Monolithic MOFs for Carbon Capture

CCUS Innovation 2.0

Key Knowledge Deliverable 1.1, 1.2 & 3.

Contents

The Market Opportunities

1.1 Introduction

The Paris Agreement[1] of 2015 was signed to limit the increase in global temperatures to well below 2°C above pre-industrial levels, and ideally to limit the temperature increase to 1.5°C.

However, power plants fuelled by coal and gas continue to dominate the global electricity sector. In absolute terms, power generated from fossil fuels has increased by 70% since 2000, with the rise in global demand.[2]

For the first time in recent years, hard-to-abate sectors such as oil and gas, steel, cement and chemicals in general have reduced absolute emissions of carbon dioxide (CO_2), achieving a 0.9% drop from 2022 to 2023.[3,4] Despite this, hard to abate sectors still account for 40% of global CO_2 emissions, with oil and gas at 10%, steel at 7%, cement at 6% and primary chemicals at 3%.

To achieve carbon emission reduction targets in line with climate change policies while maintaining their competitiveness, these hard-to-abate sectors are exploring efficient carbon reduction technologies and striving to reduce associated costs. Carbon capture technology presents a large-scale CO_2 reduction solution with immense potential. Absorption technologies involving aqueous amine solutions having existed for decades, utilising the reversible reaction between amines and acidic gases.[5]

However, there is a multitude of drawbacks with aqueous amine solutions: their CO_2 uptake needs to be significantly improved upon,[6] they are highly corrosive in nature,[7] and they suffer poisoning and deactivation by SOx and NOx gases that are present in most flue gases.[8] In addition, they incur a high energy penalty for regeneration, at one point reportedly up to 40% of the energy output of a power plant.[9]

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1 https://unfccc.int/process-and-meetings/the-paris-agreement

2 Why carbon capture technologies are important – The role of CCUS in low-carbon power systems – Analysis - IEA

3 Here's how heavy industries can decarbonize faster | World Economic Forum

4 Net-Zero Industry Tracker 2024 | World Economic Forum

5 The application of amine-based materials for carbon capture and utilisation: an overarching view - Materials Advances (RSC Publishing)

6 H. A. Patel , J. Byun and C. T. Yavuz , *ChemSusChem*, 2017, **10** , 1303 —1317

7 E. E. Ünveren , B. Ö. Monkul , Ş. Sarıoğlan , N. Karademir and E. Alper , *Petroleum*, 2017, **3** , 37 —5

8 B. Dutcher , M. Fan and A. G. Russell , *ACS Appl. Mater. Interfaces*, 2015, **7** , 2137 —2148

9 K. Z. House , C. F. Harvey , M. J. Aziz and D. P. Schrag , *Energy Environ. Sci.*, 2009, **2** , 193 —205

Metal organic frameworks (MOFs) constructed from organic linkers and metal ions or clusters, have emerged as prominent candidates in CO_2 capture due to their large specific surface area, well-defined porous structure, and tuneable chemical properties. One of the most significant reasons that MOFs are not more widely used is that they almost always form as micron-scale powders that present significant challenges in industrial processes; they can create massive system level pressure drops, clog valves, and can escape downstream from equipment. Therefore, for most applications MOF powders are pelletised with a high percentage of binder, leading to inefficient gas storage capacity. Immaterial's patented monolithic MOF technology enables greatly improved material packing, leading to large improvements in gravimetric and volumetric CO_2 capture performance, and addressing these challenges to industrialisation.

It is this performance advantage that leads to the improved techno-economics described compared to traditional amines system and the reduced threshold of chemical regulations required compared to amine scrubber systems make m-MOFs are potentially attractive solution for the hard to abate industries highlighted.

1.2 Cement

Cement accounts for 2.4 Gt CO_2e in Scope 1 and 2 emissions with the emission intensity remaining stable between 2018 – 2022[10]. Carbon Capture Utilisation and Storage (CCUS) and material efficiency strategies are expected to reduce around 75% of the cement sectors emissions, but significant investments will be required. The industry is forecast to reduce emissions intensity by 22% by 2030 compared to 2023 levels (according to the IEA's Net Zero Scenario), and absolute CO_2e emissions are expected to be 1.91 Gt in 2030.

