Hydrogen Innovation Initiative (HII)

Deep Green Hydrogen

Feasibility Study by: Clo Carbon Cymru

Commissioned by: Offshore Renewable Energy Catapult

In Partnership with : Pembrokeshire County Council

July 2023

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The Hydrogen Innovation Initiative

The Hydrogen Innovation Initiative's mission is to accelerate the development of critical technologies and supply chains in the UK for the fast-growing hydrogen economy. The Hydrogen Innovation Initiative's partners include the Catapult Network, the Advanced Propulsion Centre, the Aerospace Technology Institute, the Net Zero Technology Centre and the National Physical Laboratory. The Hydrogen Innovation Initiative is supported by Innovate UK.

The Offshore Renewable Energy Catapult

The Offshore Renewable Energy (ORE) Catapult, a real living wage employer, was established in 2013 by Innovate UK as part of a network of Catapults set up in high growth industries. It is the UK's leading innovation centre for offshore renewable energy. Independent and trusted, with a unique combination of world-leading test and demonstration facilities and engineering and research expertise, ORE Catapult convenes the sector and delivers applied research, accelerating technology development across offshore wind (fixed and floating), wave & tidal energy, reducing risk and cost and enhancing UK-wide economic growth. Active throughout the UK, ORE Catapult has operations in Glasgow, Blyth, Levenmouth, Aberdeen, the Humber, the East of England, the Southwest, and Wales and operates a collaborative research partnership in China.

The UK energy system is facing unprecedented challenges to meet carbon emission reduction targets, including Net Zero by 2050. It will require intensive expansion of low-carbon electricity generation technologies and decarbonising heat and transport sectors using electrification and hydrogen. This transition will provide many opportunities for UK innovators to grow and thrive, and policymakers will face several key decision points that will determine the prospects for UK plc, outcomes for consumers, and the overall impact of the transition on UK gross value added (GVA).

Pembrokeshire County Council

Pembrokeshire County Council are committed to the decarbonisation of the Council's estate and assets. The Council owns a significant number of county farms and recognise the huge contribution agriculture makes to the county and the region. The Council are pleased to partner in this study which looks at innovative ways to decarbonise farming activity whilst enhancing ecosystems. The Council are pursuing emerging green economy opportunities to expand whole energy system decarbonisation efforts in heating, transport, electricity systems and infrastructure. The Council recognise that Smart Local Energy Systems can play a key role in a just energy transition to a zero carbon society. The Council are thus committed to continued collaboration with Welsh and central governments, experts from the private and 3rd sectors, the SW Wales Corporate Joint Committee, Pembrokeshire Public Services Board and Swansea Bay City Deal partners to maximise these opportunities to decarbonise.

Clo Carbon Cymru

Clo Carbon Cymru design Emission Reduction and Carbon Dioxide Removal (CDR) strategies for the agricultural sector, built around the principles of Mixed Farming and Agroforestry Systems. Climate-catastrophe is best avoided through strategies which actively support the creation of localised economies. The foundations of these new economies are built on cross-sector collaborations, which connect localised consumer demand with farmers. By design, these strategies also aim to prevent the singular focus on ‘carbon’ from concealing the equally pressing issues of poverty, biodiversity loss, housing, food security, employment and well-being.

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Summary

In March 2019, UN General Assembly President María Fernanda Espinosa Garcés informed delegates at the opening of the seventy-third session (high-level meeting on climate and sustainable development), that humans have fewer than 11 years to avert complete climate catastrophe (1).

Between 2019 and 2023, the frequency of human-induced disaster events have increased at unprecedented levels:

- Antarctic sea ice extent has broken the record low set in 2022 (2)
- A majority of countries in the Northern Hemisphere experiencing record heat-waves in excess of 2°C - 4°C above the average (3)
- Exceptional 'winter' heat-waves across Europe (4)
- Fossil fuel emissions are 48% higher than they were in 2000 - 37.5 billion tonnes CO_2 (5)
- Record levels of methane sent to the atmosphere as wetlands collapse (6)

- Climate change affects human health; about 37.0% (range 20.5 - 76.3%) of warm-season heat-related deaths can be attributed to anthropogenic climate change and that increased mortality is evident on every continent (7).

- Early forecasts suggest El Niño will return later in 2023, exacerbating extreme weather around the globe and making it "very likely" the world will exceed 1.5$^{\circ C}$ of warming. The hottest year in recorded history, 2016, was driven by a major El Niño (8).

- Globally, the air is getting hotter & drier, which means droughts and risky fire conditions are developing faster & more frequently (9)

- Sea levels are rising faster than anytime previously, bringing a "torrent of trouble" to almost a billion people (10)

> “When global crises are interlinked, the most effective solutions are those working at the nexus of them all.”
>
> R. Edwards. Co-Founder Clo Carbon Cymru

Despite these predictions, humanity still has time to challenge climate change by developing strategies that actively support the effort to maintain global temperature increases below 1.5°C.

The design of those strategies should begin with reinforcing the foundations of localised economies, which must prevent the singular focus on ‘renewable energy’ from concealing equally pressing issues of poverty, biodiversity loss, housing, food security, employment & well-being.

These economies would be built on enhanced cross sector collaboration & integration, which connect farmers with localised consumer demand.

Purpose
This study will:

- Chiefly aim to explore the production of hydrogen fuels within a conceptual model that considers the impact that climate-change is likely to have on farming practices in Pembrokeshire.
- Focus on the design of energy generation models at two dairy farms in Pembrokeshire.
- Test the hypothesis, which suggests that relatively small-scale dairy farms (producing between 2,500m^3 and 7,500m^3 of slurry annually), can develop viable hydrogen-based generation systems.
- Explore in detail the opportunity to establish collaborations between multiple farms to develop localised hydrogen co-operatives.
- Validate a wide range of technologies, including methane plasmalysis and the integration of micro-scaled pyrolysis, gasification and anaerobic digestion technologies.
- Consider the need to reduce emissions of greenhouse gases alongside the very urgent need to develop on-farm strategies that seek to improve the management of existing farm assets - woodland, hedgerows and soil. Also explore the economic arguments for adoption of complimentary farming practices, that could provide feedstocks / raw materials for hydrogen production.

- Explore the opportunity and viability of establishing a rural network of hydrogen fuel supply chains that support the ambition of car manufacturers, and hydrogen supply companies to locate hydrogen fuel 'filling stations' across Wales. Working with both private and public sectors.

- Seek to build the report within the ambition of the Well-being of Future Generations Act (Wales) 2015, which “requires public bodies in Wales to think about the long-term impact of their decisions, to work better with people, communities and each other, and to prevent persistent problems such as poverty, health inequalities and climate change.” (11)

- The Act makes it clear that listed public bodies must work to achieve the seven ‘Well Being Goals”

  A Prosperous Wales
  A Resilient Wales
  A More Equal Wales
  A Healthier Wales
  A Wales of Cohesive Communities
  A Wales of Vibrant Culture & Thriving Welsh Language
  A Globally Responsible Wales

- Take account of the Environment Act (Wales) 2016.

- Will consider, and where possible and practical, include the principles of the Low-Carbon Economy, the Just Transition Economy, the Well-being Economy, the Foundational Economy, the Cultural Economy and the Circular Economy.

Introduction

Clo Carbon Cymru designs Mixed Farming and Agroforestry Systems (MiFAS) that benefit the climate, environment and society in general.

MiFAS can be designed to operate within a single field, a farm, between farms or even across an entire landscape or food-chain. The concept aims at optimising the use of resources through collaboration and diversified production (energy, crops, trees, livestock) where the different enterprises benefit from each other (12).

Our economic models focus specifically on the urgent need to prepare our communities for the impact that climate-change, failing food-supply chains and financial uncertainty will deliver over the next 3-5 years.

Government in Wales has developed key instruments that act to catalyse ambitious economic models. In many cases, these instruments are undervalued, misunderstood and/or ignored.

By choosing to design economic models that consider the full impact that these instruments carry, Clo Carbon Cymru positions itself at the forefront of the effort to challenge many of the issues that the agricultural sector (and society) faces in Wales.

Designing economic models and strategies that focus on a single issue is wasteful. Similarly, focussing on a single point of greenhouse gas emissions, e.g., agriculture, is unlikely to drive the multiple actions required to reduce global emissions by the 50% specified in warnings from the United Nations.

Hydrogen

"Hydrogen has the ability to touch every part of our future energy system, delivering clean affordable energy to consumers across transport, heat, power and industry." (13)

Hydrogen is a chemical element which rarely exists on its own on earth. It is not a primary source of energy, and must be produced using existing energy. In essence, hydrogen is best thought of as an energy carrier, not dissimilar to a battery. But given the huge amount of energy needed to produce, transport and store hydrogen it is a very inefficient energy carrier. It's likely it will not be available for use at a large scale (14).

In its free state, hydrogen consists of two atoms (H2) which, when combined with oxygen (O) during its use (combustion or, more commonly, in a fuel cell), generates water (H_2O) as a by-product. Hydrogen generation via water electrolysis is a simple method, whereby a low voltage current flows through water to form oxygen and hydrogen gas. Hydrogen defined as 'green' is obtained through electrolysis of water powered by electricity produced from renewable sources (solar, wind and hydroelectricity, etc).

By its nature, hydrogen is difficult to transport and even more challenging to deliver to refuelling stations. Distributing hydrogen to homes, with a view to replacing fossil-derived gases (methane and 'natural' gas), would require a new delivery infrastructure (pipelines) unless natural gas-hydrogen mixtures with a low hydrogen content are used (15).

Producing hydrogen fuels from fossil-fuels generates excessive pollution:
Between 9-10 kg of carbon dioxide are produced for every kilogram of hydrogen obtained. About 95% of all the hydrogen currently being produced around the world uses fossil-based fuels, releasing more than 1 billion tonnes of carbon dioxide into the atmosphere annually .

Shades of Hydrogen

Green Hydrogen

Green hydrogen is made by using direct and surplus electricity from renewable energy sources, such as solar or wind power, to electrolyse water

Blue Hydrogen

Blue hydrogen is produced mainly from natural gas, using a process called steam reforming, which brings together natural gas and heated water in the form of steam. Carbon dioxide is produced as a by-product. The definition of blue hydrogen includes the use of carbon capture and storage (CCS) to trap and store this carbon.

Grey Hydrogen

Currently, this is the most common form of hydrogen production. Grey hydrogen is created from natural gas, or methane, using steam methane reformation. Grey hydrogen is essentially the same as blue hydrogen, but without the use of carbon capture and storage.

Black & Brown Hydrogen

Black and brown hydrogen are produced using fossil-fuels, predominantly black coal or lignite (brown coal). This is the most environmentally damaging form of hydrogen.

