



Industrial clusters

Working together to achieve net zero

 **accenture**

In collaboration with the
World Economic Forum

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Contributors

We would like to extend our gratitude to the knowledge partners that have played a vital role with their insightful, informative contributions. Over the course of our research, we held several interviews and discussions with the following companies that challenged our thought process, inspired our solutions and improved our understanding of the complex topics at hand:

Acciona Energia

Admin. Committee of Suzhou Industrial Park

Asian Development Bank

Agora Energiewende

Asia Pacific Urban Energy Association

BASF

**UK Government Department for Business,
Energy & Industrial Strategy**

Borealis

British Steel

Chinese Academy of Social Sciences

**China Association of Plant Engineering
Consultants**

**China Institute for Studies in Energy Policy –
Xiamen University**

Drax

DTEK

EDF Energy

Enel

Enesource

Envision Digital

Equinor

Everbright Environment

Fortia Energia

Global CCS Institute

Heliogen

Hitachi ABB Power Grids

Iberdrola/Scottish Power Renewables

L'Oréal

National Grid Ventures

**National Renewable Energy
Laboratory (NREL)**

Ørsted

Peak Energy AG

Port of Rotterdam

RMI

Saipem

Schneider Electric

Sempra Energy

SSE Thermal

Vattenfall

The background image shows a modern, brightly lit hallway with a curved glass ceiling and a reflective floor. Several people are walking through the hallway, their figures blurred to suggest motion. The overall color palette is dominated by blue and white tones, creating a clean, professional atmosphere.

Executive Summary

Industrial Clusters: The Net-Zero Challenge

According to the United Nations, almost 70% of the global economy will have committed to net zero in 2021. To fulfill these commitments, demand centers such as cities and industrial clusters need to play a key role.

Net-zero emissions targets by 2050/2060

By law



Proposed Legislation



In-Policy Document



Non-exhaustive

Demand centers will play a key role in achieving targets

Industrial Clusters



Cities



With industry responsible for 30% of total global CO₂ emissions, industrial clusters will be a critical player in accelerating the path to net zero.

Industrial CO₂ emissions are considered some of the most difficult to abate on the path to a net-zero future. There are many existing initiatives and papers dedicated to reducing industry emissions, focusing on specific technologies or sectors. While these efforts are important and welcome, what is lacking is an emphasis on an integrated approach across sectors.

Industrial Clusters, geographic areas where industries are co-located, provide opportunities for scale, sharing of risk and resources, aggregation and optimization of demand.

This report recommends a multi-stakeholder, integrated approach toward a net-zero future for industrial clusters. We have identified four solutions that can help lower emissions:

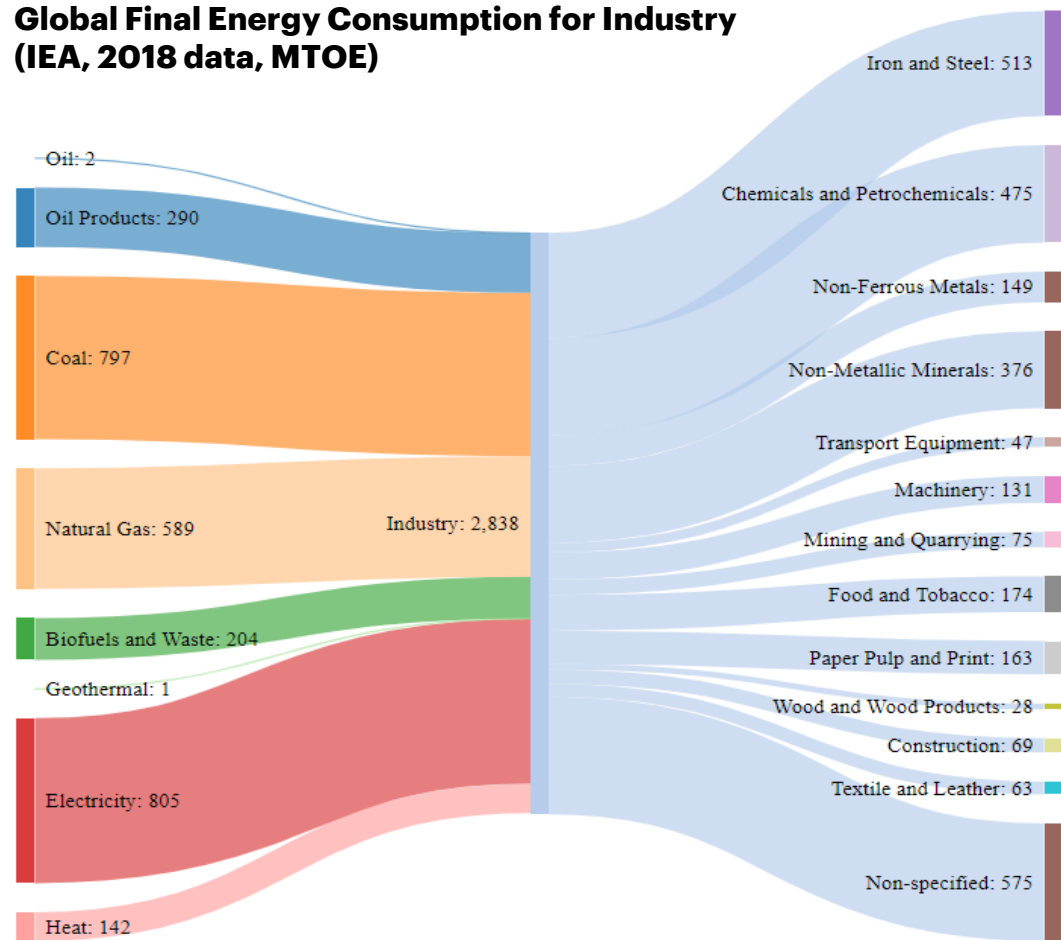
- **Systemic Efficiency and Circularity**
- **Direct Electrification and Renewable Heat**
- **Hydrogen**
- **Carbon Capture, Utilization and Storage**

Implementing these solutions is more impactful when pursued through a cross-sectoral, multi-stakeholder approach, where different industries within a cluster can create synergies.

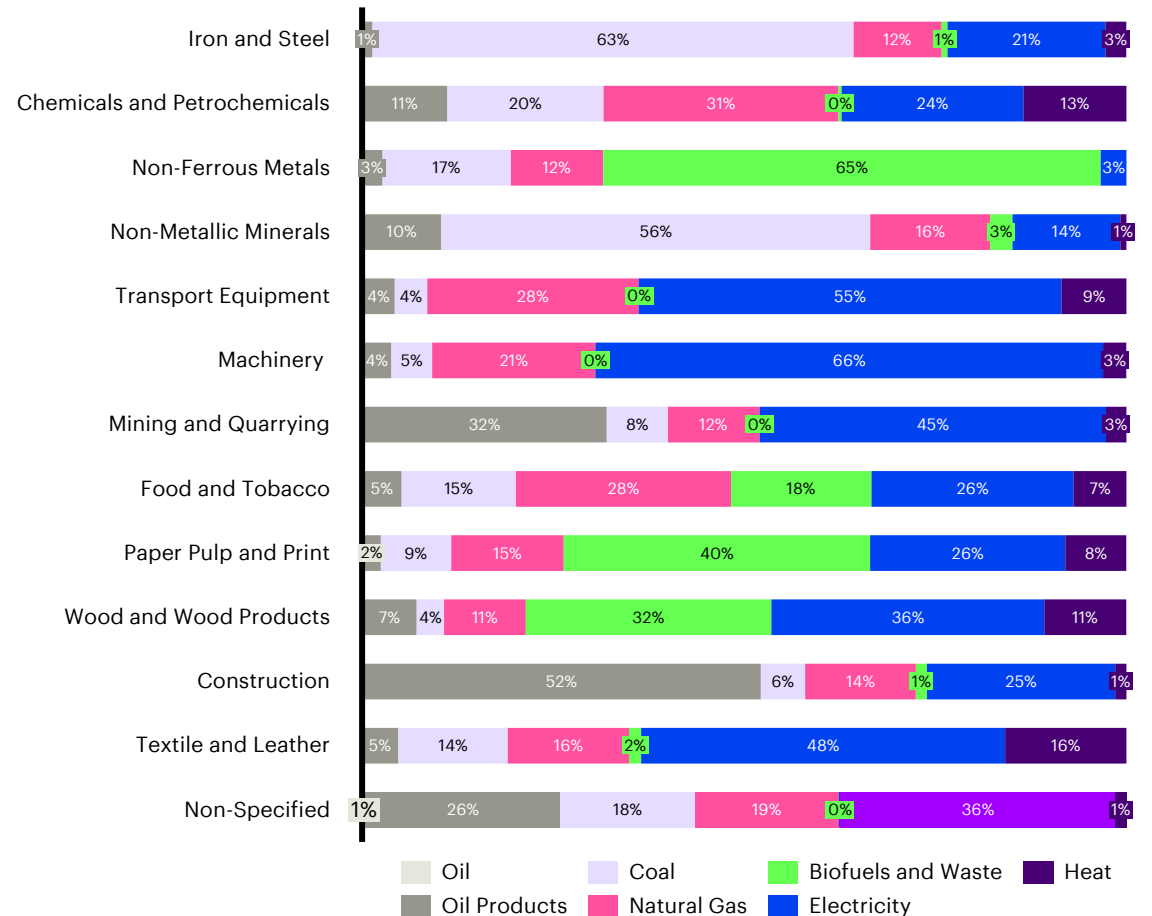
Global Energy Consumption from Industry

An industrial cluster can consist of both heavy industry (such as iron and steel) and light industry (such as food and machinery). Approximately half of industrial emissions come from light industries that are less energy-intensive and easier to abate.

Global Final Energy Consumption for Industry (IEA, 2018 data, MTOE)



Global Energy Consumption by Sector (IEA, 2018 data)



MTOE = millions of tonnes of oil equivalent

Industrial Emissions Abatement by the Numbers

While industry faces several challenges on the path to net zero, there are also sizeable economic opportunities from investments in low-carbon technologies.



Challenge

~37%

The industrial sector accounted for 37% of total global final energy use in 2018

~11 GT CO₂

Industrial emissions represent 30% of GHG emissions globally

Up to 2-3x

Increase in current carbon price from current levels (€24 average in 2020) to as high as ~€89² in Europe by 2030 to support zero-carbon investments



Opportunity

\$40 billion

Global investments in industrial efficiency, with China and North America accounting for approximately 47% in 2018

~40%

Industrial emissions by 2050 can be abated via electrification of light industries using commercially available technology

~\$175 billion

Estimated global hydrogen market value in 2019

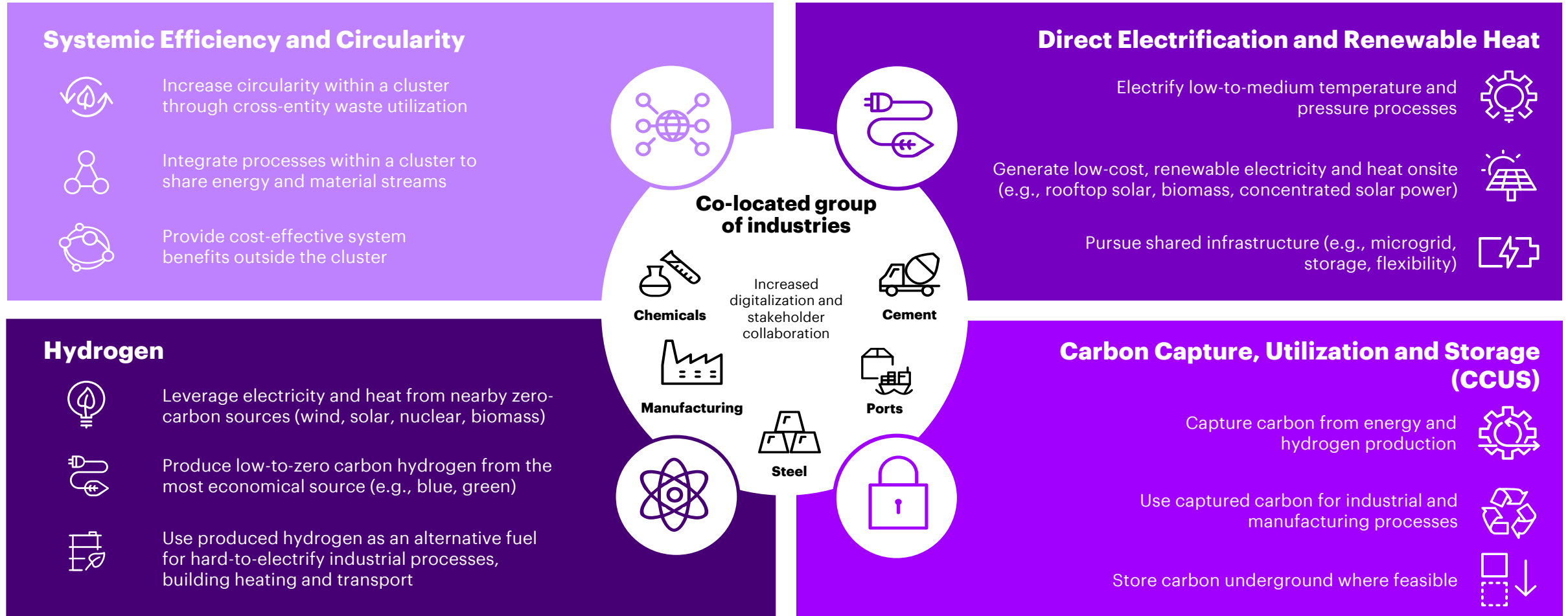
900 MT

Captured global emissions by 2030 from carbon capture and storage (CCS)

Notes: (1) Monetary figures refer to USD unless otherwise stated; (2) High end of forecasts from a group of analysts including BNEF, Refinitiv, Energy Aspects, etc.

Net-zero Solutions for Industrial Clusters

There is a menu of abatement opportunities, and a holistic approach to industrial clusters is required to optimize emissions solutions and create an integrated energy system that maximizes system value outcomes.



Industrial Cluster Characteristics

Industrial clusters can differ significantly in their foundational characteristics, which influence the applicability, impact and economic feasibility of potential solutions for reducing their emissions.

Industrial Cluster Foundational Characteristics



Industry composition

Characteristics specific to each industry within a cluster will influence feasibility or economics of potential solutions

Can waste by-products of one facility be used by another? Are industrial processes low or high temperature, pressure?



Geography

Some clusters will be able to take advantage of their surroundings to pursue specific solutions such as CCS and water cooling

Is the cluster located close to CO₂ geological storage sites? Near urban centers to connect into district heat networks?



Existing infrastructure

The presence and quality of existing infrastructure and assets can enable or block solution viability for clusters

What infrastructure currently exists that can be leveraged or repurposed? Are assets nearing end of life and need replacement?



Energy costs and policy

The cost profile and policy related to fossil energy and electricity can significantly influence decision-making

Is electrification a cost-effective solution? Is policy and regulatory support needed to make solutions cost-competitive?