The European Union (EU) is leading the way on decarbonising the cement industry, with larger players taking steps to reduce emissions by 2030.[11] Producing a metric tonne of grey cement produces, on average, 0.6 tonnes of CO_2. The European Union typically produces in the order of 182M metric tonnes of cement each year[12], therefore a 30% reduction in Scope 1 CO_2 emissions equates to approximately 33Mtpa of CO_2 reduction required. But with current production technologies a significant drop in emissions beyond 2030 can only be achieved by additional new technologies such as CCUS.

[10] Energy Technology Perspectives 2020 – Analysis - IEA

[11] Decarbonizing cement: How EU cement-makers are reducing emissions while building business resilience | S&P Global

[12] EU: cement production volume 2022 | Statista

The top European and UK cement companies for Immaterial to target include Buzzi Unicem, Cementir Holding, Cemex, Heidelberg Materials, Holcim Ltd, Tarmac, Titan Cement International and Vicat SA.[13]

One of the largest actors in the European region, Heidelberg Materials, has several water/amine-based carbon capture and storage activities. Their most advanced CCS cement project is in Brevik, Norway, and is part of the Norwegian government's Longship programme. The evoZero cement project is planned to start production in 2025.[14,15] Supported by the EU Innovation Fund, the GeZero project in Geske in Germany is with partners Thyssenkrupp Polysius and has a 2000 tpd CO_2 potential capture. A CO_2 transportation solution by rail with interim CO_2 storage hub are part of the project development.[16] In Slite in Sweden, Heidleberg aim to capture up to 1.8Mtpa CO_2 by 2030, costing an estimated €900M invested in the facility.[17] In the UK, Heidelberg's British subsidiary, Hanson UK, is a partner in the UK's HyNet Northwest, including Hanson's Padeswood cement plant. Mitsubishi Heavy Industries (MHI) and Worley have been awarded the FEED contract, to remove 800,000 tpa CO_2.[18]

The Titan Group are funded by the EU Innovation Fund with project IFESTOS at the Kamari plant. Thyssenkrupp Polysius was selected for the FEED for the potential reduction of 1.9mtpa.[19] The French cement company Vicat have put forward the Hynovi project under the Important Projects of Common European Interest (IPCEI). 40% of the CO_2 emitted by Vicat's Montalieu-Vercieu cement plant will be captured and combined with Hynamic's low-carbon hydrogen to produce carbon-free methanol.[20] The Portuguese company Cimpor, and Limak in Turkey are both assessing carbon capture.

1.3 Steel

Steel accounts for 2.8 Gt CO_2e Scope 1 and 2 emissions, with a global rise in emissions of 3% between 2022-2023, driven by the development of demand in China and India, and high emission production. The blast furnace and basic oxygen furnace process releases the highest carbon emissions with 2.33 Mt of CO_2 emission per tonne

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13 Top Cement Companies in Europe

14 Brevik CCS – World's first CO_2-capture facility in the cement industry | Brevik CSS

15 First, Large-Scale CO_2-Capture Plant in Cement Production Halves Emissions

16 thyssenkrupp cooperates with Heidelberg Materials for the GeZero carbon capture project | World Cement

17 Slite CCS, one of Sweden's most significant climate transition projects

18 Mitsubishi Heavy Industries, Ltd. Global Website | MHI and Worley Awarded FEED Contract for UK's First CO_2 Capture Plant at a Cement Production Facility -- Contract Awarded Following Successful Pre-FEED in 2022, Further Promoting Decarbonization of the Cement Industry –

19 09102024_TITAN_Group_signs_engineering_contract_with_thyssenkrupp_Polysius_for_project_EN.pdf

