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CO2 Capture, Utilisation & Storage

A patent landscape analysis

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CCUS Patent Landscape: Executive Summary

Overview

Carbon Capture, Utilisation & Storage (CCUS) technologies are critical for achieving climate neutrality hard-to-abate sectors and supporting net-zero strategies. This analysis, conducted by Mynd-Ware for Essenscia, provides a patent-based perspective on the CCUS innovation landscape. The study examines 20,346 patent families published over the past decade, using AI-driven topic modelling to identify trends, key players, and emerging opportunities across capture, storage, and utilisation technologies.

Key Findings

23% annual growth: CCUS patent activity shows a CAGR of 23% (2020–2023), nearly 9x the global IP average of 2.7%.

Global innovation leadership: China leads in volume; USA and Europe follow. Japan dominates corporate filings (8 of top 25 companies), while Chinese innovation originates primarily from universities.

Top corporate players: Saudi Aramco, Air Liquide, and Mitsubishi lead patent filings. Storage remains underrepresented among top players, creating differentiation opportunities.

Capture technologies dominate: Absorption and adsorption-based solutions lead, with emerging strength in advanced materials (MOFs, COFs, mxenes) and ion-exchange membranes.

Fuel conversion accelerating: Utilisation pathways, particularly conversion to fuels (diesel, aviation, gasoline), show the fastest growth. Aviation fuel represents one of the hottest patent areas.

Storage gaining momentum: Though lower volume than capture (~1:10 ratio), all storage approaches show positive growth, signaling investor interest in this nascent domain.

Opportunities

Storage technologies: Top players underinvested; attractive entry point. **Fuel conversion:** Fastest-growing segment; strong commercialisation potential. **Advanced materials**: Membranes and sorbents show sustained momentum. **Biotic solutions**: Emerging link between carbon management and land-use applications.

Full Analysis

For a comprehensive analysis including field maps, detailed trend plots, and company-specific activity heatmaps, please consult the complete CCUS Patent Landscape Report.

Analysis based on 20,346 patent families (priority date 2016–2025) | Methodology: Derwent Innovation database + AI-driven unsupervised topic modelling (Mynd-Ware). Report prepared by Dr. Jelle Demeulemeester, Mynd-Ware | November 2025

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Introduction

Carbon capture, utilisation and storage (CCUS) refers to a suite of technologies that capture CO_2 from large point sources such as power plants, refineries and industrial facilities, or directly from ambient air, and then either use it in products and processes or store it permanently. By preventing CO_2 from entering the atmosphere – or embedding it in long-lived products – CCUS is widely recognised as a critical option for decarbonising hard-to-abate sectors and supporting net-zero strategies alongside energy efficiency, renewable energy and demand reduction.

In practice, CCUS spans a diverse chain of activities. Capture technologies separate CO_2 from gas streams using solvents, sorbents or membranes. The CO_2 can then be transported and either stored in geological or biotic reservoirs (such as depleted oil and gas fields or saline aquifers) or utilised as a feedstock for fuels, chemicals, materials and other products. This diversity is reflected in a rapidly evolving innovation landscape, where new materials, processes and applications are being developed in parallel.

This report provides a quantitative, patent-based perspective on that landscape. It is based on a dataset of 20,346 patent families published in the last decade. To move beyond traditional metadata statistics, the analysis uses Mynd, a SaaS platform powered by an AI-driven unsupervised topic-modelling engine. These machine-generated insights were reviewed and interpreted by domain experts, ensuring that the resulting maps and trend plots are both data-driven and contextually meaningful.

The report focuses on four main analytical dimensions:

1. **Metadata trends**
   A review of overall patent activity since 2016, including growth rates, the evolution of new patent family initiations, and geographic patterns based on country codes. This includes a closer look at leading jurisdictions and how their recent activity compares in terms of recency.

2. **Applicant landscape and strategic focus**
   An analysis of the top 25 corporate players, their relative patent volumes and recency scores, and a heatmap of how their activity is distributed across capture, storage and utilisation. This highlights both areas of concentration and visible "white spaces" in corporate CCUS strategies.

3. **Contextual topic map of the CCUS field**
   A field map generated by Mynd, showing how major themes in CCUS patents cluster and relate to each other. The map provides a high-level overview of central topics (e.g. general capture systems and materials) and more specialised clusters (e.g. biotic technologies, structural components,

reaction systems), as well as recency signals that indicate the temporal dynamics in these fields.

4. **Deep-dive trend analysis in capture, storage and utilisation**
   A detailed examination of key concepts within the three core domains:
   - **Capture**, with separate trend analyses for absorption, adsorption and membrane-based technologies;
   - **Storage**, distinguishing between abiotic and biotic storage routes;
   - **Utilisation**, covering both conversion products (biotic utilisation, fuels, materials, chemicals) and conversion processes (e.g. mineralisation, hydrogenation, electrochemical routes).
     For each, volume–recency plots are used to position concepts along the innovation lifecycle, from emerging and high-potential topics to mature mainstream areas and declining niches.

By combining rigorous patent retrieval, unsupervised topic modelling and expert interpretation, this report offers stakeholders – including policymakers, project developers, industrial strategists, investors and researchers – a structured, quantitative view of how CCUS innovation is evolving. It aims to support informed decision-making by clarifying where activity is concentrated, which technologies and pathways are gaining momentum, and where gaps and opportunities remain across capture, storage and utilisation.

Methods

About the data

Derwent Innovation was used as the primary data source and search engine for this report. The database covers 76 jurisdictions and augments patent records with name harmonisation at different levels, field indexing, and “DWPI text fields”. In the latter, the title, abstract, and claims of a large fraction of patents are rewritten in more accessible, non-patent language, enhancing both keyword-based search and readability. In addition to its built-in analytics tools for metadata, the database allows records to be exported for further analysis with other tools, such as Mynd.

About the analysis

The analysis was conducted using Mynd, a SaaS platform powered by an AI-driven, unsupervised topic-modelling engine. Mynd is designed to automatically generate a hierarchical classification of topics discussed in extensive textual datasets, such as patents or academic papers. This approach provides professionals with both a comprehensive overview and a detailed understanding of published developments across various domains. Although academic papers could have been included, this study only uses patent data, as to focus on corporate activity and economic interest.

By leveraging an unsupervised methodology, the model identifies a diverse array of topics, including applications, materials, technologies, processes, properties, and functionalities. This enables researchers to discover and map concepts of interest comprehensively, without having to sift through thousands of documents or possess extensive prior knowledge.

In addition to topic classification, Mynd incorporates innovation-focused metrics such as the "recency" indicator. This metric analyses activity curves and growth rates and compares them with overall trends within the dataset. It helps quantify mainstream trends and identify declining or emerging patterns. Throughout this report, the recency metric is used to shed light on the latest dynamics and trends in the analysed datasets. More detailed information about the interpretation and behaviour of this innovation-oriented metric can be found in this review paper.[1]

[1] Van Huele A. *et al., AI-driven scientometric analysis with recency insights: lower urinary tract symptoms in older and frail populations,* World J Urol. 2025 Jul 16;43(1):438.

1. Search Strategy

To achieve the goal of this patent landscape study, a patent pool was carefully constructed using a hybrid query strategy. The query consists of three parts: one part relying purely on Cooperative Patent Classification (CPC) codes that are unambiguously linked to CO_2 capture, utilisation or storage; a second part relying purely on relevant keyword usage in the title, abstract or claims; and a third part using a hybrid approach in which relevant yet slightly ambiguous CPC codes are combined with keywords in the title, abstract or claims to ensure the patents are exactly on topic.

For each part of the query, several iterations were performed. In each iteration, a random set of 50 patents was carefully examined and categorised as either signal (relevant) or noise (irrelevant). For patents classified as noise, an assessment was made to determine whether their inclusion could have been avoided. Where possible, the query was adjusted accordingly. These iterations were repeated until at least a 90% signal-to-noise ratio was achieved.

A more detailed overview of the query parts is provided below:

- **Pure CPC code-based query**
  The following CPC codes were identified and included with OR logic:
    - Y02C002040: Capture, storage, sequestration or disposal of greenhouse gases [GHG]; CO2
    - Various maingroups within Y02P (climate change mitigation technologies in the production or processing of goods), specifically mentioning CCUS
    - H01M00080668: Removal of carbon monoxide or carbon dioxide
    - C10G000250: Cracking hydrocarbon oils; production of liquid hydrocarbon mixtures from carbon dioxide
    - C25B00032: Electrolytic production of organic compounds; reduction of CO2
    - C07C000112: Acyclic or carbocyclic compounds; preparation of hydrocarbons from one or more compounds; from carbon dioxide with hydrogen
    - B01D00531475: Removing carbon dioxide by absorption
    - B01D2257504: Separation, components to be removed; carbon dioxide

- **Keyword-based query**
  A general good practice in constructing a keyword-based query is to use as few keywords as possible, in order to minimise bias towards specific terminology. The keywords were searched using proximity search in title, abstract or claims:

(("co2" OR "carbon dioxide") NEAR3 (captur* OR stor* OR utiliz* OR utilis* OR conver* OR mitigat* OR sequestr*))

- **Hybrid CPC–keyword query**
  For the hybrid query, several CPC codes that were strongly, but not exactly, linked to CCUS were combined with more specific CCUS terminology (AND logic) to increase the signal-to-noise ratio:
  - CPC codes: Y02C* OR B01D0053526 OR B01D00531462 OR B01D00538618 OR C01B000332 OR B01D 2256/245 OR C01B 32/50 OR B01D2258/0283
  - Keywords: (("co2" OR "carbon dioxide") AND (captur* OR stor* OR utiliz* OR utilis* OR conver* OR mitigat* OR sequestr*))

The scope of this landscape spans a 10-year timeframe, including all patents with a priority date on or after January 1, 2016.

