of Anaerobic Digester plant
- Potential for larger volume of Biomethane production
- Better quality of biogas
- Alternative Fuel source to fossil fuels
- Potential to reduce nitrogen emissions from farm operations
- Roadmap for producing green hydrogen on farm
- Reduce fuel costs
- Reduce cost to consumer for curtailed wind
- Defer grid investment costs (Particularly Rural Area)
- Reduce emissions (Partially displace Nitrogen)
- Manage Pollutants (Ammonia)
- Create Circular sustainable Green Economies in Production
- Provide fuel security
- Provide Food security through affordable fuel sources
- Provide manufacturing longevity through implementation of affordable fuel sources

After the Phase 1 report is published, a copy will be disseminated to key industry stakeholders H2M consulted with during the feasibility study. All project partners will maximise exposure to industry and other interested parties using a variety of dissemination activities. Prior to Phase Two commencing, H2M project partners will present the findings of the report to the AD Bio resources association, Hydrogen Ireland Conference (Including NI) and to local authorities and Government departments. A presentation will also be made to Manufacturing Networks and Agri Food associations.

A sample of the dissemination activities that will be conducted by H2M during Phase Two are:

- Consultations with manufacturing bodies across Northern Ireland, Ireland, and UK
- Presentation to AD Associations, Dairy and Poultry Associations
- Press releases and attendance at Wind, AD, Agricultural and Food Security Conferences
- Presentation to Public Bodies – help attract Foreign Direct Investment
- Academic Presentation and white paper reports to Industry Bodies
- Presentation to Hydrogen Networks and associations
- Academic and Industry Seminars online and offline
- Presentation to Gas installer networks, engineering associations and EPC contractors
- Consultation and knowledge transfer to policy Groups and Quality Standards agency
- Findings will be shared with insurance companies, underwriters, policy departments and regulators

6.1 Project Risks and mitigations

- Supply of Hydrogen – A major aspect of the project is to demonstrate that hydrogen can co-exist and work with biogas using biological means and hydrogen blending to obtain a consistent and high calorific value fuel source. The H2M consortium has contingency plans in place through discussions with electrolyser manufactures.
- Mechanical and electrical risks – Since the system being proposed has never been installed at a commercial level, the system must be designed and engineered from scratch. Lagan Meica have developed experience through design and integration of an electrolyser into a NI water wastewater treatment plant. Lagan MEICA operate an Integrated Management System (IMS) covering the requirements of ISO 9001:2015, ISO 14001:2015, ISO 45001:2018 and the relevant legislation and industry standards. This covers the Head Office at Rosemount House in Belfast: Kinnegar Offices in Holywood and all Construction Sites where Lagan MEICA have a liability.

With the exception of where Lagan MEICA undertakes work as part of a joint venture, where the terms of the joint venture will clearly identify the management system to be used and Lagan MEICA will be satisfied that the system chosen is at least equivalent to their own Integrated Management System. In these circumstances provision will be made to ensure Lagan MEICA personnel assigned to the joint venture are trained in the operation of the alternative system. Lagan MEICA undertakes the environmental engineering including contracting for the design and construction of water, wastewater and energy sectors.

Lagan MEICA have several personnel with a wealth of experience in the petrochemical and energy sectors including syngas and synfuels which include Hydrogen and Oxygen production. Due to the specific risks identified within the H2M project, additional layers of collaborative decision making will be introduced such as LOPA (Layer of Protection Analysis) which is a process using quantified probabilities and explicit tolerable frequencies for specific consequences as the decision criteria for risk assessment. LOPA is generally used for higher severity consequence events which have been previously identified through other process hazard analysis (PHA) tools such as Hazard and Operability (HAZOP)study. The advantage of LOPA is that it is a semi-quantitative method which helps drive higher quality decisions for severe consequence events when compared to a HAZOP that relies solely upon qualitive information. It uses order of magnitude values to approximate the risks of a scenario.

As the feasibility study was taking place, the project consortium engaged with key stake holders, both public and private to determine if there were any other unanticipated risks. The project has since been identified that it can affect a much wider market than originally anticipated. Not only is the project beneficial to the agri-food business but a wider manufacturing scope. The project has been identified as a bottom-up model. The price of biogas production will be unique to individual AD sites depending on their biological feedstocks. The system design illustrated in this study is replicable in nature, ensuring the fuel switch is easily transferable to other systems. For a similar business to HCRS the initial payback on investment is less than 10 years. TRNSYS models will be created during Phase 2 enabling individual sites to be integrated into the system design, providing insight to each companies' individual energy needs and the feasibility of implementing the system.

