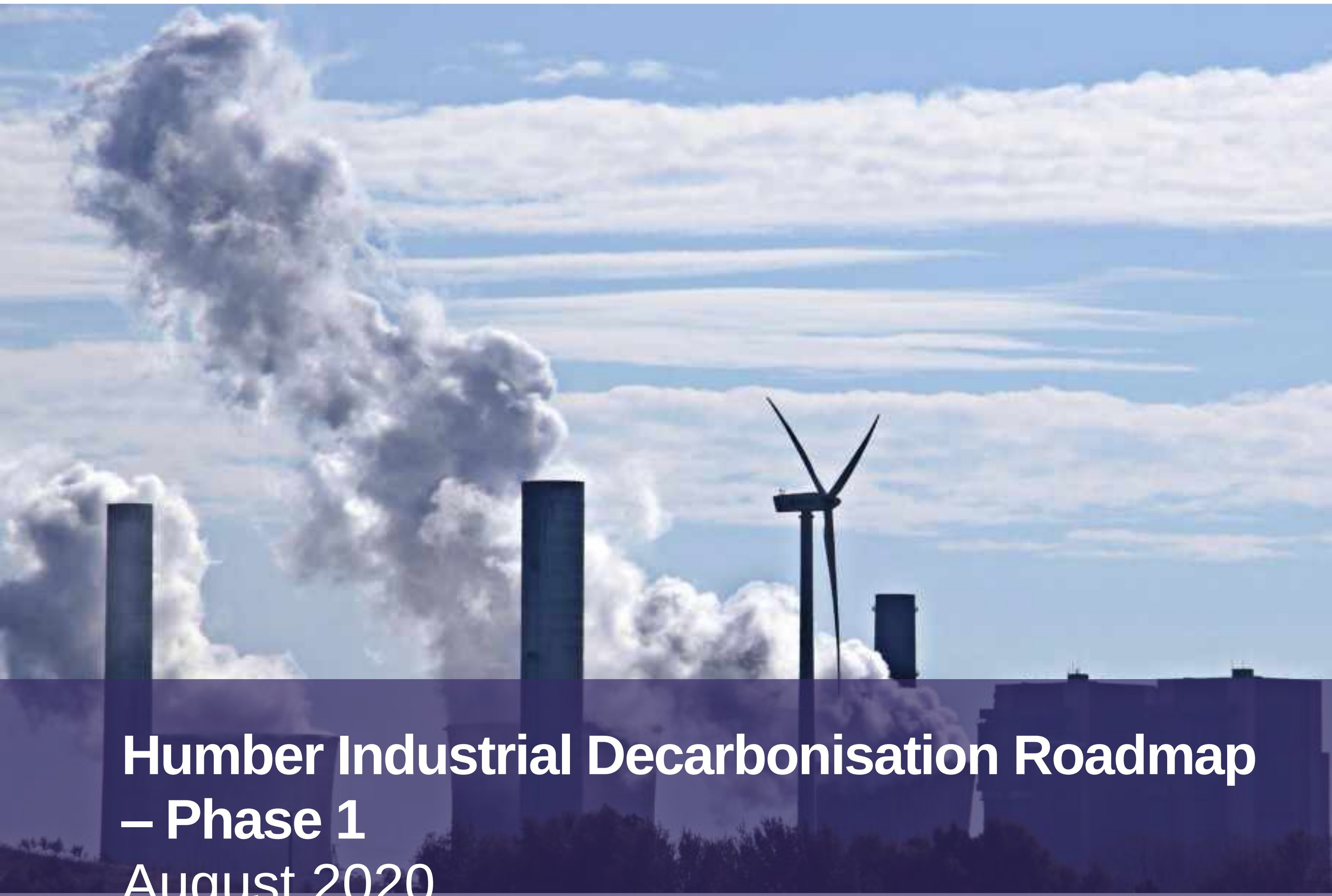

Humber Industrial Decarbonisation Roadmap – Phase 1

August 2020

1 Executive Summary

The LEP and membership organisation CATCH secured a contribution from the Industrial Strategy Challenge Fund (ISCF) to develop the strategy for a Humber Industrial Decarbonisation Roadmap (HIDR), establishing the pathway for the Humber industrial cluster's carbon emissions to be net zero by 2040 and significantly reduced by 2030.

The Humber emits more CO2 than any other industrial cluster whilst a quarter of Humber GVA and 1 in 10 jobs depend on these industries. Clean growth, including achieving net zero by 2040, is therefore at the centre of the Humber's Local Industrial Strategy and developing HIDR is identified as a critical early action.

Work undertaken for Phase 1 focused on the following key areas of feasibility:

- Collection and presentation of relevant data about the Humber industrial cluster with the development of 'business-as-usual' scenarios that assess how emissions from the cluster may evolve until 2040 if no deep decarbonisation measure is implemented.
- An overview of technology options for decarbonisation
- A review of project pipelines and their role in scenario development
- An appraisal and needs analysis of systems modelling
- Development of a strategy to develop a roadmap

1.1 Work package 1: Baseline Local Emissions

1.1.1 The Humber today

Emissions from the Humber industries were estimated to be 14.8 $MtCO_2$ in 2017, including:

- 10.6 $MtCO_2$ emitted by 30 large industrial sites, with most of the emissions arising from the refining and iron and steel sectors.
- 1.3 $MtCO_2$ emitted by a multitude of smaller sites.
- 3.0 $MtCO_2$ emitted by combined heat and power (CHP) plants to generate steam used by the Humber industries.

A further 5.0 $MtCO_2$ was emitted from 13 power generators located within the Humber geography, which brings overall emissions from power generators and industries in the Humber to just under 20 $MtCO_2$.

1.1.2 Source of Emissions

Two main sources of industrial emission can be defined:

- Fossil fuel combustion to supply energy (often heat) required by the industrial processes - this is the source of 93% of all industrial emissions.
- Industrial processes that include chemical processes which emit CO_2 - the remaining 7% of all industrial emissions arise from processes within the cement and lime, iron and steel, and refining sub-sectors.

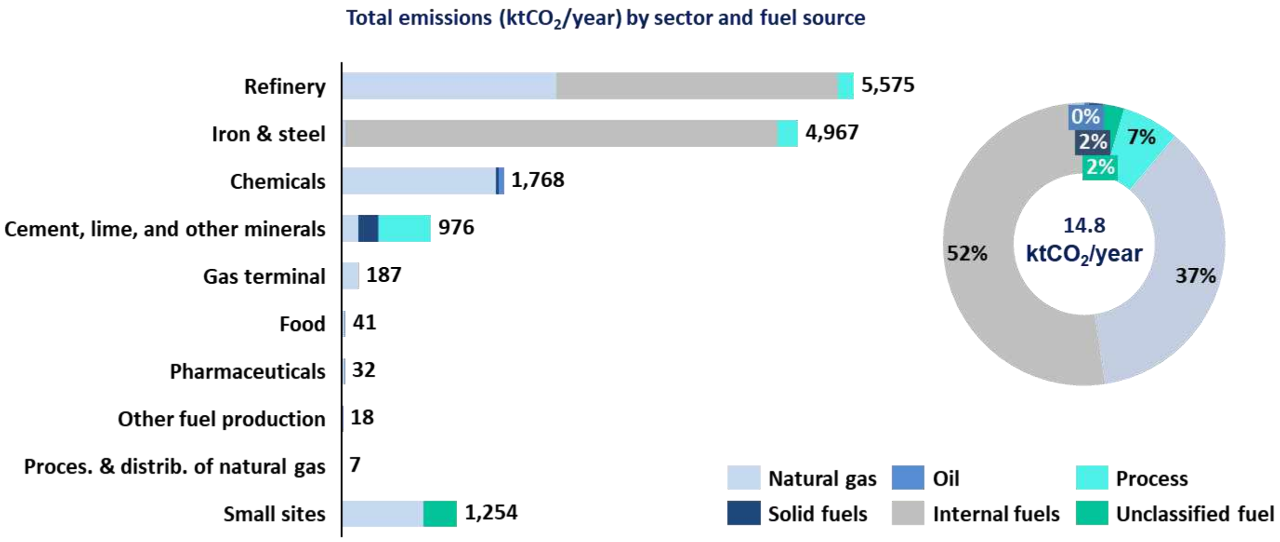

Figure 1: Breakdown of industrial emissions by source

1.1.3 Business as usual scenarios

Emission reductions of 2-18% between 2017 and 2040 are estimated to occur under the different ‘business-as-usual’ scenarios. The iron and steel and refining sectors are expected to be the biggest contributors to overall emissions reductions in most scenarios, which is primarily due to their large relative size compared to other sectors.

1.2 Work Package 2: Technology Overview

1.2.1 Technologies for industrial decarbonisation

The variety and complexity of the Humber cluster suggests that a decarbonisation strategy will need to combine a broad range of technologies and approaches, including but not limited to CCS, fuel switching to hydrogen, and electrification.

Previous research and modelling by ETI suggests that energy system decarbonisation will start in the power sector before tackling the more difficult and expensive sectors such as freight transport and aviation. The industrial sector has often been classed as “hard to treat” but new routes to decarbonising the sector have been identified that would lead to significant emissions reduction.

The technologies that are likely to support decarbonisation in the Humber are described in more detail in the main body of this report and are summarised below.

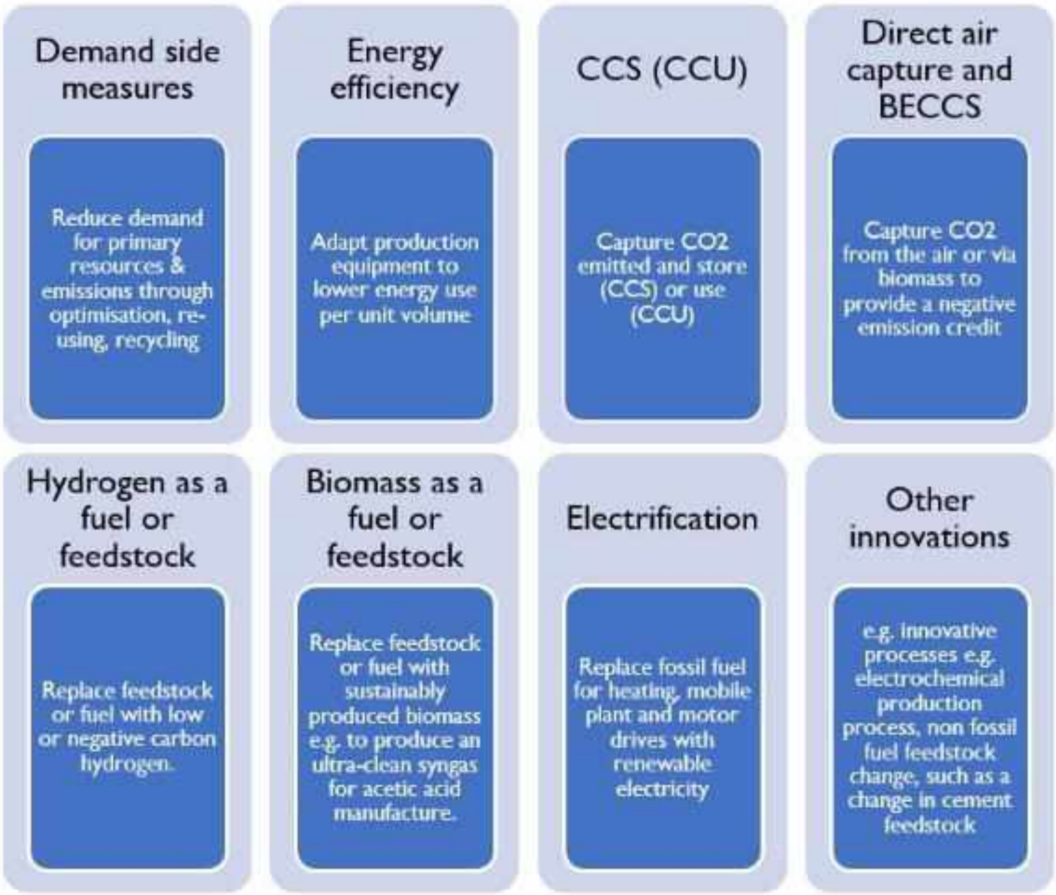

Figure 2: Technology Options Summary

A combination of these technologies will be required to decarbonise the Humber, though it should be noted that the technology options that will be needed are, in the main, emerging, new to the UK technologies therefore costs are still very uncertain.

1.3 Work Package 3: Scenario Development

Multiple industry and power sector stakeholders have already been developing plans for deep decarbonisation, and several projects involving some of the largest emitters in the wider region are currently in development.

These projects broadly support the vision of establishing in Humber the first net-zero industrial cluster by 2040, and seek to deliver substantial emissions abatement via fuel switching to hydrogen (green or blue) and CCS and could set the foundations for a net-zero industrial cluster, by installing key infrastructure and providing knowledge to others both within the Humber cluster as well as within the UK and beyond.

1.3.1 Potential Decarbonisation Activity

Reviewed projects include the two ISCF-supported deployment projects known as 'Humber Industrial Decarbonisation Deployment Project' (Humber-DP) and 'Green Hydrogen for the Humber', as well as related projects 'Gigastack', 'Humber Zero', and 'Zero Carbon Humber'. These projects investigate multiple ways to deeply decarbonise industry, including:

- Green hydrogen, which could be produced via the electrolysis of water (or 'water splitting') powered with electricity from nearby offshore wind farms.
- Blue hydrogen, which could be produced in natural gas reformers equipped with carbon capture.
- CCS, also in combination with bioenergy (BECCS) to achieve negative emissions, applied to both industrial processes and to CHP plants.

Although these projects are at an early development stage, they aim to deploy substantial decarbonisation infrastructure by the mid-2020s, which could potentially generate the necessary momentum to transform the Humber into the first net-zero cluster by 2040. On this basis there is a strong rationale for embedding them at the centre of strategy development.

1.3.2 Key considerations

- There are a number of decarbonisation initiatives and projects. This adds complexity to stakeholder mapping.
- The major emitters are each involved in some level of decarbonisation planning, scoping or deployment – the top two emitting sectors (refining and iron and steel) are completely included. This means that there is an advantage to capitalising on existing or planned knowledge, data and infrastructure in developing the roadmap.
- CCS and hydrogen (both green and blue) are the key technology options spanning the extent of the Humber and principle emitters. The CCS schemes presented, however, have a dependency on the timely delivery of an appropriate CO2 transport and storage infrastructure.
- There is a need to understand the impact of not or only partially addressing emissions from the refining and iron and steel sectors. Different drivers are affecting different decarbonisation choices compared to the refining and chemicals sectors.
- In a net zero scenario, CO2 capture efficiencies may become important and will need to be further investigated. However, BECCS will be crucial to meeting any net zero target as it will be impossible to avoid all sources of anthropogenic CO2 emissions – the negative emissions BECCS can provide will offset these unabated emissions.
- BECCS requires access to a CCS T&S network. Further potential for negative emissions including application to biofuels facilities at Saltend and near Immingham on the South Bank of the Humber should also be investigated.