Initial findings indicated that the patent dataset contained a significant portion of single Chinese patents. Since Chinese patents with no other patent family members hold little value for this type of analysis, these single-family Chinese patents were omitted.

The final query resulted in a patent dataset of 20,346 family representatives since 2016. Based on a random sample of 50 patents from the combined pool, the noise ratio was determined to be less than 5%, which is considered an excellent benchmark.

2. Meta data analysis

Patent Activity

Figure 1 shows how annual patent publication activity has evolved over time. The black bars represent all patents in the dataset (including those filed in China), while the cyan bars isolate patents filed in jurisdictions other than China. The graph does not track all patent publications, but specifically the initiation of new patent families. It therefore reflects the rate at which new inventions enter the CCUS space, rather than the extent to which they seek broader geographic protection.

A key caveat is important when interpreting recent years. Patent applications can take up to 18 months to become publicly available. As a result, the counts for 2024 and especially 2025 are incomplete and are expected to increase substantially.

Several patterns stand out. The low counts for 2016 indicate that, prior to this year, CCUS was still a marginal topic in patenting terms. Within less than a decade, however, activity has expanded to a substantial volume of more than 20k patent families. Between 2020 and 2023, the CCUS patent space grew at an average compound annual growth rate (CAGR) of 23%, corresponding to a doubling of the annual rate of new inventions roughly every 3.3 years. This growth far exceeds the global average growth rate[2] of 2.7% for intellectual property filings reported in 2023, underscoring the sustained interest in—and strategic importance of—CCUS.

[2] Global IP filing activity in 2023 reported by WIPO (IP Facts and Figures)

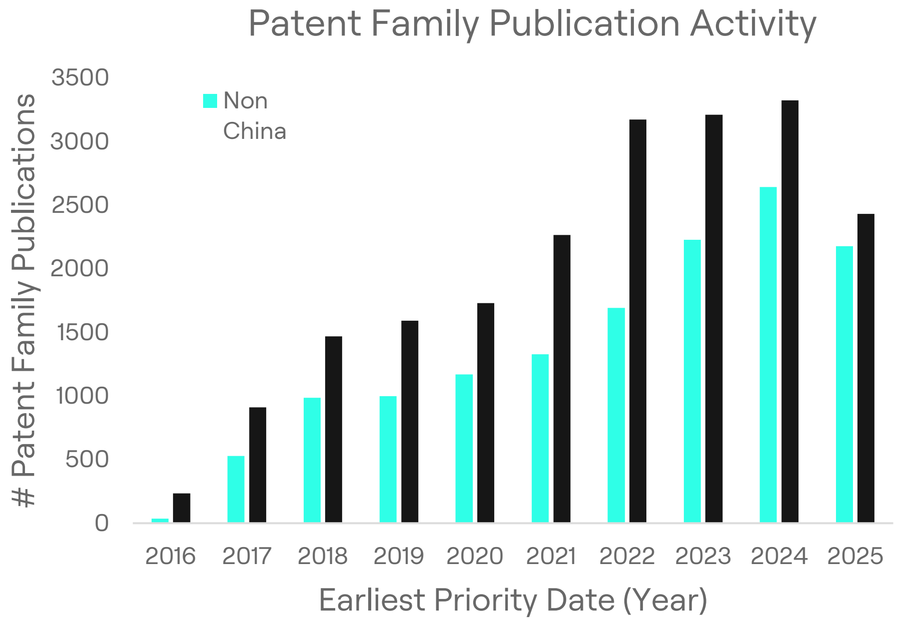

Figure 1: Publication activity of patent families as a function of year. The black bars represent all patents in the dataset (including those filed in China), while the cyan bars isolate patents filed in jurisdictions other than China.

Geographical Spread

Figure 2 presents the results of a country-code analysis, providing a detailed view of global patent filing trends. The analysis takes into account the country codes of all family members, offering a comprehensive picture of where organisations perceive market potential and, consequently, choose to seek patent protection.

The top map visualises publication volumes per country using a cyan colour scale, with darker shades indicating higher filing volumes. The bottom map highlights recency trends: orange indicates countries with a very high growth rate compared with the global average, whereas yellow indicates significantly below-average growth. The bar chart on the left-hand side provides a more quantitative overview of the top 10 country codes, with a colour code indicating the recency score. Patents filed with the WO country code were omitted from this graph, and all EU country codes were aggregated together with the EP country code into the bar "Europe".

China holds the largest number of patent families, followed by the USA and Europe, which together complete the top three. It should be noted that, because all single patent families from China were omitted, the actual number for China is higher. Moreover, China has a distinct patent filing culture: it not only produces an exceptionally high volume of patents—often criticised for questionable quality—but also consistently outpaces global averages in annual patent filing growth across numerous sectors.[2] The top 10 is further completed by four other Asian countries (South Korea, Japan, India and Taiwan), as well as Australia, Canada and Brazil.

Apart from Brazil and Canada, which show a clearly lower recency score (indicating slower activity growth in recent years compared with other countries), the remaining countries in the top 10 exhibit similar recency levels. This suggests that most leading jurisdictions are progressing at a comparable pace in filing new CCUS-related inventions.

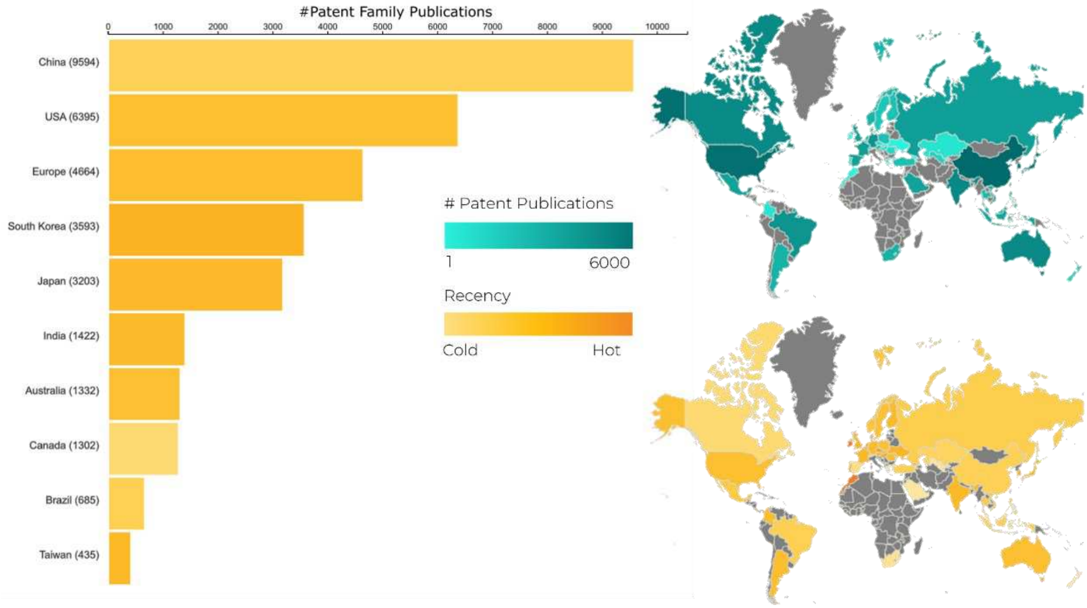

Figure 2: Country code analysis of global publication activity. The analysis includes all family members (not only family representatives) to provide a complete overview of where organisations are seeking patent protection. The top map shows the relative distribution of patent filings per country, while the bottom map illustrates the relative differences in recency of filing activity across countries. The bar chart on the left-hand side offers a quantitative view of filing volumes and recency scores for the top 10 country codes. For clarity, patents with the WO country code are not shown, and all EU country codes are consolidated together with the EP code in the bar labelled "Europe".

Applicant Analysis

Figure 3 provides an overview of the top 25 corporate players in patent filings. Bar length represents the number of patent families filed by each company, while the colour scale captures the recency of their activity, with orange indicating the most recent patenting activity.

The number one position in sheer patent publication volume is shared between the Saudi Arabian Oil Company and Air Liquide, closely followed by Mitsubishi. The top three therefore comprise a Western company, a Middle Eastern company and an

Asian company. Although Air Liquide shares pole position in terms of portfolio size, its recency score indicates that its CCUS patent portfolio has been expanding at a slower pace in recent years compared with the other two leading players. As noted throughout this report, no assessment is made here of the quality, innovativeness or commercial potential of individual patent filings. Below the top three, there is a marked drop in filing volume: ExxonMobil has 166 patent families compared with 248 for Mitsubishi.