7 Conclusions

The H2M project has the innovative capacity to disrupt the market, with more producers of hydrogen this will create competition driving down the cost of hydrogen and leverage dependency on leading fuel Giants and Hydrogen Producers, creating circular renewable hydrogen economies whilst enabling longevity and security of supply. Gas prices are increasing drastically as there is little to no alternative in the market at present. The H2M project provides an alternative pathway for producing hydrogen on site, in rural and off grid locations. By reducing the consumption of fossil fuels through utilisation of local production capacity through the paradigms of the H2M project, this will inevitably reduce the price of fuel whilst decarbonising the production eco system and maintaining biodiversity. The H2M Feasibility study has developed a pathway for Industrial fuel transitioning, achieving the cheapest production mechanisms to produce blended fuels, leveraging dependency on subsidies or gate fees. This scalable solution is flexible by design with a potential (assuming 10% penetration of industrial manufacturing operations) to be deployed to approximately 36,000 Industrial operations. H2M project are at the forefront of decarbonising the rural and Industrial fuel Market. By repurposing existing industrial and agricultural assets to carry hydrogen as a blended fuel into the future. The curtailed wind can contribute to circular energy economy, mitigating wastage of energy and enabling the production of high-quality grid injectable Green Hydrogen, reducing market price for rural industrial operations. Moreover, falling renewable energy prices coupled with the dwindling cost of electrolysers and increased efficiency due to technology improvements—have increased the commercial viability of green hydrogen production. The H2M project can reverse the paradigms of how fuel is traditionally distributed, leveraging dependency on Large Industrial Players and providing a roadmap for SME (both agri and Industrial) to adapt Blended fuel sources at low level production costs, enabling fuel switching. In addition to this, H2M has the capacity to deliver an economically efficient outcome which should reduce electricity network congestion, curtailment of renewables and electricity network reinforcement costs, facilitating Flex programmes and harnessing a bottom-up approach. The H2M project improves hydrogen production economics and ultimately lower hydrogen cost to consumers by minimising the impact on the electricity grid and making the most efficient use of existing gas and electricity infrastructure.

Key achievements:

- H2M production costs: Cost of blending fuel is £0.12 per kWh based on an estimated £5,625,000 capex and £6,456,056 OPEX over 10 years (without subsidies or gate fees) – Note current blended gas (16% H2) price is £0.47/m^3. This cost was based on Hillside Combined Renewable systems site and is scalable across multiple site operations across UK
- 99.9% of Carbon emission savings
- H2M project has capacity to bridge the gap for large scale displacement of fossil fuels meeting the net-zero target and facilitating a closed loop circular economy
- Roadmap for protein diversification enabling net-zero economy
- Capacity to meet 10% of the industrial fuel demand across the whole of the UK, with surplus protein waste necessitates recycling in a circular economy scenario.
- The fraction of hydrogen that can be ramped up as production costs lower, results in CCUS being mitigated over time
- £106k savings per annum
- Design of model is replicable across the whole of the UK and has potential to be exported

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9 Abbreviations and Acronyms

AD: Anaerobic Digestion

DfE: Department for the Economy (NI)

LPG: Liquid Petroleum Gas

DAERA: Department for Agriculture, Environment Rural Affairs

Capex: Capital Expenditure

Opex: Operational Expenditure

IEA: International Energy Agency

HCRS: Hillside Combined Renewable Systems

QUB: Queens University Belfast

kW: kilowatt

MW: Megawatt

CPD: Continuing Professional Development

CO_2: carbon dioxide

SME: Small Medium Enterprise

ROCs: Renewable Obligation Certificates

RTFO: Renewable Transport Fuel Obligation

FTE: Full time employees

GHG: Greenhouse Gas

CHP: Combined Heat and Power

BEIS: Department for Business, Energy and Industrial Strategy

OEM: Original Equipment Manufacturer

NPD: New Product Development

NIE: Northern Ireland Electricity

SGN: Scotia Gas Networks

NFU: National Farmers association

CH_4: Methane

O_2: Oxygen

H_2: Hydrogen