Pink Hydrogen

Pink hydrogen is generated through electrolysis powered by nuclear energy. Nuclear-produced hydrogen can also be referred to as purple hydrogen or red hydrogen.

Turquoise Hydrogen

This is a new entry in the hydrogen colour charts and production has yet to be proven at scale. Turquoise hydrogen is made using a process called methane pyrolysis to produce hydrogen and solid carbon.

Yellow Hydrogen

Yellow hydrogen is a relatively new phrase for hydrogen made through electrolysis using solar power.

White Hydrogen

White hydrogen is a naturally occurring, geological hydrogen found in underground deposits and created through fracking. There are no strategies to exploit this hydrogen at present.

Deep Green Hydrogen

Deep Green Hydrogen (DGH)

Clo Carbon Cymru has defined Deep Green Hydrogen as:

‘A process that utilises agricultural waste-streams, improvements in the management of existing farm-based natural resources and the establishment of new agroforestry systems, designed around the integration of anaerobic digestion, micro-scaled pyrolysis and biomass gasification technologies, to produce hydrogen fuels'.

The concept of DGH has been developed from a project in Hokkaido (17), where waste from dairy farms (slurry and manure) are being used to generate hydrogen to establish a ‘circular economy’.

Clo Carbon Cymru has taken the basic process design from this project and built-on strategies and approaches to emission reduction and carbon dioxide removal - CDR (18), which enable farm-scale systems to function more effectively and efficiently, in terms of carbon management.

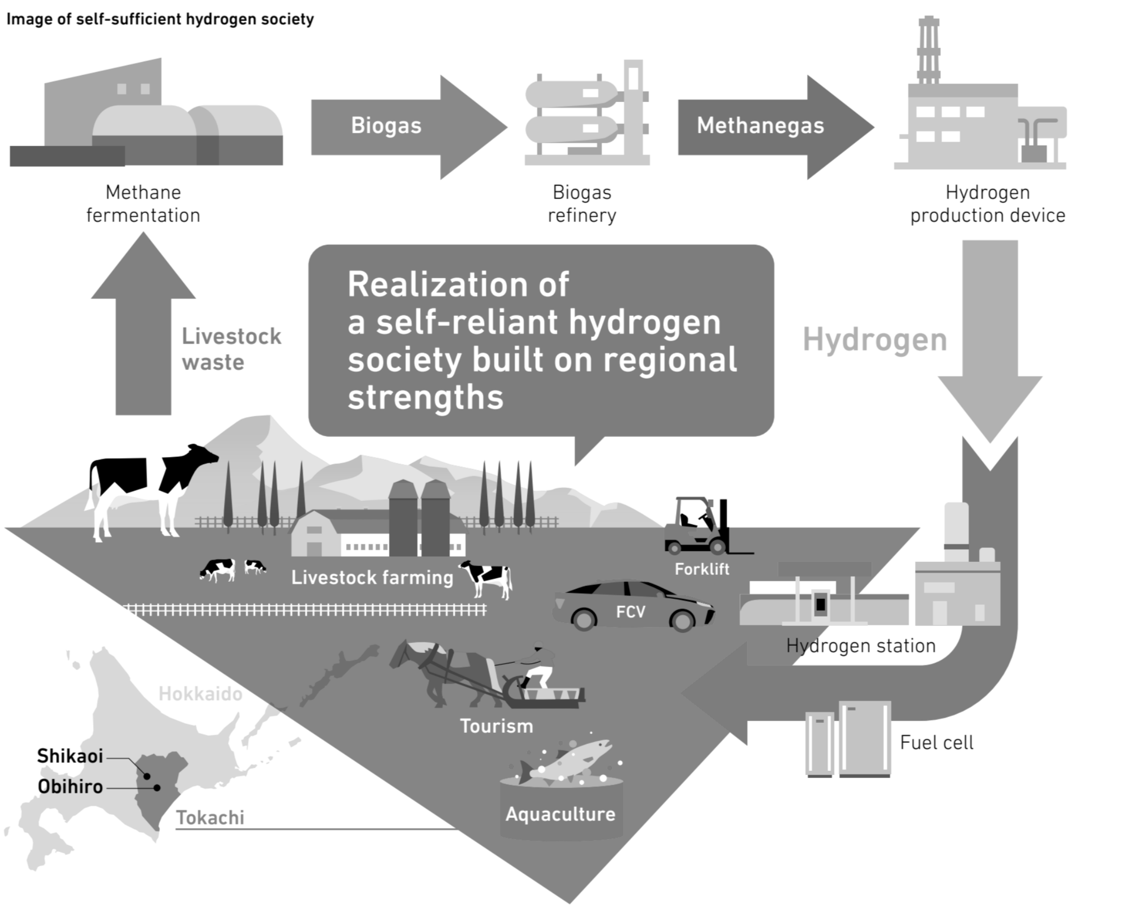


Fig 01

Deep Green Hydrogen
Feasibility

The report explores three processes to produce hydrogen:

1. Electrolysis
2. Steam Methane Reforming
3. Methane Plasmalysis

1. Electrolysis

Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyser.

Electrolysers can range in size from small, appliance-size equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse-gas-emitting forms of electricity production.

Electrolyser investment costs are difficult to compare across systems due to a lack of information about key system parameters, such as temperature, voltage, current density and pressure. According to Fraunhofer ISE researcher Marius Holst (19), the costs of alkaline (AEL) and proton exchange membrane (PEM) water electrolysers almost equalise when the effort for downstream compression is also taken into account.

“In total, system costs of approximately €400 to €500/ kW can be expected in 2030, but decentralised, smaller systems will remain significantly more expensive,” he concluded.

Currently, capital expenditure (CAPEX) requirements are in the range of £400-£1,200/ kWe for alkaline electrolysers and £900-£1,500/ kWe for PEM electrolysers: estimates for solid oxide electrolyser cell (SOEC) electrolysers range across £2,400-£5,000/ kWe (20).

A kilogram of hydrogen contains 39.4 kWh of energy *, but typically costs around 52.5 kWh of energy to create via current commercial electrolysers. Australian company Hysata says its new capillary-fed electrolyser cell slashes that energy cost to 41.5 kWh, smashing efficiency records while also being cheaper to install and run. The company promises green hydrogen at around US$1.50 per kilogram within just a few years (21).

* Higher Heating Value - HHV

2. Steam Methane Reforming

Steam methane reforming (SMR) is a process in which methane - sourced most often from natural gas is heated with steam and usually with a catalyst, to produce a mixture of carbon monoxide and hydrogen used in organic synthesis and as a fuel/ for energy (22).

Steam methane reforming is the most widely used process for the generation of hydrogen. This is largely due to its cost effectiveness in obtaining a high level of purity produced, which can be used in industrial processes and in fuel cells.

Although hydrogen itself is an emission free fuel, the feedstock to produce the hydrogen via SMR, often comes from natural gas which results in the emissions of greenhouse gases. Additionally, the SMR process requires vast amounts of heat and is therefore highly energy intensive (23).

Linde (24), one of the world's largest producers of hydrogen, recently produced a report detailing the carbon footprint associated with the individual SMR process steps. The report concluded that **9.3 kilograms of CO_2 are produced for every kilogram of hydrogen produced (39.4 kWh of energy) via the SMR process.**

For comparison, 4.55 litres of petrol (1 UK gallon) produces 9.1 kg of CO_2 when combusted (not counting the upstream carbon emissions from extraction, transportation of crude oil and subsequent refining processes).

Of course, that is just the carbon footprint of hydrogen production. To use the hydrogen for power, it still must be compressed, transported, and either combusted or converted to electricity in a fuel cell. The fuel cells themselves must also be built, and there are carbon emissions associated with those construction processes.

3. Methane Plasmalysis

An emerging technology in the area of hydrogen production is methane plasmalysis. One of the earliest academic references is from the International Journal of Hydrogen Energy in 2009 - Production of hydrogen and nano carbon powders from direct plasmalysis of methane, written by Cheng-Hsien Tsai and Kuan-Ting Chen.(24b) In this study, they demonstrated, that from methane, they could produce high-purity hydrogen gas and large volumes of powdered carbon (50 nm average particle size), through the use of a microwave plasma reactor that was run at atmospheric pressure.

Personal meetings and discussions with the authors and members of the Hydrogen Advisory Council Hydrogen Advisory Council - GOV.UK (www.gov.uk) (24c), indicated that this particular technology was not currently on the radar of the UK Government and therefore was not being considered as a potential source of hydrogen generation (and therefore sequestered solid carbon).

Graforce (25) is a German hydrogen technology company that manufactures modular plasmalysis plants, based on technology that produces a high-frequency plasma field, generated by renewable electricity, which splits hydrocarbons such as methane into their molecular components: hydrogen and solid carbon (carbon black).

Their plasmalysis technology produces carbon dioxide-free or carbon dioxide-negative hydrogen and synthetic feedstocks – with highest efficiency and lower infrastructure costs in the multi-megawatt range. Graforce claim (26) that their plasmalysis technology decarbonises fossil-based power and can be applied within the industrial, heat, transport and building sectors. The company is currently in the process of expanding its strategic partnerships to quickly scale its hydrogen technology worldwide.

Compared to water electrolysis, plasmalysis only requires 20% of the energy to produce the same amount of hydrogen. Since the CO_2 is sequestered in products, i.e., carbon black, over the long term, the technology is also being promoted as the first market-ready alternative to carbon capture storage (CCS) (27). Unfortunately, the methane-containing biogas has to be upgraded to a suitable purity, adding a further technological step and therefore additional processing cost.

Case Study: Graforce

Graforce has a working system in place at The Mercure Hotel MOA, in Berlin. This is set to become the first hotel and event location worldwide with a negative CO_2 balance when generating heat.

"The MOA Berlin is no longer heating with natural gas but with hydrogen from biogas. The methane plasmalysis technology splits the biogas into hydrogen and solid carbon. Using electricity from renewable energies, methane plasmalysis is just as climate-friendly as electrolysis " but the costs are significantly lower.

For the zero-emission heating process, the MOA Berlin uses modified gas condensing boilers fueled by a mixture of green hydrogen and biogas. The mixing ratio is controlled by the methane plasmalyser. The heat generation is started with 30 vol.% hydrogen and 70 vol.% biogas. In the following months, the share of hydrogen will be gradually increased.

The solid carbon can be used as an industrial raw material, for paints and ceramics or, as in the case of the MOA Berlin, for producing asphalt. Thus, CO_2 is permanently bound.

The gas heaters used at the MOA Berlin before would have emitted up to 800 tons of CO_2 per year. In order to absorb this amount from the atmosphere, the equivalent of more than 65,000 trees is needed.