Spotlight on Suzhou Industrial Park, China

- Mostly lighter industry with low process heat requirement, e.g., electronics and light manufacturing
- Inland region near metropolitan area
- Minimal existing infrastructure for repurposing
- General government support for industrial emissions reduction initiatives

Outcome

Emissions reduction focus on systemic efficiency, circularity and electrification with zero-carbon power sources

Spotlight on Humber, UK

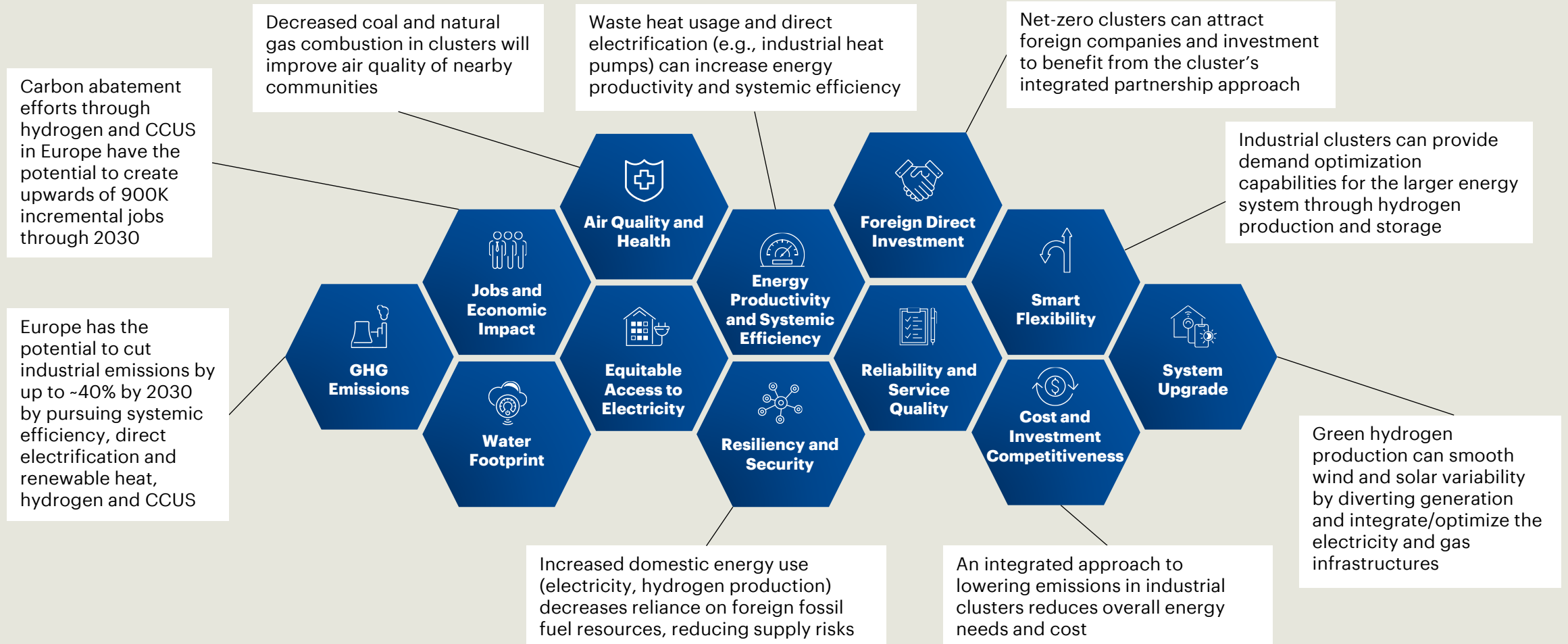
- Mostly heavy industry with high temperature processes and hard-to-abate emissions, e.g., steel, refining
- Close to large-scale saline aquifers suitable for CO₂ storage and abundant offshore wind resource
- Located near large offshore wind farms and natural gas pipelines
- Government funding, commercial and regulatory support for carbon capture and hydrogen development

Outcome

Emissions reduction focus on development of hydrogen (green and blue) and CCS infrastructure

Maximizing System Value Through Clusters

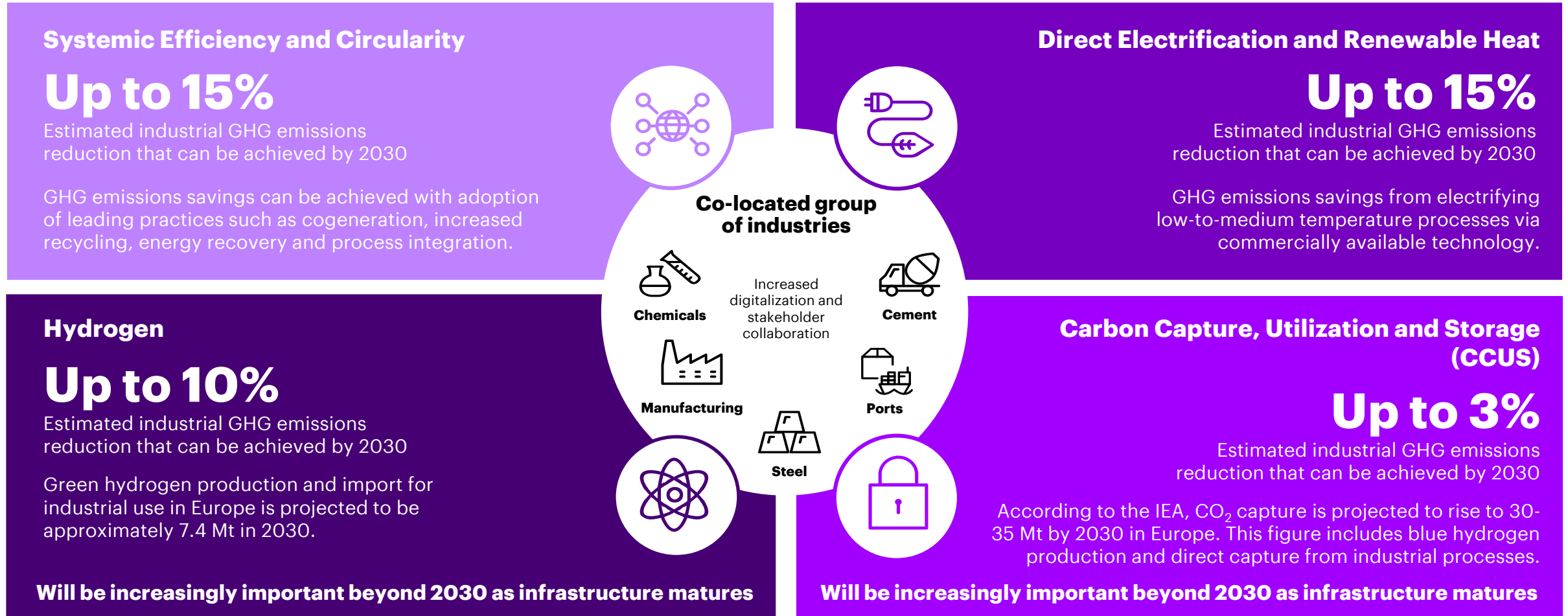
Industrial clusters need to select the solutions that maximize system value beyond GHG emissions, pursuing collaborative actions that improve outcomes across the economy, the environment, society and the energy system.



Emissions Reduction Potential by 2030*

A combination of solutions—systemic efficiency, electrification, hydrogen and CCUS—have the potential to reduce industrial GHG emissions footprint by up to 40% (from 2019 base) by 2030.*

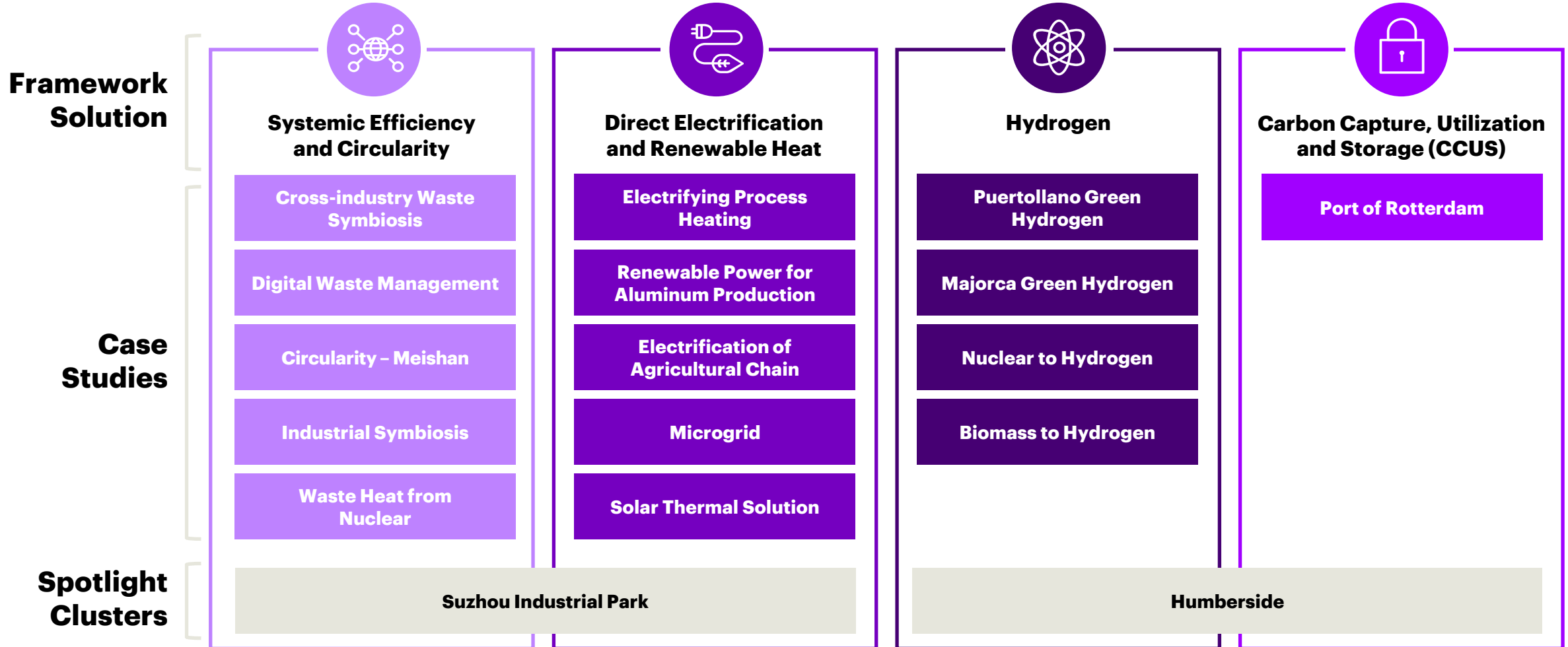
*Analysis based on EU



Note: Emissions savings from blue hydrogen are captured in CCS.

Applying the Framework

We highlight two spotlight cluster case studies and several smaller case studies to illustrate how the solution areas in Systemic Efficiency and Circularity, Direct Electrification and Renewable Heat, Hydrogen and Carbon Capture, Utilization and Storage have been applied to reduce emissions and maximize system value.



Enablers and Risks for Net-Zero Clusters

In all spotlight clusters and case studies, a mix of supportive policies, available financing and incentives and, increasingly, cost-competitive technologies were required. Further development in these areas is needed to reduce risks and accelerate the path toward net zero.

Enablers



Policy support

- **Negative value on CO₂** – High carbon pricing, carbon border adjustments and other regulatory support measures such as subsidies and tax are recognized as effective tools for improving the economics of emissions reduction initiatives.
- **Energy market reform** – To value and support the development, production and use of alternatives to unabated fossil fuels.
- **Path to sustainable commercial models** – Clear roadmaps with achievable milestones and commercial frameworks conducive to adoption of low-carbon technologies and sustainable business models.



Financing of investments

- **Government commitment of capital for infrastructure** development to demonstrate intent and provide certainty to private industry and investors.
- **Funding commitments and shareholder activism from long-term institutional investors** (pension/sovereign wealth) driven by customer/LP pressure to invest in sustainability-related sectors and influence industrial and energy companies to pursue sustainability-linked initiatives.
- **Risk-sharing contracting models and cluster-level markets** that support long-term offtake and supply commitments and integration of processes.



Technology

- **Electrification** of low-to-medium temperature processes in light industries using commercially available technology.
- **Cross-sector funding** of R&D facilities to unlock new technical and digital capabilities.
- **Ongoing reduction in cost curve** of low-carbon technologies such as renewables, electrolyzers, CCUS, industrial process efficiency and electrification.

Risks



Policy risks

- Changes in government and/or specific policies toward climate targets and associated regulations can negatively influence much needed investment confidence by adding **instability and uncertainty for the long-term financial viability** for low-carbon investments.



Investment risk

- Lack of clarity or suitability over **sustainable business models** (e.g., regulated asset base, contract for differences payments) for low-carbon technologies that require scale and significant upfront infrastructure investment, such as hydrogen pipelines, could deter interest from prevent private industry and delay path to net-zero emissions.

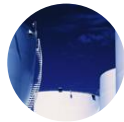


Stranded assets

- Rapid policy changes as opposed to a phased-out approach for older assets without carbon-mitigation potential could lead to accumulation of stranded assets, which could have wider economic consequences on jobs, health of private industry and financial institutions.

Opportunities Through Collaboration

Through multi-stakeholder collaboration, industrial clusters provide the opportunity to create system value and not only help reduce emissions, but also help deliver economic benefits in terms of job creation and health benefits from better air quality.



Industrial Companies



Governments



R&D Innovation and Digital Services



Energy Companies



Financiers

Value Opportunity

- Reduce emissions to **avoid potential carbon taxes** and associated financial consequences.
- **Business opportunity through development of premium low-carbon products** (e.g., zero-carbon steel or cement) attractive to customers in domestic and/or international markets.

- Governments can **demonstrate global leadership** in taking decisive actions to achieve net-zero emissions targets.
- **Exporting knowledge** of policy frameworks, commercial models and infrastructure for low-carbon technology.
- Unlocking **system value benefits** such as **job creation, improved air quality linked health benefits, GHG emissions reduction.**

- **Patents** and published **academic literature** demonstrating **reduction of cost curves** and **improvement of efficiency** for key technologies, e.g., electrolyzers, AMR.
- Development of **commercial frameworks and suitable business models** to enable adoption of low-carbon industrial initiatives.

- Increased **visibility on industrial demand** for different sources of energy to aid **CapEx planning and strategic outlook** for energy companies.
- Potential for **expansion of business lines and/or products** (e.g., new class of utility business to include CO₂ transport, storage).
- Significant **expansion of renewables, demand optimization and integrated energy management services.**

- Fulfill **climate commitments** and **pledges** to shareholders by expanding scope of **ESG asset** class via investments in low-carbon infrastructure for new technologies such as CCS and hydrogen.

What's Needed

- **Broad-based collaboration** within and across industries, as well as with government stakeholders.
- Commitment of **capital, willingness to share resources** and development of **structured plans** to match emissions reduction ambition. Companies must have **“skin in the game,”** i.e., capital at risk, in order to see material progress.

- Government can **commit capital** toward infrastructure and support business models to reduce risk for private industry by creating a financial environment that supports achieving net-zero targets, including through the creation of **subsidies and tax credits.**

- **Cross-sectoral platforms** including academia, government and industry.
- **Allocation of resources** for further research and innovation in the energy transition space.
- **Cross-sector funding** of R&D facilities to unlock new technical and digital capabilities.

- **Leadership** from power generation and utility companies to **actively collaborate** with industrial demand centers to **integrate low-carbon sources of energy** into the overall system.
- Commitment of **capital and resources** to develop new integrated energy systems at scale.

- Willingness to **commit capital** with the purpose of developing cross-sector, low-carbon infrastructure projects.
- **Shareholder activism** to encourage investee companies to pursue initiatives to reduce emissions.

Actions to Accelerate Net-Zero Clusters

Collaboration between government and industry is critical to develop and implement roadmaps on a cluster-by-cluster basis to reduce industrial emissions and achieve net-zero targets.

Options for Government

Policy Support

- Set binding **commitments for industrial clusters to achieve net-zero emissions** within a specified time frame.
- Develop **alternative economic models** to support low-carbon infrastructure, e.g., contract for difference (CFD) payments.
- **Support for R&D investment** into emissions reduction initiatives, e.g., tax deductions, U.S. President Biden's ARPA-C proposal, partnerships with national labs.