Given that China has the largest overall volume of patents (Figure 2), it is noteworthy that Chinese companies do not dominate the top 25. Only two Chinese companies (China Huaneng Group and Xian TPRI) appear in this ranking. One explanation is that Figure 3 focuses solely on corporate applicants. A separate analysis of all applicants (not shown) indicates that much of China's patenting activity in CCUS originates from a large number of Chinese universities rather than from corporate entities. By contrast, Japanese companies play a prominent role in the top 25: Mitsubishi,

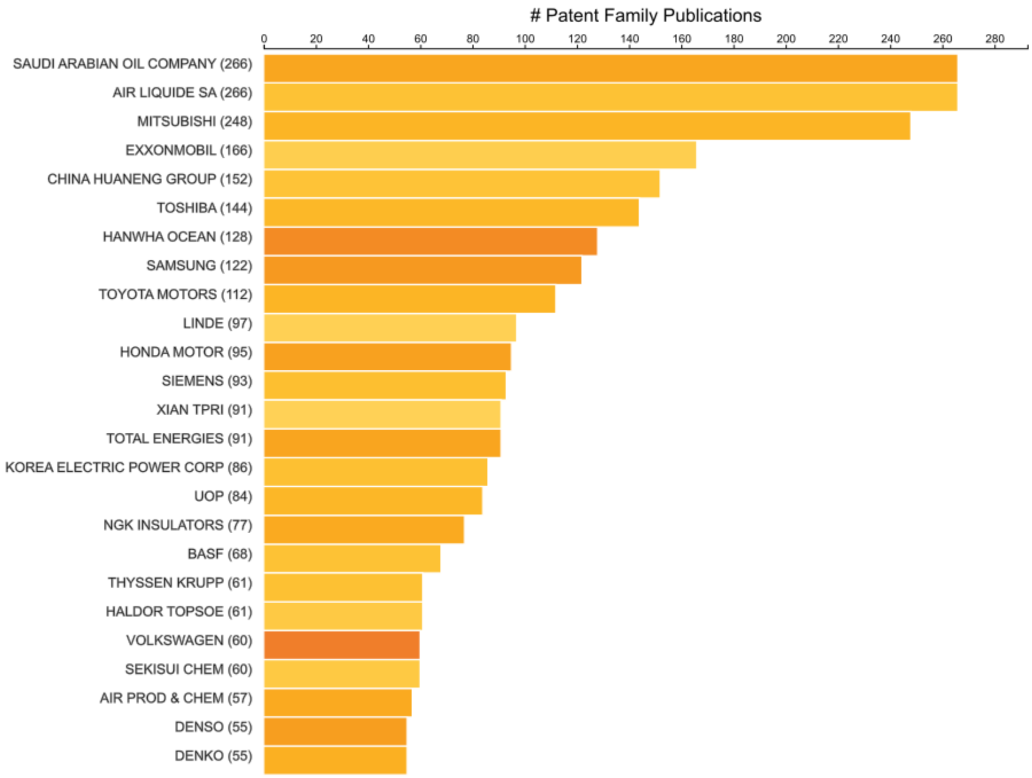

Figure 3: op 25 corporate patent filers in the field of CCUS. The x-axis shows the publication volume (number of patent families) for each company, while the yellow-to-orange colour gradient indicates the recency of their patenting activity, with orange representing the highest recency values.

Toshiba, Toyota, Honda, NGK Insulators, Sekisui Chem, Denko and Denso together occupy 8 of the 25 positions.

In terms of recency a number of players stand out: Volkswagen, Hanwha Ocean, Samsung, Honda Motors, Total Energies, Denso and Sausi Aramco. The high recency scores for these companies signals active recent innovation efforts to build robust patent portfolios in CCUS.

Many other well-established players, though not featured in the top 25, occupy strong positions just outside this list. Evidently, one does not have to be in the top 25 to have strong and impactful innovations in the field of CCUS.

4. Topic Model Analysis

4.1 Field Map

Mynd generates a field map by analysing the content and contextual relationships within the titles and abstracts of patents (see Figure 4). This map visually groups coherent topics and represents them as labelled circles, each indicating the field name, the volume of related patent families and a recency score.

Map visuals and interpretation

- Circle size
  The size of each circle represents the volume of patent families associated with that field. Larger circles correspond to fields with more patent activity.
- Arrows
  - Upward arrows: Coloured in gradients from black to red, these indicate trending fields with high recency scores.
  - Downward arrows: Coloured from black to blue/purple, these point to declining fields with low recency scores.
  - Horizontal arrows: Black horizontal arrows indicate fields that broadly follow the general growth trend of the overall dataset.
- Proximity of circles
  The distance between circles reflects the degree of contextual overlap between fields. Fields that are positioned close to one another share substantial terminology or concepts, forming clusters that are easier to interpret as related thematic areas.
- Central positioning
  Fields located near the centre of the map tend to share terminology broadly across the dataset. These can be interpreted as central themes within the CCUS patent landscape.
- Axes
  The x- and y-axes do not carry specific, independent meaning. Instead, it is the relative spatial arrangement of circles that is important for interpretation.

Key findings and trends

The map's unsupervised topic modelling covers diverse aspects, including materials, applications, processes, technologies and properties. While individual exploration of the field map is strongly recommended, several notable patterns stand out:

- Central fields
  The centre of the map is dominated by more general, system-level fields, such as CO_2 absorber–regenerator systems, fluid flow and vessel communication, reforming processes for gas conversion, and CO_2 capture absorption materials.
- Hottest fields
  The hottest fields with relatively large volumes are sorbent materials for direct air capture and synthesis and post-treatment of CO_2 capture materials, indicating intense and recent innovation activity in these areas.
- Right side of the map
  The right side mainly groups biotic-oriented technologies, with fields such as microalgae growth, microbial gas fermentation and bioreactors, and metabolic enzymes in CO_2 assimilation. The bottom-right area of the field map clusters capture-material topics, including imidazole-based ZIFs, diamine and dianhydride monomer synthesis, ionic liquid anions, and related materials.
- Left side of the map
  The left side is largely associated with structural components, including honeycomb structures and partition walls, plate–frame and wall structures, and systems such as washing columns and distillation tanks.
- Bottom side
  The lower part of the map contains fields focused on reactions and conversions, such as synthesis and post-treatment of CO_2 capture materials, multi-stage reactor systems, electrochemical cell components and reactions, and photoelectrochemical semiconductor systems.
- Top side
  The upper part concentrates around cryogenic and energy-related systems, including LNG liquefaction, liquefied hydrogen storage, off-gas boil-off treatment for liquefied gases, steam generation and CCS boilers.

The richness of content in the field map provides a comprehensive, high-level overview of the dynamics in the CCUS patent landscape. While general guidelines for interpretation are given here, exploring the clusters and trends through individual analysis will yield deeper insight into specific areas of innovation and growth.