"In order to counteract global warming, the generation of heat and hot water must be completely CO_2-free by 2050. There are two ways to achieve this: Either we'll heat with renewable electricity only or we decarbonise the natural gas supply with a carbon-free alternative such as hydrogen," said Graforce founder and CTO Dr. Jens Hanke.

According to the manufactures, the economics of this system are realised at around a scale of magnitude higher than a single farm can supply. The following worked example is based on an biomethane input of 560,000 m^3 per annum (3,080,000 m^3 of methane at 55% by volume). That would require slurry from 10 out of the 220 tenant farms in Pembrokeshire, assumes a revenue of €5.50 per kilo of hydrogen gas generated and mitigates <600 tonnes of CO_2 emissions. Full spreadsheet/ calculations in Appendix.

The Capital Expenditure (CAPEX) costs for the methane plasmalyser are in the region of €40,000 per kg of H2/h generated. The Operational Expenditure (OPEX) costs are estimated at 1% of the CAPEX, with electricity being the largest input cost.

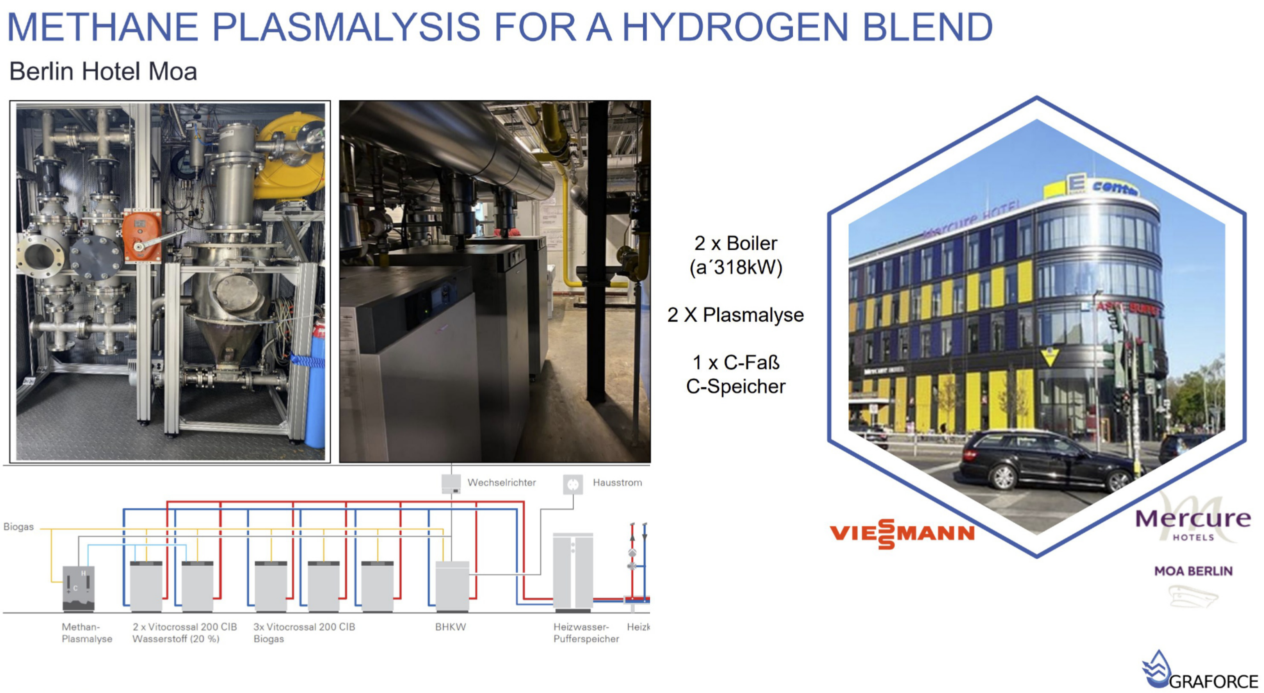

METHANE PLASMALYSIS FOR A HYDROGEN BLEND
Berlin Hotel Moa
2 x Boiler
(a´318kW)
2 X Plasmalyse
1 x C-Faß
C-Speicher
Wechselrichter
Hausstrom
Biogas
Methan-
Plasmalyse
2 x Vitocrossal 200 CIB
Wasserstoff (20 %)
3x Vitocrossal 200 CIB
Biogas
BHKW
Heizwasser-
Pufferspeicher
VIESSMANN
Mercure
HOTELS
MOA BERLIN
GRAFORCE

Fig 02

Hydrogen Uses:
Beyond Fuel

There are several niche, but high-value uses / outlets for hydrogen that lay outside standard transportation / heating. One of these is laboratory gases - which have additional markup, with additional premiums for purity and grade. The volumes and weights used are incredibly small, but there is potential to disrupt this market by offering a green alternative at a very competitive price. Obviously, the infrastructure and safety implications that arise that surround compression, bottling and transportation need to be addressed, but for large industrial laboratories, who already purchase high purity (brown/ black) hydrogen, it could be that supply contracts are formed to mutual benefit and at agreeable costs, with the added benefit of a truly renewable hydrogen product.

Bovine Economics
& Energy Potential

Calculations on the energy generated from dairy 'activities' are documented in the following: A report carried out by South Wales University (28) determined the following volumes of slurry and parlour washings at New Lawrenny Farm (Pembrokeshire, Wales):

	150 Dairy Cows + 20 young stock	170 dairy cows + 10 young stock
Volume	1,444 m^3	1,553 m^3
Potential additional volume added by drainage water	1,480 m^3	1,480 m^3

These figures assume that cattle are housed between mid October – March, an estimate of slurry volume using the Coleg Sir Gâr / Gelli Aur slurry volume calculator (29).
Figures were rounded to a minimum annual slurry production of 3,000 m^3 and a maximum of 4,000 m^3 from this particular farm. Slurry production will not be consistent across the year. Maximum production will be during winter months (October – March) (approximately 363 – 484 m^3 / month), with production in summer reducing to 153 – 204.9 m^3 / month.

A report by the Agri Food and Bioscience Institute (AFBI) (30), suggested that:

- 1 tonne of dairy cow slurry at 69 g/ kg dry matter produced 15.2 cubic metres of biogas containing 85 kWh of energy
- 1 tonne of organic matter in slurry produced 280 cubic metres of biogas (0.28 m^3/ kg organic matter)

A report by Coleg Sir Gâr (31) suggests the monthly volume of slurry produced per cow is:

- A single dairy cow producing between 6,000 - 9,000 litres of milk a year = 1.59m^3 (1,591 litres)
- A single dairy cow producing in excess of 9,000 litres a year = 1.92m^3 (1,918 litres)
- A single Heifer (2 – 12 months old) = 0.6m^3 (600 litres)
- A single Heifer (12 months - Calving) = 1.2m^3 (1,205 litres)

The average per/cow production of slurry was calculated at 19 m^3 per cow per year. In addition parlour washings totalled 20 – 30 litres per cow per day (11 m^3 per cow per year) and rainwater from a shed (built to house 100 cows) produces 1200 m^3 per year (12 m^3 per cow per year).

Bovine Gas Production
Based on:

- A single cow producing 20 m^3 slurry (annual average)
- Dry Matter (DM) (or Total Solids) 30 – 60g / litre
- Organic Matter (or Volatile Solids) 22 – 45g / litre
- Dairy System - Calving Shed - Parlour Washings and Waste Water
- Methane (CH_4) Content = 58%
- Energy Content of CH_4 = 9.98 kWh

Slurry (100 head cattle)

Annual Volume (m^3)	2,000
Biogas production potential (m^3/t)	14
Annual biogas production (m^3)	28,000
Annual gross energy production (Mwh)	162.07

Slurry (150 head cattle)

Annual Volume (m^3)	3,000
Biogas production potential (m^3/t)	14
Annual biogas production (m^3)	42,000
Annual gross energy production (Mwh)	243.11

Slurry (200 head cattle)

Annual Volume (m^3)	4,000
Biogas production potential (m^3/t)	14
Annual biogas production (m^3)	56,000
annual gross energy production (Mwh)	324.15

Calving Shed (Estimated)

Annual Volume (m^3)	1,502
Biogas production potential (m^3/t)	14
Annual biogas production (m^3)	14,000
Annual gross energy production (Mwh)	85.25

Silage Effluent (Estimated)

Annual Volume (m^3)	360
Biogas production potential (m^3/t)	14.6
Annual biogas production (m^3)	5,256
Annual gross energy production (Mwh)	31.47
CH_4 content (%)	60 %

Energy Conversion & End Uses

The efficiency of renewable energy is maximised when it is used as close as possible to the point of generation.

1 - Thermal energy (heat) via Biogas boilers

Biogas is a variable mixture of methane, CO_2 and small quantities of other gases. This is produced by anaerobic digestion of organic matter in an oxygen-free environment. A wide variety of feedstocks can be used to produce biogas, including crop residues, food wastes and animal manure. The maximum thermal energy content is calculated in the following:

Dairy System Only - Exclusively slurry

100 head cattle - 2,000 m³ per year

Biogas Production - 28,000 m³ / yr

CH_4 Content - 58%

Energy Content of CH_4 - 9.98 kWh

Gross Energy Production - 162.07 Mwh / yr

Conversion efficiency - 85%

Annual Heat Production - 137.76 MWh / yr

Parasitic Heat Demand (20% of produced heat maintains AD process) - 27.55 MWh

Heat available for end use - 110.21 MWh / yr

150 head cattle - 3,000 m^3 per year

Biogas Production - 42,000 m^3 / yr

CH_4 Content - 58%

Energy Content of CH_4 - 9.98 kWh

Gross Energy Production - 243.11 Mwh / yr

Conversion efficiency - 85%

Annual Heat Production - 206.65 MWh / yr

Parasitic Heat Demand (20% of produced heat maintains AD process) - 41.33 MWh

Heat available for end use - 165.32 MWh / yr

200 head cattle - 4,000 m^3 per year

Biogas Production - 56,000 m^3 / yr

CH_4 Content - 58%

Energy Content of CH_4 - 9.98 kWh

Gross Energy Production - 324.15 Mwh / yr

Conversion efficiency - 85%

Annual Heat Production - 275.53 MWh / yr

Parasitic Heat Demand (20% of produced heat maintains AD process) - 55.11 MWh

Heat available for end use - 220.42 MWh / yr

2 - Combined Heat and Power

Combined heat and power (CHP) generation has been the ‘standard’ operating model for the majority of commercial agricultural anaerobic digesters in the UK. CHP plants have a higher capital cost than biogas boilers. Conversion efficiencies are variable depending on scale and model: for the purposes of this report an electrical conversion efficiency of 38% and a thermal conversion efficiency of 50% is assumed.