Financial Support

- Incentives such as tax credits (e.g., PTC/ITC in United States) or avoidance charges (carbon tax, carbon border adjustment) to encourage investment into GHG-abatement initiatives.
- Financial support in the form of loans and grants for development expenditure to technologies with no immediate financial attractiveness, e.g., CCUS.

Infrastructure Support

- **Leverage existing infrastructure** for emissions reduction solutions, such as natural gas lines and storage that can be adapted to hydrogen or hydrogen blending and oil and gas reservoirs that can be used for CO₂ storage.

Actions for Industry

Cross-sectoral Collaboration

- Build **trust among cluster partners** by forming working groups with representatives from all stakeholders—industrial partners, government representatives, financiers, etc.
- Assess the **concentration of industry** within the geographic region and understanding the **diverse set of needs** (e.g., **fuel requirements** for industrial processes) within the group.
- Align on common goals (e.g., scale net-zero technologies, deploy digital services, etc.) and develop **cluster-specific roadmaps** to achieve net-zero targets by a target year.
- **Develop commercial models and risk-sharing initiatives** such as joint venture formation, public-private partnerships, long-term power purchase agreements (PPAs) and take-or-pay agreements that help accelerate implementation of roadmaps.

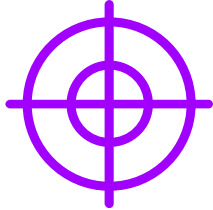


Public-Private Cooperation

An aerial, high-angle photograph of a sprawling industrial complex, likely a semiconductor manufacturing plant. The scene is dominated by a dense network of metal pipes, walkways, and structural elements, all bathed in a cool, blue light. In the lower center, a large, white, cylindrical robotic arm or piece of machinery stands out against the darker background. The overall atmosphere is one of advanced technology and industrial precision.

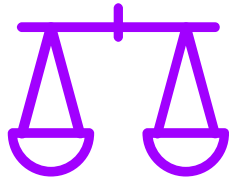
Spotlight on Clusters: Suzhou Industrial Park

China's Industrial Parks Policy



Targets

- **Peak CO₂** emissions by 2030 and **carbon neutrality** by 2060.
- As part of the 13th Five-Year Plan for Controlling Greenhouse Gas Emissions, China has highlighted near-zero-carbon zones as one of the key policies to achieve reductions, including a specific call for **50 near-zero-carbon zones by 2050**.
- Since 2013, China has been developing the pilot project of low-carbon industrial clusters. The project has included 52 industrial clusters; Suzhou industrial cluster is among the first wave.



Commitments and Considerations

- Since 2014, the Administration Committee of Suzhou Industrial Park (SIPAC) has started **a three-year action plan to close substandard enterprises and eliminate outdated production capacity** in the cluster. So far, 41 noncompliant enterprises have been shut down.
- Since 2014, SIPAC has established the **decarbonization target responsibility assessment and evaluation system**. The cluster signed target-oriented responsibility contracts with major coal-consuming enterprises to reduce the total coal consumption year by year.
- In 2016, the Environmental Protection Agency of Suzhou Industrial Cluster has developed an **energy and carbon-emission management platform** in cooperation with Tsinghua University to achieve data integration, visualization and monitoring. The platform has connected more than 200 enterprises and received energy consumption data uploaded by 13 public building projects.
- In 2017, SIPAC established the **green credits providing loans to projects offering energy savings or emission reductions**, with a 10 million RMB risk compensation capital pool.
- In 2019, SIPAC published the policy **Management of Special Funds for Green Development**, which guaranteed to begin subsidies to established distributed gas turbine and energy storage projects with 0.3 RMB per kWh of electricity generated until 2022.

Case Study: Suzhou Industrial Park

The industrial cluster at Suzhou, Suzhou Industrial Park, is pursuing steps to achieve carbon neutrality through systemic efficiency and shared energy and resource infrastructure.

Overview

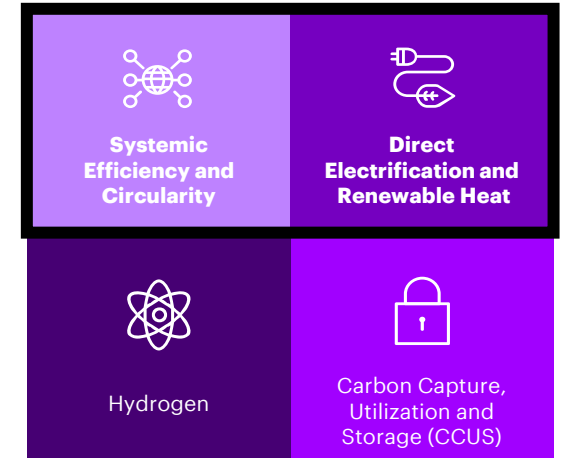
- China's Suzhou Industrial Park (SIP) was established in April 1994 as a **collaboration between China and Singapore**, covering a total area of 278 km² near Shanghai.
- Accounting for more than 3% of the city of Suzhou's area, the cluster contributes **more than 13% of city of Suzhou's GDP**.
- The **two largest industries are electronics and high-end equipment manufacturing** (\$10 billion+ industries). Additionally, three strategic emerging industries in SIP are **bio-medicine, nanotechnology and cloud computing** (\$1 billion - \$110 billion industries).
- While total energy consumption has been increasing, energy consumption per unit of GDP has **dropped by 10.3%** over the past four years. Likewise, emissions intensity relative to GDP has dropped over this time period.

Emissions Reduction Targets and Initiatives

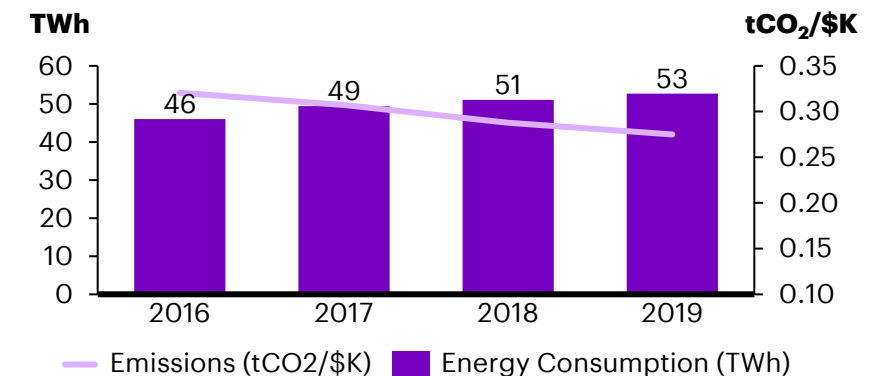
- **SIP's CO₂ emissions are also expected to peak by 2020** (11.7 million tonnes) and become carbon neutral by 2050.
- **Clean energy represents more than 75% of energy usage in SIP**, the **largest share among all national development zones in China**.
- Four key projects implemented in the SIP's carbon abatement push:
 1. Circularity of industrial by-products and waste
 2. Distributed clean energy microgrid
 3. Ubiquitous IoT service platform
 4. Integrated green transport system

Note: Exchange rate of \$1 to ¥6.54

Net Zero Framework Focus Areas

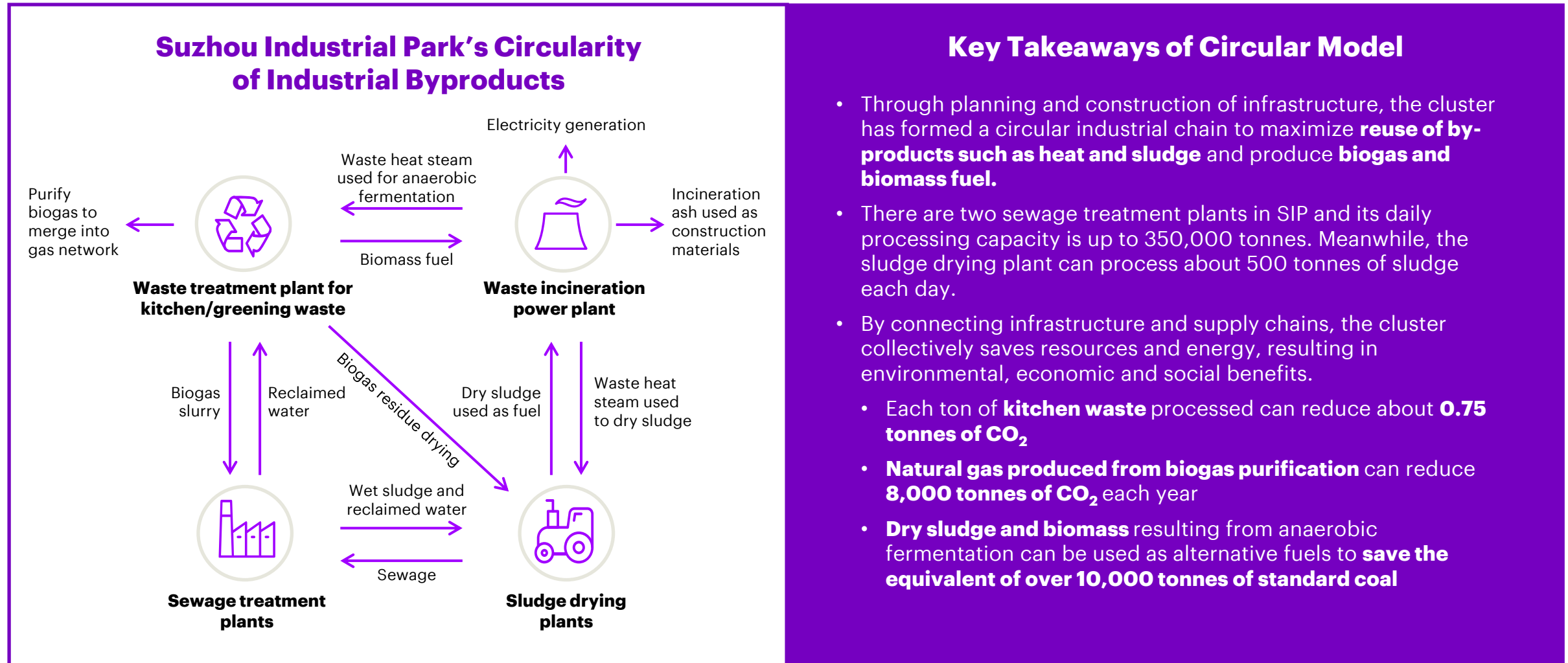


Trend in energy consumption (TWh) and emissions intensity (tCO₂/\$K) in Suzhou Industrial Park



Circularity of Industrial By-products and Waste

Suzhou Industrial Park is a leader in systemic efficiency through circularity of industrial waste and by-products.

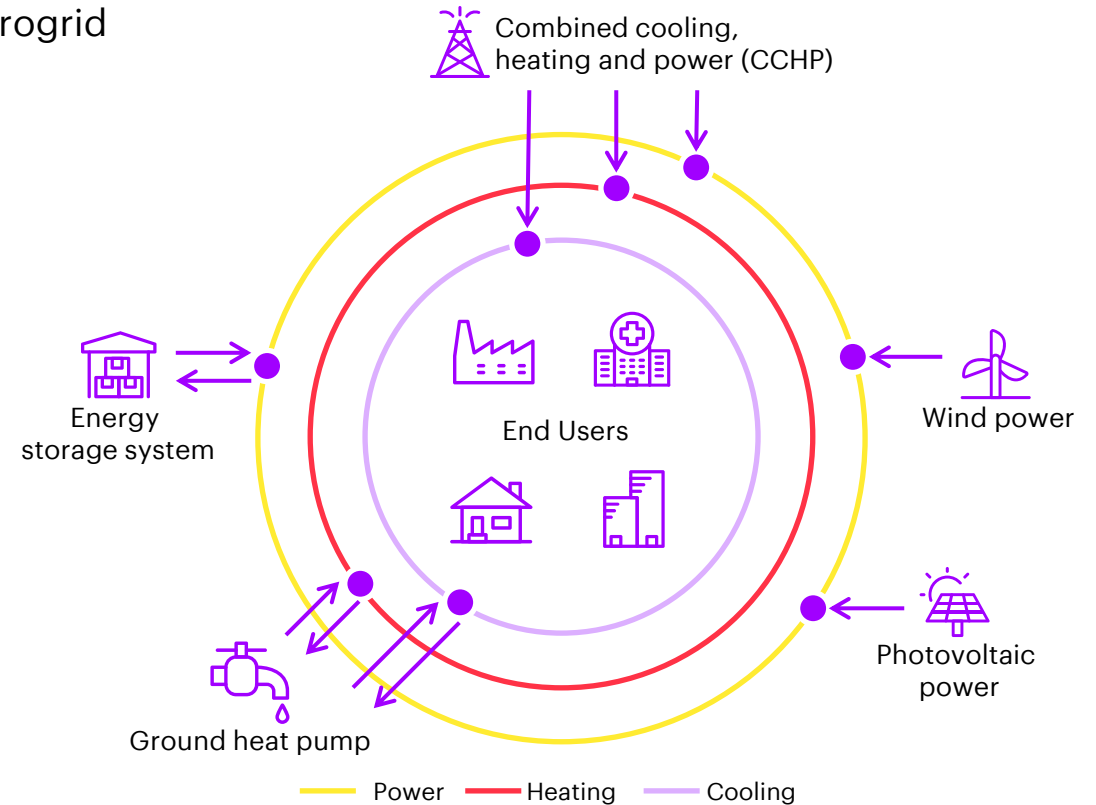


Distributed Clean Energy Microgrid Project

Suzhou Industrial Park features a “six-in-one” distributed clean energy microgrid system that helps improve systemic efficiency throughout the area.

Project Overview

- A distributed microgrid currently provides **up to 10%** of SIP’s energy consumption. It integrates green energy, microgrid benefits, energy savings, and energy creation and storage.
- The system integrates **several renewable energy sources and efficient solutions:**
 - Combined cooling, heating and power (CCHP)
 - Wind power
 - Solar PV
 - Low-level heat
 - Energy storage
- The project includes two clean energy centers, 10 microgrid systems, 100 distributed energy systems including 25MW photovoltaic generation, 50MW wind generation, 22MW storage capacity and 1,000 EVs, forming a **clean energy system that is over 1 GWh.**



Expected Future Benefits

↓ **1,100 kW**
Peak power load

3.75 GWh
Clean power

↓ **40%**
Energy consumption

> 50%
Emissions reduction

↓ **30%**
Energy investment

Ubiquitous IoT Service Platform

Suzhou Industrial Park (SIP) worked with delivery partner Enesource and AIoT platform partner Envision Digital to create an open energy, internet-shared service hub for SIP tenants to benchmark and optimize energy demand, reduce emissions and increase efficiency.

Project Overview



The project partners built a **4D digital energy network map** for SIP, a digital twin of its physical energy system, on a cloud-based AIoT platform.



This platform enables SIP to **monitor the operation of its energy system**, the relationship between energy supply and demand, and asset performance. It also allows for **better energy system planning** and **better-informed operations and construction decisions**.

Key Project Outcomes



The platform **integrates real-time data across 10,000+ devices**, 3000+ businesses and 50+ service providers, processing 48 million data points daily.



In SIP, estimated **\$316 million gross merchandise value (GMV)** on the platform by 2024.



It **optimizes 8 GW+ of assets** across SIP improving performance and energy utilization. This has led to a more than 10% **reduction in average energy cost and CO₂ emissions**.

Key Platform Features

Stakeholder Dashboard

Real-time visualization of energy production and use as well as emissions across SIP. Enables monitoring and optimization of energy consumption and energy efficiency.

Smart Park Diagnostics

Solution provides energy and infrastructure alerts and alarms to manage equipment performance, asset health and energy load optimization.

