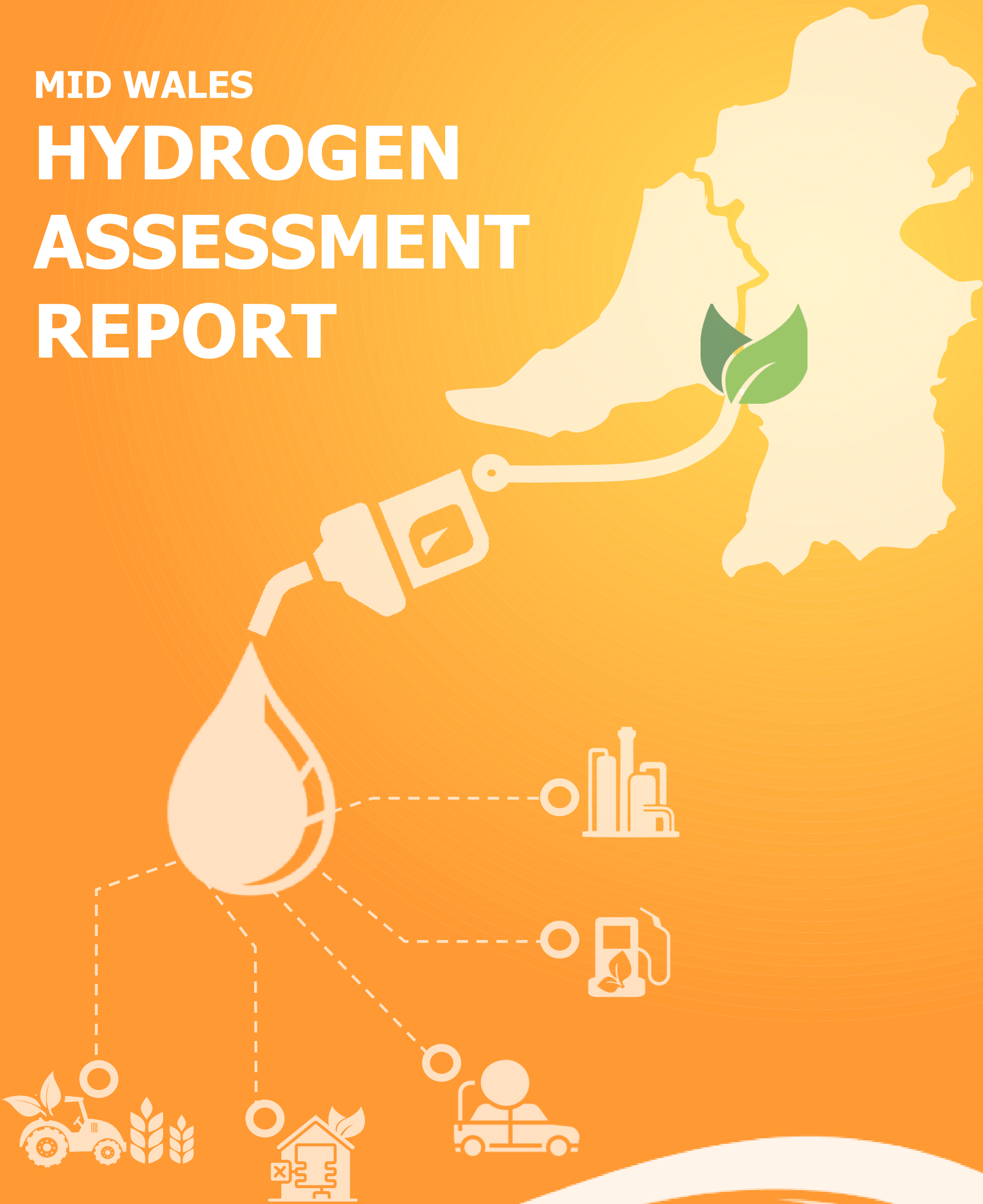
MID WALES

HYDROGEN ASSESSMENT REPORT



Tyfu Canolbarth Cymru
Growing Mid Wales

RADICAL INNOVATIONS GROUP AB

Contents

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OUR STARTING POINT

Changing UK energy landscape and implications to (Mid) Wales

We are aware of the ambitious targets set by the UK Government (UKG) to rapidly move towards low-carbon sources based on renewables and nuclear. From town gas made of hydrogen (50%), methane (~25%), and the rest made of carbon monoxide and impurities to the discovery of natural gas in the North Sea, there has been significant changes in the UK energy landscape. Today, the buzzword is "hydrogen."

Politicians, policy makers, technology experts, project developers, and businesses across sectors have one thing or the other to say about hydrogen and it's potential in decarbonizing various sectors of the UK economy. Like with all new technologies, there are groups within UK fully advocating for hydrogen and the others who are not convinced with the potential of hydrogen as a viable energy vector for the UK. While the former groups see huge potential in hydrogen in many applications, the latter group believe hydrogen is just another "hype" promoted by big corporate lobbies.

That being said, at the point of departure in this study, we have taken a neutral stand and listened to both these groups to build a reasonably balanced picture about the true potential of hydrogen and how can the region of Mid Wales prepare to play a relevant role in the future developments.

Being agnostic about hydrogen and other low-carbon energy vectors, we have explored relevant potential opportunities that can create value to the Mid Wales region. Additionally, we have studied how Mid Wales can create local market opportunities to benefit from the potential developments in the region at the same time also decarbonise various sectors in short-, medium- and long-term. Though hydrogen-based fuels are our main focus in this study, we have also assessed the potential of bio-methane and biogas.

Our primary focus is to find viable pathways to create value in the region. As secondary goal, we are exploring ways to decarbonise the energy landscape of the region. In this preliminary assessment report, we are summarizing our initial findings essentially to address following three points to certain extent, namely,

- **why**: realistic low- and zero-carbon fuels market opportunities for Mid Wales
- **what**: potential application areas and sectors that Mid Wales could target
- **how**: pathways to pursue the market opportunities within and outside Mid Wales

We have built our understanding based on various qualitative and evidence-based assessments from the ongoing developments in North, South, and Mid Wales aligning to the overall UK government priorities. For qualitative assessments, we have reached out to over 50 stakeholders so far to test waters and gather opinions. For evidence-based assessments, we have carried out desk-research and performed back-of-the-envelope calculations to understand market conditions and constraints.

This preliminary assessment report will have three main sections based on the above three questions to present the initial learnings to the steering board. In the first section, we briefly summarize the energy landscape of the region with the aim of explore the ideal (mix of) energy vector(s) that can be used to create value to the Mid Wales region. In second section, we have investigated applications areas and sectors that Mid Wales could target. In the third section, we share our thoughts on three possible market strategies (pathways) that could benefit Mid Wales given the various developments in and around the region.

Why?