Dairy System Only

100 head dairy herd

Biogas Production - 28,000 m³ / yr

Conversion efficiency (elec) - 38%

Max monthly elec prod Oct - Mar : 7.39 MWh

Parasitic Heat Demand (10% of produced) - 6.15 Mwh

Annual Heat Production - 81.35 MWh / yr

Min monthly heat prod Apr - Sept: 4.11 MWh

Electricity available for end use - 55.43 MWh / yr

Gross Energy Production - 162.07 Mwh / yr

Annual electricity Production - 61.58 MWh / yr

Min monthly elec prod Apr - Sept : 3.13 MWh

Thermal conversion efficiency - 50%

Max monthly heat prod Oct - Mar : 6.49 MWh

Parasitic Heat Demand (35% of produced) - 28.47 Mwh / yr

Heat available for end use - 52.88 MWh / yr

150 head dairy herd

Biogas Production - 42,000 m³ / yr

Conversion efficiency (elec) - 38%

Max monthly elec prod Oct - Mar : 11.09 MWh

Parasitic Heat Demand (10% of produced) - 9.24 Mwh

Annual Heat Production - 121.56 MWh / yr

Min monthly heat prod Apr - Sept: 6.17 MWh

Electricity available for end use - 83.14 MWh / yr

Gross Energy Production - 243.11 Mwh / yr

Annual electricity Production - 92.38 MWh / yr

Min monthly elec prod Apr - Sept : 4.69 MWh

Thermal conversion efficiency - 50%

Max monthly heat prod Oct - Mar : 14.59 MWh

Parasitic Heat Demand (35% of produced) - 42.54 Mwh / yr

Heat available for end use - 79.01 MWh / yr

3 - Biogas Upgrading to Biomethane

Biogas upgrading involves the separation of CH_4 from other components of biogas (CO_2, H_2S, Nitrogen, moisture) to leave a gas stream with a high % of CH_4 (>98%). The carbon dioxide content of biogas contains on average, 35–45 vol %.

The upgrading of biogas to biomethane is primarily based on carbon dioxide removal, but is also used to desiccate and separate/ remove other gases. Biomethane can be compressed, used directly as a road transport fuel for vehicles adapted to run on compressed natural gas (CNG), Liquefied Petroleum Gas (LPG) or it can be injected into the natural gas grid.

There are a number of techniques/ technologies to remove CO_2 from biogas. The most common are adsorption, absorption, cryogenic separation, and membrane separation. Large scale separation of CO_2 via a membrane separation process removes other unwanted gaseous minor compounds present in biogas such as hydrogen sulphide and water. Occasionally, other techniques and technologies are employed depending on the source of biomethane (landfill gas, anaerobic digestion etc.) to provide a highly purified gas or to remove other potential contaminants. Upgraded or even partially upgraded biogas can also be utilised as a vehicle fuel providing it has a methane content of at least 85%.

Upgraded biogas is generally referred to as biomethane. The majority of upgrading units operating on larger AD plants are delivering between 100 - 200 m^3 / hr biomethane. A small upgrading plant in the conventional sense would be in the order of 50 m^3 / hr.

4 - Methane Plasmalysis

Methane plasmalysis is the key technology for producing large quantities of high-purity hydrogen from natural gas with only a quarter of the energy required for electrolysis. With the methane plasmalysis process developed by Graforce, the methane (CH_4) is not broken down catalytically or at very high temperature, but rather split into its molecular components hydrogen (H_2) and carbon (C) using a plasma.

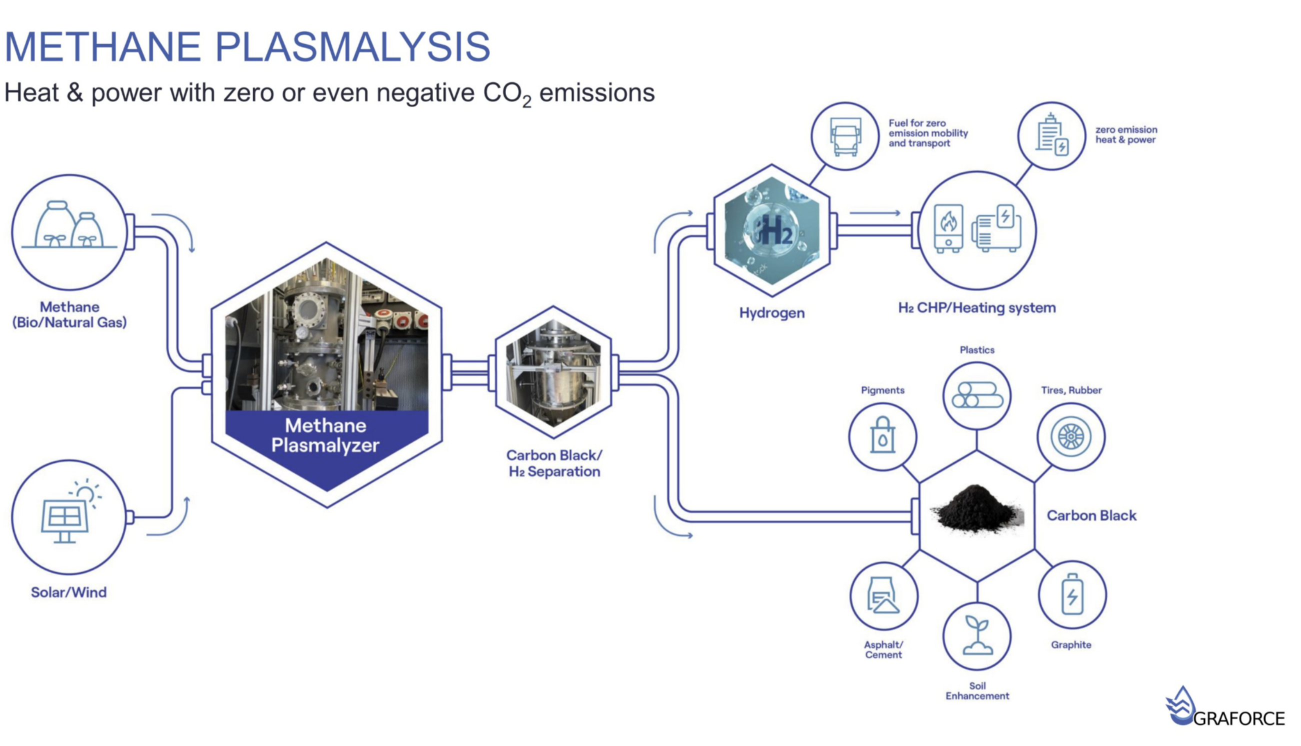


Fig 03

» Graforce literature claims that 4 kg of methane and 10 kWh of electricity produces 1 kg of hydrogen and 3 kg of elemental carbon (carbon black).

» That 1kg of hydrogen contains 39.4kWh. 4kg of methane converts to 61.76kWh, therefore, the methane plasmalysis process requires 71.76kWh of energy to produce 39kWh (1 kg) of hydrogen. The remaining 3 kg of carbon black is promoted as 'recovering' 27.3kWh, which enables the company to claim an 'energy recovery process' that is 93% efficient.

» The entire process relies on the end-user being able to market and sell the carbon black product and potentially the carbon credit attached.

» Claims rely on the carbon black being utilised in products that ensure long-term storage of the carbon.

Deep Green Hydrogen Frameworks

"There is some confusion about which kind of hydrogen should be prioritised and for which end use sectors. Many governments are considering widespread use of hydrogen in sectors where there are already cheaper, more efficient solutions available today. This is despite the Intergovernmental Panel on Climate Change recognising that hydrogen will represent, at best, 2% of total energy consumption in 2050." (32)

Agriculture can generate positive or negative environmental impacts depending on the specific activities undertaken on the farm. Agriculture is the principal land use in Wales; hence environmental sustainability in agriculture is key to achieving national level climate objectives (33)

Approximately 84% of the land area of Wales is used for agriculture.

Land use is dominated by permanent pasture grass-land, which accounts for more than 75% of the utilised area followed by 14% for croppable and 10% for common rough grazing (34).

While the production of 'renewable' energy supports the effort to reduce emissions of greenhouse gases, in most cases, as a singular action, it fails to challenge other pressing issues associated with the rural economy in Wales.

Similarly, designing an economic framework around technologies that could potentially cause environmental damage (35) does nothing more than increase 'well-being' pressures on farmers, charged with disposing of waste according to conventional practices.

Furthermore, hydrogen's potential as a clean fuel could be limited by a chemical reaction in the lower atmosphere (36). If more than 9% of the green hydrogen produced leaks into the atmosphere - whether that be at the point of production, sometime during transport, or anywhere else along the value chain - atmospheric methane would increase over the next few decades, cancelling out some of the climate benefits of switching away from fossil fuels.

It is quite clear, from data provided previously, that the production of hydrogen from dairy-waste, as a single source of feedstock, **will be seen as wasteful.** However, DGH is likely to offer greater benefits as a component part of a much wider functioning ecosystem, designed to challenge multiple issues associated with the rural economy in Wales, including climate-change and the very urgent need to capture and store increased levels of carbon dioxide from the atmosphere.