Tenant Benchmarking

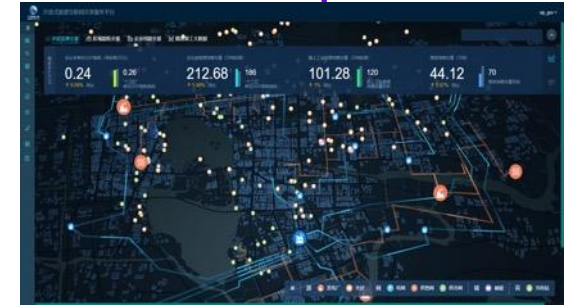
Data mining to benchmark enterprise energy usage performance, providing suggestions for energy-efficiency improvement and cost reduction.

Services e-Marketplace

B2B energy solution hub for park tenants—platform for prescreened energy and infrastructure solution providers in SIP to sell value-added services.

Public Data as a Service (DaaS) Portal

Open data platform that turns energy IoT data into a valuable public resource. Transparency on water, electricity, gas and heating systems to help accelerate research and innovation.



Suzhou L'Oréal's Path to Zero-Carbon Factory

Suzhou L'Oréal Zero-Carbon Factory: Comprehensive Utilization of Photovoltaic System, Wind Power and Biomass

Zero-carbon emission roadmap for L'Oréal factory

Photovoltaic and Wind Power

2014

- The factory constructed a 1.5 MW distributed photovoltaic power system—a national demonstration project. The system was funded by the Suzhou Ministry of Finance and the solar panels were provided by the Suzhou Guohua Technology Company.
- The same year, the factory began to utilize wind power.



- The PV system can generate **1.2 GWh** of power each year, accounting for **8%** of the factory's power consumption and reducing **1,100 tonnes of CO₂** emissions annually.
- Wind power accounts for **80%** of the factory's power consumption, reducing about **two-thirds of CO₂ emissions**.

Multiple Energy Sources

2018

- L'Oréal and the SIP administration committee sign the "Zero-Carbon Factory" project contract.
- The factory cooperated with GCL Towngas and established a distributed heat and power cogeneration system, using biomass gas as raw material to produce steam and power.



- The multi-energy supply system can generate **1.8 GWh** power each year, accounting for **12%** of the factory's power consumption.

Zero-Carbon Emission

2019

- In June 2019, the factory realized its target of carbon neutrality.



- The factory's CO₂ emissions have been reduced by **100%** while output has increased by **3.5 times** compared to 2005.
- Factory is now equipped with **+6,000 solar panels**

Integrated Green Transport in Suzhou

Similar to a city, Suzhou Industrial Park has aimed to build a low-carbon, high-efficiency transportation system that also provides premium commuting for citizens.

Overview of Transport System

- Suzhou received the **“City of Public Transportation”** award for its development pattern that emphasizes clean transport while also providing personalized, affordable travel options for citizens.
- **100% of the buses within the cluster are powered by clean energy.** The full replacement of fuel buses has helped reduce CO₂ emissions by about 240,000 tonnes per year.
- There are **nine bus charging stations and approximately 200 bus charging piles.** They cover about half of residential areas to help encourage increased use of public transportation and make commuting greener.
- SIP has a goal to **achieve 100% intelligent transportation coverage in 2023.** They will do so by accelerating the construction of intelligent transport infrastructure and information systems and investing in new energy vehicles.

Bus Type Breakdown

Category	Number of Buses	CO ₂ Emission Reduction VS. Fuel Bus Each Year (t)	Energy Cost Saving vs. Fuel Bus (%)
Electric Bus	437	20,000	40%
Plug-in Hybrid Electric Bus	236	4,000	32%

Additional Green Transport Efforts



Bicycles

- The cluster actively encourage citizens to commute by bike and promotes public bike services.
- They have built 461 public bike sites and provided 15,141 bikes. These are borrowed and returned over 200,000 times a day (cumulatively).



Electric Vehicles

- Citizens can borrow and return EVs on apps with low hourly leasing cost, up to \$23 one day.
- The service achieves zero carbon emission and is complementary to the public bus and bike systems, meeting citizens’ different commuting preferences.

Suzhou Cluster System Value Impacts

Carbon-abatement efforts around systemic efficiency and electrification at Suzhou Industrial Park have a wide range of impacts.



11.74 MtCO₂
24,000 tCO₂

SIP will reach **peak carbon emissions of about 11.74 million tonnes** in 2020 and achieve carbon neutrality by 2050

The **clean transportation system** of SIP can reduce 24,000 tonnes of CO₂ for SIP



75%
50 mg/m³

The **clean energy consumption rate accounts** for more than 75% of consumption in SIP, greatly reducing pollutant emissions

The **annual average concentrations of PM2.5 and PM10** are expected to be respectively reduced to below 50 and 70 mg/m³ in 2020



90%
130

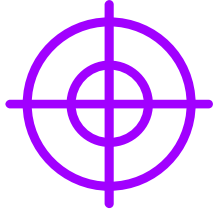
More than 90% of the investment in SIP is **from foreign-owned enterprises** and more than two-thirds of the industrial output value **is created by foreign capital**

More than **130 Fortune 500 companies have invested** in the cluster



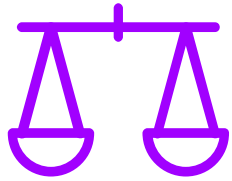
Spotlight on Clusters: Humber

UK's Industrial Clusters Policy



Targets

- National **net-zero target by 2050**
- **5 GW** of low carbon hydrogen production by 2030
- **10 MT** of carbon captured by 2030
- Facilitate **development of CCS infrastructure in at least 2 clusters by mid-2020s** and another two by 2030
- Achieve net-zero emissions in at least **one industrial cluster by 2040**
- Demonstrate **CCS and H₂ leadership** and net-zero industrial cluster ambition at COP26



Commitments and Considerations

- Invest up to £1 billion to support the **establishment of CCUS** in four industrial clusters.
- Establish a new **UK Emissions Trading System** aligned to net-zero target, giving industry confidence to invest in low-carbon technologies.
- Detail **revenue mechanisms and commercial frameworks** by 2021 to attract private sector investment, encourage regional and cross-sector collaboration between organizations, and create optimal conditions to maximize system benefits.
- The government plans to provide **CAPEX co-funding for industrial CCUS** to reduce cost and risk incurred by early adopters as well as a **contract for difference** with a strike price per tonne of carbon abated, for an agreed duration of time after carbon capture is operational.
- Create a **new utility class for carbon transport and storage (T&S) infrastructure**, given the business case for industrial CCS near-term dependence on a high carbon price (e.g., considering regulated asset base model for CCS infrastructure).
- Financially support **oversizing of T&S infrastructure** for rapid onboarding of future users and to reduce cost burden on early adopters.
- UK government's **"levelling up" agenda** to **ensure economic prosperity of industrial regions**, with low-carbon technology to play an important role in attracting industry, creating high skill jobs and potential for export of premium low-carbon products.
- Create "Super Places" in areas such as the North East, the Humber, North West, Scotland and Wales to exploit **geological and geographical advantages to implement low-carbon technologies** such as CCS and hydrogen.

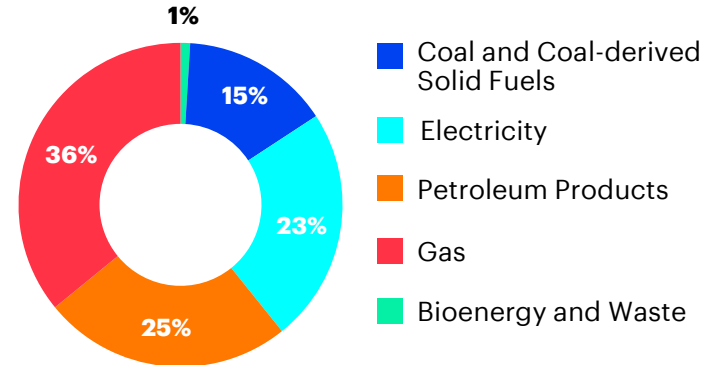
Case study: Humber Industrial Cluster

Multiple cross-sector projects are in progress to achieve net zero for the UK's largest industrial cluster, primarily via hydrogen and CCS.

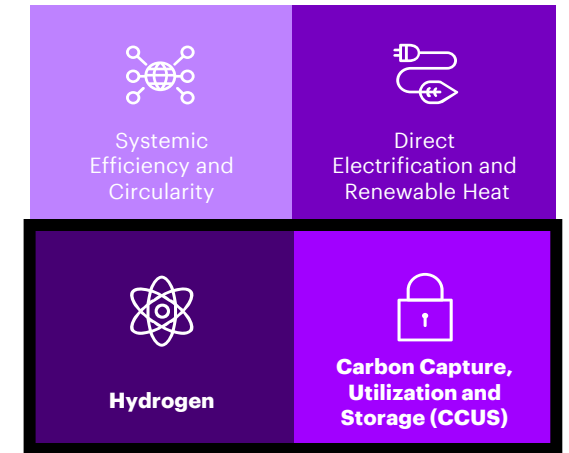
Overview of the Humber Industrial Cluster

- The Humber industrial cluster in Yorkshire is the **UK's largest cluster by industrial emissions**, emitting **10 million tonnes of CO₂ per year**, more than 2% of the UK's total GHG emissions.
- Primary industries include **steel, chemicals, cement and oil refineries**.
- **Six companies contribute to 87% of "big emitter" emissions:** British Steel's coal plant (Scunthorpe), VPI Immingham combined heat and power (CHP) plant, Saltend cogeneration plant, Phillips 66 oil refinery, Total Lindsey oil refinery and EP UK's South Humber Bank CCGT plant.
- The high concentration of heavy industry means that **6% of England's C&I energy use is from businesses in the Humber region**.
- The cluster **adds £18 billion annually to the UK economy**, a quarter of which is related to manufacturing.
- **55,000 people** are employed in manufacturing and engineering jobs in the Humber cluster, with an additional **19,000 people** employed in the energy sector.
- As many as **49,700 direct, indirect and induced jobs** could be created as a result of deploying CCS and hydrogen technologies in the Humber region by 2027.

2018 Industrial Energy Consumption in the Humber and Yorkshire (GWh)



Net Zero Framework Focus Areas



Emissions Reduction Projects

- **Three main collaborative emissions reduction projects** are being conducted in the Humber region:
 1. **Zero Carbon Humber** is a coalition of 12 entities collaborating on CCS and hydrogen infrastructure.
 2. The **Gigastack** project is working to advance green hydrogen production in the Humber area, utilizing offshore wind as a renewable energy source.
 3. Phillips 66, Uniper and Vitol's VPI Immingham CHP plant have come together to codevelop **Humber Zero**, a project that will integrate CCS and hydrogen technology.

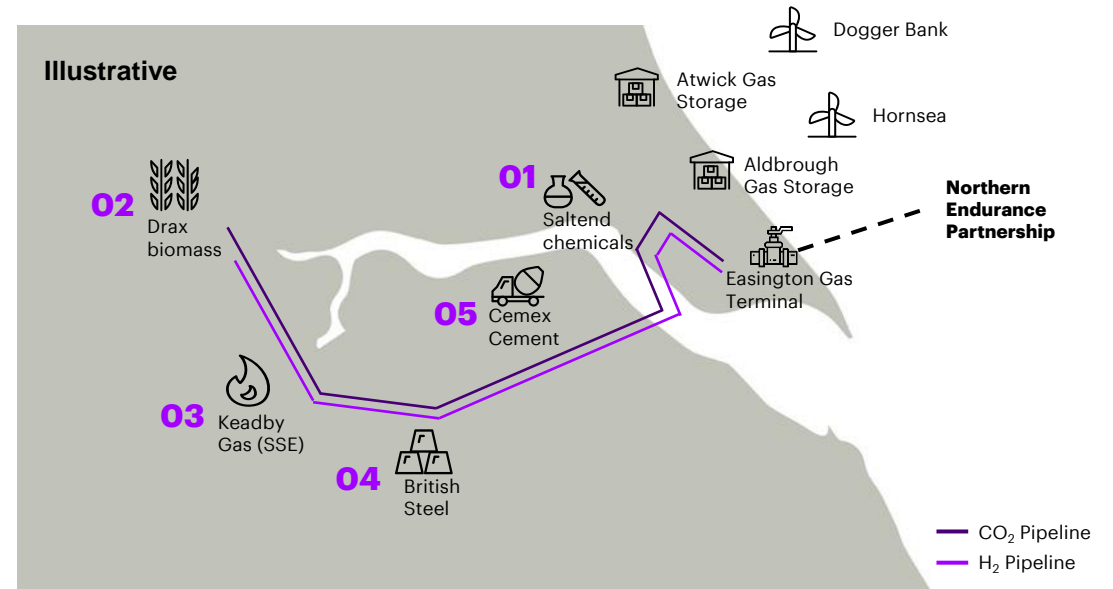
Zero Carbon Humber

Zero Carbon Humber is a coalition of 12 entities collaborating on joint CCS and hydrogen infrastructure projects.

Zero Carbon Humber (ZCH) Overview

- ZCH is aiming to establish the **world's first net-zero industrial cluster by 2040** via creation of CCS infrastructure and production of blue and green hydrogen.
- H2H Saltend will be a **first mover** in utilizing the **shared CO₂ and hydrogen transport and storage infrastructure**. This will eventually enable multiple carbon abatement projects (e.g., SSE Thermal, British Steel, Drax BECCS) in the region to scale quickly to achieve net-zero targets for the cluster and the UK.
- Industrial users will be able to reduce emissions by capturing carbon and transporting it via shared pipelines for offshore storage as part of the **Northern Endurance Partnership** – the offshore component and sister project to ZCH.
- **Access to shared hydrogen infrastructure will spur demand** for use as feedstock in industrial processes and enable potential for further use outside the cluster.
- The coalition recently applied for **£75 million in private and public sector funding** to advance Phase 2 operations, with the first infrastructure expected to go online by 2026.
- **There will be three major areas of project work:**
 1. Develop a carbon-capture usage and storage network.
 2. Produce low-carbon hydrogen and create shared hydrogen infrastructure.
 3. In the longer term, produce green hydrogen using offshore wind electrolysis.

Map of Planned Operations



Zero Carbon Humber Partners

Associated British Ports	PX
British Steel	National Grid Ventures
Centrica	SSE Thermal
Drax	Triton Power
Equinor	Uniper
Mitsubishi Power	University of Sheffield – AMRC

Zero Carbon Humber Pathway: CCS

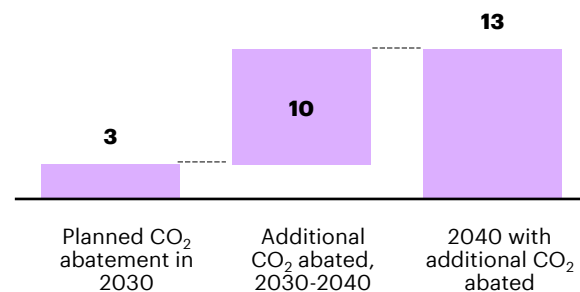
Zero Carbon Humber's CCS capabilities will enable CO₂ abatement from industry and power stations throughout the cluster.

Overview of Humber's Onshore CCS Infrastructure

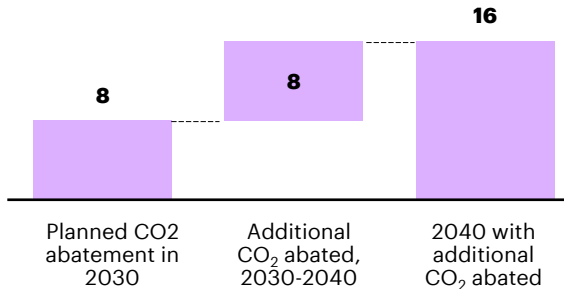
- The ZCH project will **capture CO₂ at scale from industrial sites** via pipelines that will transport emissions to compressor stations and permanent storage under the southern North Sea.
- National Grid Ventures is in the process of designing/developing the options for the CO₂ and hydrogen pipeline networks**, which will connect many energy-intensive plants and pair with the hydrogen infrastructure.
- CO₂ will be compressed at **Centrica Storage's Easington site**.
- Small-scale carbon capture technology is being deployed through Drax Power Station's bioenergy CCS system (BECCS)**. It is estimated that this production will be scaled in the 2020s to become the world's first carbon-negative power station.
- Negative emissions** through BECCS will enable Humber to **reduce emissions faster** than any other UK cluster, as it will be able to offset emissions from difficult-to-abate sectors.
- SSE Thermal is developing its Keadby 3 project, which has the potential to be the **UK's first gas-fired power station with CCS** by the mid-2020s, with an annual carbon offset of at least 1.5 million tonnes of CO₂.