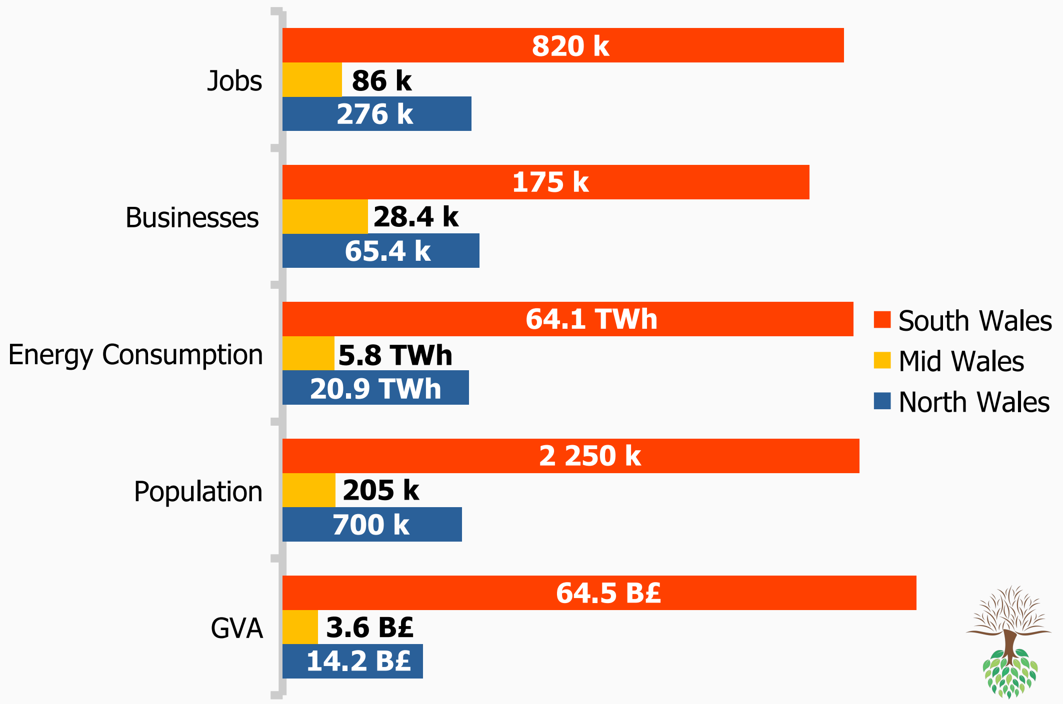
In the following, we will briefly summarize the energy landscape of the region with the aim of explore the ideal (mix of) energy vector(s) that can be used to create value to the Mid Wales region.

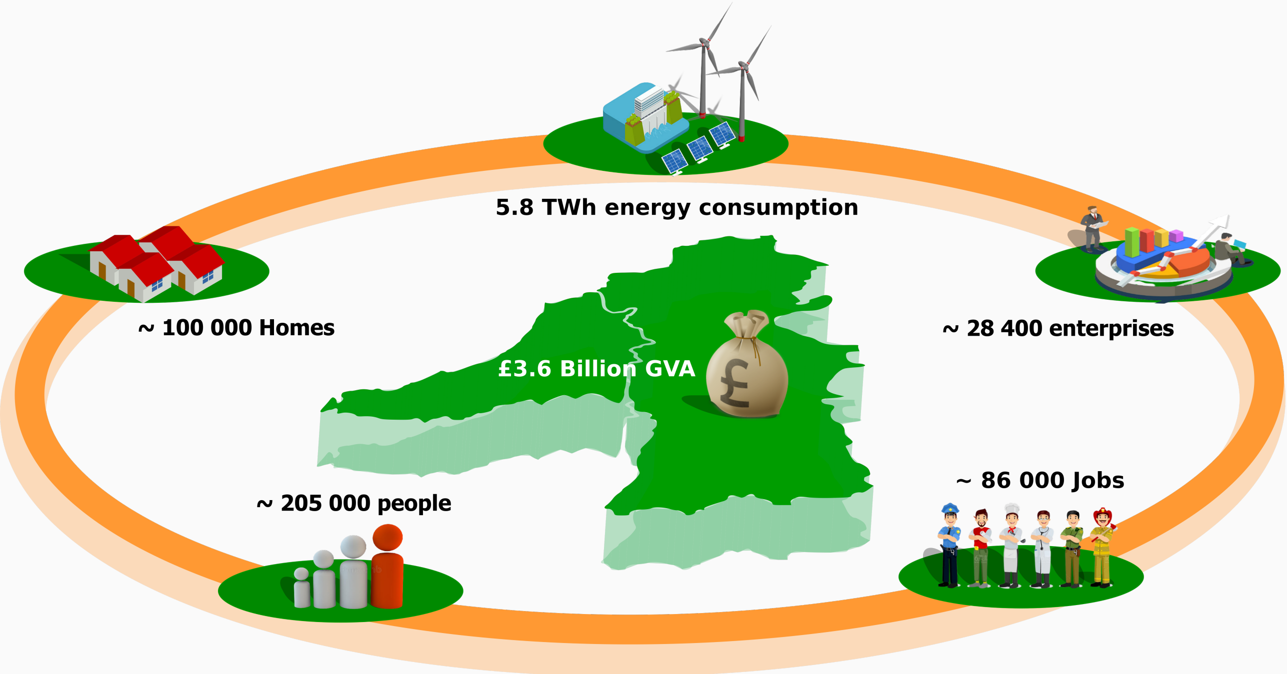
Are there energy cash-cow(s) in Mid Wales?

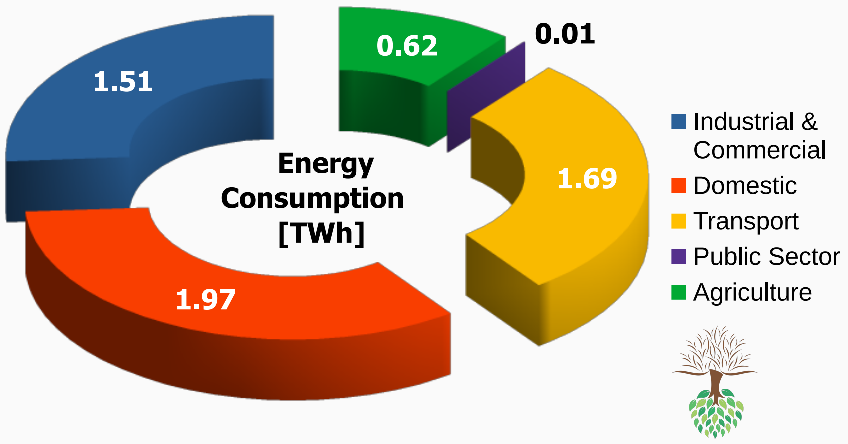
We have summarized only the relevant information about the region to build the narrative for our assessment in the following. The region of Mid Wales for all it is known is resource rich. Assets include availability of fresh water, renewable energy assets in the form of wind, hydro, and solar. There is also considerable amount of biomass in the region – thanks to the region's forests and farms. The region is seen as "under-developed" in terms of its infrastructural development and mostly rural in the context of development opportunities. The lack of infrastructure has not only severely affected growth in the region, but also isolated the region from its regional siblings – North and South Wales. Efforts to improve the infrastructure in the region in the past were dealt with local oppositions for any such improvements were not seen as adding value to the livelihoods of local population. Such initiatives to improve infrastructure were seen as a way for big firms to make money for themselves milking the regional resources. We are not clear about the status of this local opposition in present times. These background challenges, however, make one thing clear. Any development pursued in the region should win the local support and truly create value in the region at least in medium- and long-term. In other words, only milking the local resources without sharing the benefits won't work.

Any kind of value creation in the region requires reactivating the Mid Wales region's energy landscape in terms of choice of low-carbon energy vectors, improving grid connectivity, ramping renewable energy assets, etc. Without creating local market opportunities that can benefit from these improvements and focusing only on export potentials of the regions resources, we believe, there will hardly be any significant progress in the region.