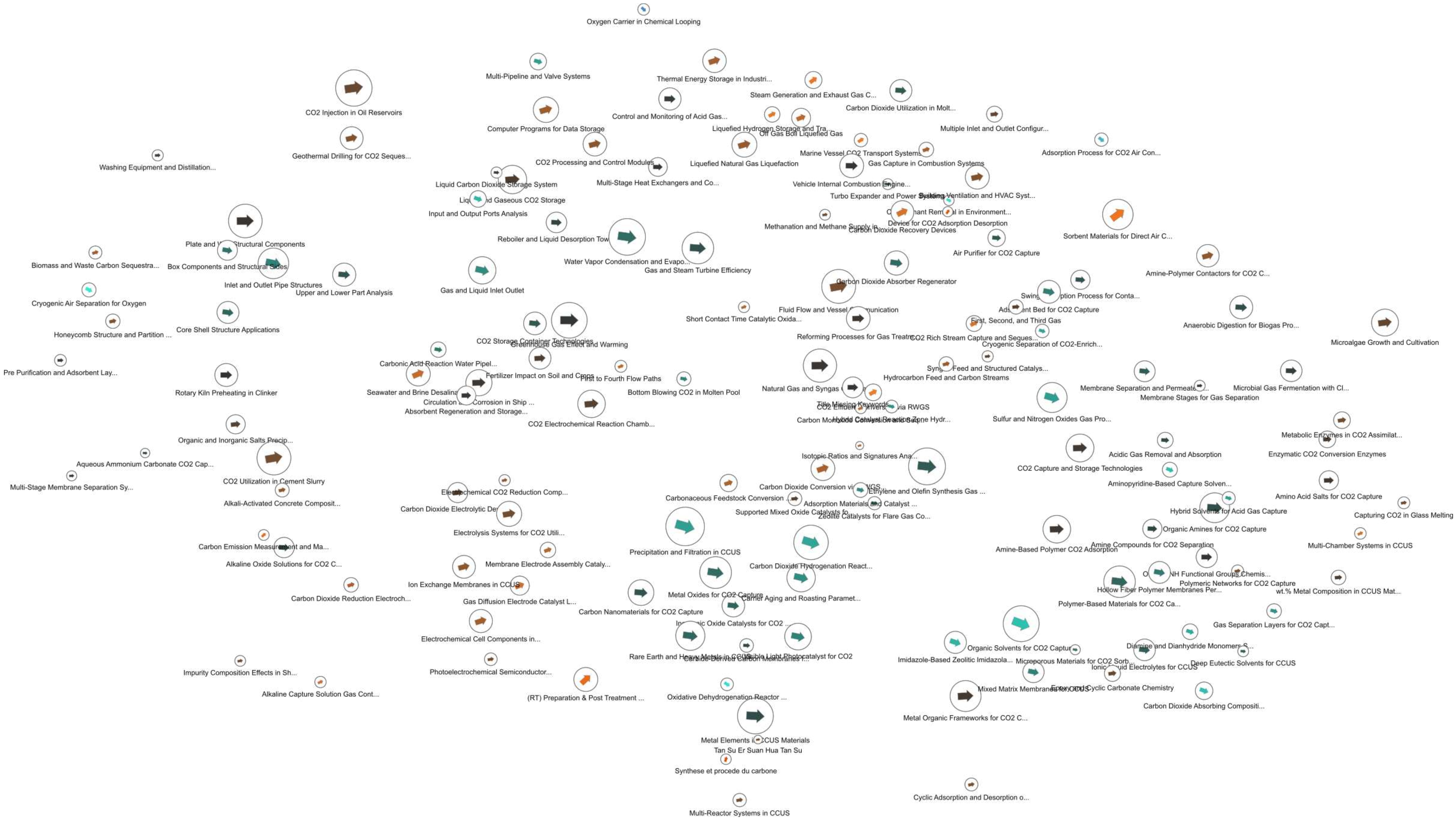

Figure 4: Mynd field map of the CCUS patent landscape. Each coherent field of discussion that was identified in the dataset by Mynd is displayed as a circle with a size, arrow (and matching colour), position and title. The size is a measure for the number of publications on this field, whereas the arrow (and matching colour) indicate the recency (Orange for hot, black for mainstream, and purple for declining. X- and y- axis don't have a specific meaning, but the distance between fields is a measure for the contextual overlap they have. The closer fields are positioned, the more context they have in common

Exploring the Contextual Content of the Patent Landscape

This section delves deeper into the contextual content of patents, categorizing the concepts identified by Mynd into distinct groups to better understand and quantify the trends within them. The categories are as follows:

- **Capture**: This category includes all technologies, systems, materials, and processes that are designed to extract, separate, or concentrate carbon dioxide (CO_2) from a gas mixture, such as flue gas from power plants, industrial process streams, or ambient air. These technologies serve as the initial step in the carbon management chain and are essential to reducing CO_2 emissions before it enters the atmosphere. Capture methods may be post-combustion, pre-combustion, or oxy-fuel based, and they may involve physical or chemical interactions. Concepts captured in this category have been subdivided in the following subcategories:
    - **Absorption**: Absorption-based capture materials/technologies rely on the dissolution of CO_2 into a solvent. This process may be either chemical (involving a reaction between CO_2 and reactive components in the solvent) or physical (based purely on CO_2 solubility without reaction), after which the solvent is regenerated to release a concentrated CO_2 stream.
    - **Adsorption:** Adsorption-based capture materials/technologies rely on the attachment of CO_2 molecules onto the surface of a solid sorbent. This process may be physical (driven by weak intermolecular forces) or chemical (involving stronger surface interactions), after which changes in temperature and/or pressure are used to release the CO_2 and regenerate the sorbent.
    - **Membranes:** Membrane-based capture technologies rely on the **selective transport of CO_2 through a membrane** that preferentially allows CO_2 to pass while retaining other gases. A driving force such as a **partial pressure, concentration, or electrical gradient** is applied across the membrane, producing a CO_2-enriched permeate stream and a depleted retentate stream without the need for a separate regeneration step.
- **Storage**: This category covers all technological approaches that aim to permanently or semi-permanently store captured CO_2 in order to prevent its release into the atmosphere. Storage solutions may involve physical injection into geological formations, biological fixation, or mineral conversion. The objective is long-term sequestration in forms that are environmentally stable and economically feasible. Concepts captured in this category have been subdivided in the following subcategories:

    - **Abiotic storage**: Abiotic storage includes all CO_2 storage approaches that rely on physical and chemical processes in non-living reservoirs, which aim to immobilise CO_2 for long timescales to (near-)permanent sequestration without relying on biological uptake.
    - **Biotic storage:** Biotic storage includes all CO_2 storage approaches that rely on living organisms and ecosystems to capture and retain carbon, primarily through photosynthesis and subsequent storage in biomass, soils, and sediments. It covers options such as managed forests, soils, wetlands, and marine ecosystems, where carbon is stored in living and dead organic matter over years to centuries rather than in purely geological reservoirs.
- **Utilisation:** This category encompasses technologies and processes that make use of captured CO_2 to create valuable products, materials, or services. Utilization can provide an economic incentive for CO_2 capture and may help reduce net emissions when combined with low-carbon energy. Utilization pathways can be biological, chemical, or physical in nature, and they vary in whether CO_2 is permanently sequestered or only temporarily retained. Concepts captured in this category have been subdivided in the following subcategories:
    - Biological utilisation: Biological utilization includes CO_2 use pathways where captured CO_2 ends up in bio-based products, materials, or services created by living systems. Typical end uses include algae- or microbe-derived fuels, chemicals and plastics, food and animal feed ingredients, and bio-based materials (e.g. construction or biomaterials), in which the carbon is stored in biomass or bio-derived products for varying periods of time.
    - Final products: Conversion products/end products include uses where captured CO_2 is converted into non-biological products and materials, such as synthetic fuels, bulk and fine chemicals, polymers, and building materials. In this subcategory, CO_2 acts as a carbon feedstock embedded in the final product or energy carrier, with the duration of carbon storage depending on the product's lifetime (short for fuels, longer for materials like polymers and concrete).
    - Conversion technologies: Conversion technologies include the processes that transform captured CO_2 into other molecules or materials through chemical, electrochemical, thermal, photonic, or biological pathways.

Understanding Volume-Recency Plots

In addition to categorising concepts, volume–recency plots (or trend plots) are used to visualise and quantify trends within each category. These plots allow both absolute and relative comparisons of how "trendy" individual concepts are. A general volume–recency plot is shown in Figure 5 for illustration. Such plots are designed to identify the forefront of innovation using two key parameters:

- **Volume (y-axis):** The number of patent documents associated with a concept, plotted on a logarithmic scale.
- **Recency (x-axis):** A measure of how recent the patents are, with higher values indicating more recent activity.

Given sufficient data points, the resulting distribution typically takes on Gaussian-like shape that reflects the innovation lifecycle:

- **Mainstream concepts**
  Located towards the top of the pyramid, these concepts have high publication volumes. They are neither new nor obsolete; instead, they represent core ideas that form the backbone of the field.
- **Emerging concepts**
  Found at the bottom-right of the pyramid, these are recently introduced concepts with low volumes. They represent areas of early research and development. Many emerging concepts fail to gain traction and gradually shift toward lower recency values, contributing to the broad base of the pyramid.
- **High-potential concepts**
  Positioned diagonally between emerging and mainstream concepts, these ideas have accumulated some volume while maintaining high recency scores. Their continued growth suggests that they merit further investment and exploration.
- **Radical innovations**
  In rare cases, a concept appears at the far right of the pyramid with both high recency and substantial volume. These represent radical innovations that have rapidly gained widespread attention and temporarily disrupt the usual innovation cycle.
- **Lagging concepts**
  Concepts on the left-hand side of the graph, with low recency values, are in decline. Those with low volumes were abandoned quickly and never gained traction. Higher-volume concepts may represent ideas that are now well implemented and mature, or areas that have ultimately proved to be dead ends.

By categorising concepts and analysing their positions within the volume–recency plot, this approach provides a clear framework for understanding the lifecycle of innovation within the CCUS patent landscape. Whether a concept is emerging, mainstream or in decline, the analysis highlights opportunities and areas for further exploration, as well as identifying truly radical innovations.