1.4 Work package 4: Systems Modelling

This section considers the methodological scope, outline approach and development costs for systems modelling in Phase 2 that will demonstrate the most effective way of delivering a net zero industrial cluster by 2040.

1.4.1 Appraisal of Analytical Approaches

An appraisal of a range of analytical approaches was carried out including qualitative, quantitative, semi-quantitative methods and systems modelling. Associated examples and application to the Humber Industrial Cluster were also explored.

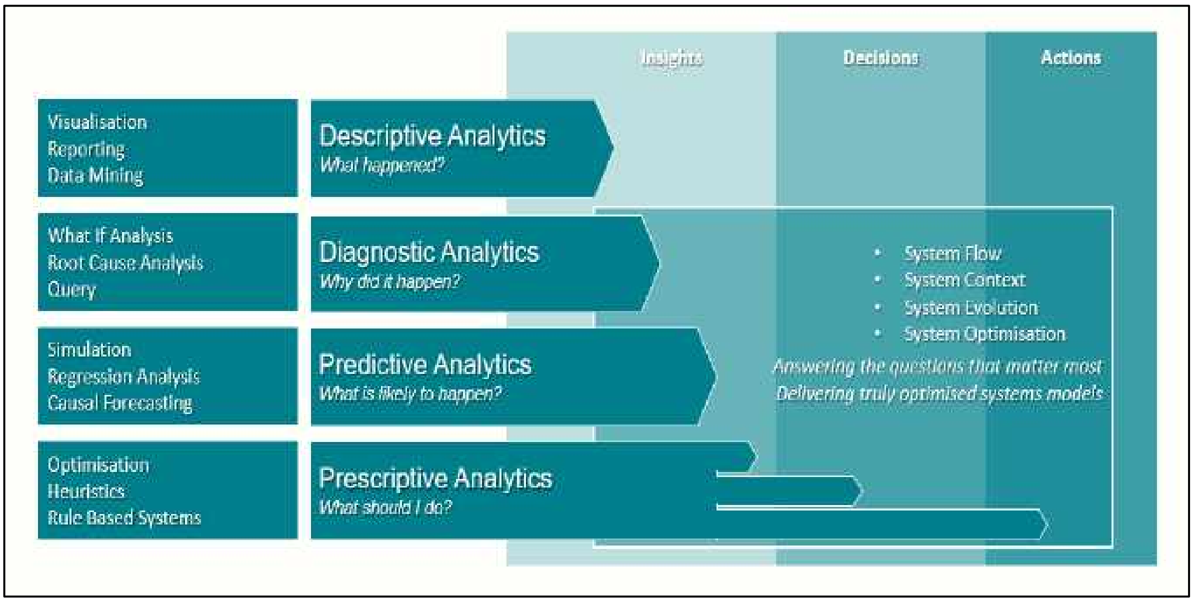

Figure 3: Analytical approaches

The appraisal concluded with a recommendation of prescriptive analytics modelling approach for Phase 2. This will allow the Roadmap team to ask questions about ‘what should happen’ in the future, taking into account interdependencies, possible uncertainties and step changes in technology which may occur.

These will be modelled using constraint-based scenario analysis and sensitivity analysis. This will facilitate the development of an optimal roadmap to net zero with no regrets / least regrets visibility, as well as providing visibility of critical technology and infrastructure lead times and potential enablers or blockers.

1.4.2 Systems Modelling

Systems modelling is required to analyse and explore the behaviour of complex systems which have significant interdependencies and uncertainties. Systems modelling is made more widely accessible through advances in prescriptive analytics and cloud computing over the last decade.

Adopting this recommended modelling approach will:

- Inform the optimal direction of the decarbonisation pathway, with no regrets / least regrets visibility.
- Enable the management of future risks and uncertainties.
- Enable the modelling of different objective functions and scenarios.

1.4.3 Solution architecture: Modules and structure

An indicative, high-level solution architecture of the model is shown below. The solution architecture presents the core elements of the proposed solution from data to system model to user interface. It also illustrates how the different user types will interact with the solution. To allow for scalability and ease of user access this architecture would be web based, ideally hosted on a cloud-based computing platform.

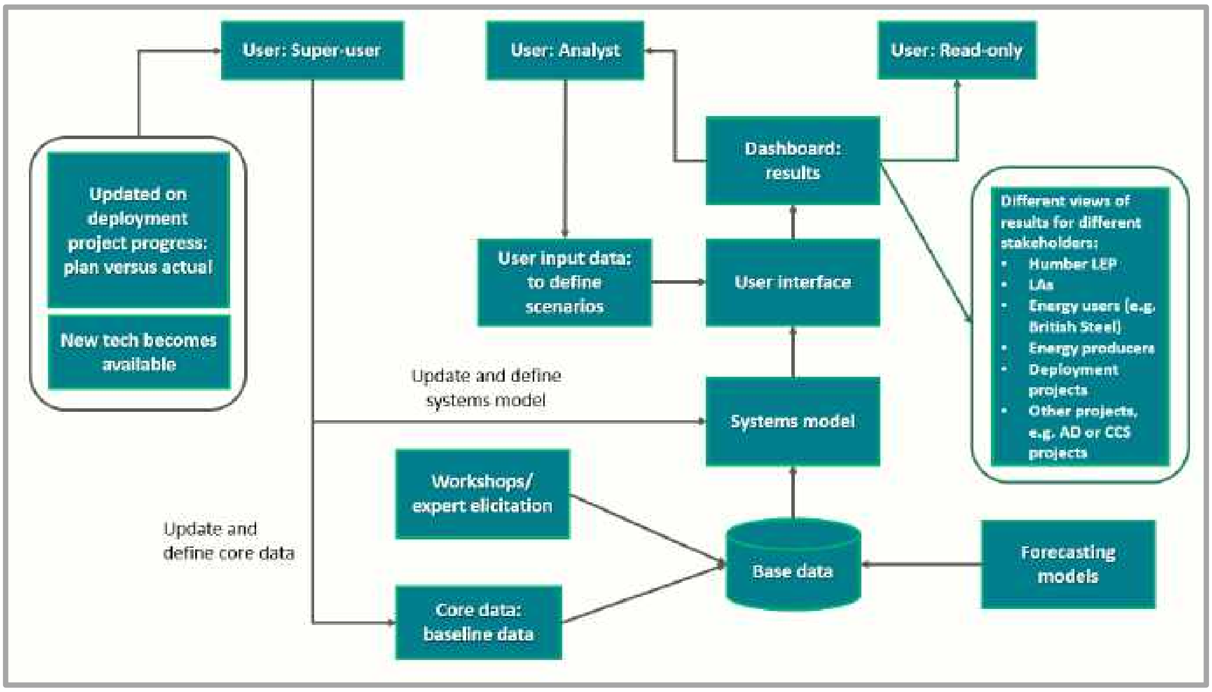

Figure 4: Solution architecture

1.5 Work Package 5 – Roadmap Development Strategy

The overarching aim for this project was to develop the strategy for roadmap delivery. The culmination of this work has resulted in a strategy that focusses on four key areas:

1. Stakeholder Engagement and communication

2. Technology deployment deep-dive
3. Systems modelling
4. Overcoming barriers to deployment

1.5.1 Stakeholder Engagement and Communication

A planned and strategic approach to achieving ongoing and uninterrupted liaison with deployment projects, other ISCF funded projects, industry and other stakeholders. This will ensure that existing momentum and interest is maintained while also providing a mechanism for maximising opportunities – particularly around the availability and utilisation of existing and new infrastructure. The diagram below illustrates the core links between the Humber Cluster Plan delivery and its stakeholders

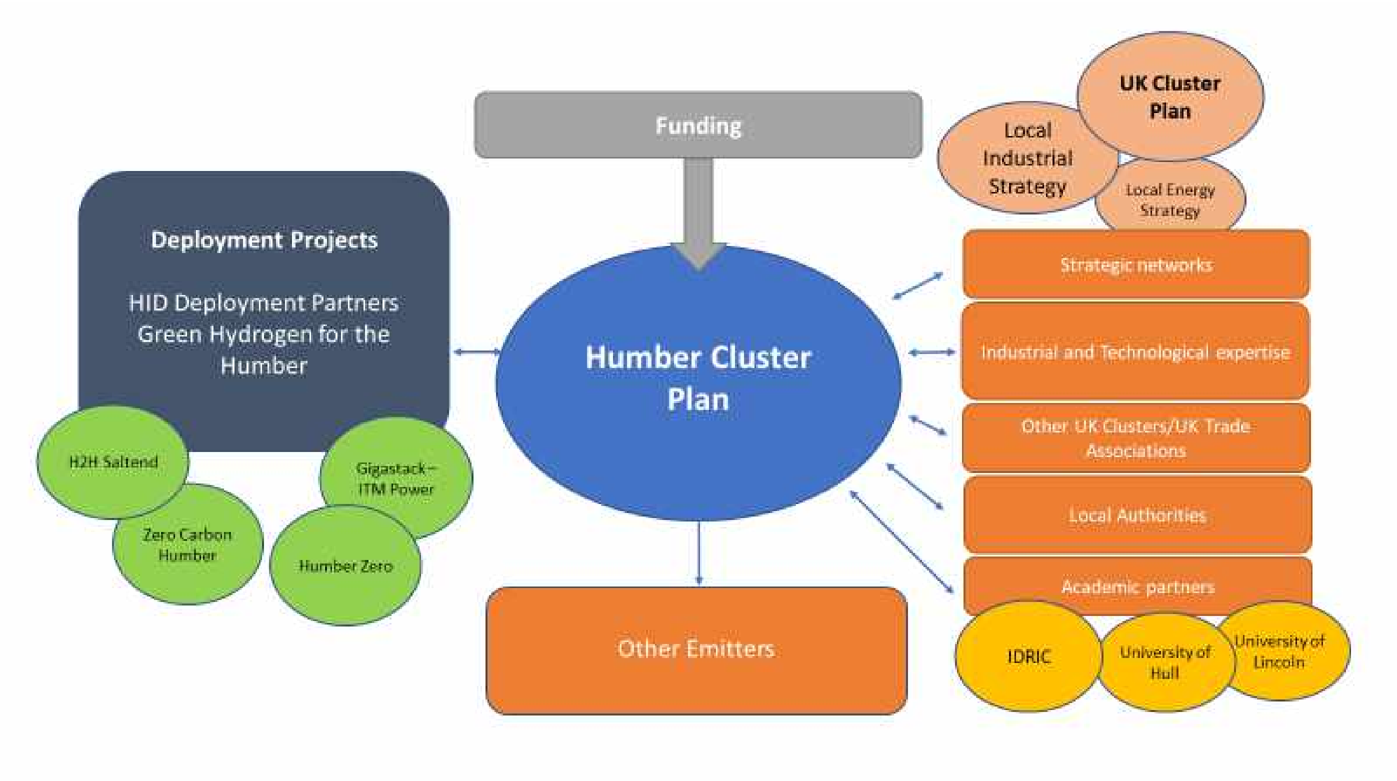

Figure 5: Humber Cluster Plan stakeholder map

1.5.2 Technology Deployment Deep-dive

Further exploration via deep-dive studies of fuel-switching (hydrogen, electricity, biomass) and CCUS supported with additional sector studies and academic peer review. This will ensure that every possibility and implication of these technologies can be fully understood and mapped in relation to the Humber's decarbonisation, reducing the potential for regret spend and cost escalation.

1.5.3 Systems modelling

Development and utilisation of an adapted systems model that is flexible and nuanced enough to accommodate the complexities of the Humber cluster. This will provide a strong and politically neutral evidence base for roadmap delivery to give confidence and assurance to industry and other stakeholders.

1.5.4 Overcoming barriers to deployment

Pro-active identification and mitigation of potential issues through audits of supply chain and skills, engagement with supply chain, planning and regulatory bodies and development of an inward investment proposition. While it will not be possible to overcome all barriers, early identification and action through valued strategic partnerships will do much to smooth roadmap delivery.

1.6 Conclusion and recommendations

Phase 1 of the HIDR has now been successfully delivered, resulting in the timely submission of a bid to Innovate UK for Phase 2. Work undertaken in Phase 1 has informed the development of the core strategy for delivering a roadmap, including identifying the optimum governance structure and work package framework, in addition to defining the scenario baselines, technology options and modelling criteria. In addition, successful stakeholder engagement in Phase 1 has resulted in a number of industry stakeholders confirming their approval of and commitment to the roadmap strategy.

The principle recommendations from Phase 1 are identified as follows:

1. A roadmap to deeply decarbonise the Humber is needed
2. Deep decarbonisation can represent an opportunity for clean growth
3. The industrial wealth and diversity of the region suggests that a technology-agnostic analysis of potential decarbonisation pathways is preferable
4. The HIDR could explore synergies across sectors and geographies
5. Strategic co-ordination is needed to address technology readiness and deployment issues
6. Further analysis, data, and market observations will be required moving forward

Contents

2 Introduction

The LEP and membership organisation CATCH secured a contribution from the Industrial Strategy Challenge Fund (ISCF) to develop the strategy for a Humber Industrial Decarbonisation Roadmap (HIDR), establishing the pathway for the Humber industrial cluster's carbon emissions to be net zero by 2040 and significantly reduced by 2030.

The Humber cluster is concentrated around the Humber Estuary. It includes the UK's main steel production centre; two oil refineries; two major chemicals clusters; and biofuel, cement, lime and glass manufacturers. It is part of the Energy Estuary, which includes the largest offshore windfarm under construction in the world; several existing and planned gas-fired power stations; and the UK's largest biomass power station - offering the potential for blue and green hydrogen production and BECCS. The UK's largest ports complex and the UK's largest Enterprise Zone underpin the area's potential for further industrial growth.

The Humber benefits from the UK's most geologically understood site for potential CO2 storage under the North Sea; the deepest UK salt deposits, ideal for hydrogen storage, already utilised for onshore gas storage; and significant natural sequestration potential around the Humber Estuary.