CO₂ abatement potential per annum (million tonnes)

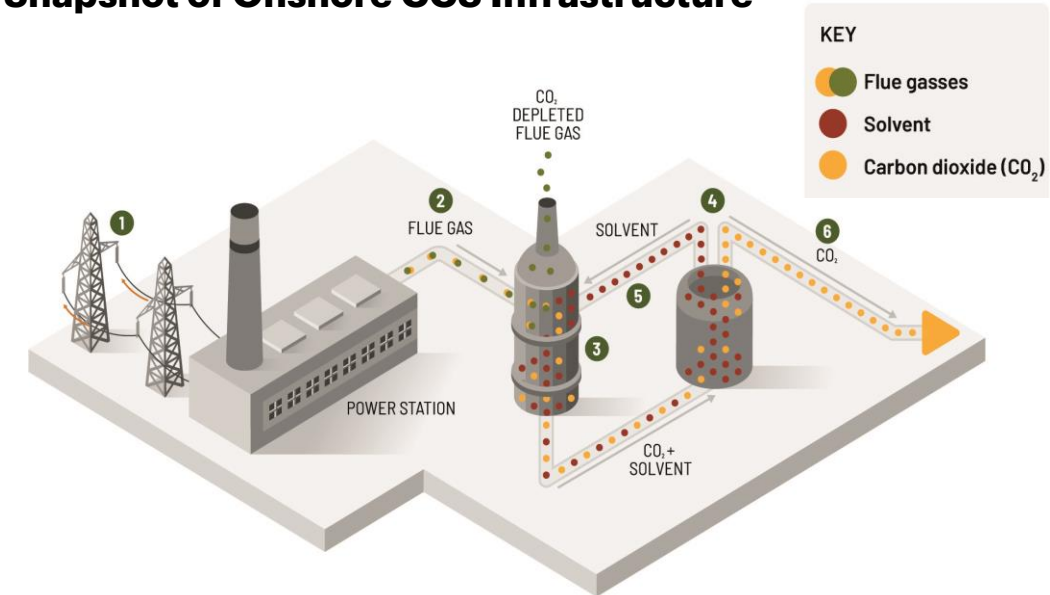
Industrial Cluster and Power CCS



Bioenergy CCS (negative emissions)



Snapshot of Onshore CCS Infrastructure



- Electricity is produced and enters the grid system
- Flue gas containing CO₂ leaves the power production process and is cooled and treated
- Inside the absorption tower, CO₂ is extracted from the flue gas and the CO₂-free gas is released into the atmosphere
- Solvent containing CO₂ is heated in a boiler, which then separates the CO₂ from the solvent
- Solvent is recirculated back into the carbon capture system
- The pure stream of CO₂ is transported via pipeline for permanent storage in the North Sea

Northern Endurance Partnership

As part of ZCH, this coalition will develop offshore CO₂ transport and storage in the UK North Sea.

Overview of the Northern Endurance Partnership

- The partnership was formed in October 2020 to **accelerate the development of offshore transport and storage infrastructure for CO₂ emissions** in the North Sea. It encompasses emissions from both ZCH and Teesside, a nearby industrial cluster.
- **BP, Eni, Equinor, National Grid Ventures, Shell, and Total** are all coalition members.
- **BP is the primary operator** with support from Equinor and National Grid.
- If successful, the Northern Endurance Partnership will enable GHG **emission reduction of almost 50% of the UK's industrial emissions.**
- The project is currently **working on securing funding** through the UK government's £170 million industrial decarbonization challenge.
- The Endurance reservoir is the **most mature large-scale saline aquifer for CO₂ storage in the offshore UK continental shelf.** The partnership has gained approval for a carbon storage license at the Endurance site.

Map of Planned Operations



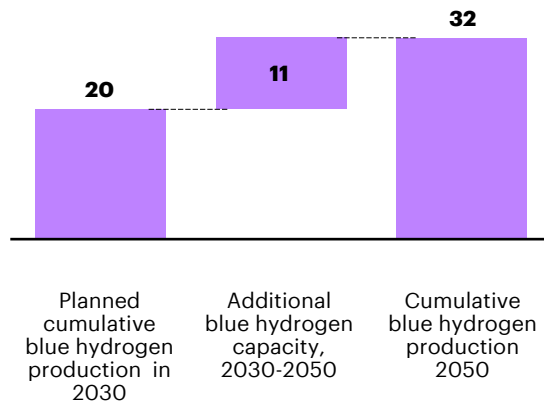
Zero Carbon Humber Pathway: Hydrogen

Blue and green hydrogen will be produced at scale to replace fossil fuels for transport and heat for industrial and residential use.

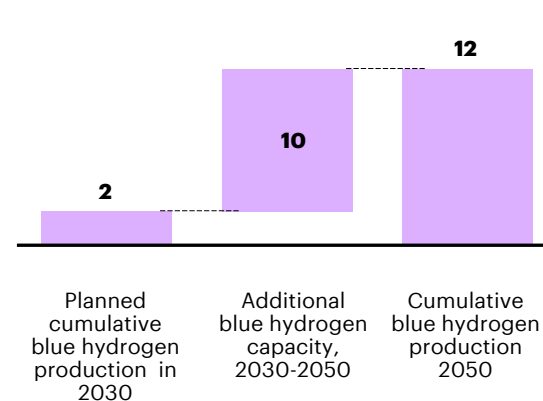
Overview of Humber's Hydrogen Economy

- As part of ZCH, Equinor is building the **Hydrogen to Humber (H2H) Saltend Chemicals Park**, which will produce hydrogen for use in existing power plants and industrial sites.
- **Blue hydrogen will be produced from natural gas** and delivered to nearby industrial plants (replacing natural gas) and power station (blended with natural gas) to reduce emissions.
- **CO₂ byproduct will be captured from blue hydrogen** production and stored offshore in the North Sea. It is estimated that Saltend will have captured and stored 8.25 million tonnes of CO₂ by 2030.
- In the longer term, it will be possible to **develop green hydrogen** at Saltend through electrolysis from offshore wind and utility-scale solar.
- **Scaled production of hydrogen** within the cluster will also allow for usage in the surrounding areas in **transport and building heating applications**.
- The project is set to **begin construction in 2024**. By 2027, it is expected that the Park will be able to expand its impact to across the Humber region.

ATR blue hydrogen cumulative production potential (TWh)

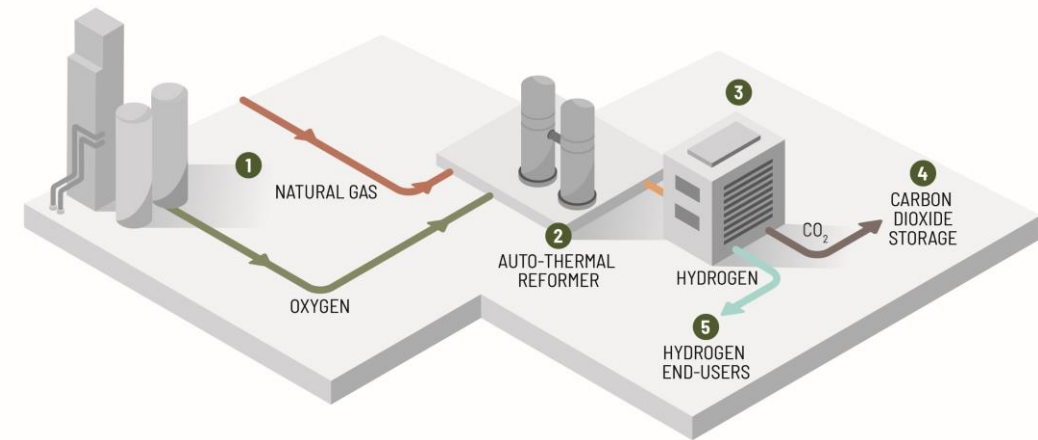


Green hydrogen cumulative production potential (TWh)



*Figure does not include non-ZCH projects

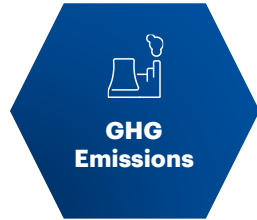
Snapshot of Blue Hydrogen Infrastructure



- 1** Natural gas and oxygen enter the reformer from an air separation unit (ASU)
- 2** A partial oxidation reaction takes place, helping to perform the reformation
- 3** Synthetic gas is produced and separated, creating pure hydrogen and CO₂
- 4** CO₂ is transported by pipeline to be permanently stored under the North Sea
- 5** Hydrogen is transported for use in power, industry, heat and transport

Zero Carbon Humber System Value Impacts

ZCH's net-zero efforts from CCS and hydrogen infrastructure will have a wide range of system value benefits.



44 MtCO₂

30%

By 2040, Zero Carbon Humber has the estimated potential to capture up to 44 Mt CO₂ per year, around 10% of the UK's current annual GHG footprint.

If ZCH's Net Zero 2040 ambition is achieved, Humber will achieve 30% of the total CO₂ reduction from CCUS that the Committee on Climate Change recommends for the UK by 2050.



50k jobs

Zero Carbon Humber will protect 55,000 current jobs and add approximately 50,000 new direct and indirect jobs across the Humber region.



£148m

Analysis by Element Energy estimates that total £148 million in public health costs could be saved between 2040 and 2050 due to Zero Carbon Humber's efforts, reducing the burden on public health services through improved air quality.



£2.9bn

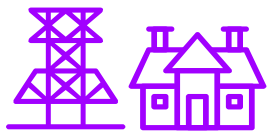
The scale up and success of zero-carbon clusters will make them increasingly attractive to investors based off reputation. If businesses across the Humber fail to reduce emissions, they could face loss of investment as well as carbon taxes of up to £2.9 billion per year by 2040 based on UK Treasury forecasts. This could put their financial future at risk and lower their ability to be competitive players in a global marketplace.

Gigastack: Green Hydrogen in Humber

Separate from Zero Carbon Humber, the Gigastack project is working to produce renewable green hydrogen at an economically viable, large scale in the Humber region.

Project Overview

- The Gigastack consortium is made up of **cross-sector partners**—Orsted, ITM Power and Phillips 66—and aims to produce **green hydrogen** to help reduce GHG emissions in Humber’s industrial cluster.
- ITM Power’s new 5 MW electrolyzer “stack” will enable the deployment of GW-scale systems, and a planned **100 MW electrolyzer** will supply **up to 30% of the refinery’s existing hydrogen demand**. Further scaling will allow costs to fall below **€400/kW**.
- The consortium of companies will highlight **regulatory, commercial and technical challenges** to be overcome with clean hydrogen production, ultimately developing a **blueprint for deploying scalable electrolyzer technology** across the UK.



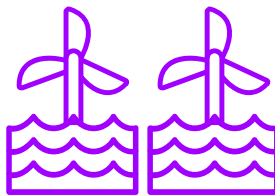
ITM Power

Will produce green hydrogen through electrolysis powered by renewable electricity



Phillips 66

Will utilize renewable hydrogen to reduce refinery CO₂ emissions



Ørsted

Will build and operate an offshore wind farm with a capacity of 1.4 GW

Project Phase 1

Timeline: Concluded in September 2019

Key Objective: A feasibility study was conducted to demonstrate the delivery of bulk, low-cost renewable hydrogen through gigawatt-scale polymer electrolyte membrane electrolysis, with funding provided by BEIS.

Project Phase 2 (current)

Timeline: 2020 to mid-2021

Key Objective: Identify and highlight regulatory, commercial and technical challenges for application of industrial-scale renewable hydrogen systems. Includes a 100 MW electrolyzer front-end engineering design study and a trial of manufacturing equipment.

Project Phase 3

Timeline: Mid-2021 and beyond

Key Objective: Deployment of a large electrolyzer in the Humber region, and creation of a blueprint for deploying large-scale electrolyzer technology across the UK for wider GHG emissions reduction. Further, enabling export of UK-built electrolyzer equipment.

Humber Zero

The Humber Zero project is also aiming to create CCS and hydrogen infrastructure off the coastline of the south Humber river.

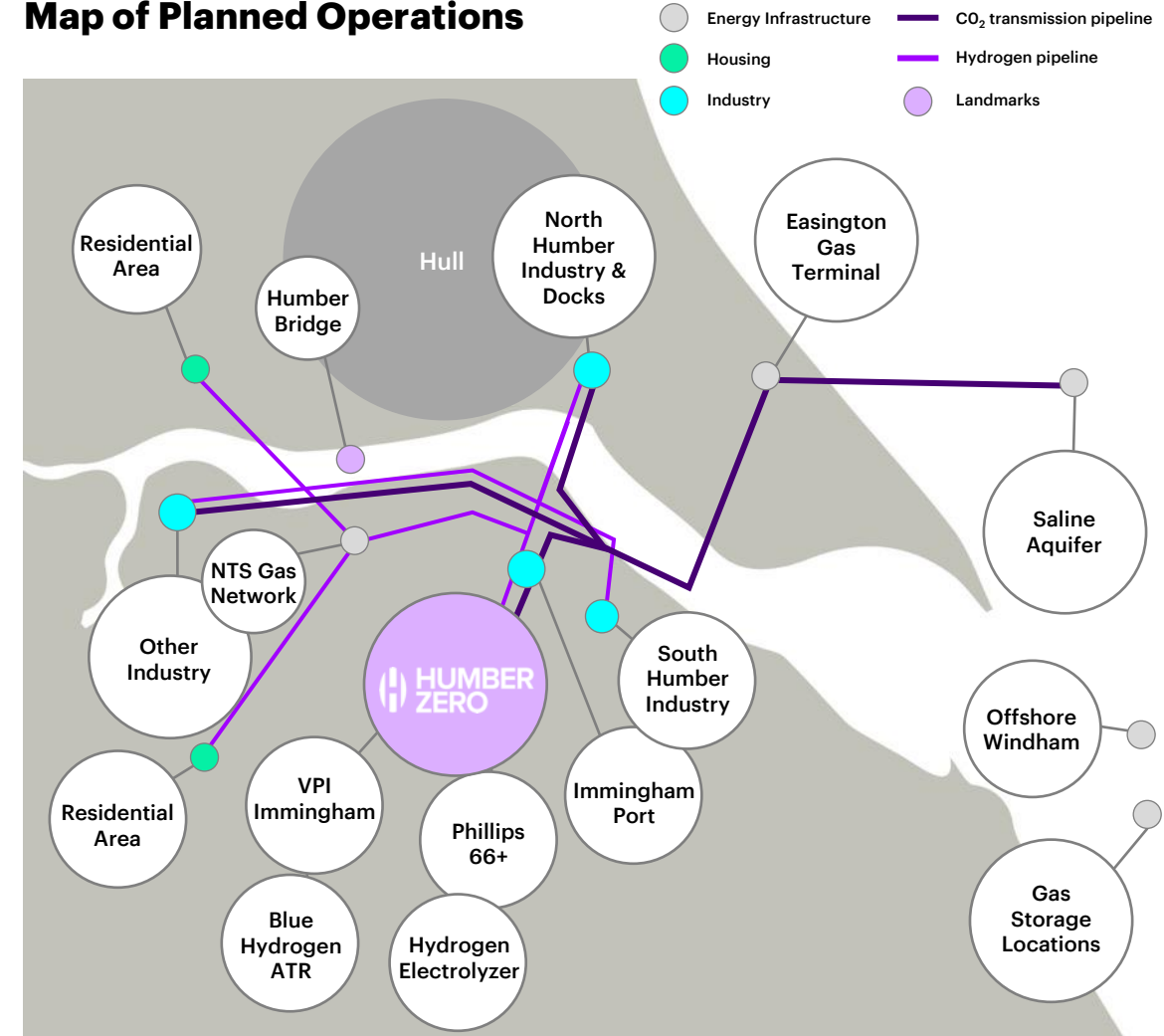
Project Overview

- Humber Zero is a **cluster of energy-intensive industries** located 1 kilometer from the coastline on the south bank of the Humber River.
- Primary partners include **Phillips 66, Uniper and Vitol's VPI Immingham power plant**, which is a combined heat and power (CHP) plant in southern Humber.
- The portside location and connectivity to critical infrastructure make the project a **natural gateway for further carbon abatement** in the region. It is expected that the infrastructure will be operational **as soon as the mid-2020s**.
- The project aims to remove up to **8 Mt/CO₂ per year by the mid 2020s** and up to 40 Mt/CO₂ annually as carbon abatement continues across the Humber region.