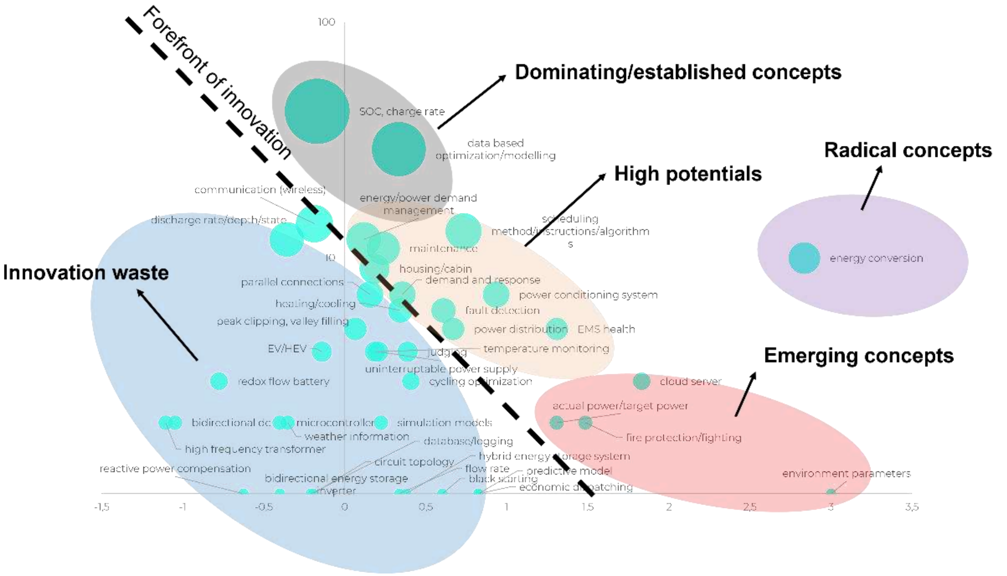

Figure 5: General volume recency plot to indicate how such an analysis should be interpreted.

4.2.1 Trends in Capturing

Absorption

Figure 6 illustrates trends in absorbents related to CCUS. The black dots predominantly represent individual absorbents, while a limited number of absorbent groups (shown in cyan) have been added to provide a more comprehensive overview at different levels of aggregation. Individual chemicals (e.g. specific carbonates versus the broader group *carbonates*) are displayed alongside their parent groups to give more granular insight within the same trend analysis.

The volume axis is plotted on a logarithmic scale, reflecting the wide range in patent

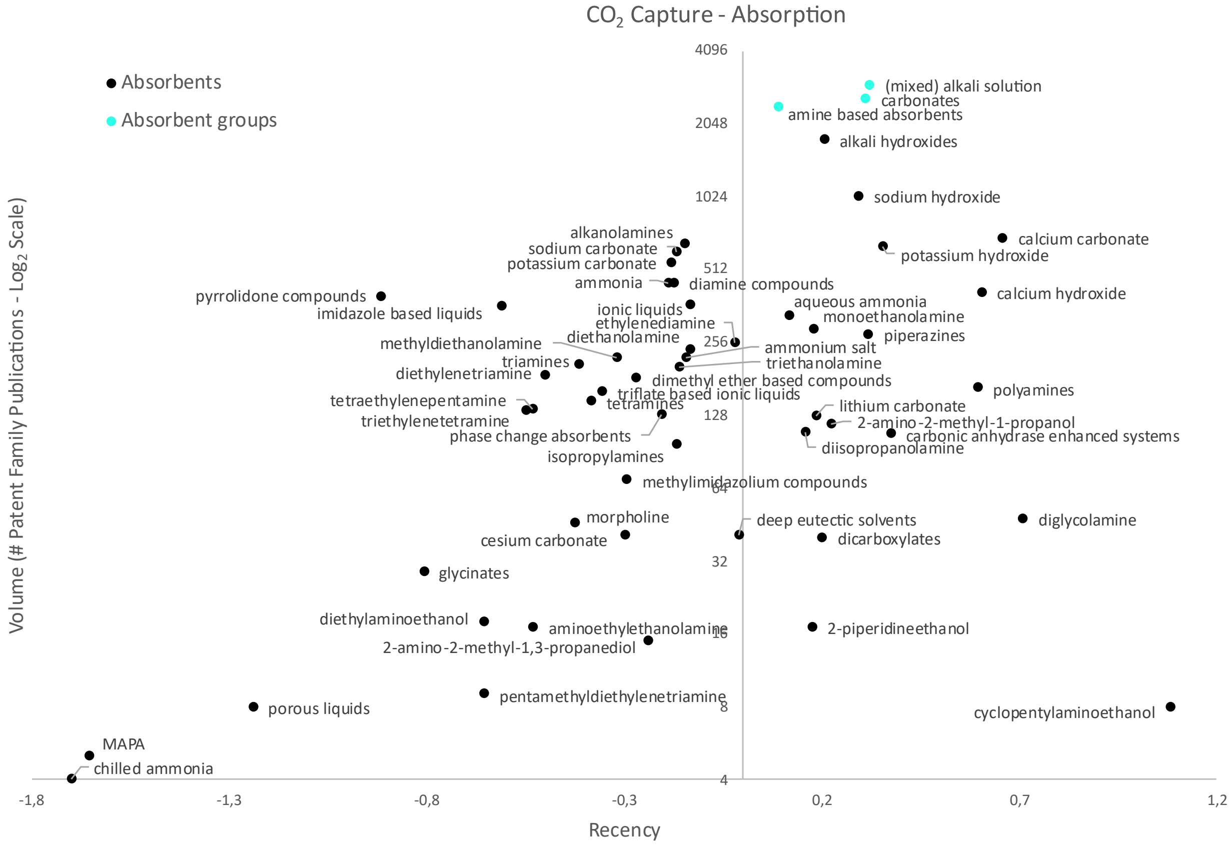

Figure 6: Volume–recency trend plot of absorption materials/technologies in the CCUS patent landscape.

publication volumes: mainstream absorbents appear in several thousand patents, whereas emerging absorbents may be covered by only a handful of documents.

Evidently, the chemical groups *alkali solutions*, *carbonates* and *amine-based sorbents* dominate the trend as mainstream absorbents, combining the highest patent volumes with strong average recency and growth parameters. They are followed immediately by individual absorbents such as alkali, sodium, potassium and calcium hydroxides and calcium carbonates. These absorbents combine both high volume and high recency, indicating that, despite their already substantial patent footprint, innovation in these areas continues to grow at an above-average rate.

Absorbents with lower volumes but high recency scores include several amines (polyamines, monoethanolamine, diglycolamine, diisopropolamine), piperazines, aqueous ammonia and others. On the lower-recency side of the graph, additional individual amines appear with high patent publication volumes. The broad spread of amines across both positive and negative recency values—yet largely within high-volume regions—indicates that amines remain a diversified and active area of research for absorption in the context of CCUS.

Adsorption

Analogous to the absorbents analysis, Figure 7 depicts trends in adsorbents within the CCUS patent landscape. The black dots mainly represent individual adsorbents, while several have been grouped into broader concepts such as zeolites, MOFs, COFs and molecular sieves.

At the mainstream level, zeolites (almost 1,000 patents), MOFs (around 500 patents) and molecular sieves feature prominently. Molecular sieves, however, exhibit a lower recency value, indicating a diminished growth rate in recent patent activity. COFs occupy a lower publication volume but show a higher recency score, pointing to a faster-growing innovation pace in this area.

Among individual adsorbents, the leading concepts include activated carbon, calcium oxide, cellulose-based materials, clay minerals, imines, carbon nanotubes (CNTs) and silanes. In the emerging area of the trend plot, one can find CALF-20 (a MOF material), acidic gas adsorption, GIS-type zeolites and mxenes, all of which combine low-to-moderate volumes with relatively high recency scores.

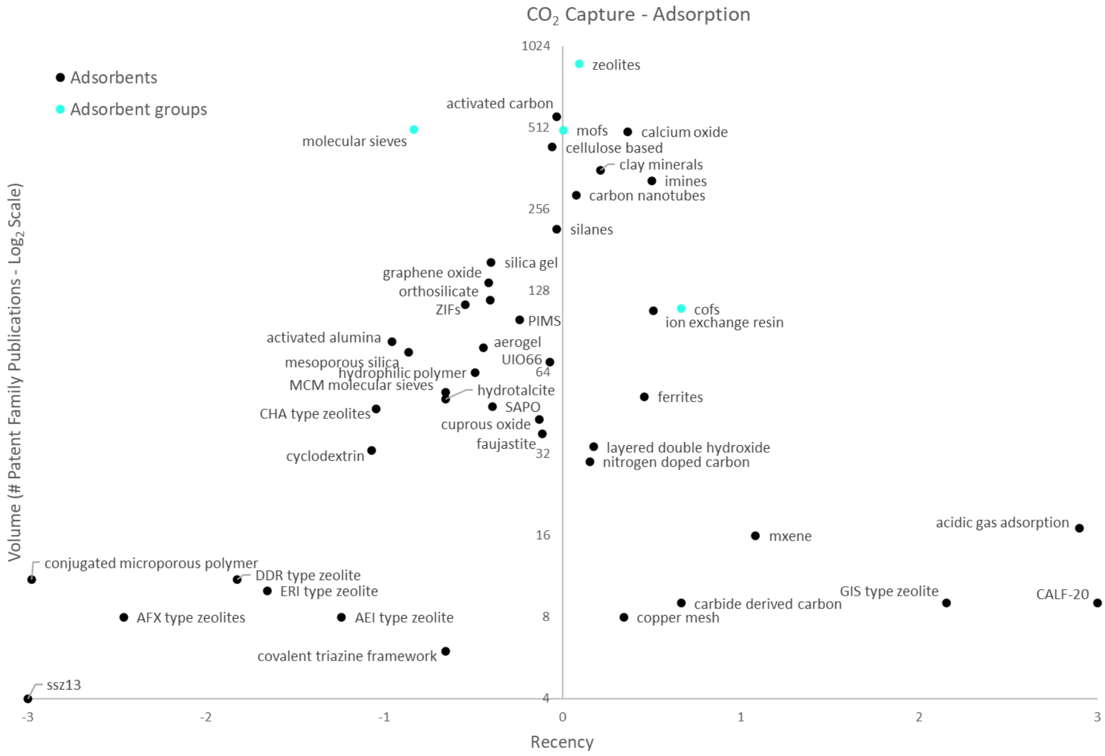

Figure 7: Volume–recency trend plot of adsorption materials/technologies in the CCUS patent landscape..