Deep Green Hydrogen
Single Farm Model

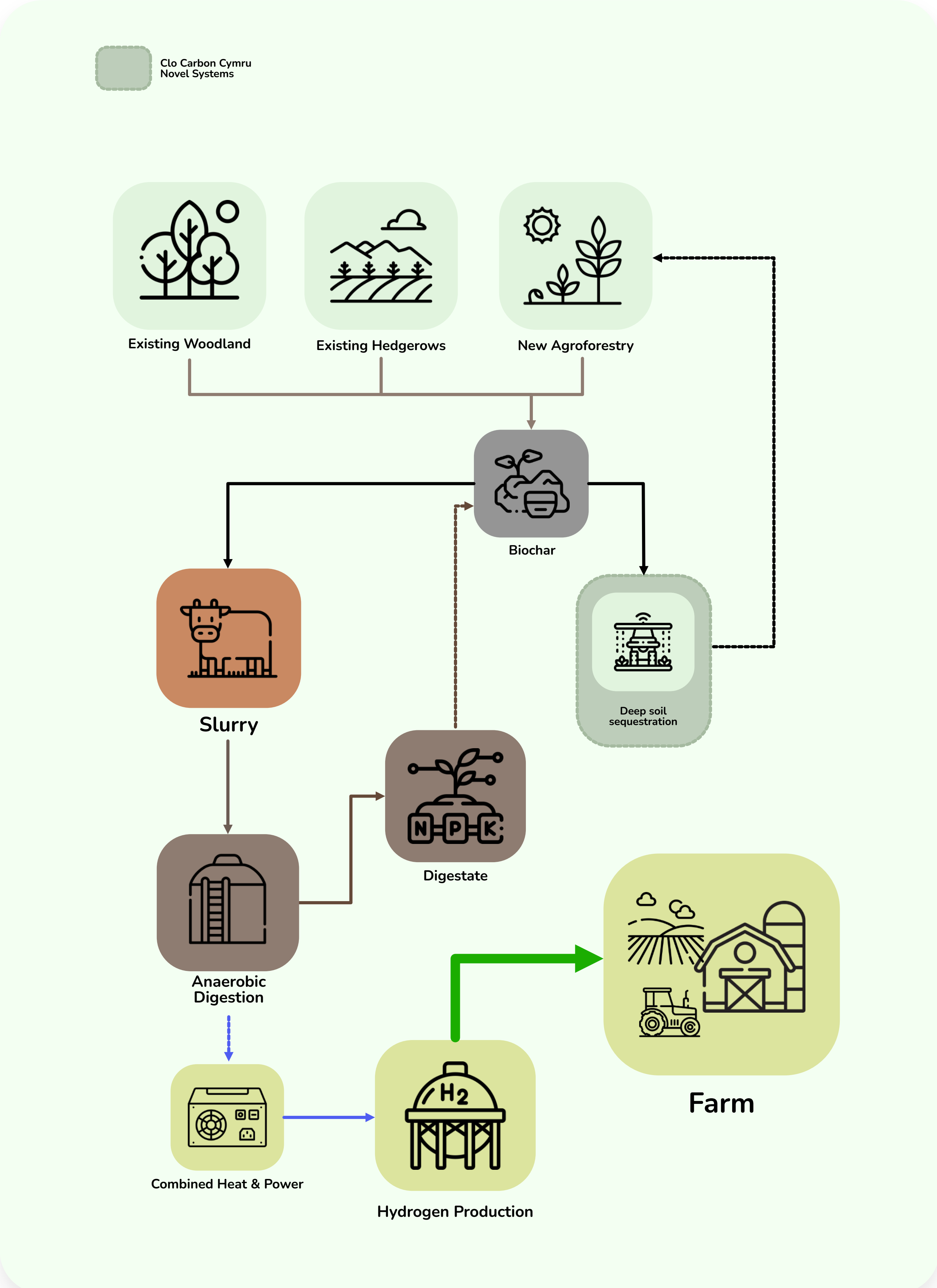
The single farm framework would encourage the farmer to improve the management of existing natural resources - hedgerows and woodlands - and establish new areas of agroforestry.

Agroforestry is defined as a land-use system in which harvestable trees and/or shrubs are grown among or around crops and/or livestock as a means of preserving or enhancing land productivity. Agroforestry is being promoted as one of the most promising systems for the 'sustainable intensification' of farming: theoretically, farmers should be able to produce more food from their land, while also reducing negative impacts on the environment (37).

The primary design objective is to provide the farmer with a resource that can contribute toward the urgent need to reduce operational emissions of greenhouse gases, and to drawdown (Lock - Clo in Welsh) carbon dioxide (CO_2) from the atmosphere.

Within this framework, woody biomass, harvested from existing areas of wood-land, hedgerows and new areas of agroforestry, would be used to manufacture biochar (38), which would be added to on-farm anaerobic digesters and/or slurry.

Biochar is known to increase the energy-density (calorific value or CV) of slurry (39) and has a positive effect on the Hydraulic Retention Time (HRT), accelerating the rate of biogas evolution. Increasing the CV of slurry would im-prove the efficiency of hydrogen production via the anaerobic stage of the pro-cess detailed below, but also aid with retention of beneficial soil minerals (phosphorous, potassium etc.) in the digestate and mitigate NO_X emissions, retaining nitrogen, through the absorption of ammonium (NH_4)+species.


Clo Carbon Cymru
Novel Systems
Existing Woodland
Existing Hedgerows
New Agroforestry
Biochar
Slurry
Deep soil
sequestration
Digestate
Anaerobic
Digestion
Farm
Combined Heat & Power
Hydrogen Production

Biomass

Existing Woodlands & Hedgerows

Farms that already have plans relating to the management of existing woodlands and/or hedgerows, would become subject to discussions with the landowner and/or woodland management consultant to determine the adoption of new strategies which could increase biodiversity and reduce the need to import wood onto the farm.

Woodland and hedgerows would provide annual volumes of raw material (including ‘low-value’ species such as willow, alder, etc) to satisfy the requirement for manufacturing biochar and deep carbon sequestration. These strategies would increase the carbon sequestration potential of existing natural resources on the farm, which would support the farmer’s ambition to achieve ‘net-zero’.

Note: The production of biochar will result in emissions of greenhouse gases to the atmosphere.

Example:

Total CO_2e in 10 tonnes dry wood = 18.35 t (~50% carbon, conversion factor from C to CO_2 = 3.67)

Total weight of Char = 2.5 tonnes @ 80% carbon (40% carbon retained) (2 tonnes of pure carbon retained)

Total CO_2e retained = 7.34 t

Total CO_2e lost = 11.01 t

Agroforestry

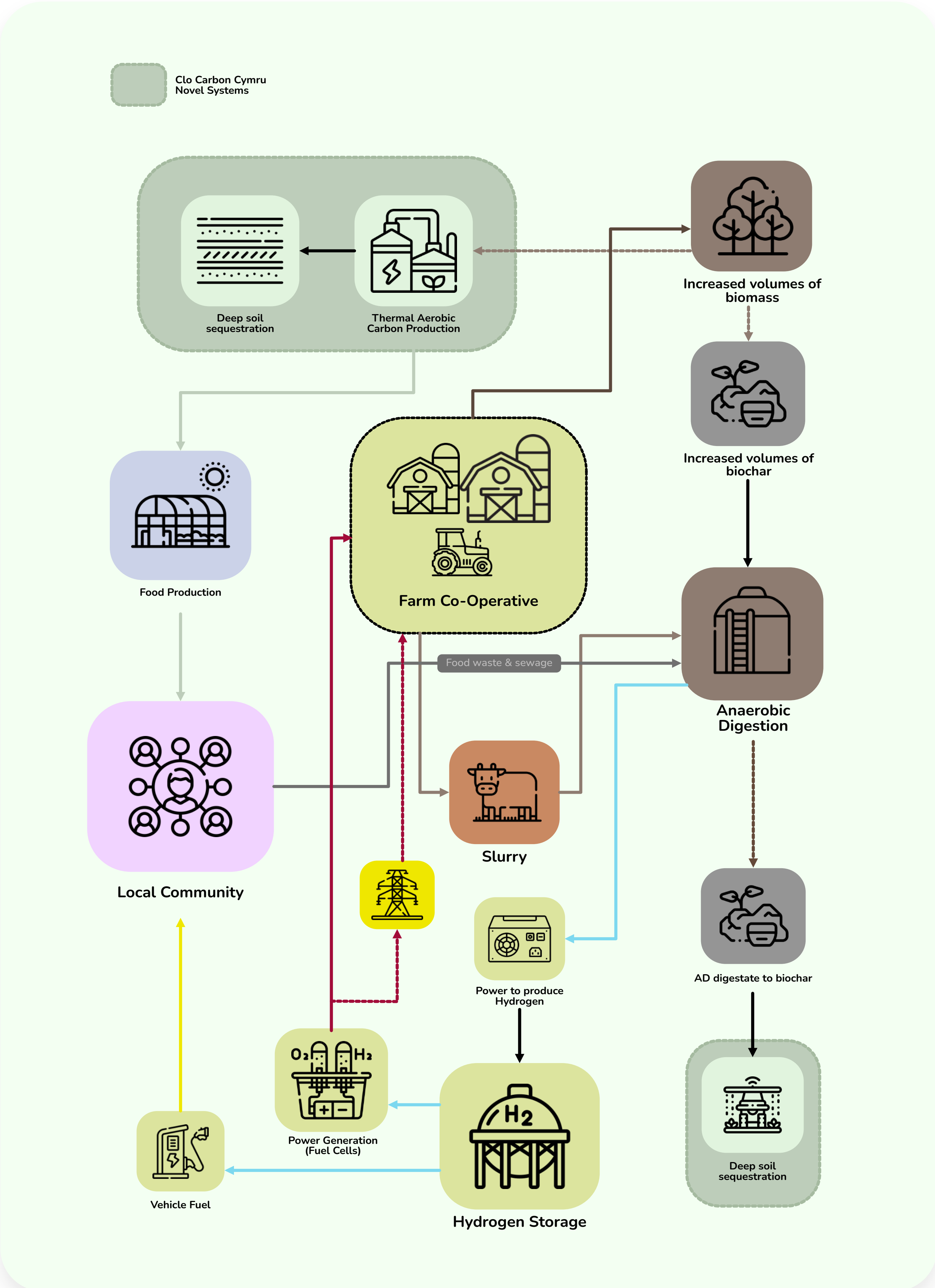
New areas of agroforestry designed around fast-growing broadleaf species (poplar & willow), feed-crops for livestock and crops that can provide feedstock (as waste) for anaerobic digestion (*Sida hermaphrodita*). Design would provide biodiversity and soil-carbon sequestration benefits as by-products (40).

Deep Green Hydrogen
Multi Farm Model

The multi-farm framework would encourage the creation of a co-operative business structure (social enterprise, community interest company, etc) and could possibly include representatives from local communities and the public/private sector.

The creation of a multi-farm model, which would be designed around a centralised location, would carry many practical implications, such as biosecurity, movement of slurry between farms, and slurry storage. In the case of an outbreak of Bovine TB, operational aspects of energy production would be severely impacted (41).

The DGH concept has been designed as a set of individual ‘antifragile’ systems (42) which combine to thrive as a result of shocks, volatility, mistakes and failures. Should one or more farms find themselves unable to export slurry to a centralised location, then other sources of raw materials should be available from other sectors of the system that will ensure that production levels can be sustained.



Clo Carbon Cymru
Novel Systems
Deep soil sequestration
Thermal Aerobic Carbon Production
Increased volumes of biomass
Increased volumes of biochar
Food Production
Farm Co-Operative
Food waste & sewage
Anaerobic Digestion
Local Community
Slurry
AD digestate to biochar
Power to produce Hydrogen
O₂
H₂
Power Generation (Fuel Cells)
Deep soil sequestration
Vehicle Fuel
H2
Hydrogen Storage

Example:

Based on a cooperative model involving four farms and all community members located within a 1-mile radius. Assumed 150-head dairy herd per farm. This framework could also consider taking other organic waste-streams/ food waste from villages within close proximity to farms.