The Humber emits more CO2 than any other industrial cluster (50% more than the next largest), whilst the area is highly vulnerable to climate change through flood risk. A quarter of Humber GVA and 1 in 10 jobs depend on these industries, making safeguarding their competitiveness imperative.

Clean growth, including achieving net zero by 2040, is therefore at the centre of the Humber's Local Industrial Strategy which is due for publication shortly. Developing HIDR is identified as a critical early action.

HIDR will enable large industrial emitters, low carbon infrastructure providers and other stakeholders to develop a shared approach to achieving net zero by 2040. This will break down the UK's biggest industrial decarbonisation opportunity into manageable parts, align it with wider local clean growth plans and build consensus around the actions required.

This coordinated approach will reduce the barriers to developing and connecting to low carbon infrastructure, enable the Humber to engage effectively together with Government on business and regulatory models, and maximise local business and community benefits from the transition.

The overarching aim for phase 1 was to undertake initial feasibility activity to develop the strategy for roadmap delivery. This report sets out the findings and key messages from that feasibility work.

3 Work Package 1 – Baseline Local Emissions

The UK government recently enshrined in law a UK-wide ‘net-zero’ emissions target for 2050. Achieving this target will require rapid deployment of decarbonisation technologies like low-carbon hydrogen and carbon capture and storage (CCS) in all sectors, including industry.

As the UK government’s Industrial Clusters Mission indicates, clusters have a key role to play in triggering the development of large-scale decarbonisation infrastructure, including that for producing and transporting hydrogen and CCS.

This study focuses on the following:

- Collection and presentation of relevant data about the Humber industrial cluster, including data on emissions, fuel use, ongoing decarbonisation projects, and other information which may influence the HIDR.
- Development of three ‘business-as-usual’ scenarios that assess how emissions from the cluster may evolve until 2040 if no deep decarbonisation measure is implemented, an eventuality that is thought to be representative of what may happen unless new policies or economic incentives are put forward to stimulate deeper emission cuts. These scenarios also represent baselines for the development of the HIDR.

The geographical focus of this study is on the region around the Humber estuary defined by the four local authorities of the Humber: City of Hull, East Riding, North Lincolnshire, and North East Lincolnshire. This is a region of great strategic significance to the UK industrial and power sectors, since it represents the largest industrial hub in the UK – a hub contributing 15% of the jobs and 23% of the GVA of the local economy – and also its powerhouse, hosting over 20% of the UK’s electricity generation, refineries that process a third of the UK’s fuel, and numerous gas terminals and gas storage facilities.

3.1 The Humber today

Emissions from the Humber industries were estimated to be 14.8 MtCO_2 in 2017, including:

- 10.6 MtCO_2 emitted by 30 large industrial sites, with most of the emissions arising from the refining and iron and steel sectors.
- 1.3 MtCO_2 emitted by a multitude of smaller sites.
- 3.0 MtCO_2 emitted by combined heat and power (CHP) plants to generate steam used by the Humber industries.

A further 5.0 $MtCO_2$ was emitted from 13 power generators located within the Humber geography, which brings overall emissions from power generators and industries in the Humber to just under 20 $MtCO_2$.

While this study specifically focuses on the Humber geography, synergies in the decarbonisation pathways of sites in and around the Humber may exist, as indicated by the partnerships established to deliver some of the decarbonisation projects reviewed below. Emissions from sites in the neighbouring regions were estimated to be just over 4 $MtCO_2$ for industry and 14 $MtCO_2$ for power generation (including the Drax Power Station).

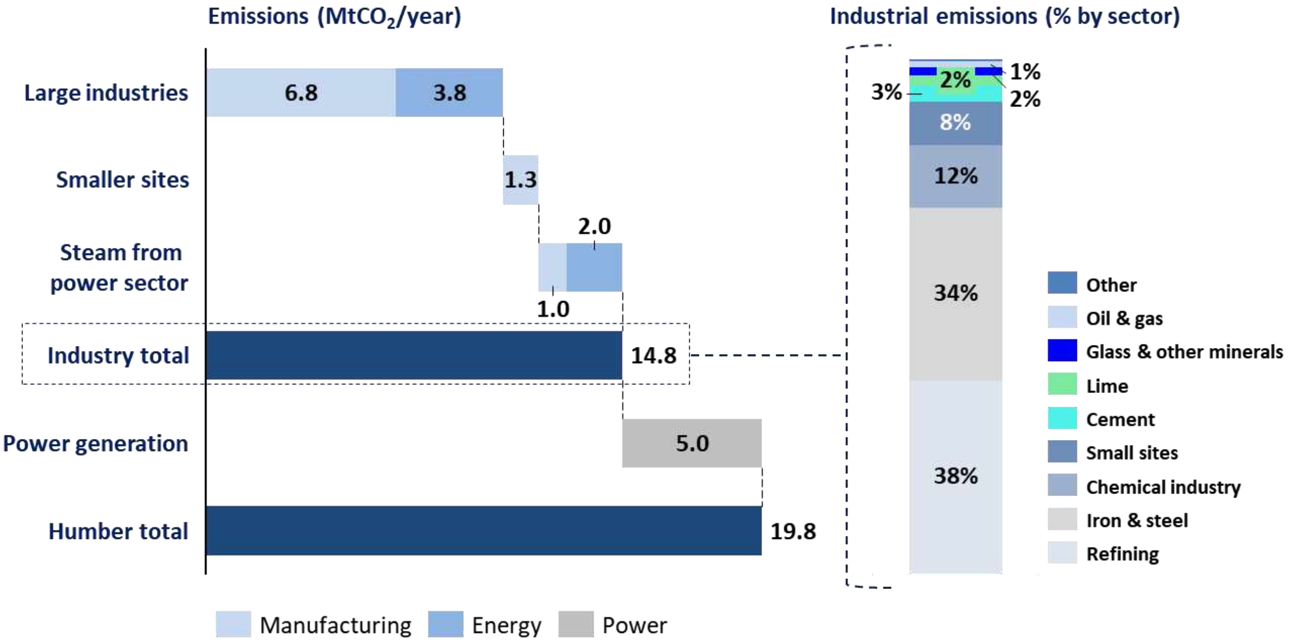

Figure 6: Emissions from the Humber industries and power generators

3.2 Source of Emissions

Two main sources of industrial emission can be defined:

- Fossil fuel combustion to supply energy (often heat) required by the industrial processes, leading to what is known as 'combustion emissions'. It was estimated that the Humber industries burn just under 50 TWh of fossil fuels every year, which is the source of 93% of all industrial emissions.
- Industrial processes that include chemical processes which emit CO_2, thus leading to 'process emissions'. It was estimated that the remaining 7% of all industrial emissions arise from processes within the cement and lime, iron and steel, and refining sub-sectors.

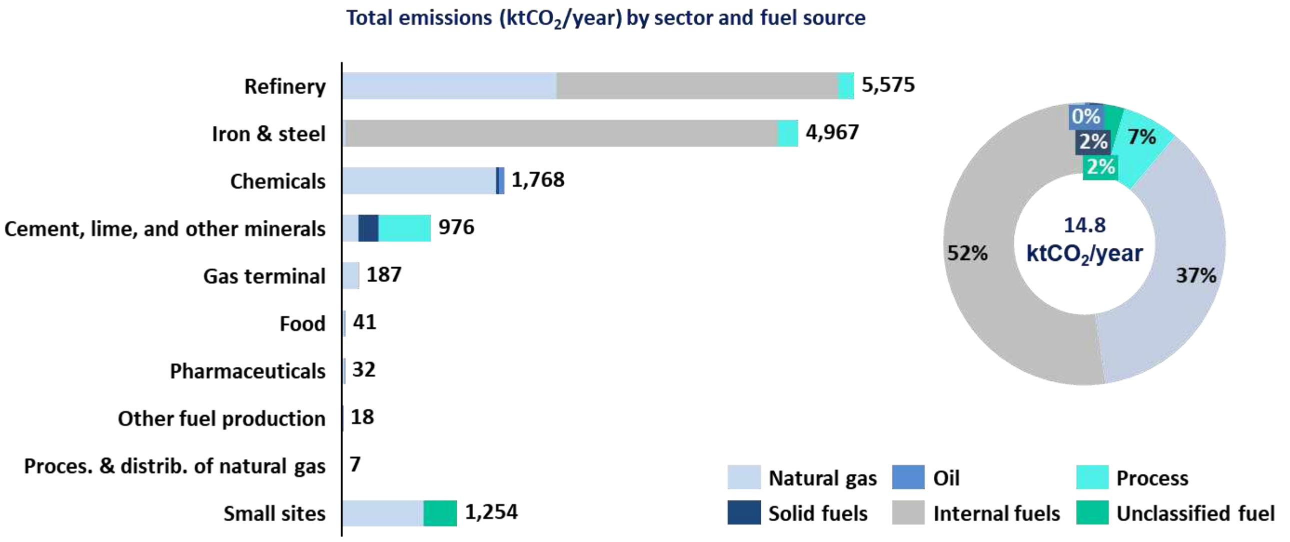

Figure 7: Breakdown of industrial emissions by source

Through more detailed analysis it was also estimated that 56% of the combustion emissions relate to *internal* fuels, which are unavoidable by-products within some of the steel manufacturing and refining processes. The remaining 44% instead originates from *purchased* fuels, most of which is natural gas.

For the purposes of the HIDR, the distinction between internal and purchased fuels is critical since emissions from internal fuels can only be abated with CCS, by changing industrial processes, or by changing products, which are the only options to abate process emissions as well. Instead, purchased fuels can also be replaced with low-carbon alternatives, i.e. via fuel switching.

3.3 Business as usual scenarios

Emissions could reduce by 2-18% under 'business-as-usual' scenarios.

Three 'business-as-usual' scenarios were evaluated in which no deployment of deep decarbonisation technologies occurs: a 'low emissions', a 'high emissions', and a 'central' scenario. Based on different sector-specific growth assumptions by UK Department for Business, Energy, and Industrial Strategy (BEIS), the scenarios are also characterised by different assumptions around the potential opening of new sites and closure of existing sited, as well as by different assumptions around the COVID-19 downturn.

Emission reductions of 2-18% between 2017 and 2040 are estimated to occur under the different 'business-as-usual' scenarios. As illustrated below, the iron and steel and refining sectors are expected to be the biggest contributors to overall emissions reductions in most scenarios, which is primarily due to their large relative size compared to other sectors.

Differences in growth rates across sectors and between different scenarios have a more limited impact on the overall reduction in emissions. Nonetheless, it is noted that the results are sensitive to the assumptions made around the economic impact of COVID-19.

Announced planned openings (e.g. the Altalto waste-to-jet-fuel plant) and closures (e.g. the Cemex cement plan) are also seen to moderately contribute to changes in emissions scenarios other than the 'central' one. Instead, the other sub-sectors give a marginal contribution to the overall change in emissions between 2017 and 2040.

These findings indicate a clear sectoral focus for the HIDR.

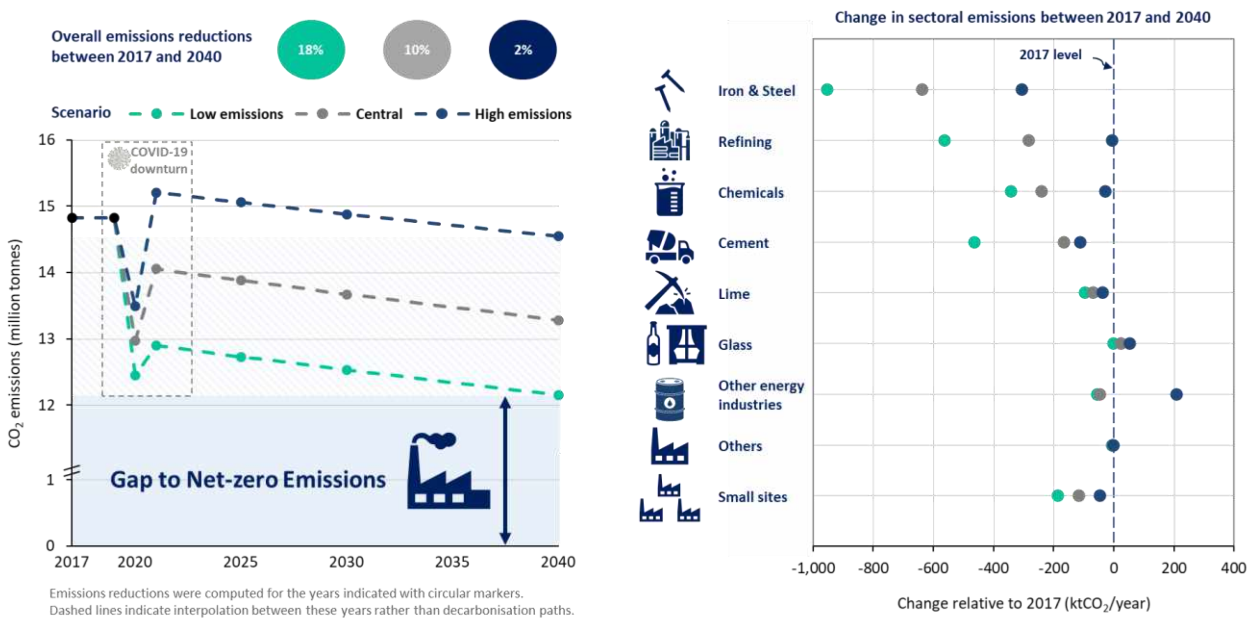

Figure 8: Overall and sector-specific emissions reductions in business-as-usual scenarios

3.4 A decarbonisation roadmap for clean growth

In conclusion, it is noted that the scenarios assessed here appear to fall short of what is required to meet the 2050 net-zero targets, unless industry decarbonises at a much faster pace between 2040 and 2050, or substantial negative-emission technologies are deployed. If all UK industries were to follow the trajectory estimated above for the Humber cluster, industrial emissions in 2040 would be 57% below 1990 levels at best, or over 75 $MtCO_2$ when assessed at the UK level. If emissions reductions continued at the same rate until 2050, emissions would reduce to 68% below 1990 levels by then. This represents a large gap that future decarbonisation projects should aim to bridge.

Considering the major contribution that the Humber cluster makes to both the UK's industrial emissions and the local economy, and in view of the existential risk faced by industries that fail to decarbonise while the world moves towards net-zero, the development of a Humber Industrial

Decarbonisation Roadmap appears necessary. By creating a shared vision for decarbonising the Humber, the HIDR could help to catalyse change among local industries. Beyond this, it could also send a signal to investors who may find the ‘net-zero cluster’ brand attractive – especially those looking to develop the industries needed in the future net-zero economy.