20 Low-carbon trajectory: Vicat and Hynamics unveil Hynovi project | Vicat

of crude steel. The emission from direct reduced iron and electric arc furnace (DRI-EAF) process is lower but still releases 1.37 Mt of CO_2 per metric tonne of steel. The scrap steel and electric arc furnace (scrap-EAF) process releases the lowest carbon emissions at 0.66 Mt of CO_2. per tonne of steel.[21] Europe is responsible for 37% of global steel production,[22] with around 170 Mt of steel annually and has 500 steel production sites throughout 23 member countries. Germany has the largest share of European crude steel production at 27%, followed by Italy 15.8%, France 9.0% and Spain at 8.4% with the UK producing 4.6%.[23]

The industry targets a 45% reduction in intensity for primary steel by 2030, and net-zero emissions (NZE) by 2050. In addition to the NZE challenge, the drive to reduce CO_2 is coming from customers demanding "carbon-friendly" steel, such as the automotive industry and growing investor and public interest in sustainability.[24] Recent studies estimate that the global steel industry may find approximately 14% of steel companies potential value is at risk if they are unable to decrease their environmental impact.

A study found that 57% of global steel plants have 8-24 further operational years,[25] therefore making retrofit carbon reduction technology like carbon capture, an attractive solution to the NZE challenge.

ArcelorMittal, Europe's top steel manufacturer,[26], [27] is one of the more active steel companies in carbon capture activity, with the €200M Steelanol project being one of Europe's leading steel carbon capture and utilisation projects, with CO_2 utilised by partner LanzaTech to convert waste bio-mass into advanced ethanol. The demonstration pilot will reduce annual CO_2 emissions from the Ghent plant by 125,000 tonnes., approximating to 340 tonnes CO_2 per day[28] For comparison, a full-scale steel plant, producing 5 Mtpa of steel would emit approximately 3 Mtpa of CO_2, 8200 tonnes of CO_2 per day. The DMXTM non-amine solvent-based carbon capture technology[29] is also being employed in the EU-funded 3D project. The project plans to demonstrate

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21 Roadmap of Europe's low-carbon steel production projects | S&P Global

22 The Top Steel Producing Countries in Europe – WorldAtlas

23 FINAL_EUROFER_Steel-in-Figures_2023.pdf

24 Decarbonization in steel | McKinsey

25 Global iron and steel plant CO_2 emissions and carbon-neutrality pathways | Nature

26 Top 50 largest Steel companies Europe • BoldData • Company Data

27 European steel giants and global rankings

28 ArcelorMittal inaugurates flagship carbon capture and utilisation project

29 CO_2 Capture | Axens

the effectiveness of the DMXTM process on a pilot industrial scale at ArcelorMittal's Dunkirk site and will capture 0.5 tonnes of CO_2 per hour.[30]

1.4 Chemicals

The chemical industry is the fourth largest emitter of CO_2 behind power generation, iron/steel and cement industries.[31] In Europe the total GHG emissions from the chemical industry accounted for 5% of total net GHG emissions. In 2021, 67% of GHG emissions from the chemical industry came from fuel combustion, with 33% from industrial processes and product use.[32]

A significant quantity of this CO_2 originates from syngas derived from fossil fuels. Syngas is the mixture of carbon monoxide, and hydrogen produced by the steam methane reforming (SMR) process to convert natural gas. Syngas is important because it acts as a versatile intermediate that can be used to produce important chemicals such as ammonia fertilisers, cleaner burning fuels, ethylene, propylene and butadiene for plastic production, and commodity chemicals such as methanol.

Methanol is the building block chemical for thousands of products, including acrylic plastics, synthetic fibres, adhesives, paints, plywood in construction and as a chemical agent in pharmaceuticals and agrochemicals. By employing carbon capture technology to the steam methane reformer, the hydrogen produced, labelled blue hydrogen, can also be used to power vehicles helping decarbonise the transport sector.

As SMR is an endothermic process it requires a large amount of heat to be supplied to drive the reaction, typically generated by burning methane thus producing CO_2. Although carbon capture technology is a potential solution to the emissions, the CO_2 produced is a dilute low-pressure stream making it more difficult and expensive to capture. The process CO_2 emissions however are in a higher concentration and pressure stream, meaning they are relatively easier to capture, and it has a more consistent composition and fewer impurities.