Agroforestry: 12 hectares (three hectares per farm) of short-rotation coppice Willow combined with Sida hermaphrodita (37) would provide the following benefits annually:

- 90 - 120 tonnes (fresh weight) of high-protein (28-34%) feedstuff for livestock, reducing reliance on imported carbon-intensive feedstocks such as soya.
- Up to 65,000 m^3 of biogas - 435.5 MWh of heat
- Up to 80 tonnes of biochar (provided on-site facilities were in operation)
- Generate local, verifiable carbon credits of up-to 234 tonnes CO_2e
- Mitigate on-farm carbon emissions by up-to 200 tonnes CO_2
- Replace 375 tonnes of fossil-based fertiliser

Net Zero Hydrogen

If we are to avoid the “climate catastrophe” highlighted by the UN, then it is incumbent on system designers to consider the full impact of the process being promoted to produce hydrogen fuels. Developing a hydrogen economy is a long path forward, yet climate science shows us we need to act today to reach our net-zero goals.

The ISO EN Standards 14040 & 14044 (43) define methods to analyse the environmental aspects and impact of product systems and manufacturing processes. The standards serve as frameworks to develop what are commonly referred to as Life Cycle Analysis or Life Cycle Assessments (LCA).

In short, an LCA is the act of measuring the environmental impact of a product or service throughout its life cycle, from the resources used to create the product or service, across its use by the user, to its final end of life destination (cradle-to-grave). In many cases, an LCA will also describe the ‘Carbon Footprint’ of a product, system or process.

An LCA measures the environmental impacts of each distinct part involved in creating and using products and services, such as energy used in production, fuel used in transport, and end-of-life (disposal/recycling) ecological costs. An LCA allows consumers to make comparisons between products, materials, and methods used, providing useful information by which to make decisions that could help the environment.

Common within the sector are claims suggesting that hydrogen can be produced using ‘carbon-free energy’ (44); and hydrogen produced from renewable energy (solar, wind, hydro, etc) is ubiquitously referred to as ‘green energy’, Both seem to ignore the fundamental principles of carbon chemistry and the fact that emissions of greenhouses gases (including carbon dioxide) have occurred in the manufacture and design of the technology being used to generate hydrogen.

While the standardisation of ‘cradle-to-grave’ accounting methodology goes some way toward placing responsibility on business to detail the ‘carbon impact’ of their work, these frameworks still seem to facilitate claims which mislead consumers. Of greater urgency, is to create LCA based on ‘cradle-to-cradle’ accounting, whereby all raw materials and products are fully recyclable/ reusable and at the end of life, feed into other (the same) processes and products.

A kilogram of hydrogen holds 39.4 kWh of energy, but typically costs around 52.5 kWh of energy to create via current commercial electrolysers (20).

“On an apples-to-apples basis, it depends on several factors, but it is likely that the conversion of hydrogen into power will have a carbon footprint greater than that of natural gas-fired power, but less than that of coal-fired power...It is also possible to produce hydrogen via lower-carbon routes which historically have been less economical” (45).

Carbon Balance

While a detailed (minimum 18-month) life cycle analysis of Deep Green Hydrogen frameworks is beyond the scope of this report, data provided via the Teagasc report (cited previously), which includes a detailed life cycle analysis of both pasture-based and confinement dairy systems (48) stand as benchmarks to determine emissions associated with the dairy-sector to the point of sale at the farm-gate.

For the purposes of this report, author-determined emissions of greenhouse gases from the average dairy farm in Wales (49) are reported as **502.5 tonnes of CO_2e annually.**

The Deep Green Hydrogen framework would provide farmers with an accountable set of strategies that would effectively counter those emissions.

Single-Farm DGH System

Baseline Data:

Annual emissions of Greenhouse Gases associated with an 'average' dairy farm in Wales: 502.5 t/ CO_2e

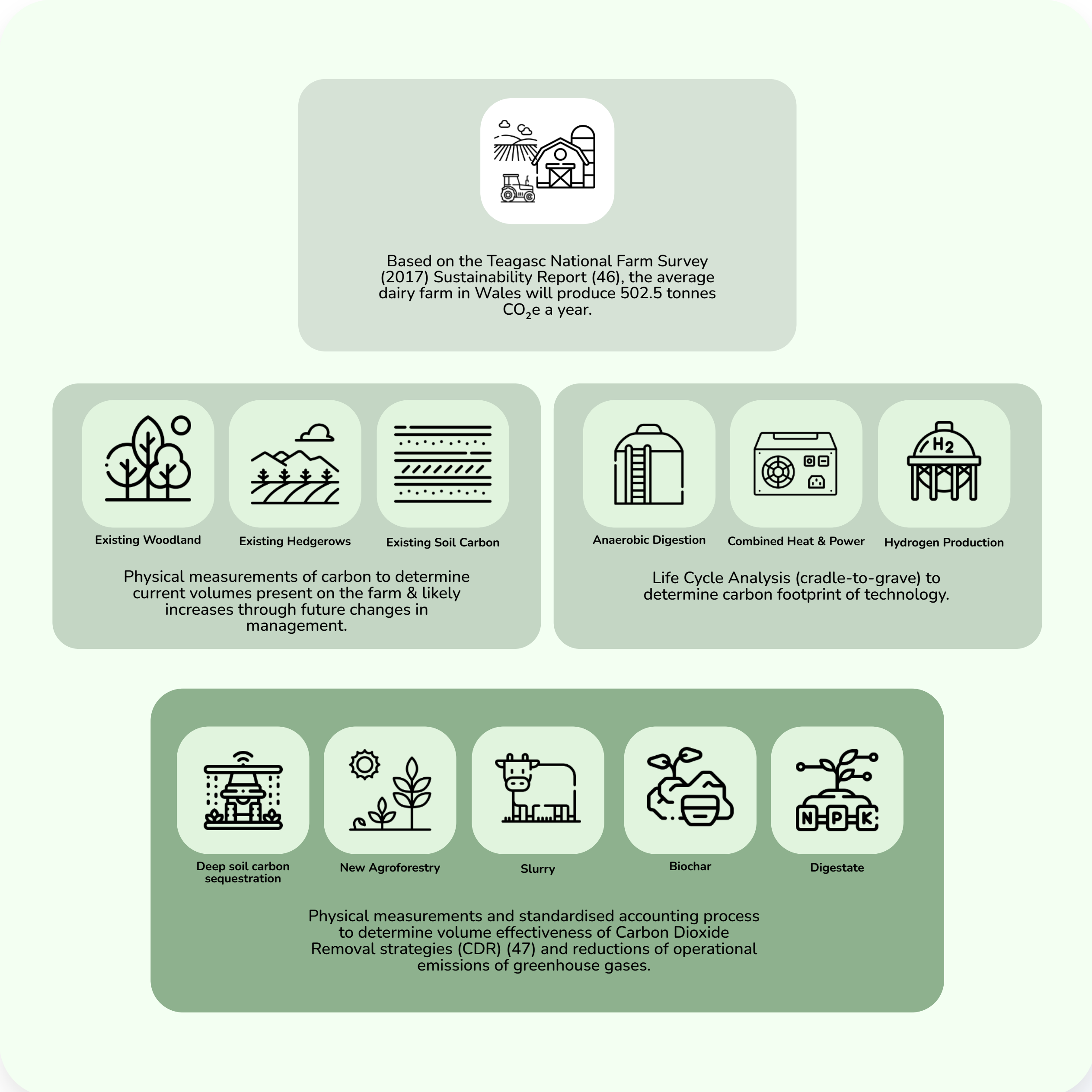
Calculated annual losses of CO_2e, derived from the conversion of biogas energy to hydrogen energy:

55.4 MWh of biogas-derived electrical power will produce 27.7 MWh of hydrogen (via a GEH2 electro-hydrogen generator (50) at 50% conversion.

The UK Government (51) reports that emissions associated with the production of biogas, via the anaerobic digestion process, stands at 22g CO_2e/ kWh.

Annual emissions associated with the production of 55.4MWh of biogas: 1.2 t/ CO_2e

The DGH process would counter the emissions associated with the farming operation and the production of biogas through the conversion of up to 2,000 tonnes of digestate (the by-product of the anaerobic digestion process) to biochar. This strategy would result in the permanent annual storage (>500yrs) of 300 tonnes of solid carbon (1,101 tonnes/ CO_2e). Biochar in this model exists within its own 'circular' carbon-economy.


Based on the Teagasc National Farm Survey (2017) Sustainability Report (46), the average dairy farm in Wales will produce 502.5 tonnes CO_2e a year.
Existing Woodland
Existing Hedgerows
Existing Soil Carbon
Physical measurements of carbon to determine current volumes present on the farm & likely increases through future changes in management.
Anaerobic Digestion
Combined Heat & Power
Hydrogen Production
H_2
Life Cycle Analysis (cradle-to-grave) to determine carbon footprint of technology.
Deep soil carbon sequestration
New Agroforestry
Slurry
Biochar
Digestate
N-P-K
Physical measurements and standardised accounting process to determine volume effectiveness of Carbon Dioxide Removal strategies (CDR) (47) and reductions of operational emissions of greenhouse gases.

Conclusions

The production of green hydrogen has emerged as a critical technology to reach net-zero carbon emissions. More than 30 countries have released official hydrogen strategies and roadmaps to ramp up their hydrogen consumption and develop the required infrastructure (52). The targets in these strategies show increased capacity of over 400-fold in this decade when compared with 2020.

Investment researchers at Goldman Sachs have suggested that a $5 Trillion investment in green hydrogen globally is needed in the clean hydrogen supply chain to achieve net-zero (53).

In June 2022, The Welsh Government published a summary of responses to its 'Hydrogen in Wales; A pathway and next steps for developing the hydrogen energy sector in Wales consultation' (54). In the intervening months, the Welsh Government has continued to progress a range of activities relating to the 'Pathway Objectives' set down in the original consultation document. Included in the pathway objectives is a desire to consider a "Place-based" approach – the concept of considering the local context and engaging with the wider community in deployment projects.

The Well-being of Future Generations Act (Wales) 2015, has been deliberately set at the centre of this document in the belief that the next generation of farmers is likely to require more support than current and previous generations, who need additional resources/ support to shift practices from conventional to more carbon-efficient use of land.

The Deep Green Hydrogen document set out to determine the economic viability and the physical practicalities associated with producing hydrogen fuels from dairy waste. The issues were considered against a backdrop of increasing pressures on the dairy sector in Wales, including:

- Achieving 'net-zero' by 2040 (55)
- Challenging greenhouse gases associated with cattle (56)
- Continual threat of Bovine TB (57)
- Land-use restrictions associated with Nitrate Vulnerable Zones (NVZs) (58)
- Increasing costs of operational energy - fertiliser, feed & energy (59)
- Reductions in market competitiveness connected to overseas trade deals (60)

The report has involved site visits and discussions with families from two dairy farms in Pembrokeshire: A privately-owned farm, with planning permission to build 39 new homes on the estate, and a tenant farmer operating on a farm owned by Pembrokeshire County Council.