In order to put things into right perspective, we have compared some numbers to understand the relative strength and weakness of the region with the neighbours, namely, North and South Wales. The gross value add (GVA), population, annual energy consumption, number of businesses and jobs are highlighted in the figure below.







Mid Wales specific statistics are given in the figures above. Though the above numbers are stating the obvious, our aim is to derive some important clues on where are the best bet for Mid Wales and what role Mid Wales could play in the larger scheme of things considering the developments in North and South Wales, and the rest of UK. In this context, we want to highlight the Mid Wales region's energy requirements and challenges.

Energy landscape of Mid Wales

As of 2018, the overall energy (electricity and fuels) consumption in Mid Wales is split between the commercial and industrial (26%), the domestic (34%), the transport (29%), and the agricultural (11%) sectors. Annual energy consumption [TWh] across different sectors in Mid Wales is given in the table below.

Energy use by sector in Mid Wales 2018 [TWh/year]					
Local authority Area	**Industrial & commercial**	**Domestic**	**Transport**	**Public Sector**	**Agriculture**
Ceredigion	0.73	0.70	0.54	0.003	0.24
Powys	0.79	1.27	1.16	0.003	0.38

It worth noting that almost all of the regions electricity consumption (97%) is catered by local renewable energy sources. Local renewables constitute predominantly onshore wind (~ 285 MW), hydro (~ 78.7 MW) and solar photovoltaic (PV) (~ 55 MW) supplying 66%, 18%, and 13% of renewable generation capacity, respectively. The region's annual electricity demand as of 2018 is 0.93 TWh. More than 50% of this is consumed by the commercial and industrial sector. Decarbonisation of the UK's electricity grid has led to decrease in the industrial energy demand (down by 10%) and emissions (down by 37%) compared to 2005-level. Though this is a good thing for the environment, there are some concerns among electricity firms as these developments has also led to drop in their revenue over these years.

We have evaluated the energy use [GWh] by the type of fuel used in Mid Wales in order to understand the consumption patterns and market price sensitivities. In the table below, we have highlighted the annual consumption of different fuels in Mid Wales.

Energy use by fuels in Mid Wales, 2018 [GWh/year]						
Local authority Area	Coal	Manufactured fuels	Petroleum products	Gas	Electricity	Bioenergy & wastes
Ceredigion	49.61	22.42	1 217.50	184.85	340.80	390.80
Powys	88.44	41.27	2 227.36	514.14	587.69	138.12

These figures show that about 12% of commercial and industrial demand is met by gas, reflecting the off-gas nature of the region – highest proportion of off-gas grid properties in Wales (62%). For example, in Powys, off-grid public sector housing stock is approximately 20% as per previous studies commissioned by Growing Mid Wales Board. According to UKG statistics, domestic and non-domestic sectors in Powys region use more petroleum products and electricity. Their usage levels is more than the average for Wales. Similar trends are noticed also in Ceredigion region. The industrial and commercial sector in Ceredigion uses very high proportion of bio-energy from waste, ranking third largest in Wales.

About 17% homes in Ceredigion and 14% in Powys experience fuel poverty due to relatively poor domestic energy efficiency. This is in spite of the fact that Powys having the highest biomass heat capacity in Wales (total thermal capacity 132 MW) and Mid Wales as a whole having highest deployment of renewable heat installations in Wales with nearly 2% of homes having a heat pump or biomass boiler. These facts hint that heat pumps and biomass are not ideal choice for domestic heating in the region largely due to poor insulation and efficiencies of houses.

Furthermore, tackling the decarbonisation of off-gas homes, representing circa 22% of Welsh homes, is one of Mid Wales' key challenges. The relatively high upfront cost of heat pumps remains the main barrier to widespread deployment. This is one of the potential area where huge market opportunity lie for low-carbon energy vectors provided clever supply chain and infrastructural solutions can be developed.

Transport sector in Mid Wales consumes about 1.7 TWh of energy mostly contributed by petroleum (1.67 TWh). Large portion of this is personal vehicles running on diesel followed by gasoline. In freight vehicles, we have heavy goods vehicles (HGV) and light goods vehicles (LGV) running on diesel and gasoline. UKG has set an ambitious target to ban fossil fuel vehicles by 2030. This presents a compelling opportunity for hydrogen-based vehicles and electric vehicles in the region.

Agriculture sector forms the main economic driver of the region. Presently, petroleum is the primary choice of fuel with around 0.62 TWh of annual consumption in agriculture sector. It is one of the most difficult sector to decarbonize given its nature of operations, equipment, and infrastructure.

Relevant low- and zero-carbon energy vectors

The overall market opportunity in the UK for low- or zero-carbon energy vectors like hydrogen, ammonia, methanol, and bio-methane in comparison with natural gas for the year 2019 is given in the table below.

Fuels	UK import [M$]	UK export [M$]
Ammonia	7.41	**73.9**
Hydrogen	**361**	29.6
Natural Gas (gas)	**5370**	1320
Natural Gas (liquid)	**2600**	304
Formic acid	**6.5**	0.849
Methanol	**78.4**	15.3

Hydrogen

North and South Wales have started several activities to produce hydrogen in a large industrial scale benefiting from various existing infrastructure and industrial activities in their region. Several ongoing activities in the rest of UK are also gearing up to produce blue and green hydrogen based on available infrastructure and ongoing large industrial-scale activities. As of 2019, UK imports about US$ 361 Million and exports about US$ 29.6 Million worth of hydrogen. This figure is meant to increase both in terms of import and export. Availability of cheap electricity, man power, and raw materials are going reduce global hydrogen price in the coming years. As far as UK is concerned, there is no standard reference price for hydrogen like in the case of petroleum products. Hence, the market dynamics in short-term is heavily volatile with price variations in the range of 50-70%. One can compare this with the short-term price variations in petroleum products which lie in the range of 5-10%. One of the reasons for this is both demand and supply levels are low. As the market demand picks up, there will be more stability and regulations in the prices.

Currently hydrogen is partly used in metal processing to yield iron reduction. Hydrogen is also employed to prevent partial oxidation of iron ore while the ore is still in the furnace. Steel industry is a particularly interesting area for green hydrogen because of the process's high carbon emissions and the relative lack of viable alternatives. Green hydrogen can be traded for producing methanol or synthetic methane as a way in the carbon capture and utilisation strategy. Other segments of interest for hydrogen is the food industry and glass industry. Hydrogenation of fats is the core area of application in the food industry. Other applications include use of green hydrogen in the semiconductor industry as a heat transfer fluid (when kept in a vacuum) and as fuel in the aerospace industry.

Power-to-gas (P2G) involves the use of renewable electricity to produce green hydrogen through water electrolysis. In some cases, the hydrogen is then converted to synthetic methane gas using captured carbon dioxide. Since there are likely to be increasing amounts of wind and solar capacity, there will at times be excess output over demand. Converting that surplus to hydrogen, or other hydrogen-based fuels like methane makes more sense than curtailing the output of wind and solar plants.

Other hydrogen-based fuels

We will briefly summarize relevant hydrogen-based fuels that have significant potential in Wales and the UK markets. Some of these fuels are already being considered by various actors outside Mid Wales, particularly, in the industrial clusters in North and South Wales.