Emissions Reduction Technology

- **Offshore wind:** The world's largest offshore wind development, Hornsea One, is currently being built near Humber Zero and will be capable of producing 2.6 GW of electricity. Excess electricity from this project will be used to generate hydrogen to power approximately 50,000 homes per year.
- **Hydrogen:** Humber Zero aims to produce a combination of blue and green hydrogen to reduce emissions from local industry and generate enough hydrogen to help power over one million homes. The project will generate green hydrogen using excess capacity from Hornsea One.
- **CCS:** CCS will be integrated into processes at both the VPI plant and its neighboring oil refineries. The post-combustion captured carbon will be transported via pipeline to either storage fields in the North Sea or to Immingham Port for export to international markets.

Map of Planned Operations



An aerial photograph of a wastewater treatment plant. The image shows several large, circular clarifiers arranged in a circular pattern. Each clarifier has a central metal structure with radial supports extending to the outer edge. The water in the clarifiers is a greenish-brown color. The surrounding area includes concrete walkways, pipes, and other industrial structures. The overall scene is a complex of circular and linear elements.

Systemic Efficiency and Circularity

Levers for reducing industrial emissions

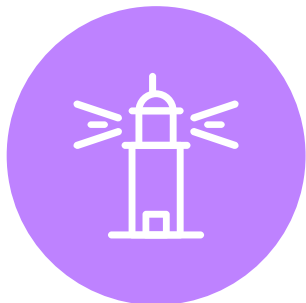
Systemic Efficiency and Circularity



Why does Systemic Efficiency and Circularity Matter?

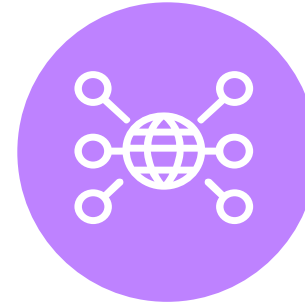
Systemic efficiency is the most underutilized lever in the carbon abatement of industrial clusters and is one of the key areas in China's plans to reduce emissions from industry. Although much progress has been made in the energy efficiency of individual plants and sharing of utilities and products is common in chemicals clusters, much more can be achieved at a cluster level in areas around the world.

Key Barrier: Commercial contracting and lock-in of operating models



Spotlight Cluster Example of Systemic Efficiency and Circularity: Suzhou Industrial Park

In Suzhou, industrial byproducts and waste such as heat and sludge produce biogas and biomass fuel. By connecting infrastructure and supply chains, the cluster collectively saves resources and energy, resulting in environmental, economic and social benefits.



Systemic Efficiency and Circularity



Increase circularity within a cluster through cross-entity waste utilization



Integrate processes within a cluster to share energy and material streams



Provide cost-effective system benefits outside the cluster

Areas of exploration in this section

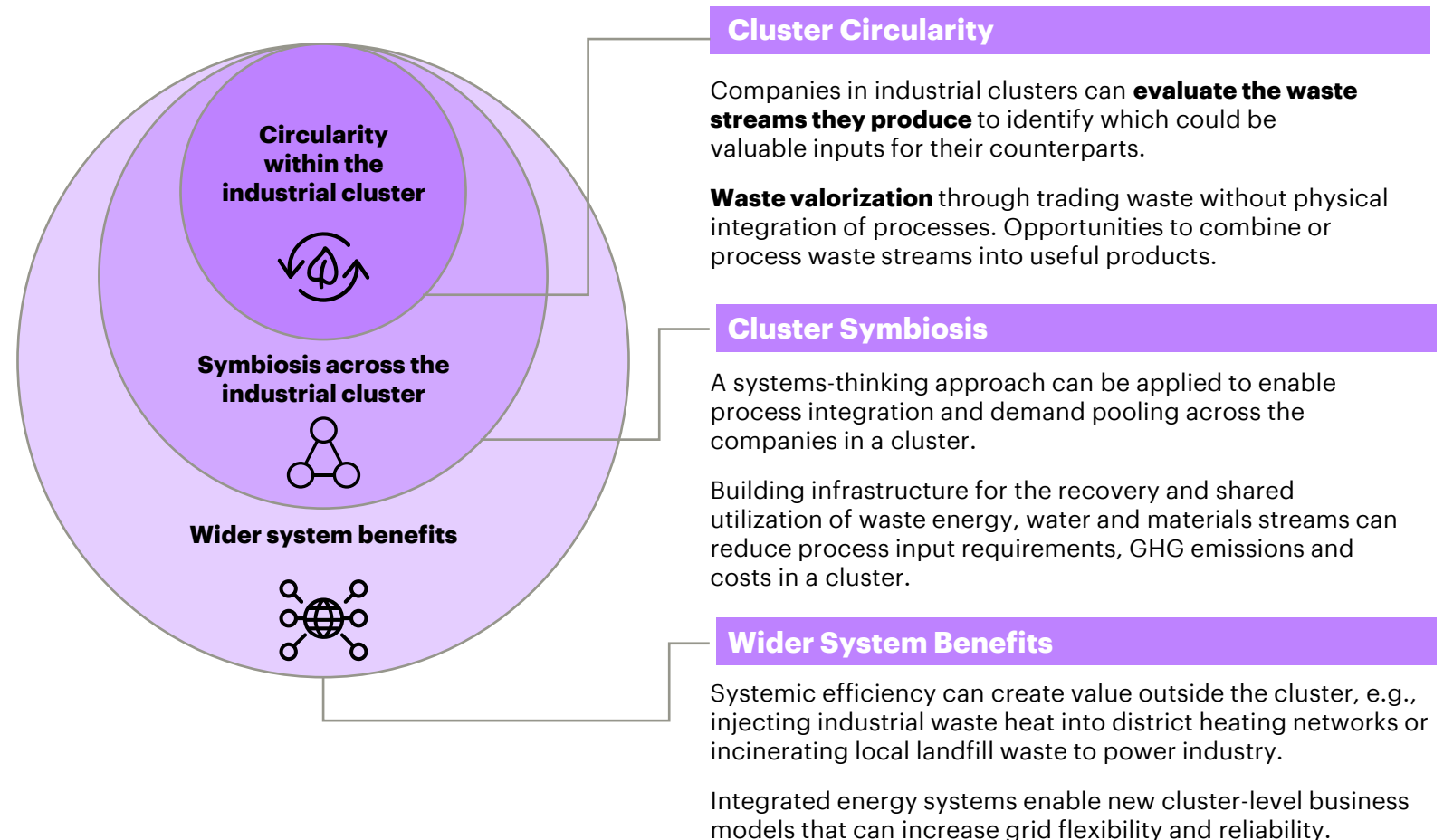
- Opportunities for circularity and waste valorization
- Opportunities for process integration across clusters
- Opportunities to utilize waste heat
- Systemic efficiency cluster case studies
- Challenges and actions for systemic efficiency

Systemic Efficiency and Circularity in Industrial Clusters

Collaboration on efficiency and circularity can deliver financial and environmental benefits to the cluster and the wider system.

Overview

- Building on the efficiency improvements in individual industrial plants and processes, clusters can further progress by adopting a **systems-thinking approach** to exploit synergies between cluster partners and processes.
- Entities in a cluster can map out their waste streams to identify opportunities for **cross-company and cross-industry collaboration to utilize waste**, consequently cutting waste disposal costs and generating new revenue.
- Through symbiotic relationships, implementing **process integration in the use of energy, water and materials**, companies can scale up efficiency gains, driving shared value across the cluster and the surrounding areas.



Case Study: UK Glass Industry

The UK glass industry is prioritizing process innovation and collaboration across sectors and industries in its push to boost productivity and achieve net zero by 2050.

Overview

Several projects are being driven by consortiums of glass industry stakeholders (manufacturers, R&D labs, academia etc.), with UK government funding support, researching and piloting **initiatives for greater efficiency and emissions reduction** in the glass industry.

Some key areas of research activity include:



Raw material efficiency: The industry is looking to **reduce demand for virgin raw materials** in glass production through increased recycling rates and recycled content or changing glass compositions and the use of waste ash. Research projects such as *EnviroGlass2* led by Glass Technology Services and Sheffield Hallam University have shown the emissions reduction benefit of batch reformulations. They showed that **using waste ash can cut CO₂ emissions and replace up to 20% of conventional mined and man-made raw materials** in glass production. There is an added circularity benefit, given that UK biomass power plants currently produce more than 1 million tonnes of waste ash annually.



Fuel switching: The industry is researching alternative fuels for emissions reduction and potential energy-efficiency benefits. Glass Futures and other partners are investigating **transitioning from gas fired furnaces to biofuels, hydrogen, fully electric and hybrid fuel** furnaces.



Process technology innovation: There are further innovation projects being carried out with Innovate UK funding support. These projects are exploring areas such as leveraging **sensor technology** from the steel sector in glass and ceramic manufacturing, **hybrid sintering** techniques to increase speed and lower temperature requirements and techniques for using recovered **waste heat to generate electricity** with CO₂ fluids.

Cross-Industry Waste Symbiosis: EnviroAsh Project

This project convenes partners from across six foundation industries—glass, ceramics, steel, paper, cement and chemicals—as well as the energy sector, academia and the waste and raw material supply chain.

The main aim of this project is waste valorization. Partners will identify opportunities for waste ashes, slags, mineral by-products and filter dusts from across the industries to be converted into new raw materials for a range of products in the glass, ceramic and cement industries.

Another aim is to explore how new feedstocks created from waste might provide opportunities for cost-effective improvement of product performance. With a combination of practical lab-scale and commercial-scale demonstrations, the consortium is assessing the incorporation of the new-waste materials into existing products and processes.

Complementary Industries – Glass and Steel

The glass and steel industries can utilize each others waste to create valuable products and raw materials.

Glass – Steel: British Steel is developing a technology to convert low-grade waste glass shards to improve the skid resistance of blast furnace slag enabling it to be used as surface roadstone.

Steel – Glass: Blast furnace slag is used to make Calumite, a raw material for glass production that cuts energy consumption and emissions while improving glass quality.

Case Study: SCG



Digital platforms for waste management and circularity

Overview: KoomKah

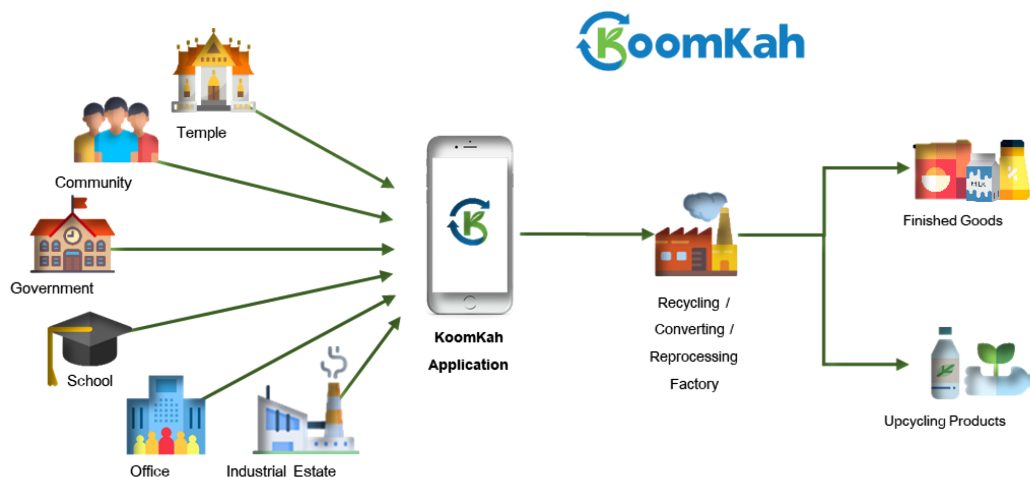
- “KoomKah” (Thai, translates to “worth for value”) is a **digital platform** that supports waste management processes such as collection and sales in industrial estate areas as well as surrounding community waste banks. The application connects suppliers and users of waste and increases the quality and scale of the waste segregated.

How it works

- Conducts and records all waste transactions digitally (buy waste, redeem items, sell waste to junkshop), and uses underlying data to create a database of waste history.

Key Benefits

- 100% digitization for all transactions (sales, collection, etc.)
- 24/7 real time data and smartphone accessibility
- 1,500 tonnes of waste exchanged in 2020
- 724 tonnes of CO₂ reduced in 2020



Overview: PaperX

- “PaperX” is a **digital circular economy platform** for paper products in operation since 2017.

How it works

- Incentivizes ecosystem partners via a digital application to collect, sort and return paper/box waste.
- The application also provides environmental savings certificates. The underlying process then converts paper product waste to recycled products that can be sold back to the market (e.g., new copy paper, paper furniture, wood-plastic composite).

Key Benefits

- Connects more than 76 commercial establishments, 250 retail and factory sites, one industrial estate and 63 condominium complexes
- Recycled over 180 tonnes of paper waste since 2017



Case Study: Meishan Near-Zero Carbon Demonstration Zone

Overview

- Meishan is an integrated urban development zone in Ningbo, Zhejiang province, China.
- It is a **hub for logistics and high-tech industries**, with its port having a container throughput of 2.2 million 20-foot equivalent units.
- Meishan has set ambitious climate targets—aiming to keep 2030 emissions at 2017 levels with a fourfold increase in GDP and threefold increase in population and **targeting carbon neutrality around 2050**.
- To achieve these targets, Meishan is **transforming energy consumption through demand optimization** alongside changing energy supply.
- The Meishan pilot uses a **“port-industry-city” integrated development model** emphasizing synergy between activities across all three facets of the system, working in tandem toward **emissions reduction and regional economic development**.



Aerial view of Ningbo Meishan Near-Zero-Carbon Demonstration Zone

Systemic Efficiency and Circularity Initiatives in Meishan

Integrated Energy Service Provider (IESP) Model

A business model that allows stakeholders to share the risk and return of delivering a more efficient, economical energy system. In Meishan, this is a joint effort between the local government and the electric utility covering: integrated energy planning, power system emissions reduction using renewables, increased energy utilization, distributed energy resources, market-based trading, and the construction of a smart grid for real-time matching of energy supply and demand.

Smart Port System

Promoting the use of clean energy by gradually electrifying container trucks, improved coordination of mass-transit railway transport and construction of high-voltage, on-dock power charging stations. This project will improve both energy efficiency and port logistics efficiency.

Multi-Stage Resource Utilization

Maximizing resource utilization across industry and the wider system. One example involves recovering the cooling load from a liquified natural gas (LNG) terminal to support a freezer warehouse and subsequent recovery of this cooling to support a snow park.