Advanced reforming techniques, such as Gas Heated Reforming and Autothermal Reforming, removes the need for a separate stream of methane for heat generation, so the CO_2 emitted from the SMR process is a single high pressure, high concentration feed.

The products made by the chemical industry contain carbon, so a carbon-free chemical industry is not possible, but the industry is looking at ways to make chemicals using renewable carbon sources such as biomass, municipal waste and captured CO_2.

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[30] DMX Demonstration in Dunkirk | 3D | Project | Fact sheet | H2020 | CORDIS | European Commission

[31] Reducing the petrochemicals industry's carbon footprint | World Economic Forum

[32] Total greenhouse gas emissions in the chemical industry (Indicator) | European zero pollution dashboards

For example, captured CO_2 and renewable hydrogen can be directly transformed into e-methanol, treated in a reverse water-gas shift reaction to produce syngas containing CO, CO_2 and hydrogen, which can be further processed through Fisher-Tropsch synthesis to make chemicals and fuels, such as Sustainable Aviation Fuel (SAF).

The world's top 50 chemical firms are listed here[33] for the 2023 fiscal year, and it is worth recognising that they also operate globally. The report states that 2023 was a particularly bad year for the European chemical industry, with high energy costs and ageing assets. European companies like BASF, Ineos, Covestro, Arkema, and Evonik Industries posted sharp declines in the value of chemical sales. In addition, new competition from China, and fertiliser prices reducing from the high of 2022, have affected profits at Mosaic, Nutrien, and Yara.

Despite the strong financial headwinds in the chemical sector there are some good examples of CCUS activity, and several of the leading chemical companies produce amine-based carbon capture technology, such as BASF, Shell and Mitsubishi Heavy Industries.

LG Chem has declared it will achieve climate neutral growth by 2030 and net zero emissions by 2050, with a cut of 20 Mtpa of CO_2 required. LG Chem is reviewing the introduction of CCUS through national initiatives, internal innovation and partnerships, and looking to utilisation of the captured carbon in product manufacturing.[34]

Yara, the world's second-largest ammonia producer is utilising renewable energy and carbon capture and storage to produce low emission ammonia, and to help decarbonise power production.[35] Yara are investing in CCS at their Sluiskil plant in the Netherlands with Yara and Northern Lights signing a binding commercial agreement, enabling the first cross-border transportation and storage of CO_2.

An example of a multi stakeholder funded project is the Innovate UK Transforming Foundation Industries Flue2Chem project,[36] looking to convert industrial waste gases into sustainable materials for consumer products. The project consists of a consortium of 15 organisations including BASF, Croda, Johnson Matthey, P&G, Unilever and other businesses, universities, and non-governmental organisations.

[33] C&EN's Global Top 50 chemical firms for 2024

[34] https://www.lgchem.com/sustainability/climate-change

[35] https://www.yara.com/siteassets/investors/057-reports-and-presentations/annual-reports/2023/yara-integrated-report-2023.pdf

[36] https://iuk-business-connect.org.uk/perspectives/industrial-gases-to-chemicals-collaborating-to-transform-foundation-industries-towards-circularity/

1.5 Energy from Waste

Energy from Waste (EfW) is the incineration of municipal or similar commercial and industrial waste not suitable for recycling and otherwise heading for landfill, and the utilisation of heat generated to create electricity via steam turbines. The energy produced is a reliable local baseload to compliment intermittent renewable energy generation.[37]

EfW mitigates CO_2 and CH_4 emissions by diverting waste from landfills but, dependent on the make-up of the waste, releases between 0.7 and 1.7 tonnes of CO_2 per tonne of waste.[38] EfW plants in the UK currently emit around 11 Mtpa CO_2, with an additional 9 Mtpa sites under construction. According to Eurostat, in the 10 years to 2016, the amount of waste incinerated in Europe increased by 30%.[39] The data also reveal that in the last 10 years CO_2 emissions from incinerators have doubled. In 2017, over 40Mt of fossil CO_2 was released by EfW incinerators in the EU countries.[40] The concentration of CO_2 in the off-gas is typically around 12% and this coupled with the fact that most EfW sites are new and predicted to have a long life, makes them well suited to CCUS investment and fitment.