For these reasons it is envisioned that the development of a deep decarbonisation roadmap for the Humber industries is not only a necessity to meet climate targets, but also an opportunity to stimulate clean growth.

4 Work Package 2 – Technology Overview

The Humber has the UK's largest industrial cluster by emissions, including the UK's main steel production centre, two oil refineries, two major chemicals clusters, and biofuel, cement, lime and glass manufacturers. It also has the UK's largest ports complex and the UK's largest Enterprise Zone and is critical to the UK economy.

The complexity of the cluster offers opportunities for trial and deployment of multiple technologies but also means that it channelling resource into just one or two key technologies is unlikely to achieve decarbonisation across the cluster.

4.1 High level overview of industry in the Humber region

4.1.1 Primary industry

The Humber currently includes Cemex in South Ferriby (though closure has been announced for this site) and Singleton Birch which produces lime for use in chemical processing. These industries have both energy and process feedstock emissions.

4.1.2 Secondary industry

Secondary industries include chemicals, refining, steel, manufacturing, food/drink, pharmaceuticals and mechanical and electrical engineering.

4.1.2.1 Chemicals and fuels

The Humber is the UK's 2nd largest chemical cluster with two principle sub-clusters centred around the Saltend Chemicals Park on the north bank and around Immingham on the south bank. The Saltend site houses eight chemicals and green energy businesses while the south bank area hosts two oil refineries including the globally important Phillips66. Alongside British Steel, the region's oil refining business comprise just over 70% of its industrial emissions, amounting to just under 15 $MTCO_2$ in 2017.

CO_2 emissions, particularly from multiple high temperature fired heaters fuelled with light fuel gases extracted from crude oils, arise in numbers of places within each of the refineries. While CCS will be an important decarbonisation technology for refineries, decarbonisation through green hydrogen fuel switching will also be important, providing there is a route to use the refinery fuel gases currently used.

Biofuel manufacture is undertaken on both the north and south Humber banks. Vivergo Fuels manufactures bioethanol from wheat grain at Saltend and Greenergy manufactures biodiesel from waste vegetable oils near Immingham. Looking forward, a waste fuelled gasification plant is planned for the south bank for the production of renewable jet fuel.

Important processes in the chemical industries requiring energy include:

- Distillation – for example, to purify bioethanol following fermentation
- Steam raising
- Calcining
- Thermal cracking
- Power for motor drives e.g. for pumps
- Lighting and utilities

4.1.2.2 Steel

A significant proportion of the Humber's industrial emissions arise from British Steel in Scunthorpe which is one of two integrated steelworks in the UK. It uses the Basic Oxygen Steel process (BOS) to manufacture around 2.8 million tonnes of steel each year.

An important consideration is the fact that large concentrations of CO_2 emissions arise in only a few locations on the plant and the uses of coal and limestone as process feedstocks. These lend themselves to the use of carbon capture and storage (CCS) and capture by carbonate looping in particular.

4.1.2.3 Manufacturing, engineering, food and drink and other light processing

The Humber has a strong manufacturing, engineering and processing base, making up a significant proportion of the Humber economy. Although the combined emission of this sector are minor compared with the iron and steel and refining sectors, there will be a need for decarbonised electricity and process heat if the Humber is to achieve net zero.

4.1.3 **Potential future industries**

Looking to the future, businesses and politicians are looking to green energy investment on both banks of the “Energy Estuary” to drive growth in the region. To date, the region has especially taken advantage of opportunities created by the offshore wind industry. With new wind farms off the Humber coast planned, these industries should be expected to grow.

The introduction of low carbon energy, the widespread availability of CCS and hydrogen in the region would be expected to benefit a variety of new industries in the region. Increases in the use of wind and solar energy will drive demand for systems to manage supply and demand including green hydrogen. There is also the potential for other storage technologies including battery storage at sites in the Humber.

The availability of CCS has the potential to increase the value of bioenergy and biofuels plants, especially if there are enhanced support mechanisms for negative emissions through, for example, contracts for difference and the Road Transport Fuels Obligation (RTFO). The Humber is well suited to playing a leading role in delivering negative emissions with existing and planned biofuels sites which could potentially consider CCS.

The region is also well placed for taking advantage of biomass either via imports, indigenous local production and/or exports. Processes requiring high temperature heat can use biomass either directly as a fuel or converted into more usable forms such as gases and liquids via gasification. Large volumes of biomass pellets are already imported into the Humber region via the port of Immingham.

The availability of low and negative carbon power for data centre cooling may also attract new digital and digital infrastructure companies as well as fast vehicle recharging infrastructure to support the roll out to battery electric vehicles.

4.2 Technologies for industrial decarbonisation

The technologies that are likely to support decarbonisation in the Humber are summarised in Figure 9 below.

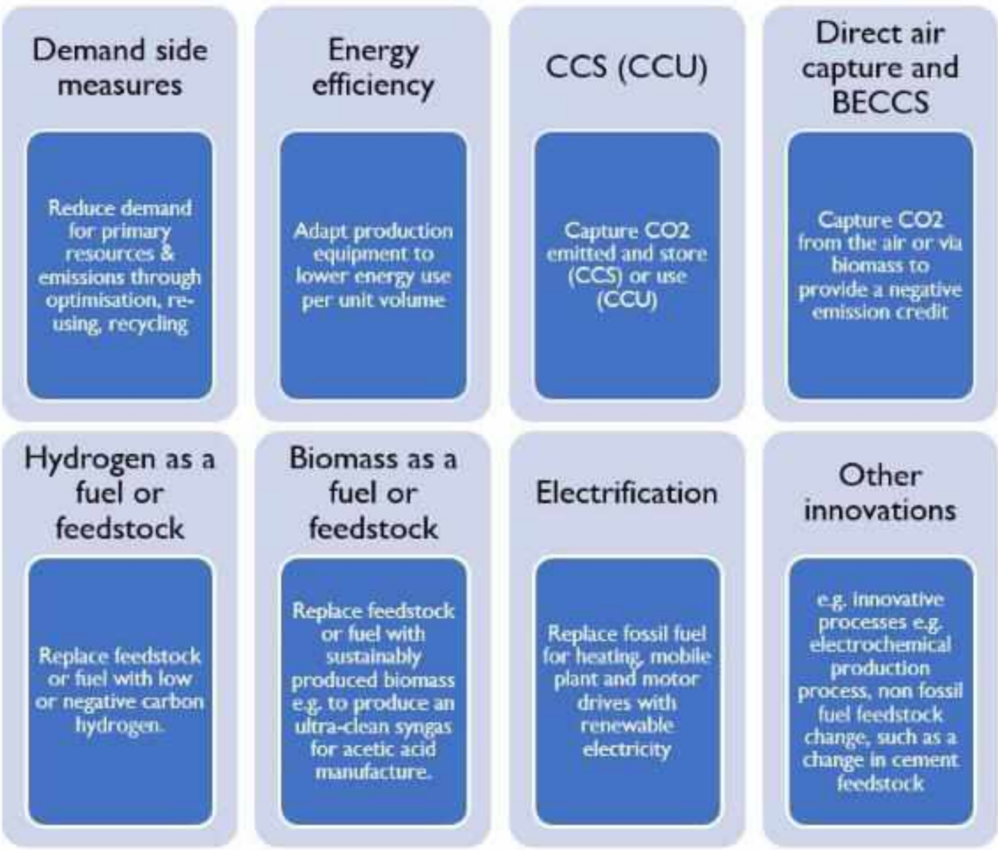

Figure 9: Technology Options Summary

4.2.1 Carbon Capture Utilisation and Storage

Carbon Capture is a technology that can capture the carbon dioxide (CO_2) emissions produced from the use of carbon bearing fuels and feedstocks in electricity generation and industrial processes. The captured CO_2 can subsequently be stored underground (Carbon Capture and Storage, CCS) which prevents the carbon dioxide from entering the atmosphere or used as a chemical feedstock to produce fuels, chemicals and materials such as cement (Carbon Capture and Utilisation, CCU).

For the deep decarbonisation targets set for the Humber cluster, CCS is preferred to the more general 'CCUS' (i.e. carbon capture, utilisation, and storage). Deep decarbonisation is only attained if there is permanent sequestration of the captured CO_2[1].

CCS technologies are already deployed and are deploying globally. Post combustion capture, based on mature amine gas separation technology, has seized the largest share of the power market and still offers opportunities for further improvements. Given the current immature status of the next generation of alternatives, amines or pre-combustion are likely to be the most investable options for the next five to ten years[2].

The application of CCS technologies to the combustion and gasification technologies described above is summarised below.

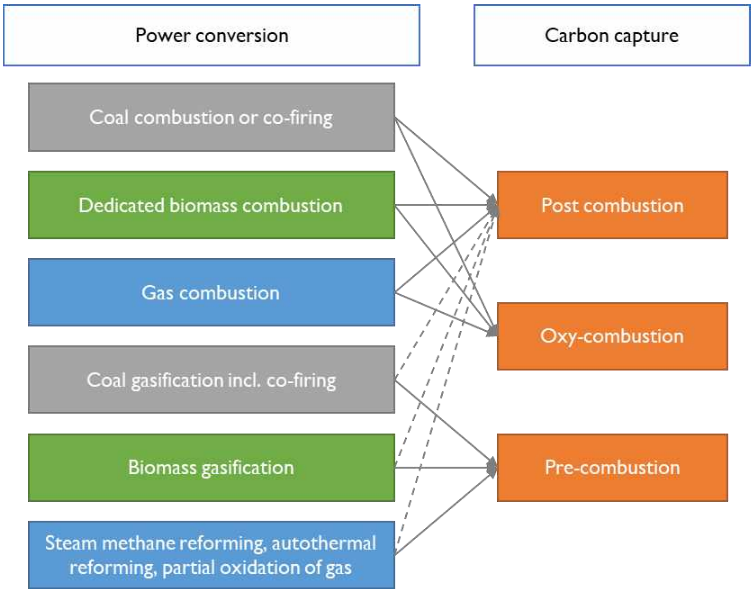

Figure 10: High level summary of combinations of power conversion and carbon capture types[3]

[1] In reading this report, the term CCS should be intended as also referring to forms of CO_2 utilisation that can ensure permanent sequestration.

[2] Gammer, D (ETI). *Reducing the cost of CCS developments in capture plant technology.* 2016. These materials are taken from a project, funded and commissioned by the ETI. Further details can be found at www.eti.co.uk.

[3] TESBIC Consortium. *Techno-Economic Study of Biomass to power with CCS; WP1 Detailed Final Report; PM01.D1.3; Biomass to Power with CCS Project.* 6 July 2011. These materials are taken from a project, funded and commissioned by the ETI. Further details can be found at www.eti.co.uk.

4.2.2 **Post-combustion**

Post-combustion carbon dioxide capture technology removes carbon dioxide from flue gases, and is applicable to any combustion process, including conventional gas, oil and coal-fired boilers, and gas turbines. It involves the addition of a chemical or other separation plant to the flue gas outlets, downstream of the current environmental control equipment.

Post-combustion capture using amines is the most mature carbon capture technology having been used for over 80 years in the process industries and is applicable to any combustion process, including conventional gas, oil and coal-fired boilers, and gas turbines.

One of the key issues with post combustion capture systems is that non carbon dioxide components in the flue gas including oxygen and the residual NOx and SOx in the flue gases can react and affect the capture unit. For example, in amine processes, these components can affect the solvent at the temperatures that apply in the scrubbing unit to form a range of degradation products and stable, non-regenerable salts. Post-combustion carbon dioxide capture systems therefore require high efficiency upstream purification systems such as particulate collection, NOx reduction and flue gas desulphurisation prior to entry to the carbon dioxide capture system.

A variety of post combustion capture techniques are available and in development:

- Conventional solvent scrubbing
- Low-temperature solid sorbents
- Ionic liquids
- Post combustion enzymes
- Membrane separation of carbon dioxide from flue gas
- High-temperature solid sorbents, e.g. carbonate looping

4.2.3 **Oxy-combustion**

Oxy-combustion involves the combustion of a fuel in a mixture of oxygen and recycled flue gas, rather than air, to produce a flue gas which comprises mainly CO_2 and water, rather than nitrogen and CO_2.

The carbon dioxide concentration in the flue gas from an oxy-combustion firing system is, therefore, significantly higher than in the flue gas from an air firing system, and hence the carbon dioxide can be cleaned, compressed and stored with significantly less downstream processing than would be necessary with air firing. The major disadvantage is the additional auxiliary power requirement of operating the Air Separation Unit (ASU) to produce the oxygen, and the CO_2 Purification Unit (CPU).

Oxy-combustion technology options include:

- Oxy-fuel boiler with cryogenic oxygen separation from air:
- Ion-exchange membrane separation of oxygen from air
- Oxy-combustion: Chemical-looping-combustion using solid oxygen carriers
- Allam Cycle

4.2.4 Pre-combustion

Pre-combustion CCS extracts the carbon dioxide from the fuel before combustion takes place. Technology options include:

- Pre-combustion: Integrated Gasification Combined Cycle (IGCC) with solvent absorption
- Pre-combustion: Membrane separation of hydrogen from syngas
- Pre-combustion: Sorbent enhanced reforming using carbonate looping

4.2.5 Carbon dioxide storage

Once captured, the CO_2 must be transported and either used or stored. Storage permanently sequestrates CO_2 underground and provides a lower risk option against later release compared to utilisation. The southern North Sea is one of the areas identified as having potential for storage.[4]

The two main categories of store are saline aquifers and depleted oil and gas reservoirs.