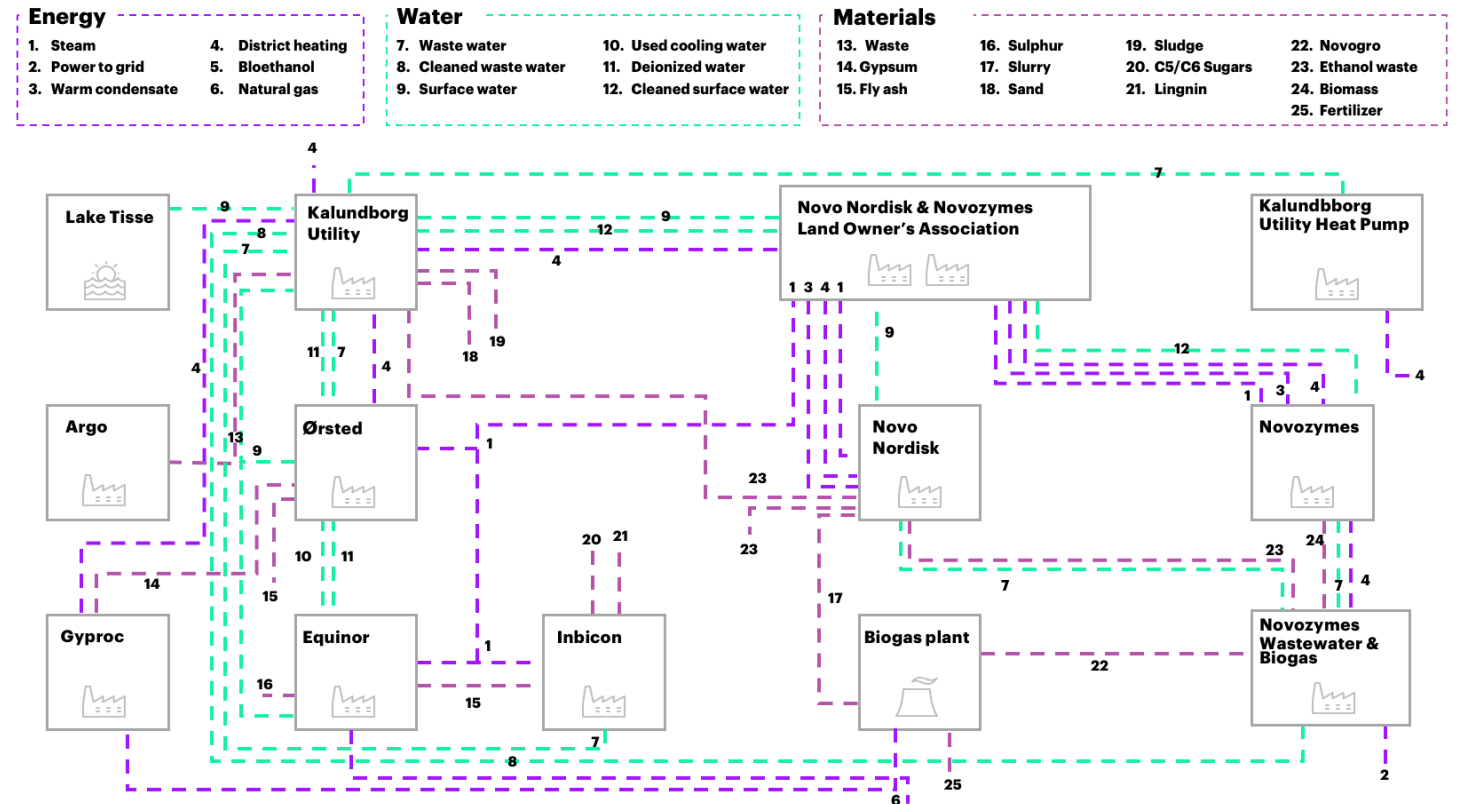
Case Study: Industrial Symbiosis

Denmark's Kalundborg Symbiosis showcases efficiency gains possible through cross-industry collaboration.

Overview

- Kalundborg Symbiosis, located in Denmark, is the **world's first functioning example of industrial symbiosis**—a local partnership where partners provide, share and reuse resources (25 different resource streams) to create shared value.
- Closed-loop **exchange of material, water, and energy streams among the industrial partners** minimizes leakage and waste in the loops, creating a local circular economy and improving resilience for the partners while reducing financial and environmental costs.
- Based on public-private partnerships and collaboration dating back to 1961, Kalundborg is an example of **cross-industry collaboration to increase systemic efficiency and circularity** and create shared value. This collaboration has cultivated an innovative culture locally, attracting several startups and demonstration projects to the area.
- Symbiosis also **triggers business model innovation**. At Kalundborg, Orsted shares high temperature steam from its CHP plant to many partners, pivoting from producing steam as a by-product of electricity generation to making it the primary product and revenue source.

Kalundborg Process Schematic



Estimated annual benefits

- Bottomline savings of €24 million
- €14 million in socio-economic savings
- 635,000 tonnes of CO₂ abated
- 3.6 million m³ water
- 100 GWh of energy
- 87,000 tonnes of materials

Industrial Partners at Kalundborg

Novozymes	Ørsted	Equinor
Novo Nordisk	Biopro	Gyproc
Unibio	Kalundborg Kommune	Argo

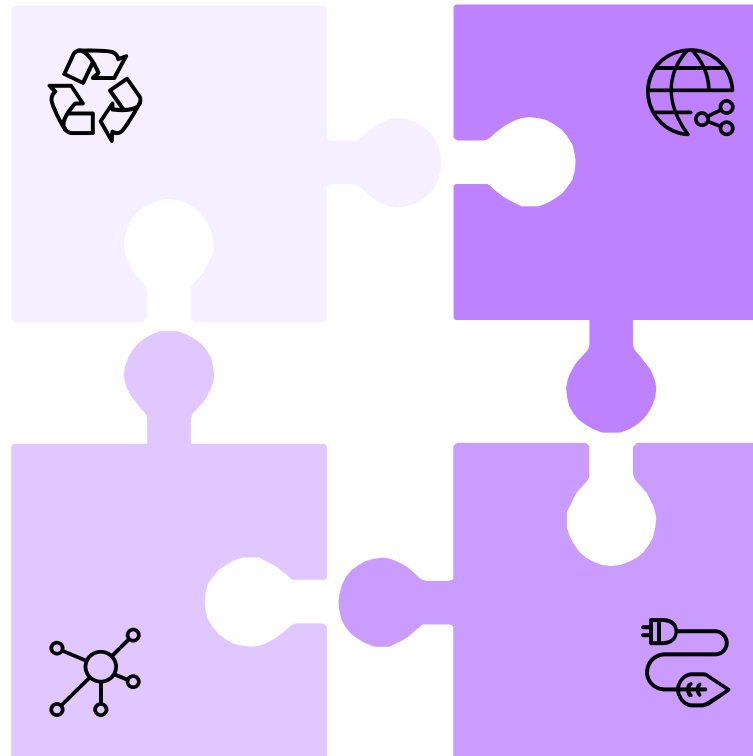
Waste Heat Spotlight

The U.S. Department of Energy (DOE) estimates that about a third of industrial energy input is lost as waste heat. While much of this waste heat is not industrial grade, it can be stepped up in quality or utilized in non-industrial lower temperature applications.

Four Routes to Waste Heat Utilization

Reuse within individual facilities

- Waste heat can be recovered using heat exchangers and then used to **reduce heat demand elsewhere in the facility**, e.g., by pre-heating input streams to another process.
- This application is demonstrated across many industries.



Supplying local heat demand

- Waste heat produced at temperatures too low for industrial use can be valorized through **supplying local residential or commercial heat demand**.
- This application is common in many parts of Europe and is being demonstrated in Dublin, with data centers set to supply waste heat to local district heating networks.

Transfer to other industries

- Varying temperature requirements across industrial processes in a cluster means **waste heat recovered from one industry can satisfy demand in another** with a lower temperature requirement.
- This is a common feature of industrial symbiosis and is demonstrated in the Kalundborg Symbiosis.

Waste heat to power

- Recovered **waste heat can be used to generate power** using a steam Rankine cycle system for high temperature heat and Organic Rankine Cycle (ORC) and Kalina Cycle for low-temperature heat.
- Widely used in the Chinese cement industry with more than 700 installations of waste heat-to-power systems.

Waste Heat Case Study-Nuclear

Waste heat recovery or cogeneration from nuclear power plants presents a low-carbon industrial process heat alternative

Overview

- Only **26% of total industrial heat demand** in the EU is **for high-temperature heat (greater than 400°C)** and the majority of this is supplied by burning fossil fuels.
- While heat generated from nuclear power plants can satisfy process heat demand and reduce resultant emissions, it **currently has limited industrial applications.**
- Industrial applications of nuclear heat include heat from a pressurized water reactor (PWR) at Gösgen in Switzerland **used in cardboard production**, and heat from a pressurized water reactor (PWR) at Stade in Germany being **used in a salt refinery.**
- The Royal Society (UK) estimates the cost of thermal energy from a nuclear reactor (based on a PWR) would be **\$7.42 – \$11.42 /GJ** compared to **\$3.5 – \$8/GJ for unabated natural gas**, while another estimate costs hydrogen heating at **\$7.59 – \$13.34/GJ** (blue and green hydrogen).

EDF Energy – Sizewell C Nuclear Power Station Proposal, UK

- Sizewell C is a proposed new nuclear power station in Suffolk, UK, being developed by EDF in partnership with CGN. A planning proposal has been submitted for the construction of two European pressurized reactors (EPRs) with a **capacity of 3200 MWe.**
- The proposed design will include valves that allow for steam to be collected after the main steam isolation valve, giving flexibility to **shift the balance between heat and electricity production.**
- Flexible cogeneration makes Sizewell C a potential **source of low-carbon process heat for light industry.** This could incentivize siting of industry in the vicinity with heat uses such as cryogenic storage, data center cooling and building heating. Likewise, the heat could be used in processes at the nearby Port of Felixstowe.

Challenges to deployment

Location: Nuclear reactors tend to be sited in remote areas and need to evaluate the hazard posed by siting industrial facilities nearby. While heat can be transported across long distances, this may not be economical. However, the advent of new reactor types such as small modular reactors (SMRs) can loosen location constraints.

Temperature: Water reactors (most prominent design) tend to generate steam at less than 300°C, too low for many energy-intensive processes. However, this temperature level is suitable for a large proportion of industrial heat demand, although these processes are less likely to be geographically clustered.




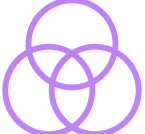
Collaboration: Industry and nuclear operators as well as their respective investors will need to overcome cultural differences and knowledge gaps to build the trust necessary for significant process integration.



Sizewell proposed design – EDF Energy

Challenges and Actions for Systemic Efficiency and Circularity

Collaborating across multiple entities in a cluster comes with challenges, but there are actions that can be taken to set up for success.

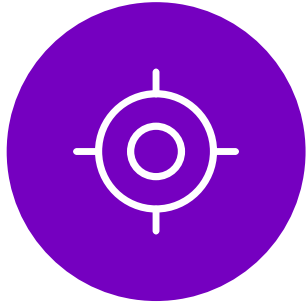
 <p>Cooperation</p>	<p>Challenges</p> <ul style="list-style-type: none"> • A systemic approach to driving efficiency in a cluster requires strong partnerships and a culture of shared value built on trust. • Joint decision-making across companies with a variety of interests and incentives could slow down progress. 	<p>Actions</p> <ul style="list-style-type: none"> • Create cluster-wide consortiums and appointing decision-making groups with clear responsibilities. • Cluster collaboration initiatives should be driven by companies with strong reputations, ambition and willingness to invest. • Agree on cluster-wide targets that align individual interests.
 <p>Investment</p>	<ul style="list-style-type: none"> • Initiatives might have high upfront costs and long payback periods. • Policy cycles are shorter than investment cycles so policies enabling investment profitability can change prior to asset depreciation. • Difficulty in capital cost allocation and differing financial positions. • Companies in a cluster may be subsidiaries of multinationals with limited ability to make major investment decisions. 	<ul style="list-style-type: none"> • Public-private partnerships can provide external funding, reducing capital outlay for the cluster and de-risking investment. • Business models that reduce dependence on specific policies and improve commercial feasibility need to be developed.
 <p>Valuation</p>	<ul style="list-style-type: none"> • Sharing waste streams across companies within a cluster will require a system of valuing byproducts. • Clusters need clear signals on the value of externally shared waste streams, e.g., heat injected into district heating networks. 	<ul style="list-style-type: none"> • Capacity for production and demand for waste streams should be evaluated and commercial agreements put in place among cluster partners in the collaboration planning phase. • Commercial agreements such as PPAs should be put in place to secure value from providing wider system benefits.
 <p>Integration</p>	<ul style="list-style-type: none"> • Process integration restricts scope to change production volume or production process, as there are obligations on input to produce for or output to consume from partners. • Barriers are erected to exiting a cluster as there is “take-or-pay” risk with process integration agreements. 	<ul style="list-style-type: none"> • Business models and flexible arrangements which reduce process rigidity introduced by integration should be developed. • Companies should invest in process integration as part of long-term strategy for operating in a certain cluster.

A photograph of a worker in a yellow hard hat and safety vest working on a large array of solar panels. The worker is leaning over the panels, which are arranged in a grid pattern. The background shows a clear blue sky and some industrial structures. The text is overlaid on the image.

Direct Electrification and Renewable Heat

Solution areas to reduce industrial emissions

Direct Electrification and Renewable Heat



Why Do Direct Electrification and Renewable Heat Matter?

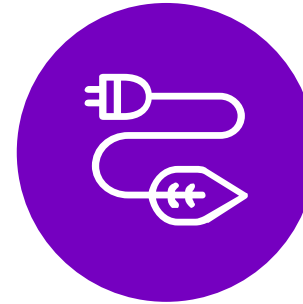
Direct electrification has not been widely implemented due to the high cost of electricity relative to natural gas and stranded investment in fossil-based assets. However, the attractiveness of electrification is rising due to carbon pricing, falling renewables costs, shared infrastructure (such as microgrids) and emissions reduction targets that eliminate the use of unabated natural gas.

Key Barrier: Cost-competitiveness of electricity against unabated natural gas and fossil-based assets not yet fully depreciated



Spotlight Cluster Example of Direct Electrification and Renewable Heat: Suzhou Industrial Park

Suzhou has implemented a microgrid, increased the renewable electricity supply through both onsite and renewable energy PPAs, and electrified transportation in the cluster.



Direct Electrification and Renewable Heat



Electrify low-to-medium temperature and pressure processes



Generate low-cost, renewable electricity and heat onsite (e.g., rooftop solar, biomass, CSP)



Pursue shared infrastructure (e.g., microgrid, storage, flexibility)

Areas of Exploration in this Section

- Direct electrification technology viability across industries
- Emergence of cluster electrification enablers such as microgrids, shared renewable generation and storage, and demand optimization
- Direct heat solutions
- Direct electrification and renewable heat case studies
- Challenges and actions for direct electrification and renewables heat

Direct Electrification Overview

Electrification provides a feasible route to reduce emissions from most industrial processes across sectors.