Ammonia

As given in the table, the UK is a net exporter of ammonia. The market is mostly in agricultural and industrial raw material sectors. The primary interest in ammonia is due to its use as a fertiliser. However, it can also be used as storage and carrier medium for hydrogen. It is cheap (30 to 40 p/kg) and offers long-term hydrogen storage capabilities. However, this process of storing hydrogen in the form of ammonia and recovering hydrogen from ammonia has a round-trip efficiency of 20–30% depending on the initial efficiency of the electrolyser technology or SMR process used. Many efforts are currently ongoing in the universities in Wales and the UK to directly use ammonia as a fuel in engines and solid oxide fuel cells. Furthermore, ammonia can also be cracked onsite to recover hydrogen that can be fed into hydrogen fuel cells. Companies such as Mitsubishi, Siemens, Baker Hughes and MAN Group have been working to develop and commercialise turbine technology that could generate energy from 100% ammonia fuel. This is being closely monitored as it is a remarkable opportunity for countries with several operating natural gas turbines. Green ammonia is increasingly seen as a convenient hydrogen-derived fuel for zero-carbon-emission power.

The market opportunity for ammonia is growing as it is a better carrier of hydrogen and provides excellent hydrogen storage features. As a material, ammonia has a long history in the industrial sector and hence the supply chain is well established both in the UK and abroad.

Methanol

Currently, UK is net importer of Methanol with about US$ 78.4 Million and exports about US$ 15.3 Million. As technological advances are made in alternative fuels and fuel cells, methanol is increasingly used in many applications in the UK. It is worth mentioning that South Wales Industrial Cluster (SWIC) is looking at decarbonization schemes using carbon capture and utilisation methods to produce methanol using industrial emissions and green hydrogen in South Wales. Moreover, methanol in an interesting raw material for the chemical industry as it is highly versatile building block for manufacturing countless everyday products such as paints, carpeting, plastics and more. There are commercialising efforts to use methanol as a fuel for cars and trucks, marine vessels, boilers, cook stoves and kilns. If there is a cash-cow, this surely is one of the interesting ones. That being, we are still not sure, if this is the right one for the region and we need to investigate further about its potential.

Synthetic methane

Another valuable hydrogen-based fuel, particularly for European countries and policy makers who are exploring renewable hydrogen applications, is **synthetic methane**. When synthesized using carbon capture methods or using biomass synthetic methane can be highly appealing because it allows for the continued use of current natural gas infrastructure and avoids the need to replace or retire existing natural gas assets. Synthetic methane also has the added advantage of being easier to generate at larger scales and across a wider range of locations than biogas or bio-methane, which has long been seen as a means of "greening" the gas supply.

Only a few pilot projects are currently generating synthetic methane. Most of them extract their carbon from anaerobic digesters linked to agricultural or land fill waste. A demonstration project in Italy, however, sources its carbon from directly through air capture technology. It should be remarked that whether sourced through biomass, waste or captured from air, all these options can be considered carbon-neutral. Another interesting project is that of Uniper's "STORE&GO" in Germany, which uses wind-powered electrolysis and carbon from biomass to produce up to 1 400 m^3 of synthetic methane a day – approximately 14 500 kWh of energy.

Biomethane and biogas

Biomethane and biogas production in the region is highly distributed and small-scale. In the Mid Wales region, anaerobic digester (AD) plants contribute roughly 4.4 MW electric and 3.6 MW thermal capacities. Most of the available capacity from AD for heating applications in Wales is in Mid Wales. Though there are many ways in which bio-methane and biogas can drive the decarbonisation activities in the region, AD deployment and bio-methane production are very limited in the region. As a renewable fuel, bio-methane has many market opportunities but local production is highly limited by availability of raw materials (waste and biomass).

According to Anaerobic Digestion & Bioresources Association (ADBA), there were circa 90 agricultural biogas plants injecting bio-methane in the gas grid in the UK in early 2017. This had an effect in reducing the UK's natural gas demand by 0.6%. When biogas is refined into bio-methane, it is chemically identical to natural gas and hence it is gas-grid ready and can power all applications like conventional gas.

However, UKG has reduced subsidies for bio-methane and biogas injection into the grid under the non-domestic Renewable Heat Incentive (RHI). The most recent cut effective from April 2017 resulted in 10% reduction in bio-methane injection tariff, and a 5% reduction to the small, medium, and large-scale biogas tariffs. Adding more twist to the story, in December 2017, UKG also announced new biogas and bio-methane plants would only receive support if at least 50% of the gas comes from feedstocks that are wastes or residues – reflecting growing concern that crops are being used as feedstocks resulting in agricultural lands used for cultivating energy crops and directly competing with food crops cultivation. The Renewable Energy Directive further plans to increase the biofuel carbon savings compared to fossil fuel equivalents from 35% to 70% in 2020. This measure is aimed to exclude many energy crops from the biogas or bio-methane production.

Adding more salt to the injury, we believe that the biogas and bio-methane producers in the UK will not be cost-competitive as the present production cost for bio-methane are likely to stay around £50–105 per MWh, which is quite some way current UK wholesale gas prices of around £40 per MWh.

That being said, synthetic methane discussed above can come to rescue methane industry if can align with Carbon Capture and Utilization (CCU) strategies of industries that are presently large-scale CO_2 emitters. In this context, synthetic methane can become more relevant and price-competitive when carbon emission and pollution taxes are introduced that can incentivise production.

In the table below, we have compared these zero- or low-carbon fuels against various parameters.

Compared to LPG / domestic heating oil / Gasoline / Diesel	Hydrogen	Ammonia	Methanol	Synthetic methane and bio-methane
energy content [MJ/kg] Diesel / Gasoline (42 – 46) Domestic heating oil (43 – 47) LPG (46 – 51)	120 – 142	22.5	22.7	45.4 – 55.1
Price [£ / tonne] LPG (900 – 1000) Domestic heating oil (300 – 550) Diesel / Gasoline (1500 – 2000)	Low: 1500 High: 7000 *	Low: 300 High: 400	Low: 350 High: 400	Low: 200 High: 700 **
direct usage in existing (installed) machineries and applications	low	medium	high	very high
storage and transport challenges	high	low	low	low
health and safety concerns	medium to high	medium to high	medium to low	medium to low
environmental concerns	low	medium	medium	medium

* this range includes for both SMR and Green hydrogen
** on lower extreme the price depends on Natural gas prices and on the higher extreme depending on the pathway used to produce bio or synthetic methane (Anaerobic Digester or green hydrogen + CCU pathway)

From the above discussions, we get an overview of different low- and zero-carbon energy vectors that are relevant for the region. As previously highlighted, the scope of biogas and bio-methane is very limited, regional and ad hoc in nature. Hence, going forward we will not include them in our assessment. From those low- and zero-carbon energy vectors that can be produced by using the resources, namely, freshwater, renewable energy, and existing or future infrastructure in the region, green hydrogen, ammonia, methanol, and synthetic methane require further investigation.

What?

We had two assessment approaches at our disposal to investigate potential application areas and sectors that Mid Wales could target. One focusing on the external (North and South Wales, and the UK) and internal (Mid Wales) market opportunities for locally produced low- or zero-carbon fuels as a driver for development in the region. The other focusing on identifying opportunities for decarbonising local transport, heating, industrial and commercial sectors as key drivers for increasing local demand for these green fuels in Mid Wales. We have taken both these approaches to assess the situation from different perspectives and to identify what roles Mid Wales could play in the large scheme of things emerging in and around the region. Furthermore, we also evaluate if and how Mid Wales could align and partner with other actors in the North and South Wales, and the UK in an effort to carry out a more detailed study in the next phase of this project.