As most of the waste collected is from urban areas, and the electricity and heat generated can be used to power and heat urban buildings, the majority of EfW plants are located near to urban areas. This potentially makes EfW a very good fit for Immaterial's m-MOF carbon capture technology, as the smaller footprint and reduced regulatory barriers compared to the competitor amine-based system are a desired value proposition.

The top EfW companies in Europe include Hitachi Zosen Corp, Mitsubishi Heavy Industries, A2A SpA, Veolia Environmental SA, Suez SA and STEAG Energy Services.[41]

Suez, a large player in the UK, has worked with pre-FEED contractors for two of its carbon capture projects in the East Coast Cluster in preparation for an application to the Industrial Carbon Capture Track 1.[42] Fluor is also supporting Suez in a pre-FEED study at the existing facility at Haverton Hill on Teesside, and Technip Energies has

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[37] CEWEP - The Confederation of European Waste-to-Energy Plants

[38] assets.publishing.service.gov.uk/government/file/869265/Pollution-inventory-reporting-incineration-activities-guidance-note.pdf

[39] www.eea.europa.eu/themes/industry/industrial-pollution-in-europe/a-decade-of-industrial-pollution-data

[40] www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2019/european-union-greenhouse-gas-inventory-2019

[41] https://www.mordorintelligence.com/industry-reports/europe-waste-to-energy-market-industry/companies

[42] https://www.sustainable-carbon.org/uk-suez-moves-forward-in-carbon-capture-projects-with-support-of-technical-design-contractors/

partnered at the Wilton site. Veolia partnered in 2017 with the London start-up Carbon Clean In the UK and is expected to start piloting the technology soon.[43] Viridor, a recycling, renewable energy and waste management company owned by KKR, has a carbon capture plant at its Runcorn facility, and will be on the one the first EfW carbon capture projects in the world and is proposed to capture 900,000 tonnes of CO_2 annually. Runcorn is part of the Hynet industrial carbon capture cluster.[44]

EEW states itself as the market leading EfW company in Germany, with activities also in Luxembourg and the Netherlands. EEW says they are exploring innovative solutions to their carbon emissions, such as CCUS, with CO_2 available as a raw material to the chemical industry. They intend to capture 500,000 tonnes annually by 2032.[45]

1.6 Power Generation

Europe, including the UK, use natural gas for electricity generation, domestic (or household) heating and cooking, and other purposes such as industrial processes. In 2023 the European Union was the 4th largest power sector emitter globally with 657 Mt of CO_2 from electricity generation,[46] with gas still accounting for 24% of electricity generated.

According to the IEA NZE scenario[47], the European Union needs to reduce their emissions from the power sector to near-zero by 2035, with wind and solar making up 50% of electricity generation by 2030.

EMBER has published data of the top European power plant emissions based on the latest EU Emissions Trading System data, with a total of 660 Mtpa of CO_2 emitted from 391 sites. Of these sites, 174 are powered by gas with 145 Mtpa CO_2, and 109 powered by coal with 193 Mtpa CO_2. Italy emits the largest quantity of CO_2 from gas power generation with 44 Mtpa, followed by Spain 23, Germany 17, Netherlands 11, France 11 Mtpa.[48] In 2022 Electricite de France SA, Enel SpA, Iberdrola SA, and ENGIE SA were the top 4 power plant owners in Europe by capacity.[49]

The IEA state[50] governments should consider policies to support CCUS deployment at gas-fired power plants including carbon pricing programmes, emission reduction

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[43] https://www.veolia.com/fr/planet/capture-du-CO_2-solutions-generant-emissions-negatives#:~:text=Selon%20un%20rapport%20interne%20de,%C3%AAtre%20valoris%C3%A9es%20dans%20le%20processus

[44] https://www.viridor.co.uk/our-ambition/runcorn-ccs-project/

[45] https://www.eew-energyfromwaste.com/en/newsroom/press-releases/articles/eew-energy-from-waste-publishes-5th-sustainability-report/#:~:text=Our%20goal%20is%20to%20capture,Operating%20Officer%20of%20EEW%20Group