Membranes

Figure 8 presents a trend plot for specific membrane technologies in the CCUS patent landscape. Compared with absorption and adsorption, fewer distinct membrane materials appear as individually patented concepts. Ion-exchange membranes sit at the top of the trend analysis: in addition to having the highest patent activity, they display a markedly above-average growth rate, signalling intensive and sustained innovation in this field.

Hollow fibre membranes and polydimethylsiloxane-based membranes also account for substantial patent volumes, but their recency scores indicate slowing growth compared with the dataset average. By contrast, patenting activities in polymer electrolyte membranes and bipolar membranes are growing at an above-average pace, positioning these as dynamic areas of membrane research.

The most emerging membrane technology in the context of CCUS is spiral membranes, which combine relatively low volume with high recency, marking them as a nascent but rapidly developing topic in the patent landscape.

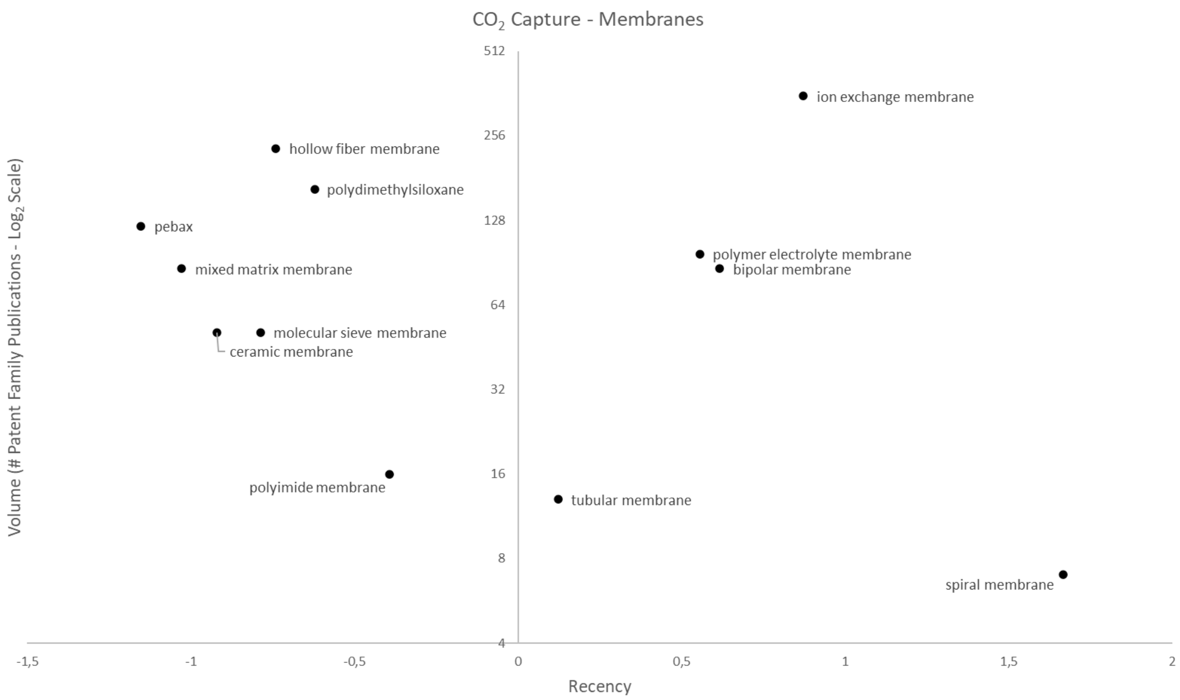

Figure 8: Volume–recency trend plot of membrane materials/technologies in the CCUS patent landscape.

4.2.2 Trends in Storage

Figure 9 presents trends in patent activity related to CO_2 storage solutions. Biotic storage solutions are shown in cyan, while abiotic storage solutions are shown in black. A high-level inspection of the trend graph reveals several observations.

First, the overall patent volume for storage solutions is roughly an order of magnitude lower than for capture technologies (a few hundred versus a few thousand patent families). Several factors may help explain this difference. Capture technologies offer many opportunities for patenting individual materials and configurations: each new tweak in structure, formulation, operating window or process configuration can constitute a separate invention. In addition, capture technologies are often scalable, widely applicable and relatively easy to license to third parties.

By contrast, storage solutions are typically tied to specific reservoirs or hubs at defined geographic and geological locations. As a result, storage is predominantly engineering-driven, with project-specific solutions whose underlying know-how is not always easily valorised or transferred to other projects.

Second, despite the lower volumes, the recency values for storage concepts are generally more positive than for capture. All detected storage concepts—except coal seams—show positive to strongly positive recency values, indicating a clear awakening in IP activity on this front.

Within the biotic group, algae biomass accounts for the largest number of patents, although biotic solutions overall tend to have lower recency values than abiotic storage options. In the abiotic group, enhanced oil recovery stands out with the largest patent volume.

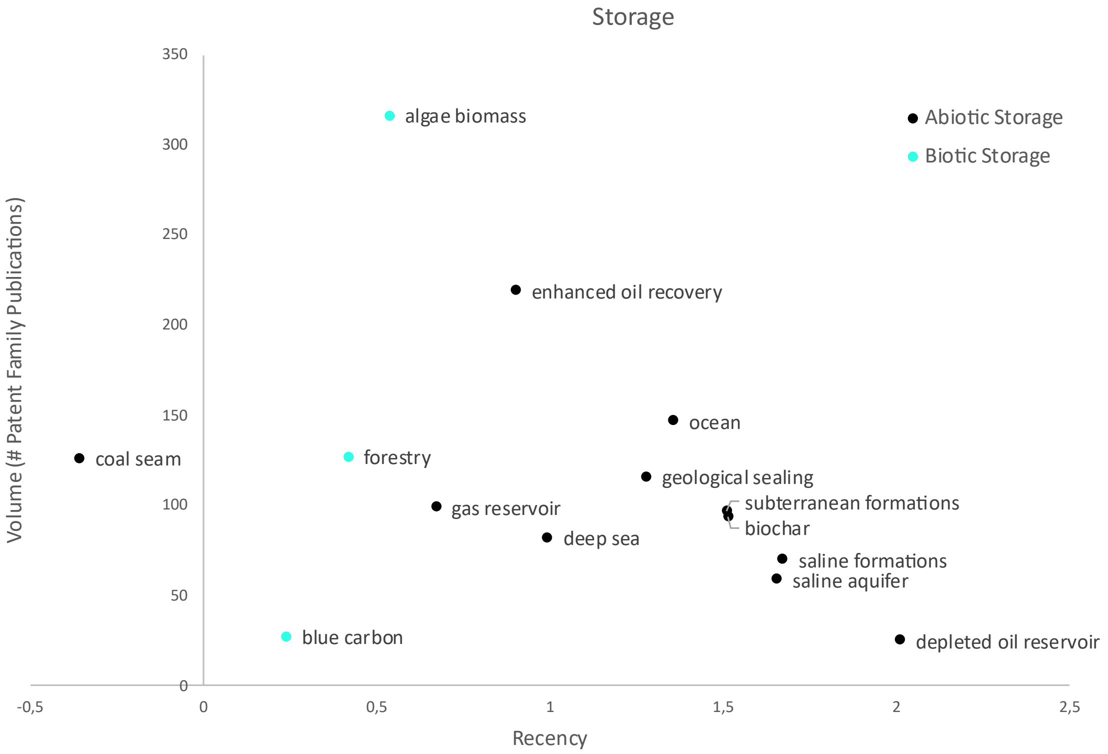

Figure 9: Volume-recency trend plot of the storage solutions in the context of CCUS.

4.2.3 Trends in Utilisation

Conversion products

Figure 10 illustrates trends in concepts related to conversion products and biological utilisation of CO_2. The highest patent volumes are associated with mineral carbonation and bicarbonates. Both also achieve relatively high recency scores, indicating that innovation activity in these fields is still accelerating rather than plateauing.

In the area of biological utilisation, *plant growth*, *algae biomass* and *fertilisers* all score high in terms of both volume and recency, signalling sustained interest in CO_2 use pathways that link directly to biomass and land-based applications.

Focusing on the right-hand side of the graph (the high-recency region), conversions of CO_2 into fuels stand out: fuels in general, as well as diesel, aviation fuel, gasoline, biofuels and LPG, all exhibit significantly higher innovation growth rates than many other utilisation routes. Aviation fuel, in particular, is marked as one of the fastest-growing areas of patent activity.