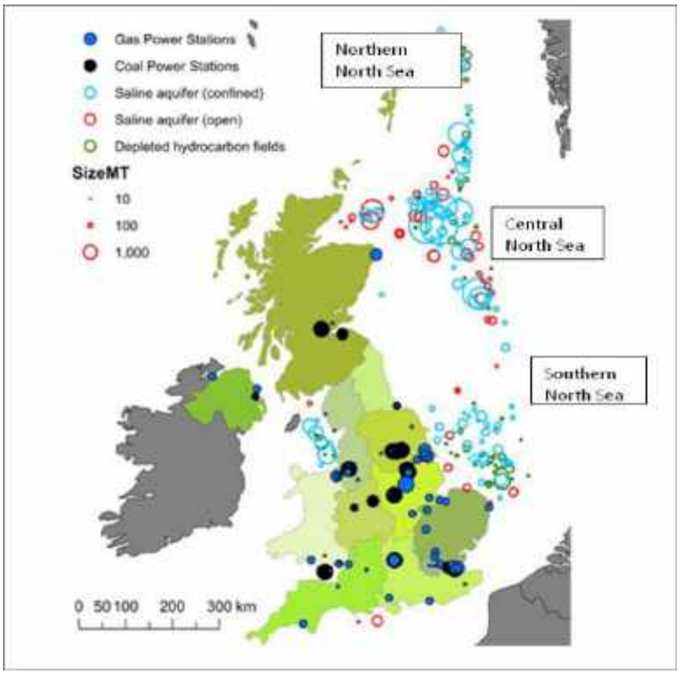

Figure 11: Distribution of potential CO_2 storage in UK[5]

[4] Gammer, G (ETI). *A picture of CO2 storage in the UK - learnings from ETI's UKSAP and derived projects.* 2013. These materials are taken from a project, funded and commissioned by the ETI. Further details can be found at www.eti.co.uk.
[5] Ibid

4.2.6 Carbon capture with utilisation

Instead of storing captured CO_2 underground, it could potentially be re-used in the following processing sectors:

- Food – particularly in carbonated drinks
- Mineralisation
- Fertiliser
- Conversion to liquid fuels
- Process blanket gas

Alone, CCUS will not sequestrate the CO_2 and provide the deep decarbonisation of industry required for a net zero target, but could make a small contribution to the wider decarbonisation agenda and warrants further investigation.

4.3 CCUS variants

4.3.1 Biomass Energy Carbon Capture and Storage (BECCS)

BECCS has the potential to provide negative emissions which are needed to meet net zero since it will be almost impossible to eliminate all emissions sources. This ability to deliver negative emissions makes biomass unique as a renewable energy source.

BECCS uses the same technologies as described above to deliver a purified CO_2 stream ready for storage or utilisation. For biomass, however, the gasification technology needed for pre-combustion capture is not yet commercial with only a few projects at the TRL 7 level (demonstration plant built but not yet proven).

A key challenge is scale of operation since the economies of scale required for CO_2 pipelines are very high.

4.3.2 Direct Air Carbon Capture with Storage (DACCS)

The Energy Systems Catapult's latest report highlighting two scenarios to meeting the UK's 2050 decarbonisation target (net zero) indicates that with existing technologies, only about 90-96% decarbonisation will be achievable[6]. Beyond that, improvements to existing technologies and new technologies not yet deployed will be needed. One of these is Direct Air Capture with Storage (DACCS).

The concept of DACCS is shown below. Conceptually, DACCS can be partnered with a power to fuel plant such that emissions not capturable by a fuels plant are captured from the air at the same or at a second, separate site.

[6] Energy Systems Catapult. *Innovating to Net Zero.* 2020. © Energy Systems Catapult 2020. All rights reserved.

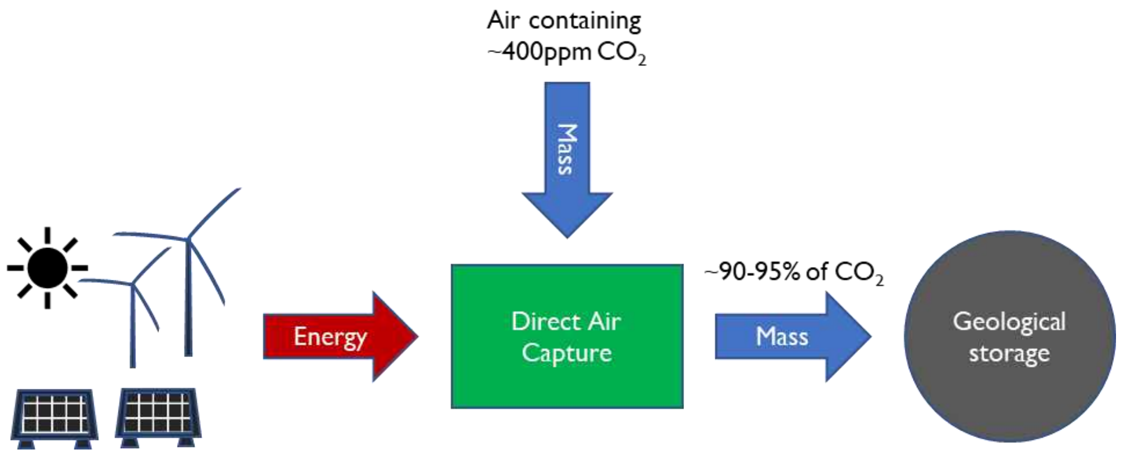

Figure 12: DACCS concept[7]

DACCS is currently at the demonstration stage, with a small number of pilot scale test facilities in operation globally.[8]

4.4 Biomass / bioenergy / biofuels

Biomass is a varied resource which can deliver fuels for transportation, heat for industry, electricity, materials and chemicals. Combined with CCS it is the only renewable resource that can deliver negative emissions which will be needed to meet net zero[9].

However, biomass is a limited resource with varying degrees of quality, not only in terms of utilisation but also in terms of its decarbonisation potential[10]. ETI estimated that biomass has the potential to deliver around 10% of the UK's future energy demand.

There are a variety of biomasses available to use in the UK setting for energy and products. These include:

- Sugar crops
- Starch crops
- Oil crops
- Forestry products
- Energy crops
- Agricultural residues

[7] *Closing the carbon cycle to maximise climate change mitigation: power-to-methanol vspower-to-direct air capture.* H. A. Daggash, C. F. Patzschke, C. F. Heuberger, L. Zhu, K. Hellgardt, P. S. Fennell, A. N. Bhave, A. Bardow and N. Mac Dowell. s.l. : Royal Society of Chemistry , 2018, Sustainable Energy Fuels.
[8] CCC. *Net Zero The UK's contribution to stopping global warming.* May 2019. CCC copyright. https://www.theccc.org.uk/copyright-terms-conditions/.
[9] Ibid
[10] Newton-Cross, G and Evans, H (ETI). *Delivering greenhouse gas emission savings through UK bioenergy value chains.* Bioenergy. 2015. These materials are taken from a project, funded and commissioned by the ETI. Further details can be found at www.eti.co.uk.

- Wastes derived from Municipal Solid Wastes (MSW), Commercial and Industrial wastes (C&I), waste wood, sewage sludges.

For industry therefore, biomass could be viewed as both an energy resource in which, for example, wood pellets are combusted in a boiler to provide steam for process heat and/or power, and as a chemical feedstock, for example to produce low carbon acetic acid.

4.5 Hydrogen for fuel switching

CCUS allows industry to address chemical feedstock emissions and to continue using carbon-based fuels (including biomass). An alternative option, unless the fuel used is a by-product of the feedstock as in refining, is to instead use hydrogen to provide heat and power. Using hydrogen at an industrial site will eliminate CO_2 emissions and so avoid the need to connect the site up to a CCS transport network. However, the site will need to be connected to a hydrogen distribution network.

"Clean" hydrogen can be produced in the following ways:

- Green hydrogen
  - Via electrolysis of water using renewable electricity
  - From biomass with and without CCS
- Blue hydrogen
  - From natural gas with CCS
  - From coal with CCS

4.6 Process electrification

In addition to taking advantage of processes specially designed for using electricity (e.g. electrolysis), there is also the possibility to replace gas and steam fired heaters, motors, on site transportation and potentially mobile plant with electrically powered alternatives[11]. Use of electricity has potential to decarbonise and to increase production efficiencies.

[11] CCC. *Net Zero The UK's contribution to stopping global warming.* May 2019. CCC copyright. https://www.theccc.org.uk/copyright-terms-conditions/.

4.7 Relative costs of industrial decarbonisation options

Research and modelling by ETI[12] suggests that energy system decarbonisation will start in the power sector before tackling the more difficult and expensive sectors such as freight transport and aviation. The industrial sector has often been classed as "hard to treat" but new routes to decarbonising the sector have been identified that would lead to emissions of 10 million tonnes CO_2/year in 2050 at an average abatement cost of around £120/tonneCO_2e[13]

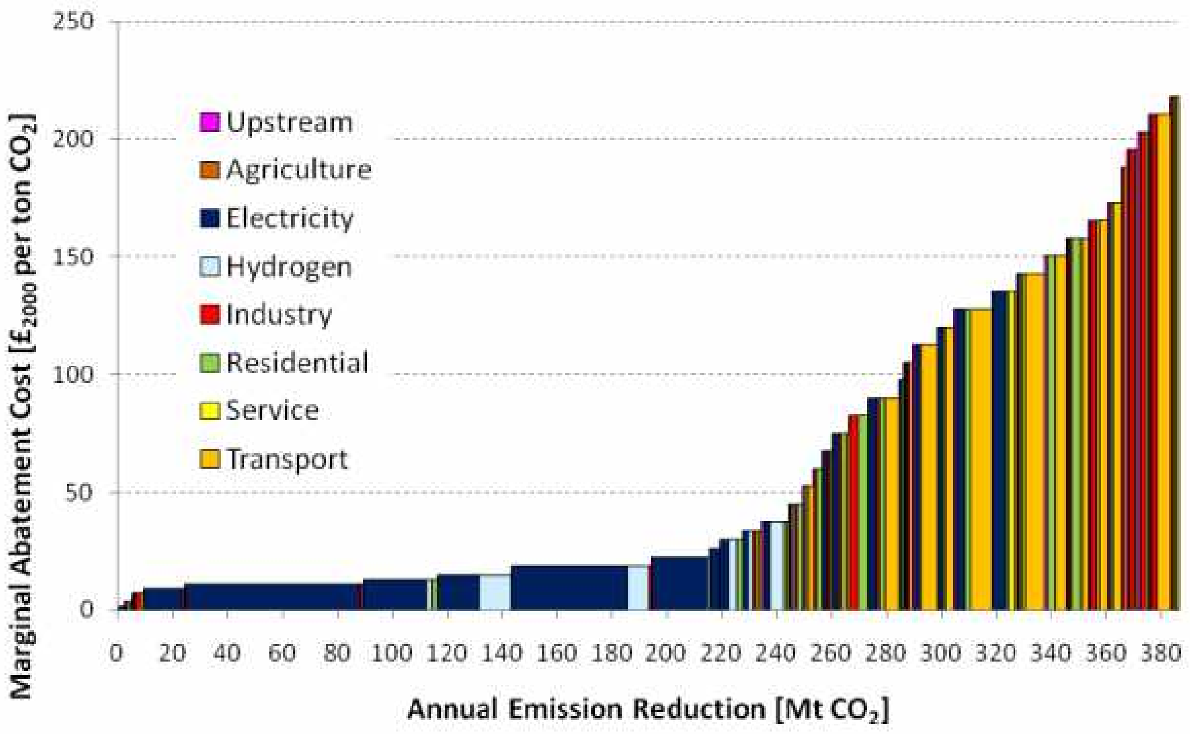

Figure 13: Marginal Abatement Cost Curve for the UK Energy Sector in 2030 (low fossil fuel production costs)

Energy-efficiency improvements have the potential to reduce CO_2 emissions by 15 to 20 percent and can be cost effective in the long run. This is a good starting point but is insufficient to achieve the greenhouse gas reductions that are needed. Additionally, energy-efficiency improvement options can be very site specific.

Below, costs of CCS, low carbon electricity for electrification, biomass, BECCS, DACCS and hydrogen are outlined. A wide range of assumptions in the design of decarbonisation technologies, how heat is integrated with a manufacturing plant, and how energy or steam sources are considered are apparent in the literature.

ETI estimated the costs of a gas fuelled power station with CCS, consisting or four Combined Cycle Gas Turbine trains with a capacity of 3 GWe, at approximately £5.05 billion (2017). Total

[12] Energy Technologies Institute (ETI). *Options Choices Actions - UK scenarios for a low carbon energy system.* 2015. These materials are taken from a project, funded and commissioned by the ETI. Further details can be found at www.eti.co.uk.
[13] CCC. *Net Zero The UK's contribution to stopping global warming.* May 2019. CCC copyright. https://www.theccc.org.uk/copyright-terms-conditions/.

calculated operational costs varied year on year ranging from £237.42 million/year in year 1 to £265.56/year in year 6.[14]

CCC shows that low carbon electricity can be provided at average costs of between £47 and £98/MWh in 2025, reducing to between £41 and £79/MWh in 2050[15].

As for CCS, biomass costs on a project by project investment basis can be high, but, on a total system basis are competitive. McKinsey report that using biomass as a fuel or feedstock is financially more attractive than electrification of heat or the use of hydrogen in cement production, and in steel production at electricity prices above about $20/MWh/£15/MWh[16].

Hydrogen can be produced (Levelised Cost of Hydrogen) for around £33/MWh$_{H2\ LHV}$ with an LHV efficiency of 76%.[17]

4.8 Technology Readiness

TRL is a tool used for estimating the maturity of technologies (Figure 14, below). At TRL 1-5, progress is usually academia led – from 6-9, industry typically leads. Any technology that is commercially available will be TRL9. A technology for which there is a demonstrator but which has yet to be fully tested would be TRL7.

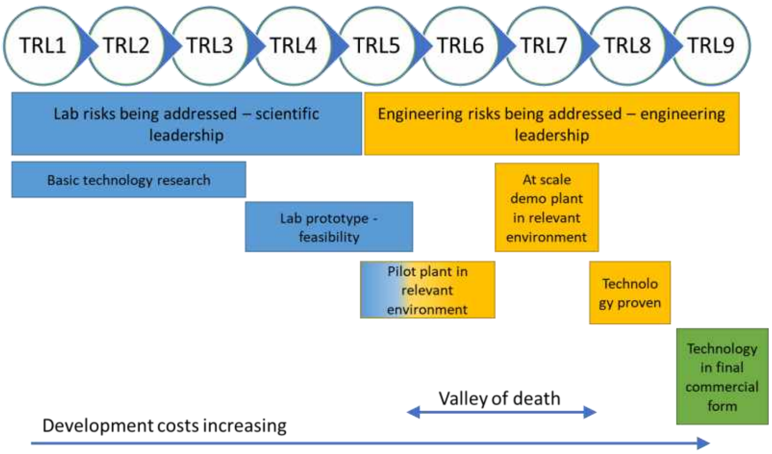

Figure 14: Technology Readiness Levels

[14] *Thermal Power with CCS Final Report Doc Number: 181869-0001-T-EM-REP-AAA-00-00006 Revision A05.* SNC Lavalin, Aecom, University of Sheffield. s.l. : Energy Technologies Institute, 22 August 2017.
[15] CCC. *Net Zero The UK's contribution to stopping global warming.* May 2019. CCC copyright. https://www.theccc.org.uk/copyright-terms-conditions/.
[16] *Decarbonization of industrial sectors: the next frontier.* McKinsey & Company. June 2018.
[17] International Energy Agency. *IEAGHG Technical Report 2017-02.* 2017.