Both farms have a winter (October - March) electrical demand of between 250 - 300 kWh / day, which would equate to between 45 - 54 MWh over that six-month period.

A 150-head dairy herd would produce enough slurry to generate about 65 MWh of energy over the same period of time. That energy would be produced from biogas converted to heat and electrical power via a Combined Heat and Power (CHP) unit running directly from biogas produced from an anaerobic digestion system.

The development of 39 new homes at one of the farms would generate a demand for electricity of around 42.55 MWh / yr. In theory, the farm could establish its own power-supply company (61) and charge homeowners for the supply of electricity via a private network. The 2023 average cost of a unit of 'domestic' electricity in the UK is £0.34 (62).

The sale of electricity from a biogas system would generate about £14,467 in revenue annually (42,550 kWhe x £0.34/ kWh). Furthermore, the CHP unit would also generate up to 79 MWh of thermal energy (low-grade heat) which could either be used to provide the homes with hot water, via a micro-scaled 'district-heating' system or to grow food in polytunnels, extending the food production season. The result is a reduction of imported goods, more mitigated carbon emissions as a result and a potential lucrative further source of farm income or development of a circular community model. Further details are outlined at www.clocarbon.cymru.

In principle, the most effective method of utilising the energy from the slurry on this particular farm, would be to provide electricity that would be used to generate heat in the houses via heat-pumps, utilising the low-grade heat mentioned above, via a large water-based thermal store, which would enable 1 kWh of electrical power to be converted to

Fig 04

at least 3-4 kWh of thermal energy - thus, the AD system could, theoretically, be providing most of the heat and power that the new housing development would require over a 12-month period. Excess electrical and heat production could be used on the farm through several viable processes - the production of locally grown food being favoured here.

An International Energy Agency survey (63) puts the cost of micro-scaled anaerobic digestion in the range of £3,000 – £6,915 per kWe (kilowatt of electric capacity). The IEA offers a 'rule of thumb' that slurry from 200 dairy cows requires 200 cubic metres of digester space and produces about 20 kWe continuous power. To this must be added the costs of feasibility studies, planning permission and any assessment and licences – typically 10% to 15%. Suppliers of 'micro-scaled' anaerobic digestion systems in the UK include Qube Renewables (64), Biolectric (65).

Currently, there is no economic model that would support the conversion of biogas to hydrogen to satisfy the need to generate and utilise electrical and thermal energy on either farm, without the collaborative efforts of at least 10 dairy farms at the larger end of the type included and with significant infrastructure investment in the upgrading/ compression of hydrogen and fuel-dispensing capabilities for fuel use.

However, if the larger-scale methane plasmalysis or electrolysis plants could be delivered in the context of continuing rising cost trends for thermal energy, then the use of compressed hydrogen for heating may be viable. The fast-pace of developments in this area and the magnitude of funding for projects means that viability will be rapidly approaching, so preparations are to be made that will allow seamless integration, like the building of multiple on-farm AD plants capable of storing biogas.

Deep Green Hydrogen
Discoveries & Next Steps

The authors set out to discover whether hydrogen has a place within the agricultural sector in Wales. Our conclusions find in favour of the need to manufacture hydrogen, but the end-use would be specific to the concept of Deep Green Hydrogen.

» The Deep Green Hydrogen concept has been designed purposely to support the agricultural sector in Wales and beyond. The concept encourages farmers to take a leading role in redeveloping localised economies through a range of strategies that are required to meet national and international climate targets.

Current systems of conventional farming are less likely to withstand the economic and emotional stresses caused by shifting land-use trends and current levels of government belligerence toward farmers. Unreliable weather patterns across Europe, Africa and Asia will continue to impact longstanding food-supply links, which will lead to an inevitable shortage of basic foodstuffs - as witnessed recently across the UK with empty supermarket shelves (66).

The cost of living crisis is exposing the severity of food poverty in the UK. Millions are being pushed below the breadline as food prices soar, with many struggling to feed themselves and their families. Food prices increased by 16.7% in the 12 months up to January 2023. That is a 45-year high, with the costs of essentials rising at exceptionally high rates (67)

The Trussell Trust saw record numbers of people seeking help between April and September last year, with 320,000 people forced to turn to the charity's food banks. That is a 40 per cent increase in comparison to the previous year. The charity has warned that need is outstripping donations for the first time in its history – forcing it to launch an emergency appeal to ensure that food banks can meet the "alarming level" of need in their community (68).

» The Deep Green Hydrogen process has been designed specifically to place energy production as a by-product of a system that increases the capacity of farm-land in Wales to sequester carbon.

Farmers in Wales must satisfy the regulations on Nitrate Vulnerable Zones (NVZs) to protect watercourses, where the current regulations (69) do not differentiate between slurry and digestate [the matter that remains after anaerobic digestion] but NVZs will encourage/require slurry storage, which will indirectly provide opportunities for AD.

» The Deep Green Hydrogen framework would enable dairy farmers in Wales to achieve net-zero faster than any other decarbonisation pathway. Emissions associated with individual dairy farms can be 'off-set' against processes and strategies that can be verified against international certification standards.

The carbon footprint of the average dairy farm in Wales amounts to **502.5 tonnes of CO_2e annually**.

An appropriately-scaled AD system, located on a dairy farm with 150-head of cattle could produce up to 2,000 tonnes of digestate (a by-product of the anaerobic digestion process) a year.

That resource could be converted into approximately 375 tonnes of biochar at 80% carbon content (300 tonnes of pure carbon). If the biochar is manufactured to established international standards, then it can be converted into CO_2 Removal Certificates (CORCs) and sold via reputable trading companies, such as on the Puro platform www.puro.earth (70).

Three hundred and seventy five tonnes of biochar could be worth between **£75,000 - £150,000 to the farmer each year.**

This moves the economic argument away from the sole focus of production of energy from slurry, as this is by far the lowest value product. The annual production of 375 tonnes of biochar would result in:

the permanent storage (>500yrs) of up to 1,101 tonnes of CO_2e annually.

This figure excludes the mitigated emissions of methane and NO_X from slurry.

In addition, the application of this biochar to the land will reduce the requirement for fossil-fuel-intensive ammonia fertilisers, mitigating upstream carbon emissions, increase soil health and crop yields (70a/b) and return trace minerals in a truly circular manner, thus breaking the chain of extractive farming practices.

“We find that despite variability introduced by soil and climate, the addition of biochar to soils resulted, on average, an increased aboveground productivity, crop yield, soil microbial biomass,rhizobia nodulation, plant K tissue concentration, soil phosphorus (P), soil potassium (K), total soil nitrogen (N),and total soil carbon (C) compared with control conditions.” (70a)

At this point of system development, the dairy farm no longer has an issue with net-zero.

It will have effectively decarbonised.

Deep Green Hydrogen
Next Steps

Deep Green Hydrogen
Establishing Frameworks

» Deep Green Hydrogen facilitates the establishment of a set of very effective land-use strategies that seek to maximise the gains from an extremely efficient approach to the management of carbon that enables hydrogen fuels to be produced as a by-product.

A micro-scaled anaerobic digestion system for the average-sized dairy farm in Wales (including delivery, installation, commissioning, and VAT), capable of generating up to 250 kWh of electrical energy daily, is likely to cost between £150,000 - £200,000.

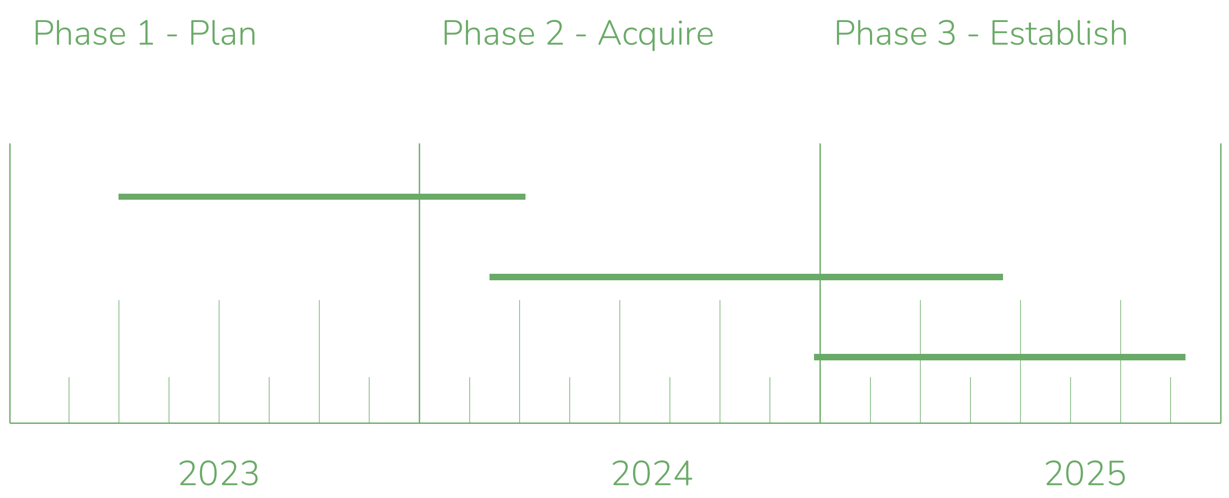
The addition of a hydrogen generator at a cost of up to £250,000, which results in the loss of 50% electricity from the AD system, would be too wasteful for even the most evangelical hydrogen developers. It is therefore hard to justify the expense at this time.