[46] Global Electricity Review 2024 | Ember

[47] https://www.iea.org/reports/global-energy-and-climate-model/net-zero-emissions-by-2050-scenario-nze

[48] Repeat offenders: coal power plants top the EU emitters list | Ember

[49] Power & Utilities - Top 10 Power Plant Owners in Europe by Capacity – GlobalData

[50] Gas – IEA

regulations to incentivise investment, capital grants to projects to improve upfront costs, feed-in tariffs and contracts to differentiate CCUS-equipped gas-fired plants to deliver greater revenue stability, policy incentives such as tax credits and public procurement requirements and simultaneous support for CO_2 transport and storage infrastructure.

Of the top four power plant owners, EDF and Iberdrola SA have various carbon off-setting activities rather than carbon capture announcements and Enel have stated that they will phase out gas by 2050 to reach their net-zero target, rather than employ carbon capture technologies.[51]

Orlen Group, as part of its investments in the Net Zero strategy, will realise a number of projects in the coming years, using the best and most emission-efficient technologies, including CCU and CCS.[52] By 2030 it will be capable of storing or utilizing up to 3 Mtpa of CO_2.

ENI state carbon capture is a key lever for their energy transition and have launched projects in the UK (Hynet North West) and Italy, Ravenna, a joint venture between ENI and Snam.[53] Phase 1 of the Italian project, started towards the end of 2024, and will remove 25,000 tpa from the natural gas plant in Casalborsetti, with Phase 2 to be started before 2030.

In the UK, VPI Power is working to develop a carbon capture and storage network in the Humber, known as the Viking CCS Cluster,[54] part of the UK's Track 2 programme. SSE Thermal and Equinor are actively developing Keadby 3 in the Northeast of the UK, which could become the UK's first power station equipped with carbon capture technology by the mid-2020s.[55] SSE and Equinor are also actively exploring carbon capture technology at Peterhead in Scotland. RWE currently operates approximately 7 GW of conventional, efficient gas-fired capacity in the UK and are considering carbon capture projects to provide a decarbonised future for a number of our existing gas-fired power stations, and a new-build carbon-capture enabled power station.

Uniper has awarded process design package contracts to Technip Energies and Aker Carbon Capture for the proposed post-combustion carbon capture plant at their Grain

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[51] https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/enel-to-get-out-of-gas-by-2050-says-carbon-capture-will-not-solve-the-problem-62378510

[52] https://www.orlen.pl/en/about-the-company/media/press-releases/2023/September-2023/ORLEN-to-store-carbon-dioxide-beneath-seabed

[53] https://www.eni.com/en-IT/actions/energy-transition-technologies/carbon-capture-utilization-storage.html

[54] https://vpi.energy/news/archive/vpi-immingham-a-case-study-for-ccs-in-power/

[55] https://www.sse.com/our-technologies/carbon-capture-and-storage/

power station in the Southeast of England. Grain Carbon Capture has the potential to remove over 2 Mtpa of CO_2 during the electricity generation process.[56]

2. The Potential Impact

The 5 hard-to-abate sectors discussed in Section 1 can be split into 2 categories of CO_2 concentrations, with the gas fired power generation resulting in low-CO_2 flue gas concentrations circa 4%, and the remaining 4 sectors, cement, steel, chemicals and energy from waste all producing high-CO_2 flue gas concentrations over 10%. The m-MOF product manufactured, and the techno-economic comparison compared to amine clean up are different and treated separately.

Potential cost savings for a high and a low CO_2 emission site are taken from internal data and examples from the preceding sections:

For the high CO_2 emissions, an example from one target company aiming to capture circa 2Mtpa CO_2 by 2030, and predicted to deliver a potential saving of up to €140M in carbon capture costs annually. Included in this is a depreciation saving corresponding to the avoidance of CAPEX of circa €300M for the m-MOF compared to the amine system.

For the low CO_2 emissions, an example is one target company aiming to capture circa 3Mtpa CO_2 by 2030. The potential operating savings utilising m-MOF technology instead of amines would be in excess of €120M pa.