4.8.1 Carbon capture and storage (CCS)

CCS uses a combination of proven technologies combined into new value chains but the high capital cost means technology risks have to be carefully managed. Below is a summary of the technology readiness levels of a range of carbon capture technologies.

Table 1: Estimated carbon capture technologies' technology readiness levels[18]

Capture technology	2011 TRL	Estimated 2020 TRL	Key technical issues	UK deployment potential
Amine scrubbing	6-7	8-9	Scale-up, amine degradation, potential losses to environment	Immediate capture retrofit opportunities, long-term doubtful
Dedicated biomass with amine scrubbing	4	6	Scale-up, amine degradation, potential losses to environment	Numerous capture retrofit opportunities, high long-term potential
Carbonate looping	4-5	5-6	Calciner firing, degradation, large purge of CaO	Immediate capture retrofit opportunities, cement integration
Oxy-fuel with cryogenic or membrane O_2 separation technologies	6	7	Corrosion, O_2 energy costs, slow response	Near-term retrofit opportunities
Dedicated biomass oxy-fuel with cryogenic or membrane O_2	5	6	Corrosion, O_2 energy costs, slow response	Numerous capture retrofit opportunities, long-term potential

[18] TESBIC Consortium. *Techno-Economic Study of Biomass to power with CCS; WP1 Detailed Final Report; PM01.D1.3; Biomass to Power with CCS Project.* 6 July 2011. These materials are taken from a project, funded and commissioned by the ETI. Further details can be found at www.eti.co.uk.

separation technologies				
Dedicated biomass chemical looping	4	5	Loss in activity, reaction rates, dual bed operation	Likely first demos in Europe. Good long term potential
IGCC[19] with solvent absorption	5-6	7	Complex operation, slow response, retrofit unattractive	No current UK plants
Dedicated biomass BIGCC[20] with solvent	4	5	Complex operation, slow response, tar cleaning, retrofit unattractive	No current UK plants, demo unlikely by 2020. High long-term potential

CCS has been highlighted as one of the most important decarbonisation options available to industry. However, key barriers limit its potential for rapid deployment:

- Lack of operating framework for owners and operators.
- High capital costs.
- Interfacial risks between capture, transport and storage elements.
- Technology risks.
- Geographical limits between emitters and availability of CO_2 transport networks.

Additional work has been undertaken to estimate the TRL of other key technologies with results as follows:

Table 2: Estimated technology readiness levels for additional technologies

Technology	Estimated TRL	Note
BECCS	6	Estimated for the BECCS pilot plant at Drax
DACCS	8	Direct air capture with utilisation of captured CO_2.
Bioenergy / biomass	6-7	Only a few projects delivered in the UK
Green hydrogen	7-9	
Blue hydrogen	9	
Electrification	5-9	

[19] Integrated Gasification Combined Cycle
[20] Biomass Integrated Gasification Combined Cycle

Understanding how best to cost, deploy and phase these technologies in the Humber industrial sector to achieve net zero by 2040 is a complex task which will involve large quantities of data and a high level of sensitivity testing to fully understand dependencies. This can only functionally be achieved through systems modelling to allow the true complexity of the industrial energy system to be reflected.

5 Work Package 3 – Scenario development

Multiple industry and power sector stakeholders have already been developing plans for deep decarbonisation, and several projects involving some of the largest emitters in the wider region are currently in development.

These projects broadly support the vision of establishing in Humber the first net-zero industrial cluster by 2040, and seek to deliver substantial emissions abatement via fuel switching to hydrogen (green or blue) and CCS and could set the foundations for a net-zero industrial cluster, by installing key infrastructure and providing knowledge to others both within the Humber cluster as well as within the UK and beyond.

5.1 Potential Decarbonisation Activity

Reviewed projects include the two ISCF-supported deployment projects known as ‘Humber Industrial Decarbonisation Deployment Project’ (Humber-DP) and ‘Green Hydrogen for the Humber’, as well as related projects ‘Gigastack’, ‘Humber Zero’, and ‘Zero Carbon Humber’. These projects investigate multiple ways to deeply decarbonise industry, including:

- Green hydrogen, which could be produced via the electrolysis of water (or ‘water splitting’) powered with electricity from nearby offshore wind farms.
- Blue hydrogen, which could be produced in natural gas reformers equipped with carbon capture.
- CCS, also in combination with bioenergy (BECCS) to achieve negative emissions, applied to both industrial processes and to CHP plants.

Although these projects are at an early development stage, they aim to deploy substantial decarbonisation infrastructure by the mid-2020s, which could potentially generate the necessary momentum to transform the Humber into the first net-zero cluster by 2040. On this basis there is a strong rationale for embedding them at the centre of strategy development.

Table 3: Major decarbonisation projects in the wider Humber area

	Green hydrogen	Blue hydrogen, CCS, BECCS
Projects	Gigastack Green Hydrogen for the Humber	Humber Industrial Decarbonisation Deployment Project (Humber-DP) Humber Zero Zero Carbon Humber
Infrastructure	Multiple 100 MW electrolysers powered by offshore wind at the Phillips 66 refinery and other sites in Immingham. A 'Gigafactory' near Sheffield to manufacture up to 1 GW/year of electrolysers by 2025.	Large-scale CCS network including BECCS at the Drax Power Station and CCS at the VPI Immingham CHP plant and Humber refinery. Hydrogen production hubs near the Drax site and in Immingham. Aims to develop initial infrastructure by themid-2020s.
Stakeholders	ITM Power; Ørsted; Phillips 66.	Associated British Ports; Centrica Storage; Drax Group; Equinor; National Grid Ventures; Phillips 66; PX Group; SSE Thermal; Saltend Cogeneration Company; VPI-Immingham; Uniper.
Timeline	*Gigastack*: FEED study since Feb '2020 *GHFH*: feasibility study since Apr '2020	*Humber-DP*: feasibility study since Apr '2020 Other projects: unknown.

5.1.1 Green Hydrogen for the Humber

Building on their Gigastack2 project in which they are developing new electrolyser manufacturing infrastructure, prototyping a 5MW electrolyser stack and developing a major FEED study for a 20 MW+ deployment for Phillips 66's Humber Refinery with Orsted, Phillips 66 and Element Energy, ITM Power as lead is moving forwards with this follow on project to demonstrate the feasibility of large scale renewable hydrogen deployment in Humberside industry leading to the bulk delivery of renewable hydrogen at the Gigawatt scale[21]. This project will use Gigastack as an anchor and expand the supply of renewable hydrogen to other local users. Thus, renewable hydrogen will be increasingly used as a new fuel supply for these customers, using electrolysers deployed in incremental modules of increasing size towards 2030.

The project consortium anticipates that the first 20 MW+ electrolyser will be commissioned by 2023. A successful Phase 2 ISCF application will fund the first modular installation in the period between Q2 2021 and 2023[22].

The project has been awarded financial support by the UK Government's Industrial Strategy Challenge Fund (ISCF) competition 'Decarbonisation of Industrial Clusters' managed by Innovate UK. The project could be eligible for a share of the £131 million funding support available to Phase 2 projects that will proceed with the implementation of significant decarbonisation measures.

5.1.2 Humber Industrial Decarbonisation Deployment Project (Humber-DP)

Like the Green Hydrogen for the Humber project, the Humber-DP project was also awarded financial support by Innovate UK[23] to pursue their phase 1 feasibility study, and likewise aims to access the support available to progress phase 2.

The Humber-DP project is led by Equinor and consists of stakeholders from industry and the power generation sector: Associated British Ports; Centrica Storage; Drax Group; National Grid Ventures; Phillips 66; PX Group; SSE Thermal; Saltend Cogeneration Company (Triton Power); VPI Immingham; Uniper. Prior to the project winning Innovate UK support, subsets of the same stakeholders had already entered partnerships to develop other deep decarbonisation projects 'Zero Carbon Humber' and 'Humber Zero'.

The Humber Industrial Decarbonisation Deployment Project ('Humber-DP') was set up to develop the most appropriate, timeliest, cost effective and efficient route to maximise emission reductions in the Humber industrial sector and to develop a world leading industrial CO2 transport and storage system. Three groups were set the task to develop business cases around potential "anchor" projects.

The three anchor projects are:

- H2H (Hydrogen to Humber) Saltend – development of blue hydrogen production and CCS at Saltend Chemicals (selected to progress to Phase 2 through the ISCF route.

[21] Hydrogen project: Ørsted, ITM Power and Element Energy won funding from the UK Government. *Sea Wanderer.* [Online] January 2020. [Cited: 30 June 2020.] https://seawanderer.org/hydrogen-project-orsted-itm-power-and-element-energy-won-funding-from-the-uk-government.
[22] (ITM), J McMaster. *Gigastack2 (presentation - private communiication to HIDR team).* 21 May 2020.
[23] January 2020

- Humber zero
- Zero carbon Humber

5.1.2.1 H2H Saltend

The project initially aims, to build a 600MW autothermal reformer with CCS to produce blue hydrogen from natural gas for use by energy users at Saltend and including the Triton power CHP plant which will switch to a fuel consisting of 30% hydrogen/70% natural gas.

Estimates suggest that this will reduce emissions from the Saltend Chemicals Park by almost 900,000 tonnes CO2 per year.

5.1.2.2 Humber Zero (refining sector)

The project focusses on the Humber’s two refineries and two power generators operated by VPI and Uniper near Immingham offering the key opportunity for decarbonising the region’s refining capacity.

Humber Zero is projecting the availability of green hydrogen at the refineries from 2024 onwards and CO2 exports, depending on the availability of an export infrastructure, from 2026 onwards.[24]

5.1.2.3 Zero Carbon Humber

Zero Carbon Humber aims to explore the potential to scale up the BECCS pilot project already in operation to create negative emissions at the site in the 2020s and also to examine the potential to develop large scale hydrogen production at the Drax site within the same decade. With four of the six generating units at Drax converted to biomass, this could lead to the last units being converted to hydrogen.

5.1.3 **British Steel**

British Steel operating from a single site in Scunthorpe is responsible for 34% of the Humber’s industrial emissions. It manufactures 2.8 million tonnes of steel per year via their Basic Oxygen Steel making process, employs circa 5000 and has an annual turnover of around £1.5billion.

As there will be increasing costs of carbon, the ongoing viability of the site depends on an urgent need to address mitigation options. Significant data has been compiled already and the business was an original member of the EU Horizon 2020 project for Carbon Capture and Storage. A range of mitigation opportunities are being explored.

[24] 14. VPI and Uniper. *Humber Zero (presentation - private communication to HIDR team).* 1 June 2020.

5.2 Key considerations for scenario development

There are already a number of decarbonisation initiatives and projects in the Humber, each consisting of multiple stakeholders with some stakeholders working within more than one scheme. This adds complexity to stakeholder mapping and also means that the majority of the main emitters (including the top two emitting sectors - refining and iron and steel) are involved in at least one decarbonisation initiative. This means that there is a clear advantage to capitalising on existing or planned knowledge, data and infrastructure to provide the parameters for the scenarios roadmap scenarios.

CCS and hydrogen (both green and blue) are the cornerstone technology options spanning the extent of the Humber and principle emitters. It is believed that green hydrogen ex electrolysis can be delivered in advance of CCS, although the timescales presented by all extant projects are relatively short, with a number of decarbonisation schemes hoped to be operational from around 2023 onwards. The CCS schemes presented, however, have a dependency on the timely delivery of an appropriate CO_2 transport and storage infrastructure and therefore it is imperative that this is integral to roadmap scenarios.

In a net zero scenario, CO_2 capture efficiencies may become important and will need to be further investigated. However, out of the initiatives and projects reviewed, only Drax can provide negative emissions via BECCS which will be critical to delivering net zero in the Humber. BECCS will be critical to meeting any net zero target, as it will be impossible to avoid all sources of anthropogenic CO_2 emissions – the negative emissions BECCS can provide will be necessary to offset these unabated emissions.

BECCS requires access to a CCS T&S network and so the temporal relationship between Drax and a T&S network will need to be defined. Further potential for negative emissions, including application to biofuels facilities at Saltend and near Immingham on the South Bank of the Humber, will also need to be investigated.

Given the need to prioritise decarbonising the refining, iron & steel and chemicals sectors, uncertainties around the deployments of CCS alongside green and blue hydrogen for fuel switching need to be far better understood. Further, it is highly likely that achieving negative emissions will be necessary to offset the anthropogenic CO_2 emissions from these sectors which are impossible to abate.

There is still a need to fully understand the impact of not or only partially addressing emissions from the refining and iron & steel sectors. Only British Steel has so far shown an interest in CCU, but has concluded that it has limited deep decarbonisation potential. Different drivers are affecting different decarbonisation choices for industry compared to the refining and chemicals sectors.

6 Work Package 4 – Systems Modelling

This section considers the methodological scope, outline approach and development costs for systems modelling in Phase 2 that will demonstrate the most effective way of delivering a net zero industrial cluster by 2040.

6.1 Appraisal of Analytical Approaches

An appraisal of a range of analytical approaches was carried out including qualitative, quantitative, semi-quantitative methods and systems modelling. Associated examples and application to the Humber Industrial Cluster were also explored. The appraisal concluded with a recommendation of prescriptive analytics modelling approach for Phase 2. Figure 10 below illustrates the potential of different analytical approaches.