Beyond fuels, there is substantial interest in the conversion of CO_2 into methane, methanol, concrete, formate, ammonia and refrigerants. At the more emerging end of the spectrum, the use of CO_2 for pH control appears as a rising niche application.

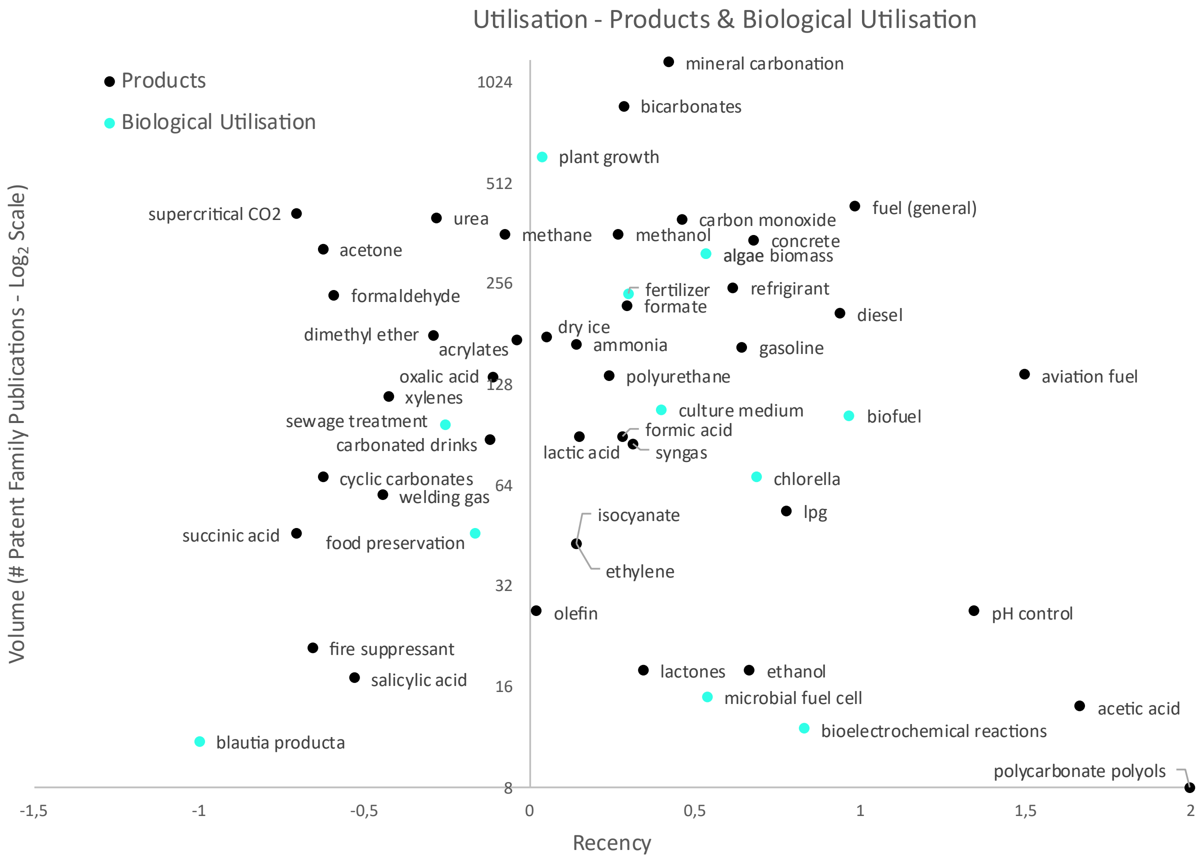

Figure 10: Volume-recency trend plot of biological utilisation and other utilisation products in the context of CCUS. biological utilisations are indicated in cyan, whereas other final products or utilisation cases are indicated in black.

Conversion Processes

The trends in the patent landscape for conversion processes are shown in Figure 11. All biological and physico-chemical pathways are displayed on the same graph to enable direct, relative comparison.

With over 1,000 patent families, *mineralisation* and *mineral carbonation* form the largest cluster by volume. This aligns with the high-volume trends observed for mineral carbonation and bicarbonates on the products side. The next tier—at less than half this patent volume—includes processes such as hydrogenation, electrochemical reduction, methanolation and methanation.

Among the more dynamic technologies, *oligomerisation* emerges as one of the most strongly emerging concepts, while *reverse water–gas shift* exhibits the highest recency score combined with a respectable patent volume. Together, these trends suggest a broad and increasingly diversified innovation landscape in CO_2 conversion pathways.

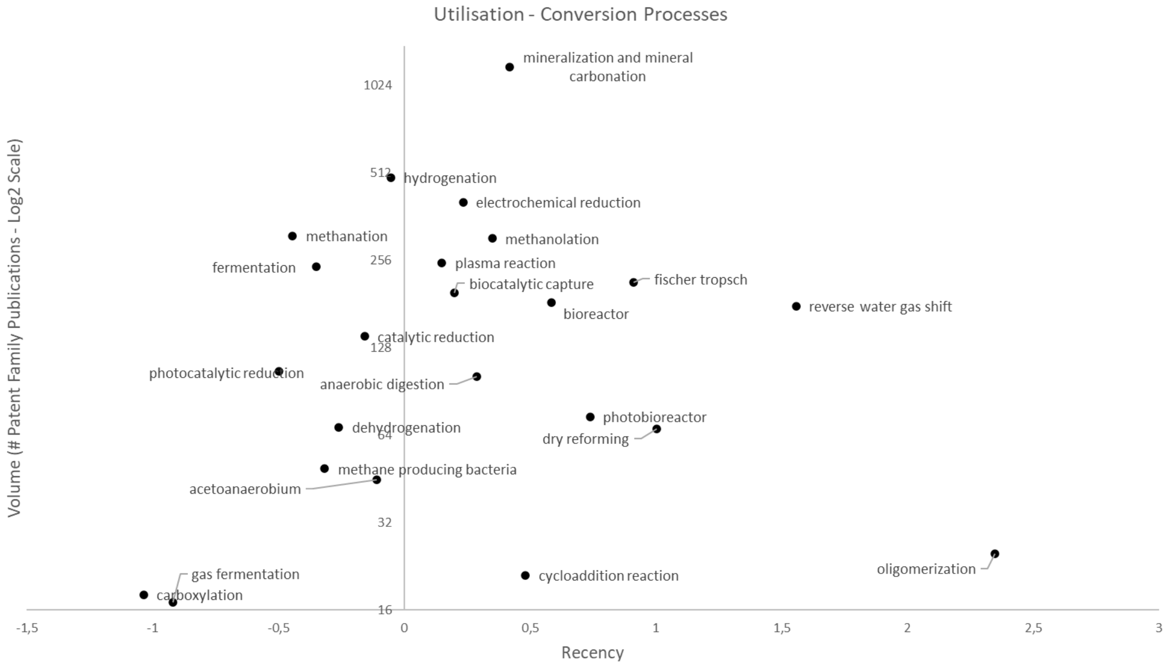

Figure 11: Volume-recency trend plot of conversion technologies in the context of CCUS.

[1]The figure presents the topics "methanol synthesis," "methanation," and "reverse water–gas shift" as distinct elements, reflecting how they are referenced in the patents. However, readers should keep in mind that these technologies also fall under the broader umbrella term "hydrogenation," which also appears in Figure 11.

[2] The "Oligomerization" topic relates to the linking of CO2 units with other molecules or itself to form larger compounds such as polymers, cyclic carbonates, carbohydrates etc..

4.2.4 Top player activity

Figure 12 presents a heatmap of the top 25 corporate players plotted against their patent activity in the three main categories: capture, storage and utilisation. The colour scale reflects the recency of patenting activity in each category, while the size/intensity of the cells indicates the relative volume of patents. The companies on the y-axis are clustered so that organisations with similar activity patterns across these categories are positioned close together, making it easier to spot common strategies and outliers.