3. Exploitation Plan

3.1 Activities - Year 1 (2025)

- Finalise sector and region customer mapping.
- Customer Engagement across the identified target sector and regions.
- Further promotion through Abstracts / Presentations at Industry events / Expos / networking opportunities. Supported by selected membership of industry associations.
- Agree and enter into NDA’s with customers to explore pilot demonstration of the technology.
- Secure PO’s for Feasibility / Techno-economic studies to provide customers with KPI’s / credibility of the technology benefits to move to pilot demonstration.
- Prove scalability of materials through pilot manufacturing site.
- Identify other potential grant funding routes UK / Europe that can support pilot demonstration of FOAK technologies.

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[56] https://www.uniper.energy/united-kingdom/news/uniper-awards-design-study-contracts-for-grain-carbon-capture-project/

- Generate legal framework to protect Immaterial's Confidential Information and IPR when working with Customers / Affiliates / EPC's – in the form of NDA's, Consultancy Agreements, T&Cs, Material Agreements.

3.2 Activities - Years 2-3 (2026 / 27)

- Pilot demonstration unit commissioned and proving capture rates / purity. Providing customers with justification to move to larger pilot demonstration units.
- Operating the pilot demonstration unit will provide feedback / learning – allowing the system and materials to be modified / improved to enhance operation performance. Immaterial use this opportunity to file new IP as and when relevant.
- Continue customer engagement / development across the identified target sectors and regions.
- Continue with presentations at Industry events / Expos / networking opportunities. Supported by selected membership of industry associations. Using information gained from operating pilots to create case studies and marketing literature to provide potential new customers with credible performance data for Immaterial's technology.
- Secure PO for larger pilot demonstration units.
- Enter discussions around Industrial-scale systems
- Continue to explore other grant funding support opportunities in UK / Europe for both small pilot demonstration (for Low CO_2) and large pilot demonstration units.

3.3 Activities - Years 4-5 (2028 / 29)

- Large pilot demonstration units commissioned and proving capture rates / purity. Providing customers with complete techno-economic / scalability proposition to justify full-scale industrial capture systems.
- Explore funding routes with customers for Industrial-scale capture systems.
- Continue with presentations at Industry events / Expos / networking opportunities. Using the new information gained from operating the large pilots to create further case studies and marketing literature to prove scalability of material manufacture and system designs.
- Take and use the learnings from the operation of the larger pilot demonstration units to continue to improve material and system design performance whilst maintaining our IP strategy by increasing our portfolio.
- Continue customer engagement / development across the identified target sectors and regions.

3.4 Target - 2030

First industrial scale carbon capture system using Immaterial's m-MOF materials and system designs.

4. IP

The disruptive nature of Immaterial's technology will provide our customers with significant financial benefits in both Capex and Opex savings. Therefore, the IPR protection of the materials and designs are critical to Immaterial's uniqueness and company valuation.

Immaterial has a proactive IP strategy focussing on Metal Organic Framework (MOF) chemistries, manufacturing processes, and carbon capture applications.

Immaterial has carried out an extensive landscaping of the Intellectual Property (IP) in the context of carbon capture in conjunction with an external search specialist (J&B Partners) to assess freedom to operate for the solutions being developed by Immaterial.

5. Dissemination, Trade Memberships and Events

5.1 Dissemination Activities Undertaken During the Project

During this project, Immaterial have identified, approached, and engaged with emitters from all target sectors listed. This has resulted in positive discussions about our technology, leading to quotations for feasibility studies and techno-economic work packages, with a view to progressing to pilot technology demonstration.

To this end Immaterial have;

- Agreed strict NDA and T&Cs with our customers to maximise protection of our Intellectual Property Rights (IPR)
- Received Purchase Orders and completed work packages for both High and Low concentration CO_2 applications

The outcomes from these work packages have allowed Immaterial to showcase the substantial financial benefits our technology can provide when compared to the incumbent amine solutions at industrial-scale. Combining substantial savings in both capital and operational expenditures with the smallest system footprint enables Immaterial's technology to achieve the lowest cost of capture.