Applications suitable for hydrogen and hydrogen-based fuels

Having discussed different low- and zero-carbon energy vectors, we shall now look into specific energy applications where direct hydrogen and other hydrogen-based fuels can be useful. The purpose of this this discussion is to identify target markets locally and outside Mid Wales for the green fuels.

On demand electricity generation and renewable energy storage

Storing renewable energy in the form of fuels is increasingly recognized. Green hydrogen produced from renewable resources like wind, solar, or hydro is an excellent value proposition for region like Mid Wales provided we understand the market opportunities thoroughly and create strategic partnerships in the supply chain (industries, consumers, grid supplier, etc.) Storing hydrogen is energy intensive, hence, other fuels like ammonia and methanol are increasingly recognized as cost effective carriers of hydrogen.

Heating applications (space, water heating and cooking)

Hydrogen is currently being explored for heating applications wherever grids exist. We have also closely following the ongoing work in Leeds H21 project. They plan to feed hydrogen by steam reformation of natural gas into natural gas pipelines. However, the current grid infrastructure does not support 100% hydrogen feed. The small hydrogen molecules are much more prone to leaking than larger natural gas molecules. Blending hydrogen with natural gas is currently under trials with limited success up to 20 to 25% hydrogen blending. This can only decarbonize maximum 5 – 6% of heating sector.

Using hydrogen to heat homes isn't cheap either for consumers. The electric option using heat-pumps, on the other hand, require higher upfront cost for installation but the running cost is much lower than hydrogen-based heating. Furthermore, heat pumps are not a viable solution for homes with poor thermal insulations and thermal efficiencies. Hydrogen can be competitively used for space and water heating only in the case of district heating networks under current price levels and grid infrastructure limitations. International Energy Agency emphasizes retrofitting buildings with insulation to make them energy efficient and switching boilers for heat pumps as the most promising route for the vast majority of buildings. That being said, hydrogen should be reserved for applications where there are few or no green alternatives available. However, other hydrogen-based fuels such as ammonia, synthetic methane, and methanol are good contenders for this application with or without grid infrastructure. In the case of Mid Wales and other places where gas-grid infrastructure is limited these hydrogen-based fuels will be the best options for heating applications that can reduce the carbon footprint and also cost for the end user.

Fuel for transport

For transport applications using internal combustion technologies direct hydrogen is not a viable option given it's high cost compared to petroleum-products and resulting NOx emissions. However, ammonia, synthetic methane, and methanol are price competitive alternatives. Ammonia has some concerns due to NOx emissions. But this issue is well studied and can be handled with appropriate catalytic reduction techniques.

Fuel system developers such as Alfa Laval and engine developers such as Japan Engine Corporation have announced plans to include ammonia in their offerings. Furthermore, as already mentioned above, several companies including MAN Energy, Mitsubishi, and Siemens have announced efforts to produce ammonia-powered marine engines. Methanol and synthetic methane are already commercially used as fuels for many transport applications.

The best way to use direct hydrogen is using fuel cells which does not have any NOx emission issues. Vehicles powered by hydrogen fuel cells have a similar driving range and can be refuelled as quickly as internal combustion engine vehicles running on petroleum products. This is another important reason for using direct hydrogen for long-haul and heavy-duty transport. With the UK government planning to ban fossil fuel vehicles from 2030, hydrogen fuel cells potentially can help in decarbonising freight and public transport segment. It is expected that majority of hydrogen demand within the transport sector in the UK will come from heavy goods vehicles (HGV) and public transport. The market success for direct hydrogen in private vehicles depends on the retail price of hydrogen, availability of fuelling infrastructure, and price levels of fuel cell vehicles. More investigation is required to understand the potential in this section of the market.

Industrial furnaces and heating

Heavy industry represents second most polluting sector in the UK after transport accounting for 21% of the UK's total carbon emissions. Major contribution to these emissions come from industrial furnace and kiln applications that require very high temperatures. Furnaces in the steel industry are generally powered by fossil fuels. Heating in industry is mostly fuelled by natural gas. If we have to decarbonize industrial sector, both petroleum products and natural gas have to be replaced with low or zero carbon alternatives. Direct hydrogen and hydrogen-carrier fuels can be ideal for such applications. However, clever design of furnaces, nozzles, spark injections are required to reduce NOx emissions. However, Ammonia oxidation catalyst and catalytic reduction can be applied in order to reduce NOx emissions. There are different NOx reduction technologies becoming increasingly available in the market.

Other industrial applications

Presently, hydrogen is used in oil refining to react with and remove unwanted sulphur compounds. Most of the hydrogen used in the UK is derived from steam methane reforming (SMR) or other fossil fuels. It is important to increase the production of green hydrogen using renewable resources to replace the high-carbon fuels powering industrial processes.

Fuels for machineries

Many of the machineries in rural and urban systems such as agricultural equipments, tractors, trucks, etc. are heavily dependent on fossil fuels. Immediate shifting to direct hydrogen-base fuels will be challenging given the high cost of hydrogen and safety concerns related to handling hydrogen. Furthermore, present equipment and machineries that run on fossil fuels are incompatible with pure hydrogen. Other hydrogen-based fuels such as methanol and ammonia could be more cost competitive and are easy to handle. However, ammonia has the higher NOx emission challenge compared to methanol and hydrogen.

Applications sectors for hydrogen and hydrogen-based fuels

Having looked at the energy vectors and their applications, let us briefly look into the application sectors. We have not separately looked into provisions, incentives, and grants that could be relevant to drive green fuel economy in Mid Wales at this point. But we aim to carry out this in our next phase. Our emphases at this point were to gather various pointers relating to the potential for green hydrogen-based fuels in different application sectors based on

- discussion with stakeholder communities in different sectors;
- evaluation based on existing literature and research documents;
- availability of infrastructure;
- availability of commercially-viable solutions;
- readiness or resistance of the sector to change; and
- supply-chain readiness and sustainability

The results of this preliminary evaluation for three hydrogen-based fuel are given in the table below.

applications	present primary fuel	present secondary fuel	blue and green hydrogen
Industrial	Electricity	Petroleum	**Potential**: **High** **Remarks**: Hydrogen is directly competing with electricity and petroleum in this sector. The market opportunity for hydrogen is very high as it offers better quality of service compared to existing vectors at a competitive price. In specific, industrial furnaces are the major applications that require very high temperatures. Hydrogen can satisfy this requirement better than electricity and petroleum at the same time completely decarbonize application. However, NOx emissions are still a concern when burning hydrogen directly in air. **Market**: limited within Mid Wales and existing and increasing in North and South Wales Industrial Clusters and the rest of UK.
Commercial	Electricity	Petroleum	**Potential**: **Low** **Remarks**: Hydrogen doesn't have competitive advantage in the commercial sector where most of the requirements are for heating and cooking applications. Here electricity and petroleum-based products have edge over hydrogen in terms of price, safety, storage, supply chain, and logistics. The existing grid is limited in connectivity and cannot handle 100% hydrogen. As hydrogen burns with an invisible flame, there would be safety concerns of using pure hydrogen in the national gas grid for the purposes of cooking. Furthermore, under current cost-levels hydrogen will only be a distraction from other cheaper green alternatives. **Market**: low within Mid Wales and the rest of Wales and UK
Domestic	Petroleum	Electricity	**Potential**: **Low** **Remarks**: Hydrogen doesn't have competitive advantage in the domestic sector where most of the requirements are for