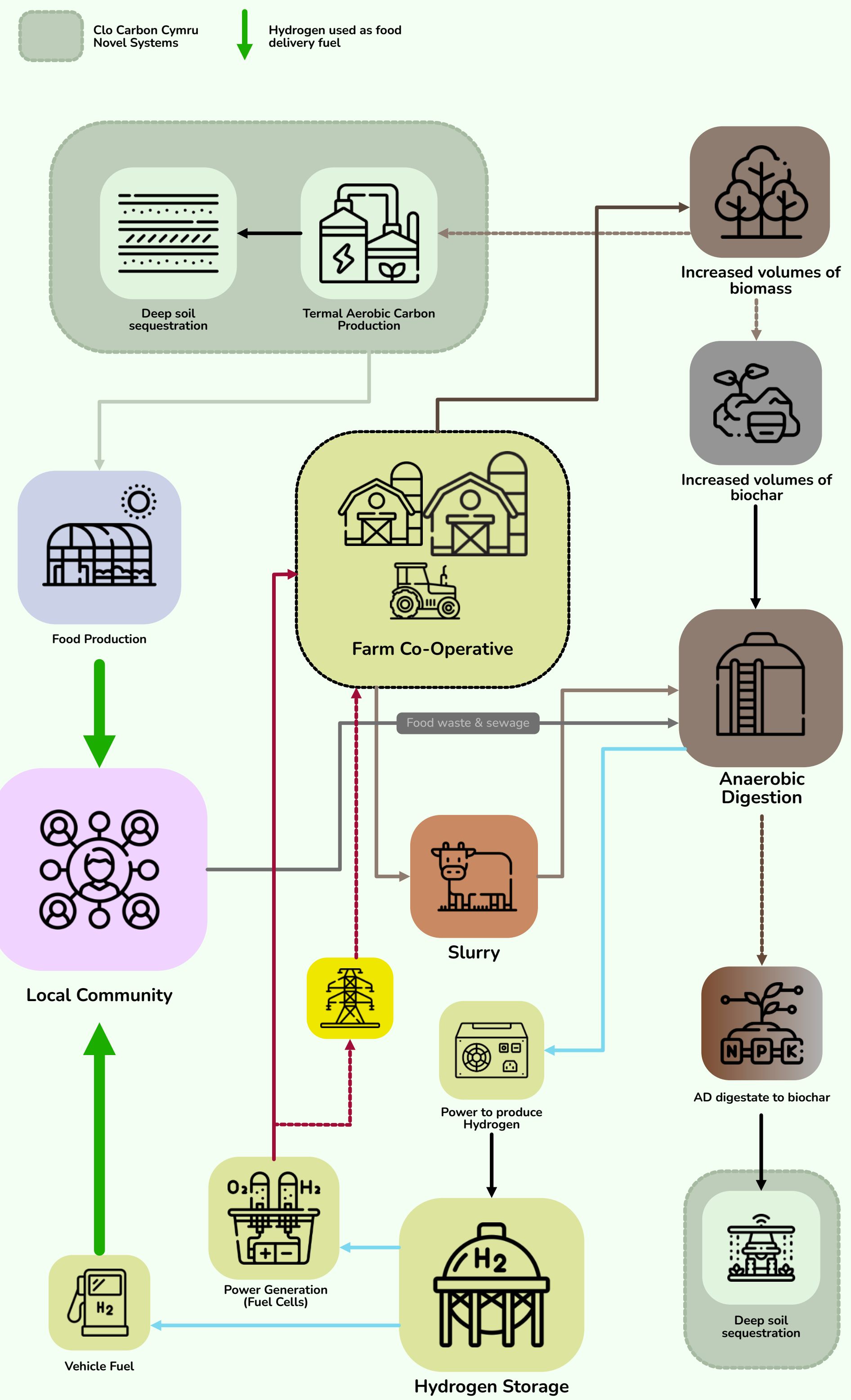
However, although current Hydrogen energy conversion efficiencies to electricity stand between 30% - 40%, the level of investment currently being directed at the hydrogen sector will result in conversion rates **increasing to about 95% within the next 2-3 years** (71).

Therefore considered planning and futureproofing to match technology development is required. It will take between 2-3 years to establish a Deep Green Hydrogen system on a farm.

At the proof-of-concept stage, each individual farm is likely to require a unique design approach that could require at least 12-months to plan and up to 18 months to secure and plant the crops. (These timelines would likely reduce dramatically as they become optimised with wider rollout & at economies of scale) Crops would become productively established by Yr3.

Between 2023 - 2025, **Clo Carbon Cymru**, working with several other partners, will have supported the creation of 5-7 community-driven ‘food-hubs’ across the South and West Wales region. Those hubs will be capable of processing food from local farms (including butter, yoghurt and cheese).




Clo Carbon Cymru Novel Systems
Hydrogen used as food delivery fuel
Deep soil sequestration
Termal Aerobic Carbon Production
Increased volumes of biomass
Increased volumes of biochar
Food Production
Farm Co-Operative
Anaerobic Digestion
Food waste & sewage
Local Community
Slurry
Power to produce Hydrogen
AD digestate to biochar
N P K
O_2 H_2
Power Generation (Fuel Cells)
H_2
Hydrogen Storage
Vehicle Fuel
Deep soil sequestration

It is here that the production & use of hydrogen on dairy farms makes complete economic sense:

fueling the transportation of food (protein and calories) into communities to establish carbon-neutral food supply chains.

End

Generating hydrogen, via anaerobic digestion, as a by-product from farm-waste and biomass offers farmers in Wales a genuine opportunity to transition from conventional to more carbon-efficient approaches to land-use.

The utilisation of hydrogen-based energy can play a key role in decarbonising the agricultural sector in Wales. At the same time, the Deep Green Hydrogen frameworks encourage more detailed consideration of what livestock eat, how that feed is produced and how consumers gain benefits from a more localised approach to energy and food production, which are intrinsically bound together through this report.

Clo Carbon Cymru has attempted to present a clear vision of how we see farm-generated hydrogen energy becoming an integral component of a much wider approach to challenging societal and environmental issues that affect us all.

Our approach here has considered a much wider body of work that the company is developing with the support of the farming unions, public and private-sector businesses, housing associations, county and local councils and organisations that design and build economic models around common-wealth, biodiversity and well-being.

There is a genuine need to develop 'next-generation' energy systems around a raft of issues that society faces in general - transporting energy, in the form of protein and calories, from the farm-gate directly to the consumer would offer an example of how to decarbonise food-supply chains, which are likely to be among the earliest victims of a changing climate.

We welcome comments from within the hydrogen sector and from farmers and land-use practitioners and, furthermore, we genuinely look forward to presenting our work to interested parties in future.

Cai Matthews, **Dr Robert Johnson**, **Richard Edwards**.

Founders of Clo Carbon Cymru

Glossary & Acronyms

» AD	Anaerobic Digestion
» Antifragile	“Things that gain from disorder - strategies designed to thrive on volatility, instead of shattering in the encounter with it” (Nassim Nicholas Taleb)
» Biogas	A methane-rich gas containing carbon dioxide, generated through anaerobic digestion
» CAPEX	Capital Expenditure
» CCS	Carbon Capture and Storage - usually in the context of continued fossil fuel use (e.g. SMR with CCS).
» CDR	Carbon Dioxide Removal
» CHP	Combined Heat and Power
» CO_2	Carbon Dioxide
» CO_2e	Carbon Dioxide Equivalent - is a metric measure that is used to compare emissions from various greenhouse gases on the basis of their Greenhouse Warming Potential by converting amounts of other gases to the equivalent amount of CO_2
» CH_4	Methane
» CORC	CO_2 Removal Certificates - generated through validation of CO_2 capturing systems/products
» GWP	Greenhouse Warming Potential
» HRT	Hydraulic Retention Time
» ISO EN	The International Organization for Standardization
» kWe	Kilowatt of electric capacity
» kWh	Kilowatt hour
» LCA	Life Cycle Assessments
» MWh	Megawatt hour
» NO_x	Nitrous Oxides
» NVZ	Nitrate Vulnerable Zone
» OPEX	Operational Expenditure
» SMR	Steam Methane Reforming
» VAT	Value Added Tax

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Appendix

Input Methan-Plasmalyse Biomethane

location	medium	volume	CH4-Concentration	CH4-Flow	CH4-Mass	CO2-Mass
Eisenhüttenstadt	Biomethane	560,000 Nm3/a	55.0%	308,000 Nm3/a	215,600 kg/a	
		70 Nm3/h	NB: bei Biogas 65%			

balance sheet mass

	Methan-Plasmalysis	
Hydrogen	53,900 kg/a	6.7 kg/h
Carbon Black	161,700 kg/a	20.2 kg/h
avoided CO2-emissions	591,959 kg/a	

Molare Mass	Molare Mass [g/mol]	Density [kg/Nm3 bzw. kg/L]
Hydrogen	1.00794	0.089
Nitrogen	14.007	1.25
Methane	16.04	0.7
Carbon Dioxide	44.04	1.977
operation hours per year	8,000 h/a	

balance sheet electric energy

Energy demand CO2/CH4-division	-62 MWh/a	
Energy demand Plamalysis	-539 MWh/a	-67 kWh/h
Energy demand div. Equipment	-108 MWh/a	
energy elec. Total	**-708 MWh/a**	**-89 kWh/h**
optional		
H2-cleaning for Hydrogen 5.0	*-162 MWh/a*	
Energy demand H2 compression (330 bar)	*MWh/a*	
Total incl. Options	*-870 MWh/a*	

Energy demand CO2/CH4-Separation (Amin scrubber)	0.11 kWh/Nm³
Energy demand Methane Playmalysis	10.0 kWh/kg H2
Energy demand div. equipment	2.0 kWh/kg H2
Energy demand PSA for purity 5.0	3.0 kWh/kg H2
Energy demand compression (330 bar)	0.00 kWh/kg H2

balance sheet thermal energy

energy demand Amin scrubber	-280 MWh/a	-35.0 kWh/h
available waste heat from Plasmalysis	270 MWh/a	
thermal energy surplus	**-11 MWh/a**	

Energy demand thermal (Amin scrubber)	0.5 kWh/Nm³
	5.0 kWh/kg H2

balance sheet finance

costs of elec. Energy	-174,020 €/a	
costs of thermal energy	0 €/a	
cost of methane	0 €/a	
OPEX per year	-2,695 €/a	1% p.a. of CAPEX
amortisation	-104,645 €/a	
costs total	-281,360 €/a	

costs:	
price electric energy	200 €/MWh
cost of methane	0 €/MWh
price thermal energy	0 €/MWh
amortisation period	10 years

earnings Hydrogen	**296,450 €/a**
THG	**161,700 €/a**
earnings CO_2-negative Carbon Black	**59,344 €/a**
earnings CO_2-certificates	**0 €/a**
earning waste heat	**-735 €/a**
earnings total	**516,759 €/a**

earnings:	
Hydrogen	**5.50 €/kg**
THG	**3.00 €/kg**
CO_2-negative Carbon Black	**0.37 €/kg**
CO_2-certificates	**0.00 €/kg**
waste heat	**0.07 €/kWh**

result	**235,399 €/a**

first indication Invest

first indication		
Amin scrubber	0 €	
Methane Plasmalysis	269,500 €	
Infrastructure Plasmalysis	26,950 €	*10 % Invest*
PSA for Hydrogen 5.0	750,000 €	
Compression system	0 €	
Filling station	0 €	
Invest total (indicated)	**1,046,450 €**	
CO2- avoided via Methane-Plasmalysis	**592 t CO2/a**	
CO2-avioded over 20 years	**11,839 t CO2**	
relation INVEST / CLIMATE over 20 years average	**88 €/t CO2**	

***40,000* €/kg H2/h**

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