Next stage work package discussions are underway for technology demonstration.

Develop a pipeline of potential customers in UK/Europe with industrial 'use cases', who have the appetite to adopt new technology to achieve their decarbonisation targets.

5.2 Trade Memberships

Having extensively researched the relevant industry sectors for Immaterial's technology during this project we have identified and acted in obtaining membership for strategic industry trade associations to exploiting the technology. We have joined 2 trade associations.

Global Cement and Concrete Association **(GCCA)** – 46 Global Cement manufacturers with access to National and Regional Association Partners.

Carbon Capture Storage Association **(CCSA)** – is the lead European association accelerating the commercial deployment of carbon capture, utilisation and storage (CCUS) with over 120 member companies.

Membership to these associations allows Immaterial to exploit a variety of opportunities to engage with emitters. For example, through working groups, networking events, member showcases, membership conferences as well as presenting case studies and testing results.

The association memberships are complemented by active involvement in selected trade exhibitions in varying ways such as submitting abstract for presenting Immaterial's technology, exhibiting, and attending. During the project Immaterial have attended various events which have produced meaningful connections that have developed into activities around potential pilot demonstration. The list below is a selection of the events we have attended during the project.

5.3 Event Attendance

Innovation Zero - Attendance of 10,000+ over the 2 days including funders, policymakers, business leaders and innovators. Over 500 influential speakers, and more than 300 decarbonisation solutions providers.

Foresight NetZero Live - 300 attendees, 40 speakers and 30 exhibitors

GET Congress (Italy) - Over 7,000 visitors, 1,500 delegates and 300 Ministers, CEOs and business leaders for 3 days of high-level discussions.

CCSA UK Conference – Over 800 attendees at this flagship annual CCUS event. Providing networking opportunities for UK, Europe and N. America.

6. Summary

Of the 5 target sectors identified, each sector is committed to adopting carbon capture to enable their transition to climate neutrality. These sectors understand that amine technologies are initially the current default option due to technology readiness levels. However due to high costs and other concerns relating to amine technology, they all

acknowledge that evaluation of next generation carbon capture technologies is crucial, with expectations that these new technologies can support the stated GHG emission targets for 2030 and beyond in a more cost-effective manner. Each company, in each sector, has different challenges (location, available space, environmental permitting, pipeline accessibility, conversion and use). Immaterial have developed a capture solution to positively address these concerns.

We have mapped the total addressable market for the identified applications, target companies and contacts for each industry, mapping out sites, locations, emissions, GHG targets and activities in new technology evaluation. As CO_2 becomes a valuable feedstock commodity for alternative fuels we believe that capturing CO_2 molecules at the lowest cost will open the scope of opportunity for Immaterial to be adopted into more CCU (Carbon Capture Use) projects.

6.1 Project Outcomes

The primary objective of this project was to produce new materials for carbon capture and integrate them into modified Swing Adsorption systems. The combination of newly developed mMOF materials and system design integration increases the volumetric capacity resulting in more CO_2 molecules being adsorbed within our materials, whilst also improving the systems operating efficiency. These outcomes allow Immaterial to offer significant advantages over both powdered MOF and amine technologies. By increasing the capture capability of our materials, it allows the system footprint to be reduced resulting in a lower capital expenditure and smaller operational expenditure.

Immaterial have completed UK CCS infrastructure mapping now and future, target emitter mapping to infrastructure, company profiling and reach outs, engagement at events such as UK 6th CCUS and Hydrogen summit, CCSA 2025 conference, Carbon Capture Global Summit (QEII Centre), Innovation Zero London.

This provides Immaterial with a compelling case for generating financial benefits for the emitter. The feasibility / techno-economic studies undertaken during this project have allowed Immaterial to produce a comparable capacity solution. The results are compelling, with a system footprint size of less than one quarter of incumbent technologies with potential capital expenditure cost savings of hundreds of millions of pounds. With operational expenditure also reflecting low energy penalties, the Immaterial solution provides emitters with a solution to capture CO_2 molecules at the lowest cost.

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