			heating and cooking applications. This is mainly because of the grid limitations. Even in places where there are existing grids, maximum range of hydrogen that can be fed is in the range of 20 – 25% which can only decarbonize maximum 5 – 6% of domestic sector. Here electricity and petroleum-based products have edge over hydrogen in terms of price, safety, storage, supply chain, and logistics. Furthermore, using hydrogen for domestic applications require alteration to existing equipments, valves, and fittings. This is a barrier in short- and medium-term. Under current cost-levels hydrogen will only be a distraction from other cheaper green alternatives. **Market**: limited in Mid Wales because of grid constraints and distributed population. In other locations where grid connectivity is not a constraint still retrofitting will be an issue which requires further investigation.
Road transport LGV	Petroleum	-	**Potential**: Medium **Remarks**: Hydrogen is still very expensive, so it can be used primarily where there are no low-emission alternatives, and where other advantages outweigh higher costs. Here petroleum-based products have edge over hydrogen in terms of price, safety, supply chain, and logistics in short- and medium-term. Until there is no ban on fossil fuel usage in private vehicles and there are no incentives to switch to low- or zero-carbon alternatives there will be less opportunity for hydrogen in this market segment. **Market**: presently limited and development is uncertain under current constraints of price levels and transition costs.
HGV and Rail transport	Petroleum	Coal	**Potential**: **High** **Remarks**: This is one of the high potential opportunities for hydrogen. However, there are still concerns related to safety that needs to be investigated further. Freight (trucks to trains) and aviation can benefit from liquid hydrogen's very high energy density. With the UK government set to ban fossil fuel vehicles from 2030, hydrogen fuel cells could do much of the heavy lifting in decarbonising freight and public transport where maximum hydrogen demand in transport is likely to come from. **Market**: opportunity is high provided fuel cell technology becomes cost competitive. Hydrogen fuel cells have an edge over state-of-the-art electric vehicles in terms of ease of refuelling and extended range of travel. Aligning with the Global Center of Rail Excellence (GCRE) is very important to Mid Wales if we want to benefit from the developments.

Public Sector	Petroleum	Coal	**Potential**: High **Remarks**: Hydrogen can be used in public sector buildings heating and electricity requirements as a greener alternative to exiting CHP fuels based on petroleum products. However, the current price levels of hydrogen compared to petroleum products is a barrier. **Market**: public sector offices such as county buildings, hospitals, schools, etc. where CHP systems are used, hydrogen can be a viable alternative. Unless there is going to be a ban on fossil fuels for these applications market opportunities for hydrogen will be limited because of price disadvantage.
Agriculture	Petroleum	-	**Potential**: Low **Remarks**: Hydrogen is not seen as a viable fuel for agricultural requirements given the constraints related to storage and safety. Furthermore, the farm equipments and machineries are not readily adaptable to hydrogen fuels, which will be a big barrier to overcome. **Market**: limited both within and outside Mid Wales.

We have discussed the potential for ammonia as a viable zero-carbon hydrogen-based fuel and also as an excellent storage and carrier medium for hydrogen. Recent developments in North and South Wales also addresses using ammonia as a viable storage medium and fuel. Other than being used as fuel or hydrogen carrier, ammonia is used in agricultural sector as raw material and as feedstock in industries for plastics and other products. As mentioned above, UK is a net exporter and the market for ammonia is in agricultural and industrial raw material sectors.

applications	present primary fuel	present secondary fuel	potential for ammonia
Industrial	Electricity	Petroleum	**Potential**: High **Remarks**: The biggest challenge is the NOx emissions on burning ammonia as fuel. However, recent developments in combustion technologies are promising to reduce NOx formation. This will open new opportunities for ammonia as a viable fuel. Based on a high-level cost comparison, with further technology development the use of ammonia as a fuel rather than a hydrogen carrier should become the more economical choice in future. The supply chain and logistics of ammonia are matured compared to that of hydrogen. This will provide new opportunities in the future. **Market**: The market opportunity for ammonia is very high for use in various industries as a stabilizer, neutralizer and a source of nitrogen and hydrogen.

Commercial	Electricity	Petroleum	**Potential**: Medium **Remarks**: Ammonia is competitive in price with electricity and petroleum in the commercial sector where most of the requirements are for CHP applications. Wherever there is grid connectivity, we need to further investigate the potential for feeding ammonia or mixture of ammonia with other fuels into the grid. That being said, NOx emissions will be the main barrier to overcome. **Market**: opportunity is good both inside and outside Mid Wales given the fact that UK is net exporter of ammonia.
Domestic	Petroleum	Electricity	**Potential**: Low **Remarks**: Wherever grid connectivity is available, ammonia can be used for district heating purposes. However, as a stand alone solution for individual homes opportunities are limited. **Market**: Market opportunity for using directly ammonia for individual homes heating and cooking applications is limited both inside and outside Mid Wales.
LGV, HGV, Rail and Marine transport	Petroleum	Coal	**Potential**: Medium **Remarks**: Using ammonia as fuel for internal combustion (IC) engines dates back to the early 1800s. However, the available size and maturity of ammonia engines, turbines, or fuel cells as compared to the size and maturity of ammonia crackers, hydrogen engines, and fuel cell will need to be weighed on an individual basis for each intended application. **Market**: Utilization of ammonia for marine fuel has been more aggressively researched since 2007. In fact, fuel system developers such as Alfa Laval and engine developers such as Japan Engine Corporation have announced plans to include ammonia in their offerings. Furthermore, MAN Energy, Mitsubishi, and Siemens have announced efforts to produce ammonia driven marine operations.
Public Sector	Petroleum	Coal	**Potential**: High **Remarks**: Ammonia can be used in public sector buildings heating and electricity requirements as a greener alternative to exiting CHP fuels based on petroleum products. NOx emission reduction is a barrier. However, Ammonia oxidation catalyst and catalytic reduction can be applied in order to reduce NOx emissions. There are different NOx reduction technologies becoming increasingly available in the market. In fuel cell applications, once the energy losses due to heating, cracking, and post polishing (i.e. removal of residual ammonia) is considered, the available energy of the

			hydrogen from cracked ammonia is nearly the same as that of original ammonia. **Market**: public sector offices such as county buildings, hospitals, schools, etc. where CHP systems are used, ammonia can be a viable alternative.
Agriculture	Petroleum	-	**Potential**: Low (as fuel) / High (as raw material) **Remarks**: As a fuel, potential for ammonia in the agricultural sector is low. However, as a raw material it has very high potential. **Market**: limited for fuel applications. However, huge market is already existing in the UK and in Europe as a raw material for fertilizer and plastic industries.