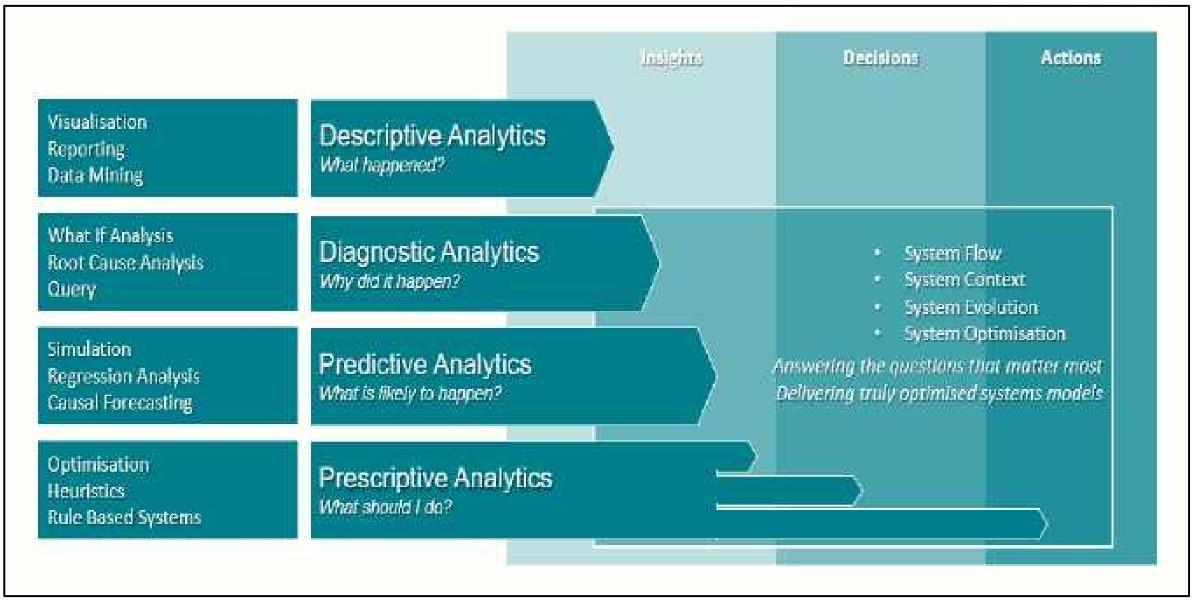

Figure 15: Analytical approaches

A prescriptive analytics approach will allow the Roadmap team to ask questions about ‘what should happen’ in the future, taking into account interdependencies, possible uncertainties and step changes in technology which may occur. These will be modelled using constraint-based scenario analysis and sensitivity analysis. This will facilitate the development of an optimal roadmap to net zero with no regrets / least regrets visibility, as well as providing visibility of critical technology and infrastructure lead times and potential enablers or blockers.

6.1.1 **Systems Modelling**

Systems modelling is required to analyse and explore the behaviour of complex systems which have significant interdependencies and uncertainties. Systems modelling is made more widely accessible through advances in prescriptive analytics and cloud computing over the last decade. There are four main aspects to systems modelling:

- **System Context:** The end to end value chain, or the interconnected elements of a system are defined by more than just the physical entities owned and operated by the client and/or third parties. A system model must reflect this end to end value chain and the business context in which those physical assets operate.

  In the context of the Humber Industrial Cluster, the end to end value chain runs from energy source through power producers, energy conversion, carbon capture and storage to power and heat provision to industries and industrial processing resulting in carbon and greenhouse gas emissions. However, this is not linear. It has many interconnections and feedback loops.

- **System Flow:** System flow parameters such as material, energy and capital can be represented either in a physical asset model or end to end value chain. It is important to capture data at points of change, connectivity and where any constraints may exist. This will enable representation of the flow through the system to be modelled.

  Within the context of the Humber, flow may for example represent physical flow of gas, hydrogen, biomass, carbon dioxide or electricity. Similarly, flows of capital, Gross Value Added (GVA) or employment levels (jobs) throughout the cluster could also be modelled.

- **System Evolution:** By their nature, most systems are dynamic and changing, as are the entities which make up the system and the context in which the system operates.

  As previously discussed, the Humber cluster is subject to evolution in terms of dynamic growth, new industry entrants and technology and infrastructure development within the region which may be generated through decarbonisation.

- **System Optimisation:** A system cannot be truly optimised through siloed optimisation of its sub-systems. Any optimisation at a whole system level may mean that some sub-systems are run sub-optimally from the perspective of the sub-system.

  In the Humber context, this means that true optimisation – that is the optimal path for decarbonisation and deployment of enabling infrastructure and technology, can only be achieved from the perspective of the regional industrial cluster. This will consider the interdependencies of industry sectors and companies.

6.1.2 Outcomes of recommended approach

Adopting this recommended modelling approach will:

- Inform the optimal direction of the decarbonisation pathway, with no regrets / least regrets visibility.
    - Including system interdependencies and uncertainties.
    - Enabling engagement with key decision and policy makers to drive technology pathways.
    - Facilitate engagement with technology developers, industry groups and academic / research institutions.
- Enable the management of future risks and uncertainties.
    - Decrease uncertainties through scenario and sensitivity analysis. This will increase conscious awareness of where uncertainty lies and the sensitivities relating to it.
    - Provide the ability to dynamically engage with the roadmap model. That is, the legacy ability to actively re-engage with the model and re-run scenarios as and when new data or information comes to light.
- Enable the modelling of different objective functions and scenarios, for example:
    - Time frame: the impact of time delay or bringing forward of the target date.
    - Cost: minimisation of cost.
    - Carbon level: Net Zero at 2040; Net Zero at 2045; Net Zero at 2050.
    - Maximise economic impact: regional employment levels (jobs) or GVA.
    - Lowest deliverability risk.
    - Other government or policy perspectives – some of which might be constraints to the model scenarios rather than objective functions in and of themselves.

6.2 Analytical Model Overview

The complexity of the Humber cluster means a complex industrial system including significant interdependencies and uncertainties. This can best be understood and analysed by a quantitative, prescriptive analytics approach to modelling which will need to combine constraint-based optimisation, scenario, sensitivity analysis and systems modelling.

A mass balance model is recommended, as this will ensure that the flow of material, and associated resource, energy demand, economic impact and emissions produced is driven by forecast demand for products or services, which creates a pull-effect through the value-chain.

6.2.1 Core model

A framework for a core model is defined with optional 'add-ons' for increased nuance. It is agreed that the core model should cover the core industrial sectors, as well as (Drax, which lies close to the boundary of the Humber and is closely affiliated with Humber industry) and refining.

Adopting this recommended core modelling approach will:

- Inform the optimal direction of the decarbonisation pathway, including system interdependencies and uncertainties.
- Enable the management of future risks and uncertainties.
- Enable the modelling of different objective functions and scenarios, e.g. time frame, cost, carbon level, etc.

6.2.2 Potential extensions

In recognition that the Humber region is intrinsically connected to other regions, clusters and national networks. Significant additional value could be obtained through extending the model in a number of areas, such as:

- **Power generators outside the Humber:** Inclusion of power generators outside of the Humber, e.g. to the south to determine whether additional value could be gained by using the CCS infrastructure to also capture emissions from power stations outside the Humber region.
- **Other decarbonisation projects and stakeholders:** Bringing in additional stakeholder interdependencies to explore any improvements to cost benefit, timeline and phasing of technology and infrastructure implementation as well as no regrets and least regrets decisions. There are possible links with:
  - Exporting of hydrogen to support the South Yorkshire region's hydrogen economy development.

- Integration with regional and national gas hydrogen transition pathways, to support the national decarbonisation of heat.
- Integration with Tees Valley in terms of shared CCS pipeline use and storage.

6.2.3 **Key Functionality**

The key functional requirements are likely to be as follows:

- Robustness and integrity to provide confidence in the approach to decarbonise the Humber.
- Provide individual businesses, informal clusterings and industry groups with knowledge around the optimal approaches and associated technology pathways.
- Help to leverage policy and decision makers to drive technology pathways where necessary. This may include working to remove identified blockers or dependencies.
- Enable the Cluster Plan to communicate key information and engage with major stakeholders.

6.2.4 **Data**

6.2.4.1 Data ingestion and pipeline

The model must be able to effectively import and transform the necessary data to develop, optimise and test a robust decarbonisation roadmap. Given the wide variety and volume of data required the data import function must be user friendly and flexible: at least able to support common file types including flat files, spreadsheets, and open database connectivity databases (such as MS SQL). To support effective data governance where multiple scenarios and users are supported the model must store data in a model relational database.

To provide assurance over data quality it will be important that the model supports an effective data pipeline (processes by which raw input data are transformed into model data). This should include automatic error trapping and data integrity testing to ensure that data quality is maintained. This is particularly important where multiple data sources will be integrated to run scenarios. A data integrity test is required to ensure that data is being integrated in a logical and consistent way for each scenario. The integrity of all further modelling and scenario development will be contingent on the quality of the underlying data.

6.2.4.2 Data Storage

For the model to support effective governance of multiple scenarios it must have a data storage module capable of maintaining a single version of the truth that is kept distinct from individual ‘what-if scenarios. For example, when a user creates a scenario a clone of the core data is taken and then manipulated as per the requirements of that scenario. While this can be achieved manually in a very basic system, such an approach would not offer any governance or auditability of scenarios. A more advanced system (as we would recommend for the HIDR phase 2) would maintain a record of what had been changed in a scenario (versus the base data) and who made those changes. This would remove the need for laborious version control and ensure the data underpinning all scenarios is robust, controlled and auditable.

Where multiple users are expected to be accessing data (whether to run scenarios or view results) it is important that data is stored on a platform that can support multiple user access. This can be achieved by using an enterprise grade modern open database connectivity database such as Microsoft SQL Server.

6.2.4.3 Data Requirements

A data framework defines the data and datasets required for systems modelling in Phase 2. It is a framework for capturing data during stakeholder engagement, research or elicitation and will provide the inputs to the model and model scenarios. The framework may look linear and two-dimensional in nature, but the information captured will feed multi-dimensional system with complex interdependencies and uncertainties. The data framework needs to remain flexible and dynamic to enable the capture of evolving or emerging datasets as work progresses and situations evolve.

A data gap analysis has been completed by comparing existing acquired data against the data framework to identify further data acquisition needs. The table below summarises each area of the data framework at a *data line* level.

Table 4: High level data gap analysis

Data Framework Area	Data Framework Data Lines	Collated by Data Project	Covered by Data Project with queries	Data Gaps (Phase 2 collection)
Energy Producers	32	16%	3%	81%
Industries	42	14%	0%	86%
Technology	23	0%	0%	100%
Transport and Storage	37	0%	0%	100%
Penalties and Incentives	13	0%	0%	100%

6.2.5 Decision Support

Leading edge systems modelling solutions offer a wide decision support capability beyond simple optimisation. By combining hard and soft constraints with flexible objective functions they offer more nuanced support for a range of questions. In order to coordinate the perspectives of multiple stakeholders with potentially competing interests and consider a wider range of impacts including carbon emissions, cost, deliverability, local jobs and clean growth plans – developing an optimal and deliverable decarbonisation roadmap for the Humber will require a solution that can support a wide range of decision support functionalities.

Put another way, it is important that the model used has the flexibility to accommodate the full range of questions and scenarios required by stakeholders which may include national and local government, partners, funders, industrial stakeholders, technology developers, and academia.

Each decision support functionality allows the user to ask different questions of the solution for example, "what would be the optimal scenario to benefit local jobs?" or "what is the trade-off between cost and deliverability?"

6.2.6 Solution architecture: Modules and structure

An indicative, high-level solution architecture of the model is shown below. The solution architecture presents the core elements of the proposed solution from data to system model to user interface. It also illustrates how the different user types will interact with the solution. To allow for scalability and ease of user access this architecture would be web based, ideally hosted on a cloud-based computing platform.

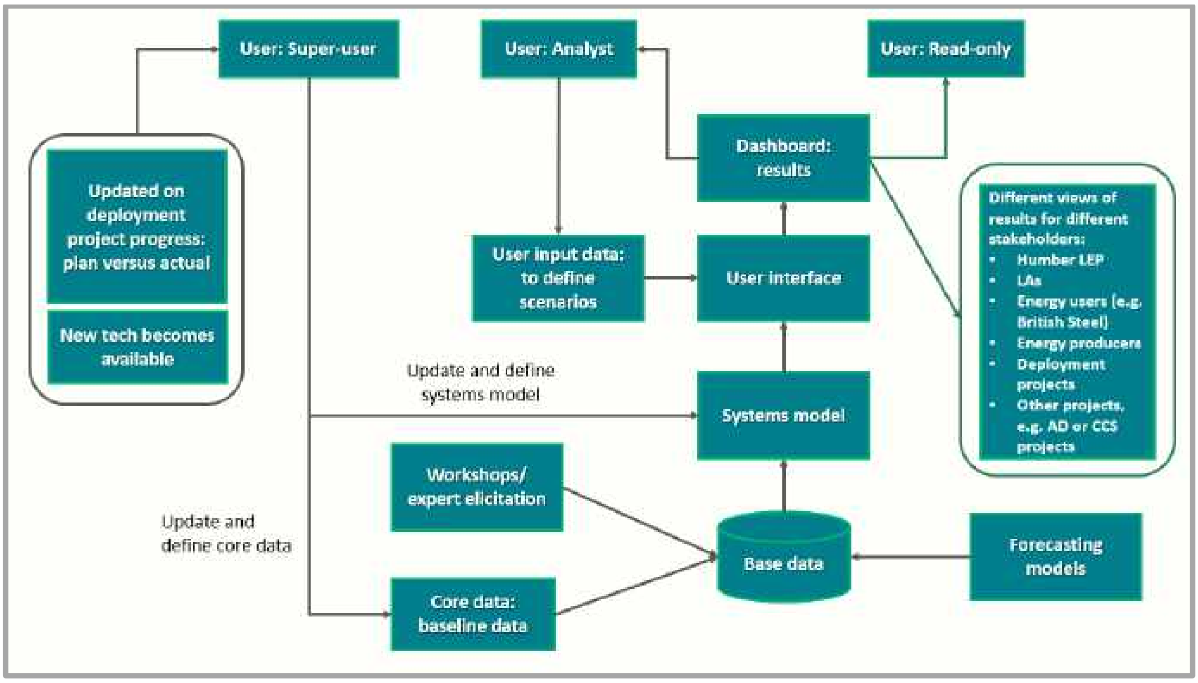

Figure 16: Solution Architecture

7 Work Package 5 – Roadmap Development Strategy

The overarching aim for this project was to develop the strategy for roadmap delivery. The culmination of this work has resulted in a strategy that focusses on four key areas:

7.1 Stakeholder Engagement and Communication

A planned and strategic approach to achieving ongoing and uninterrupted liaison with deployment projects, other ISCF funded projects, industry and others stakeholder. This will ensure that existing momentum and interest is maintained while also providing a mechanism for maximising opportunities – particularly around the availability and utilisation of existing and new infrastructure. Figure11, below illustrates the core links between the Humber Cluster Plan delivery and its stakeholders