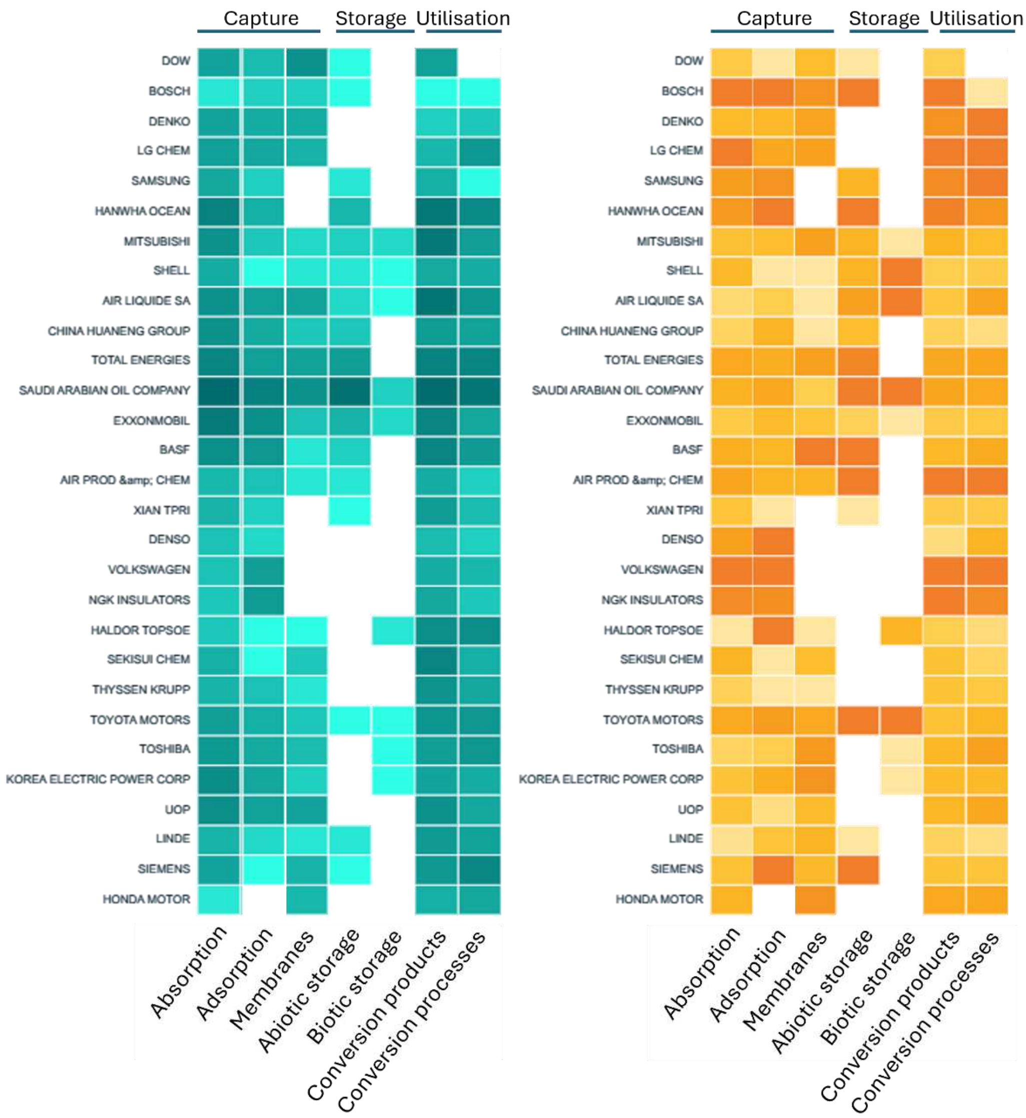

Figure 12: Heatmap of the top 25 corporate patent filers across the three main CCUS categories: capture, storage and utilisation. Cyan shading reflects the

relative volume of patent activity in each category, while orange shading indicates the recency of that act

A first observation is the presence of substantial "white spaces" in storage. Many of the top 25 companies show little or no patent activity in storage, and especially not in biotic storage solutions. At the same time, the two storage-related columns contain several dark-orange cells, consistent with the earlier finding that, although overall patent volumes in storage remain modest, activity is relatively recent and growing. Saudi Aramco stands out as a notable exception, having allocated a significant share of its IP portfolio to storage solutions.

Beyond storage, the overlap between the top 25 and membrane-based capture technologies also contains many white areas. Most leading players focus on absorption and adsorption, with a general bias towards absorption. Exceptions to this absorption/adsorption preference include Volkswagen, NGK Insulators and Bosh, which are more strongly oriented towards adsorption technologies.

A mild overall bias towards higher IP activity in utilisation compared with capture can also be observed. Not only is the utilisation column more densely populated, but the recency patterns indicate that several companies have intensified their patenting and innovation efforts in utilisation-related technologies in recent years.

5. Conclusion

The analysis of the CCUS patent landscape in this report is based on a dataset of 20,346 patent families published in the last decade, constructed through a carefully iterated hybrid CPC/keyword query with a high signal-to-noise ratio. Using Mynd's unsupervised topic modelling and concept identification, refined through human interpretation, the field of CCUS was mapped across metadata (activity, geography, applicants) and three core domains: capture, storage and utilisation. Trends were quantified via volume–recency plots to enable both absolute and relative comparison of innovation dynamics.

Below are the key conclusions, synthesised across the analysis:

1. Overall patent dynamics

- CCUS has shifted from a marginal topic before 2016 to a substantial patent domain within a decade, with more than 20,000 patent families identified.
- CCUS patent activity is characterized by a compound annual growth rate (CAGR) of 23%, far exceeding the reported global average IP growth rate of 2.7%. This implies CCUS is an area of vast innovation effort.

2. Geographic patterns

- China is the leading country in terms of patent volume, followed by the USA and Europe (aggregated EP + EU country codes), reflecting strong perceived market potential and policy relevance in these regions.
- Even after excluding single-family Chinese patents from the dataset, China remains the dominant filing jurisdiction.
- The top 10 also includes South Korea, Japan, India, Taiwan, Australia, Canada and Brazil, indicating a prominent role for both Asian and resource-rich economies.
- Aside from lower recent growth in Brazil and Canada, most leading jurisdictions are advancing at a broadly similar pace in filing new CCUS inventions.

3. Key players and strategic focus

- The leading corporate filers are Saudi Arabian Oil Company, Air Liquide and Mitsubishi, illustrating strong engagement from major energy and industrial companies across the Middle East, Europe and Asia. Japanese companies are particularly prominent, occupying a large share of the top 25.
- In contrast, only two Chinese corporations appear in the top 25, while a separate analysis indicates that much of China's CCUS patenting originates from universities rather than companies.

- The heatmap of top players versus capture, storage and utilisation reveals clear strategic patterns:
    - Most companies focus on capture, particularly absorption and adsorption, with relatively limited activity in membrane-based capture and storage.
    - Storage—especially biotic storage—shows substantial "white spaces" for many top players, even though the storage concepts that do appear tend to have high recency scores. Saudi Aramco stands out as one of the few companies with a notably strong position in storage.
    - A slight overall bias towards utilisation is visible: more companies have sizeable, and often rapidly growing, patent portfolios in utilisation than in capture, suggesting that CO_2 use routes are an increasingly important focus of corporate innovation strategies.

4. Technology trends in capture

- Capture currently forms the backbone of CCUS patenting by volume, reflecting the large number of patentable materials, configurations and process variants.
- In absorption, alkali solutions, carbonates and amine-based sorbents are established mainstream concepts that combine high volume with strong recency. The wide spread of individual amines across both high and low recency values at substantial volumes points to a mature yet still very active and diversified research area.
- In adsorption, zeolites, MOFs and molecular sieves are the core high-volume families, while COFs and a set of specific advanced materials (e.g. mxenes, CALF-20, GIS-type zeolites) appear as more emerging, high-recency topics.
- Membrane-based capture is comparatively less populated by distinct material families but shows particularly strong innovation dynamics in ion-exchange membranes, polymer electrolyte membranes and bipolar membranes

5. Technology trends in storage

- Storage solutions show patent volumes roughly an order of magnitude lower than capture, consistent with their project-specific, site-dependent and engineering-driven nature, which offers fewer modular, easily licensable inventions.
- Despite this, storage stands out for its positive innovation momentum: all storage concepts except coal seams have positive to strongly positive recency scores, signalling a clear awakening in IP activity.
- Overall, abiotic approaches currently show higher recency than biotic ones.

6. Technology trends in utilisation

- On the products side, mineral carbonation and bicarbonates dominate utilisation trends.
- Biological utilisation via plant growth, algae biomass and fertilisers also shows high volume and recency, pointing to sustained interest in bio-based and land-use–linked CO_2 applications.
- Conversion of CO_2 into fuels is a particularly dynamic area: diesel, aviation fuel, gasoline, biofuels and LPG all lie in the high-recency region, with aviation fuel emerging as one of the fastest-growing patent topics.
- Further strong interest is seen in the conversion of CO_2 into methane, methanol, concrete, formate, ammonia and refrigerants, alongside emerging niche uses such as CO_2 for pH control.
- On the process side, mineralisation and mineral carbonation lead in patent volume, while hydrogenation, electrochemical reduction, methanolation and methanation form a second tier of key pathways. Oligomerisation and reverse water–gas shift appear as particularly dynamic technologies, combining emerging status or high recency with meaningful patent volumes.
- Overall, utilisation is one of the most vibrant and diversified segments of the CCUS landscape.

7. Strategic implications and opportunity spaces

- The combination of field mapping and volume–recency analysis reveals a balanced innovation ecosystem with both strong mainstream pillars (e.g. established capture, storage and utilisation concepts) and a healthy pipeline of emerging concepts.
- Capture technologies currently anchor the CCUS patent landscape, but utilisation shows especially strong and broad-based momentum, while storage is transitioning from a low-volume niche to an area of growing strategic interest.
- The clear white spaces in storage (especially biotic storage) and membranes for many top corporate players, combined with the high recency of the concepts that are present, highlight attractive areas for differentiation, partnership and targeted investment.

Taken together, the findings suggest that CCUS innovation is in a dynamic growth phase with room for diverse strategic positioning: companies can focus on strengthening core capture capabilities, build differentiated portfolios in high-potential utilisation pathways, or move early into the still-underdeveloped but increasingly active storage domain.