We have discussed the potential for methanol as a viable low-carbon hydrogen-based fuel and also as an excellent storage and carrier medium for hydrogen. Recent developments in North and South Wales Industrial also addresses carbon capture utilization and storage (CCUS) as a priority for offsetting carbon emissions. Mid Wales could trade hydrogen as a raw material for producing methanol as a viable strategy.

applications	present primary fuel	present secondary fuel	potential for methanol
Industrial	Electricity	Petroleum	**Potential**: Medium **Remarks**: When competing against electricity, methanol doesn't have an edge. However, against petroleum it has several advantages in terms of price, emissions, and overall performance. **Market**: opportunity exists in Wales and in the UK which needs further investigation.
Commercial	Electricity	Petroleum	**Potential**: Low **Remarks**: Methanol is competitive in price with electricity and petroleum in the commercial sector where most of the requirements are for CHP applications. Wherever there is grid connectivity, we need to further investigate the potential for feeding methanol or mixture of methanol with other fuels into the grid. Methanol has a huge potential to decarbonize the commercial and domestic heating sector. **Market**: opportunity is good both inside and outside Mid Wales, Wales, and UK
Domestic	Petroleum	Electricity	**Potential**: High **Remarks**: Methanol is competitive in price with petroleum in this sector where most of the requirements are for CHP

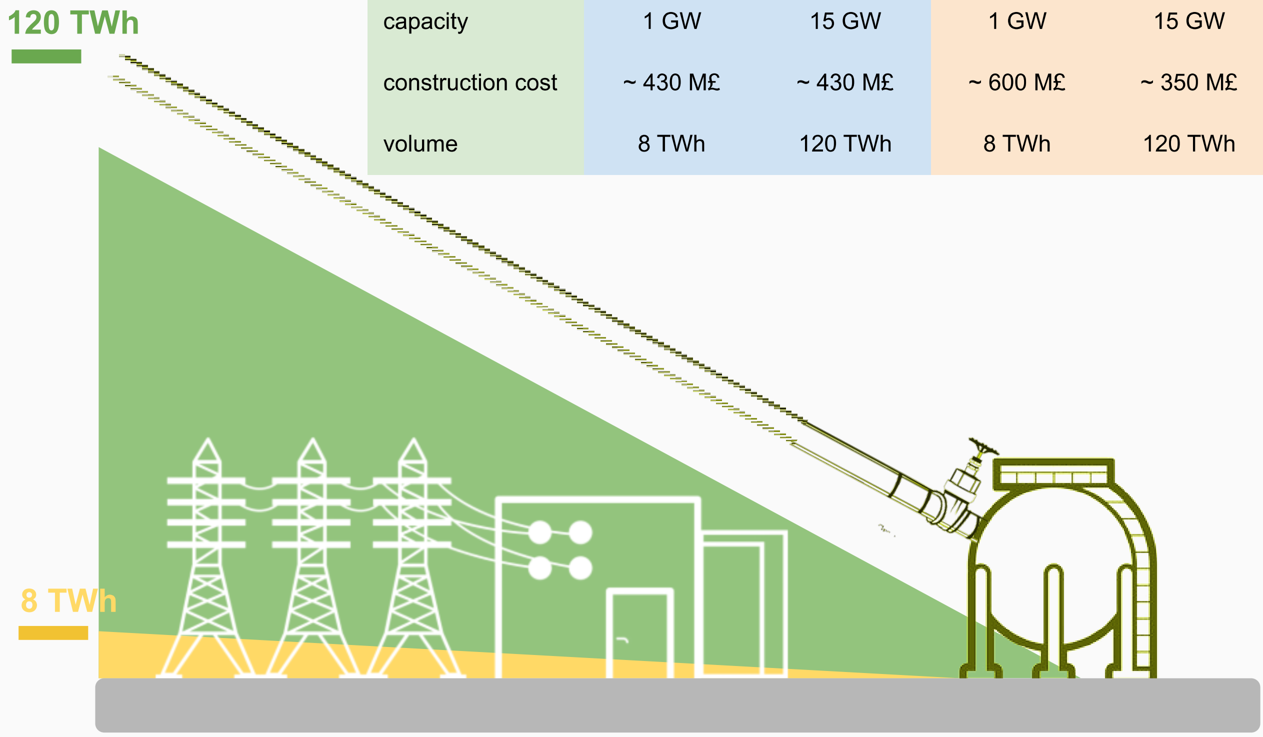
			applications. Wherever there is grid connectivity, we need to further investigate the potential for feeding methanol or mixture of methanol with other fuels into the grid. Methanol has a huge potential to decarbonize the domestic heating. **Market**: opportunity is good both inside and outside Mid Wales, Wales, and UK
LGV, HGV, Rail and Marine transport	Petroleum	-	**Potential**: Medium **Remarks**: As a high-octane vehicle fuel, methanol offers excellent acceleration and power. It also improves vehicle efficiency. Methanol can be produced, distributed and sold to consumers at prices competitive to those of gasoline and diesel with no need for government subsidies. **Market**: opportunity is good both inside and outside Mid Wales, Wales, and UK
Public Sector	Petroleum	Coal	**Potential**: Medium **Remarks**: Methanol can be used in public sector buildings heating and electricity requirements as a greener alternative to exiting CHP fuels based on petroleum products. Methanol can be produced, distributed and sold to consumers at prices competitive to those of gasoline and diesel with no need for government subsidies. **Market**: public sector offices such as county buildings, hospitals, schools, etc. where CHP systems are used, methanol can be a viable alternative.
Agriculture	Petroleum	-	**Potential**: High **Remarks**: It has a huge potential as a low-carbon alternative and replacement fuel to gasoline. **Market**: opportunity is good both inside and outside Mid Wales, Wales, and UK

How?

Before delving into potential pathways, we want to take a short detour to highlight "underlying" debates between lobbies supporting gas pipelines and electricity grids.

Essentially, there are two contrasting viewpoints. One based on electricity-demand-boosting agenda and the other based on positioning gas grid as an ideal solution. Gas grids, when they exist, are more efficient and less costly than electricity for heating, and possibly also for other purposes. While this is not the case for Mid Wales where most of the properties are off-grid, the narratives are still very relevant to understand where the best bets are both within and outside Mid Wales. For sure, it is easier to transmit gas with lower energy losses compared to electric power lines. We were interested in knowing about overall cost levels and capacities. We have gathered data to put things into perspectives using four example cases. The first and second examples are that of underwater (submarine) deployments running about 250 km between UK and Netherlands. In the first case, high voltage direct current (HVDC) cables are used to transmit electricity and in the second case natural gas is supplied using pipeline. We have contrasted these with same distance deployment of HVDC overhead cables and gas pipelines deployment on the land. The differences between these cases are illustrated in the figure below.

	Submarine		On land	
	HVDC Cable (Britned)	Gas Pipeline (BBL)	HVDC Cable	Gas Pipeline
capacity	1 GW	15 GW	1 GW	15 GW
construction cost	~ 430 M£	~ 430 M£	~ 600 M£	~ 350 M£
volume	8 TWh	120 TWh	8 TWh	120 TWh



REMARK: *BritNed is a 1 GW HVDC submarine power cable between the Isle of Grain in Kent in the UK and Maasvlakte in Rotterdam in the Netherlands. The BBL Pipeline (Balgzand Bacton Line, BBL) is a natural gas inter-connector between the Netherlands and the United Kingdom. The land deployment examples for electricity and gas pipeline are based on £/km standard price level back-of-the-envelope calculations.*

Gas is the main source of heat in the UK. The UK gas grid carries about four times more energy than the electric power grid with heating demand being high at times. Supporters of gas grids argue that it is foolish to try to switch over to electric heating as the power grid could not cope without massive expansion. Such massive expansions in the Mid Wales have received oppositions from the anti-pylons protesters for various reasons discussed before.

However, the supporters of electricity take the argument of climate change in their favour conveniently. They argue that the energy system can best be decarbonized connecting power from wind, solar and other renewables to end users by wires. In other words, they believe the only way to go ahead is electrification of everything – heating, cooking, transport, etc. Against this, the gas lobbyists stress that, for heating, it makes more sense to stay with the gas grid and standard appliances but switch over to green gas. In the context, green hydrogen, ammonia, methanol, synthetic methane all makes sense. One can employ most of these green alternatives with almost no change except in the case of 100% hydrogen as explained in the earlier sections. In comparison, to use electricity efficiently you would have to install expensive heat pumps in every house. Furthermore, green gas can also be used for vehicles, as compressed natural gas is already used for transport purposes.