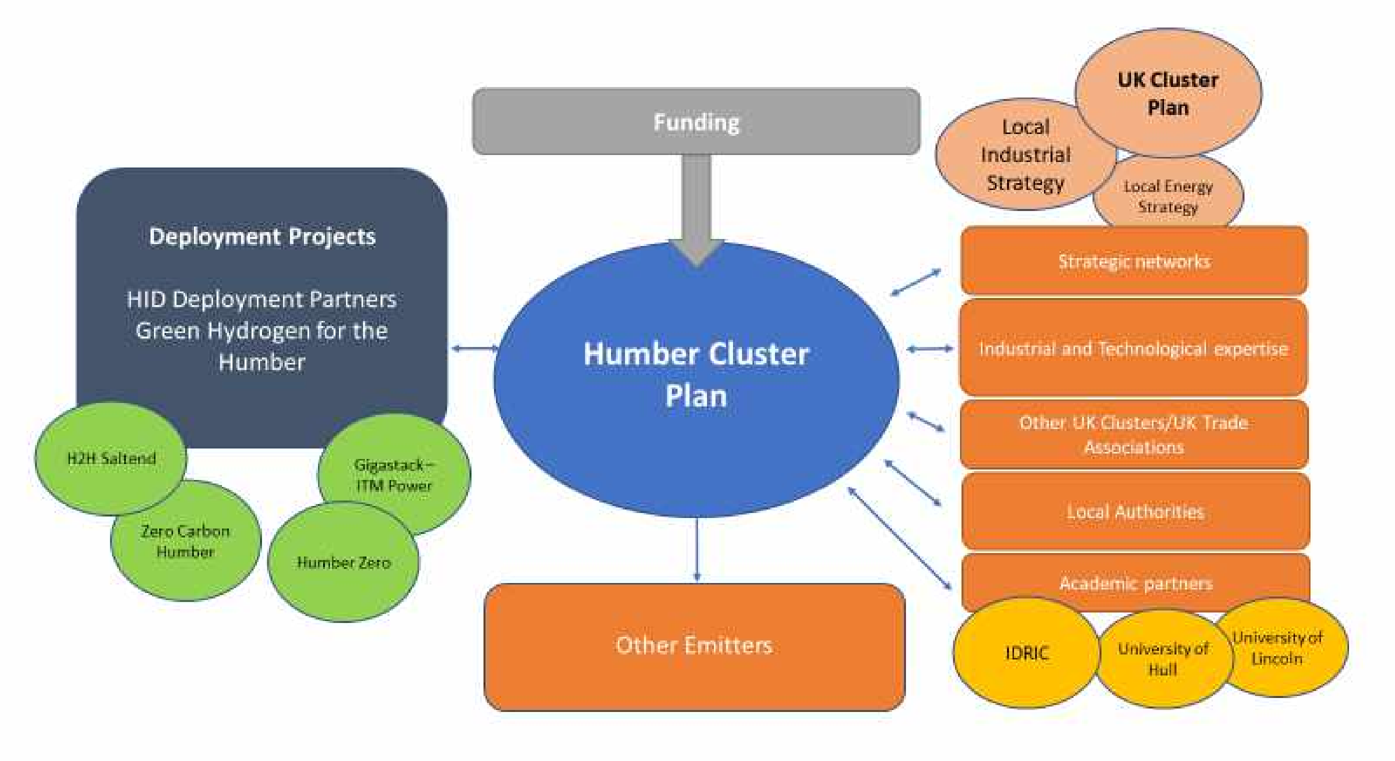

Figure 17: Humber Cluster Plan Stakeholder map

7.2 Technology Deployment Deep-dive

Further exploration via deep-dive studies of fuel-switching (hydrogen, electricity, biomass) and CCUS supported with additional sector studies and academic peer review. This will ensure that every possibility and implication of these technologies can be fully understood and mapped in relation to the Humber's decarbonisation, reducing the potential for regret spend and cost escalation.

7.3 Systems modelling

Development and utilisation of an adapted systems model flexible and nuanced enough to accommodate the complexities of the Humber cluster. This will provide a strong and politically neutral evidence base for roadmap delivery to give confidence and assurance to industry and other stakeholders.

Developing a functional and user-friendly interface will ensure that the output from the modelling is accessible to as wide a range of users as possible. Figure 12 below offers an illustration of what this might look like.

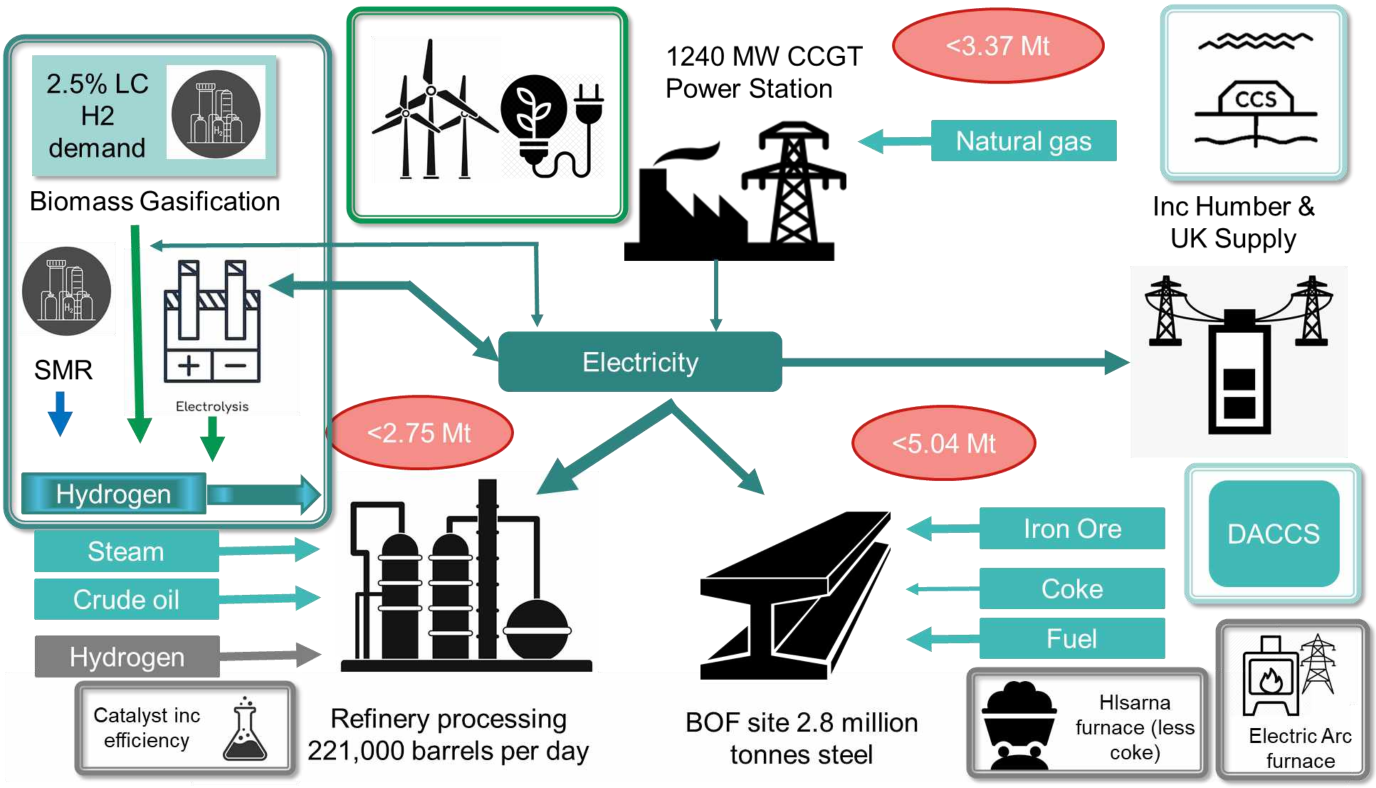

Figure 18: Illustrative user-friendly model dashboard [25]

[25] Courtesy of Business Modelling Associates, July 2020.

7.4 Overcoming barriers to deployment

Pro-active identification and mitigation of potential issues through audits of supply chain and skills, engagement with supply chain, planning and regulatory bodies and development of an inward investment proposition. While it will not be possible to overcome all barriers, early identification and action through valued strategic partnerships will do much to smooth roadmap delivery.

7.5 Summary

Engagement with stakeholders and the detailed assessment of the application of technologies means that the roadmap strategy combines fuel-switching to hydrogen, electricity and biomass; and CCUS to generate a range of potential options, covering all major industrial and power emitters in the Humber (including those outside deployment projects).

The strategy utilises the innovative systems modelling approach identified in WP4 to prioritise options by various criteria (e.g. for cost, CO2 impact, deliverability, local economic value) which will inform and support decisions by industry, infrastructure providers, local authorities and government. The aim is to highlight the “no regrets” options that should be prioritised and set out the scale and phasing of investment required.

8 Conclusion and Recommendations

Phase 1 of the HIDR has now been successfully delivered, resulting in the timely submission of a bid to Innovate UK for Phase 2. Work undertaken in Phase 1 has informed the development of the core strategy for delivering a roadmap, including identifying the optimum governance structure and work package framework, in addition to defining the scenario baselines, technology options and modelling criteria. In addition, successful stakeholder engagement in Phase 1 has resulted in a number of industry stakeholders confirming their approval of and commitment to the roadmap strategy.

8.1 Recommendations

The principle recommendations from Phase 1 can be summarised as follows:

8.1.1 A roadmap to deeply decarbonise the Humber is needed

It was found that industrial emissions in 2017 amounted to just under 15 $MtCO_2$, over 70% of which is linked to the refining and iron and steel sub-sectors. An analysis of possible business-as-usual scenarios revealed that, without the implementation of deep decarbonisation measures, emissions in 2040 are likely to be only 2% to 18% lower than in 2017.

If this trend were replicated across the UK, industrial emissions in 2040 would still be 43% of what they were in 1990, which would make it challenging to achieve a potential economy-wide net-zero target by 2050. This clearly points at the need for a roadmap to achieve deep reductions in emissions from the Humber industries.

Addressing the refining and iron and steel sectors will be crucial to meeting the target for a low carbon cluster by 2030 and a net zero industrial cluster by 2040. These two sectors account for just over 70% of the total emissions from the Humber region’s industrial sector.

8.1.2 Deep decarbonisation can represent an opportunity for clean growth

The importance of energy-intensive industries to the local economy was established as essential, and that the ‘first net-zero cluster’ positioning of the region may make the Humber an attractive hub for future industrial developments.

Thus, not only would deep decarbonisation of the Humber industries reduce the risk that local emissions are simply offshored by the relocation of industries to less regulated geographies, but also it could incentivise investment in the region. Hence, it is recommended that the HIDR consider the positive impact that deep decarbonisation might have on local jobs and the economy as part of the next project phrase. It may be relevant to assess potential synergies between 'deep decarbonisation' and 'clean growth'.

8.1.3 The industrial wealth and diversity of the region suggests that a technology-agnostic analysis of potential decarbonisation pathways is preferable

It is recommended that future work on the HIDR is technology-neutral and considers a broad range of relevant technologies and decarbonisation routes. Whilst this study did not assess decarbonisation pathways that the region could follow, the sheer variety of industries in the area suggests that deep decarbonisation may benefit from combining a broad range of technologies and approaches, including but not limited to CCS, fuel switching to hydrogen, and electrification.[26]

For example, nearly 60% of the emissions from the Humber industries relate to sources that cannot be abated through fuel switching and may require CCS deployment, which should be further investigated.

However, there are a limited range of abatement options available to decarbonise the industrial sector. The Humber Decarbonisation Projects are focussed on post-combustion CO2 capture, green hydrogen via electrolysis and blue hydrogen ex natural gas.

8.1.4 The HIDR could explore synergies across sectors and geographies

It is noteworthy that emerging decarbonisation activities in the area such as the two 'deployment projects' are already investigating a variety of decarbonisation technologies (green and blue hydrogen as well as CCS). Within these, it is encouraging to observe that stakeholders from industry and the power sector are working together to assess synergies in their respective decarbonisation pathways.

Moving forward, the HIDR may also consider cross-sectoral, as well as geographical, synergies. For instance, these may include the potential of decarbonising industry and the power, heat, and transport sectors outside of the core Humber cluster by leveraging the decarbonisation efforts and infrastructure deployed in the Humber.

8.1.5 Strategic co-ordination is needed to address technology readiness and deployment issues

The technologies required to decarbonise the Humber are emerging and new to the UK. There is a risk that deployment will be slower than anticipated by Humber project developers. There is a risk that CCS availability for refining and iron and steel sectors will be delayed relative to application to the chemicals sector at Saltend Chemicals Park.

[26] E.g. electrification, process change, and demand-side measures like product diversification (possibly in line with the growing demand for low-carbon products and rise of a circular economy) as well as low-carbon hydrogen and CCS.

Green hydrogen via electrolysis should in theory be deployable by the mid-2020s. CCS and by definition blue hydrogen, are limited by the deployment (temporal and spatial) of a transport and storage network and are therefore anticipated to trail green hydrogen deployment.

However, to achieve net zero, negative emissions will be needed as it will not be possible to eliminate all anthropogenic sources of CO2 emissions. At present, the only potential BECCS project is the Drax project.

8.1.6 **Further analysis, data, and market observations will be required moving forward**

Several emerging projects in the region were investigated and whilst these projects could deliver significant emissions reductions, many of them are still at a very early-stage and their plans around low-carbon infrastructure development are today not sufficiently developed, making it difficult to assess their likely contribution to decarbonising the Humber industries.

It is recommended that real data from new industrial developments and decarbonisation projects is considered wherever possible in the next phase. This includes data around emissions, low-carbon fuel production, and infrastructure capacities which may only be obtained by engaging relevant stakeholders.

Further analysis should not only focus on the different decarbonisation pathways that the region may see, but it should also carefully consider the interplay between the variety of pathways industrial sites may deploy and the infrastructure building decisions. For example, different scenarios should be examined, considering how the scale of the emissions reductions could affect the size of the infrastructure required (e.g. hydrogen production capacity, pipeline capacities and flow rates, undersea CO_2 storage constraints).

Future work could bring together local industrial sites as well as utility providers (e.g. Northern Powergrid) and explore both the technical opportunity for electrification within industrial sites, as well as the availability of high-voltage connections in their vicinity.

Lastly, it is noted that the emissions reductions modelled in this study are sensitive to the growth assumptions employed, including those around the economic impact of the COVID-19 pandemic and the subsequent recovery. It is recommended that the growth assumptions made for this study be updated when better sector-specific data becomes available.