The situation becomes more complicated when we have another pipe option, namely, district heating network that can supply heat directly to users. Though this is not relevant in the present situation to most of Mid Wales, it is important in high-density urban environments in other parts of Wales and the UK. We have to consider this as an option to find potential partners for green gas that may be produced in the Mid Wales region. District heating can make more sense than individual domestic boilers, and heat networks could supply perhaps half of UK heat. Local gas-fired Combined Heat and Power (CHP) plants can supply heat much more efficiently than small domestic heat pumps. Heat pumps can have a coefficient of performance (COP) around 3 to 4. This means heat pumps can deliver three or four times more useful heat out of the input electricity. However, CHP plants have a COP ratings about 9 or more. Importantly, they use heat from burning fuel that would otherwise be wasted. Most CHP plants use fossil gas with high efficiencies in the range of 70–80% or more. It is worth noting that increasing the use of hydrogen, synthetic methane, methanol, or ammonia can help in drastically reducing the carbon footprint of CHPs.

Potential pathways

Having looked into potential for various green fuels, target sectors and applications, we would like to present three potential pathways as a way forward to Mid Wales. Each of these pathways differ in their short-term goals. However, all of them have similar or same medium- and long-term goals for the Mid Wales region. The pathways are namely,

- first-procure-later-produce scenario
- grid-connected-production scenario
- isolated-production scenario

First-procure-later-produce

priority:
In this strategy, priority is to align Mid Wales as a strategic partner to North and South Wales and the rest of UK to create new market opportunities inside and outside Mid Wales. Identify how Mid Wales can best support North and South Wales in creating pan-Wales hydrogen economy. Decarbonise local energy applications by procuring green fuels produced outside Mid Wales.
goals:
Short-term establish local market for green hydrogen and other hydrogen-based fuels produced outside Mid Wales in an effort to decarbonize and create sizeable local market. Learn from others' mistakes before venturing into long-term large-scale investments in Mid Wales.
rationale:

The real potentials for green hydrogen and other hydrogen-based fuels are unclear. Market developments can go either way as neither Welsh Government nor UKG has a clear actionable plan for green hydrogen and hydrogen-based fuels. Grid developments are slow and might take several years to materialize. With these uncertainties, Mid Wales can best prepare itself by playing safe but clever and position itself as a strategic partner to other regions that are acting as first movers.

remarks:

In the short-term, Mid Wales will be aiming to become strategic partner connecting North and South Wales and the rest of UK. As there are a lot of industrial developments happening in North (HyNet) and South Wales (SWIC). If we want to grow hydrogen economy in Mid Wales, we could find ways to expand HyNet to the south and SWIC to the north by using their infrastructure and creating market opportunities in Mid Wales. Given the huge potential for renewable energy in the region, Mid Wales can attract investments to produce locally various green fuels in the medium- and long-term. These investments can further be used to improve infrastructure and develop grid connectivity in the region, at the same time create new job opportunities. This strategy can be win-win in the long-term with low risk exposure in the short-term as the real potential for green hydrogen and other hydrogen-based products to decarbonise various sectors inside and outside Mid Wales is still uncertain and evolving. Mid Wales can prepare the ground to decouple previous local opposition against wind farms and pylons by strategically introducing various developments by creating local demand for different green fuels. If the market for green hydrogen is not picking up Mid Wales can play safe with minimum risks. In this strategy, if Mid Wales can position itself as a strategic partners, other regions will require Mid Wales in short-, medium-, and long-term.

Produce in Mid Wales within existing electricity grid spare capacity

priority:

The priority is to maximise existing grid spare capacity to create local value.

goals:

Immediately tap into existing grid spare capacity to locally produce green hydrogen and identify market opportunities mainly outside Mid Wales. Also explore the possibility to produce other hydrogen-based fuels like ammonia, methanol, and synthetic methane considering the market demands.

rationale:

There are some spare capacity in the existing electricity grid in Mid Wales. We are sure this is very limited and the range needs further investigation. This can be used to produce green hydrogen without building any new renewable infrastructure and supply to market opportunities outside Mid Wales. Align with electricity grid operators and create long-term fixed contracts with potential clients outside Mid Wales. Given the huge fluctuations in market prices for hydrogen, potential clients may be willing to take the risk of fixing the price.

remarks:

Mid Wales will be one of the minor production regions for green hydrogen and other hydrogen-based fuels. Production capacity, however, will be limited by the available grid spare capacity of ~100 MW. Green hydrogen produced will not be cost competitive compared to open market prices. Risk will be high as the market is very sensitive to prices. Mid Wales will be competing with North and South Wales, and the rest of UK. None of the clusters "need" Mid Wales for their activities, but Mid Wales will need other regions to find market opportunities.

Produce in Mid Wales without Grid

priority:

Maximum tap into the potential renewable resources in the region independent of the grid to increase green hydrogen production capacity.

goals:

Produce at the highest capacity using maximum renewable resources in the region to be cost competitive in the entire green hydrogen UK market. Also explore the possibility to produce other hydrogen-based fuels like ammonia, methanol, and synthetic methane considering the market demands.

rationale:
Mid Wales can only be cost competitive if it uses maximum renewable resources in the region to produce green hydrogen at large scale. Aim for establishing long-term contracts at best price levels with potential clients outside Mid Wales.
remarks:
Mid Wales will be aiming to become one of the major production regions for green hydrogen and other hydrogen-based fuels in the UK. However, huge upfront investments will be required for creating new large-scale renewable infrastructure. Actual production may happen only after several years (typically 5 to 10) as it involves getting project approvals, planning, and construction stages typical for new large-scale renewable infrastructure development projects. Potential local opposition may also oppose and delay construction of new renewable infrastructure in the region. If the market for green hydrogen is not picking up there will be a huge sunk-cost which might be difficult to recover. These market risks can be partially mitigated by producing other hydrogen-based fuels like ammonia, methanol, and synthetic methane. This strategy will be good for Mid Wales provided the above challenges can be overcome as it can strongly position Mid Wales price competitive compared to other producers in North and South Wales, and the rest of UK. That being said, Mid Wales will still need other regions to find market opportunities.

Hydrogen (green or blue) as the way it is being positioned might very well be a wishful thinking or a miracle fuel of the future. Presently, direct hydrogen has only limited market opportunities within Mid Wales and developments outside Mid Wales are still evolving. Many of the applications are not yet ready for green fuels. One has to think about a transitory period to create a pathway if green fuels have market opportunities. In this period, Mid Wales need to find realistic market opportunities as a way to support the organic growth within the region. There should be transition fuels specific to applications that can serve as a bridge between current fossil-fuels and the future green fuels. The transitory fuels should be easily usable with current infrastructure and machineries with minimum or no change. That being said, pure hydrogen has some niche market opportunities in the HGV and Public transport sectors. Synthetic methane, methanol, and ammonia could be seen as transition or ideal green fuels for many of the applications. We have discussed three possible scenarios, of which the third scenario seem to be more realistic pathway to create opportunities for Mid Wales in this preliminary assessment. These are, however, only our initial reflections based on the preliminary findings, which require further investigations.