Overview

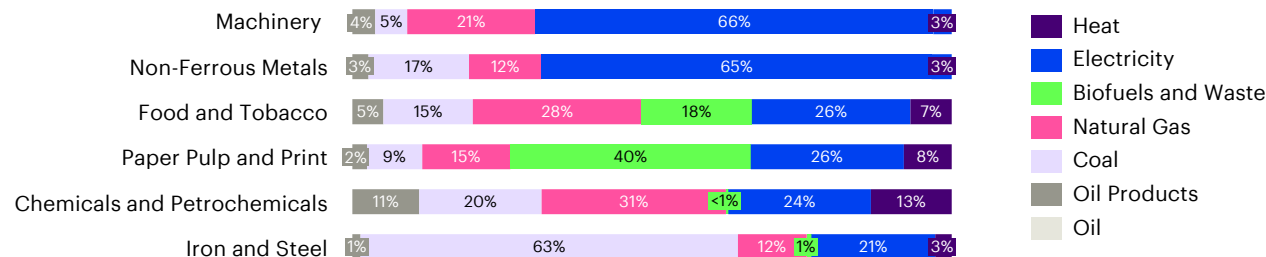
- Many industry electrification discussions focus on the technical difficulty of electrifying high-temperature processes on a commercial scale; however, research shows that **significant benefit can be achieved from electrifying low- and medium- temperature processes with commercially available technologies.**
- Research on the EU by the Potsdam Institute found that less CO₂-intensive sectors (e.g., paper, wood, textiles) can be nearly completely electrified with mature, commercially available technologies. These industries accounted for 40% of EU industrial emissions in 2015 and **electrifying these industries would cut 36% of EU industry emissions by 2050.**
- Likewise, the National Renewable Energy Laboratory (NREL) found that without changing heavy industry, it is possible to **electrify 43% of total U.S. industry fuel energy use** with commercially available technology.
- While natural gas is a cheaper energy vector, in a carbon-abatement scenario it is **more accurate to compare direct electrification to other low-carbon solutions** such as natural gas with CCUS and hydrogen or to factor in carbon prices. When feasible, electrification provides a lower cost, technologically mature and **more efficient low-carbon solution.**
- In addition to electrification of combustion-based process heating, industries currently using electricity as their main energy source can **cut emissions and save costs in the long term** by transitioning from fossil-based electricity generation to zero-carbon sources.

Easily Electrifiable Industrial Processes

- It is technically feasible to electrify most industrial processes, including heavy industry.
- The table below summarizes key processes in various industries that can be electrified with commercially available technologies.
- In addition to these processes, industrial site non-heat-related energy use such as machine drive and light-duty transport are also electrifiable.

Industries	Electrifiable Processes	Technologies
All industries (including food and textiles)	<ul style="list-style-type: none"> • Low-temperature process heat, i.e., cooling, drying, space heating, steam generation 	<ul style="list-style-type: none"> • Compression heat pumps and chillers • Electric boilers • Mechanical vapor recompression
Wood	<ul style="list-style-type: none"> • Curing 	<ul style="list-style-type: none"> • Ultraviolet curing
Paper and pulp	<ul style="list-style-type: none"> • Limestone calcination 	<ul style="list-style-type: none"> • Electric kilns
Ceramics and glass	<ul style="list-style-type: none"> • Firing ceramics • Glass melting, annealing and tempering 	<ul style="list-style-type: none"> • Resistance heating
Machinery	<ul style="list-style-type: none"> • Process heat 	<ul style="list-style-type: none"> • Induction furnace
Transport equipment	<ul style="list-style-type: none"> • Process heat 	<ul style="list-style-type: none"> • Induction furnace
Manufacturing	<ul style="list-style-type: none"> • Process heat 	<ul style="list-style-type: none"> • Resistance heating
Non-ferrous metals and secondary steel	<ul style="list-style-type: none"> • Melting • Smelting • Metals refining 	<ul style="list-style-type: none"> • Induction furnace • Resistance furnace • Electric arc furnace

Share of electricity in energy mix by sector (IEA, 2018)



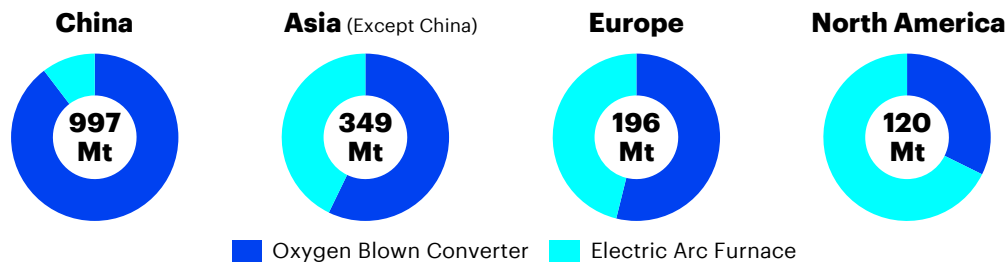
Case study: Electrification of Industrial Process Heating

There are limited commercial examples of electrifying previously combustion-based heating in industry, however, activity in this space is rising due to technological maturity and the potential to unlock wider productivity improvement.

Secondary Steel Production with Electric Arc Furnaces (EAF)

- The production of secondary steel from recycled scrap using electric furnaces is an established process, accounting for **28% of global steel production**.
- This process is highly technologically mature and **can require as little as a fifth of the energy** needed in the conventional blast furnace, coupled with basic oxygen furnace (BF-BOF) route. In addition to reduced energy intensity, using **low-carbon electricity can enable significant emissions reductions**.

Crude Steel Production by Process in 2019



Considerations for Scaling Up

- **Raw material availability:** In some regions, **steel recycling rates are high** (~85% in Europe), limiting the potential for scale up of production from scrap.
- **Value chain emissions:** Electrifying blast furnaces will reduce emissions, but similar emphasis should be placed from **coke-based iron ore reduction**. Direct reduction of iron using hydrogen is one potential solution being explored.
- **Stranded assets:** Many operating blast furnaces may not be near end of life and are unlikely to be retired soon. Other abatement measures can be used in these cases and new investments focused on low-carbon technology.

BASF – Electrification in the Chemicals Industry

- BASF SONATRACH PropanChem S.A. is a joint venture between BASF and SONATRACH, producing about **350,000 tonnes of propylene per annum** at a propane dehydrogenation (PDH) plant in Tarragona, Spain.
- In November 2017, the company **replaced a steam turbine** in the propylene purification unit of the PDH plant **with an electric motor and a frequency inverter**, investing €6 million targeted at improving energy efficiency.
- With the support of a grant from the Spanish government, this project yielded its intended outcomes and **delivered unplanned productivity benefits** across the wider production process.

Benefits achieved from electrification

Energy savings: Greater efficiency of electrical power enabled the replacement of a **19 MW steam turbine** with a **10 MW electrical motor**. Coupled with power consumption control from using a variable speed motor, **annual primary energy demand was reduced by ~80 GWh**.

Water consumption: Replacing the steam turbine reduced cooling water demand, freeing up capacity to cool other processes across the plant and **cutting annual water demand by ~500 million liters**.

Emissions reduction: Reduced energy and water consumption along with the reduced carbon intensity of the energy source resulted in a **reduction of ~34,000 tonnes CO₂ emissions** annually.

Plant performance: Reduced temperatures across the plant enabled better control of reactions, separation columns and other equipment contributing to **more than three years of continuous plant operation** instead of previously required annual technical shutdowns.

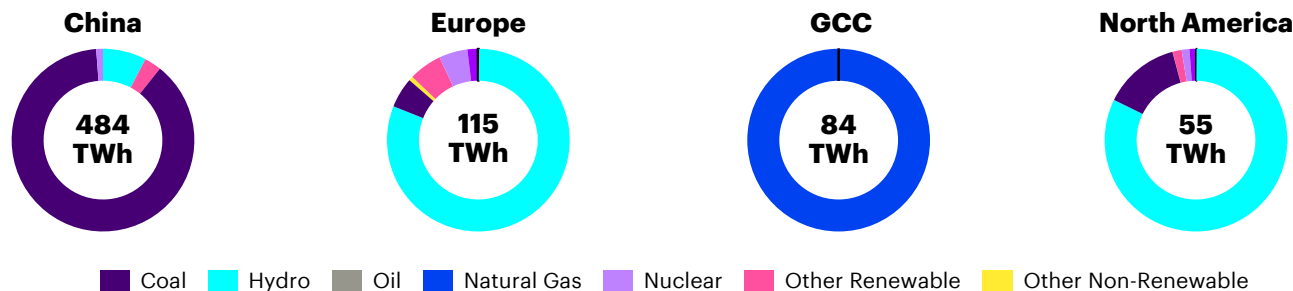
Renewable Electricity in Aluminum Production

For industries like aluminum where electricity generation accounts for a high percentage of costs and GHG emissions, changing power source is a crucial step in the path to net zeros.

Industry Context

- The aluminum industry generates more than 1.1 GtCO_{2e} annually—**2% of global anthropogenic emissions**—and this is set to grow with the increasing demand for aluminum.
- Cutting emissions in this sector is critical as aluminum is the second-most-used metal in the world by mass and a **vital resource for a net-zero future**, with end uses including manufacturing of EVs, solar panels and transmission cables.
- Already heavily electrified, **60% of aluminum industry emissions come from electricity generation**. The power sources used in aluminum smelting vary depending on geographical accessibility as shown below.
- **Electricity accounts for about a third of operating costs for aluminum smelters**. Given the low margins at which aluminum producers operate, they must use the most affordable, consistent power source and have difficulty funding the capital investment needed to transition power source.
- However, with falling costs of renewables, it will **soon be cost-competitive to invest in construction of new onshore wind or solar rather than continue operation of conventional sources**. With rising carbon prices, falling costs of storage and the availability of renewable PPAs to balance supply and demand, the time is right for the aluminum industry to transition.
- The business case for the transitioning power sources can be further strengthened by government support and incentives, **clear carbon pricing signals and low-carbon aluminum demand signals**.

Aluminum Smelting Power Consumption Mix by Region in 2019



Global Examples (Not exhaustive)



China

Coal – Hydropower Transition

- Hongqiao Group began production at a **hydro-powered aluminum smelter** in Yunnan, China in September 2020. This commences a relocation of production close to hydropower sources to **reduce reliance on coal-fired generation with rising state sanctions** on coal to support GHG emissions reduction targets.



Norway

Long-term Wind PPA

- In July 2018, Norsk Hydro signed a **29-year PPA** (a fixed-volume agreement) with Green Investment Group for a **235 MW onshore wind farm** in Sweden. This will be used to power their aluminum production and reduce carbon footprint.



Singapore

Low-carbon Aluminum Financing

- In September 2020, Trafigura Group, a leading commodities trading company, established a first-of-its-kind **“low-carbon aluminum” financing platform of up to \$500 million** in response to its growing downstream demand for manufacturers.

Cluster Electrification Enablers

Beyond direct electrification of processes, clusters and cluster entities have the potential to deploy onsite electrical infrastructure, grow renewables through PPAs and provide balancing services back to the grid.



On-site and shared Renewables, Storage and Microgrids

Through on-site renewables generation, shared dispatchable zero-carbon sources (e.g., biomass plant, SMR or hydropower), storage and microgrids, industrial clusters can increase energy autonomy and share and reduce risk associated with variability of wind and solar.



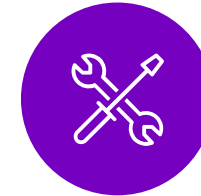
Virtual Renewable PPAs

When energy demand cannot feasibly be supplied by on-site renewables, clusters can pool demand for renewable PPAs (e.g., similar to U.S. community choice aggregation (CCAs)).



Demand Optimization

For grid electricity consumption, industry can, where possible, increase flexibility to shift production from peak price hours to lower price hours. In addition to lower costs, this can increase revenue from providing flexibility services to the grid.



Retrofitting and Hybrid Technologies

Some technologies allow for gradual transformation by retrofitting existing machines or installing hybrid systems. This allows for reducing fuel costs by switching between energy vectors.

Case Study: Genagricola

Electrification and emissions reduction of an agricultural chain

Overview

- Genagricola, a holding company of the Generali Group, is the **largest Italian agricultural company**.
- Genagricola is conducting a project to increase circularity among its companies/sites and set a **new sustainable strategy with focus on emissions reduction and electrification**.
- Enel X developed a **unique methodology to assess the circular economy maturity level of businesses** at a corporate and an energy site level (CE Energy Score) and was able to identify an improvement roadmap.
- The initial average of CE Energy Score on all 22 sites is equal to 15% while the delta average improvement is estimated in + 44%.
- Improvement areas include shared renewable energy production, energy efficiency of buildings, and implementation of shared electric mobility assets.



Electrification Initiatives in Genagricola

100% Renewable Target for Energy Consumption

Three main solutions have been adopted to transition energy consumption from traditional fossil sources towards renewables:

1. **Roof photovoltaic systems** at full physical capacity.
2. **Direct PPA** from large PV plants constructed by Enel on Genagricola's land (land-lease contract).
3. **Energy supply** from renewable sources (guarantee of origins) for the remaining consumption needs.

Electrification of Corporate Fleet

1. A **fleet electrification detailed analysis** has been conducted on all of Genagricola's fleet to identify mobility needs and provide a quantification of journeys, vehicles eligible for retrofit into EVs and localization of charging infrastructures.
2. A feasibility study is in progress to assess the **retrofit potentials of the existing trucks** suitable for the transition to the electric engine that would allow to **carry out agricultural activities avoiding the consumption of fossil fuels**.

Monitoring and Verification

To increase efficiency and save resources, an **integrated AI-based monitoring system will be installed** which will allow management to optimize processes and machineries by identifying anomalies and inefficiencies promptly.

Case Study: Microgrid Solution

As reliance on electricity in industrial clusters grows, microgrids enable clusters to boost resiliency of their electricity supply and reduce strain on the grid caused by rising demand.

Project context

- The Port of Long Beach (POLB) in California is the **second busiest container port in the U.S.**, handling \$200 billion annually in trade and supporting close to 500,000 jobs.
- As the POLB transitions to net-zero, **electrical load is expected to quadruple**. Given the large delta between port-wide base and peak load, connecting this incremental load would necessitate grid investment.
- With increasing dependence on electricity, **reliability will be critical** as failure could cause millions of dollars in damage daily in lost work hours and perished cargoes.
- To avoid a single point of failure (i.e., utility grid), the port is looking to **microgrid systems** that integrate zero-emission DERs and grid services to **add resiliency** to seaport operations, **reduce pollution** from diesel generators and **alleviate intermittent pressures on the grid**.

Benefits

- **Lower costs:** Smart load management to avoid electricity peak price hours and cheap on-site solar power generation.
- **Energy security:** Microgrid will help prevent service interruption due to power outages and reduce reliance on fossil fuels for emergency power.
- **Environmental benefit:** Microgrid enables onsite renewable electricity generation and reduced fossil fuel dependence.
- **Grid reliability:** Storage and demand response capability enable the facility to respond to utility signals and shave load during peak demand.

Solution overview

The POLB Microgrid Project, due for 2021 completion, will help achieve long-term islanding at the port's Joint Command and Control Center, a critical response facility. Key features of the project:



300 kW solar carport: For zero-emissions photovoltaic energy production.



Batteries (330 kW stationary BESS and 250 kW mobile BESS): These will **provide grid services**, such as demand response and peak shaving, during regular operation of the utility grid. Additionally, during wide-spread outages or emergencies, the **mobile battery will act to extend the microgrid** as a generator where needed, such as stormwater pump stations and refrigerated container yards.



Energy control center: Hosts microgrid controls and stationary battery.



Innovation: A key project innovation is the installation of both DC and AC bus controllers in the system, resulting in **significantly improved efficiency of stored energy** by allowing direct DC transfer of energy from the PV system to the battery.

Project Partners

Schneider Electric

NREL

California Energy Commission

Southern California Edison (SCE)

Note: Partner list non-exhaustive

Onsite Production of Renewable Heat

Renewable heat provides a low or zero-carbon option for industrial process heat.

Overview

- Process heat is the largest industry energy need and accounted for 50% of 2019 global heat demand. However, only **10% of industrial process heat was from renewable sources.**
- **Bioenergy accounts for almost 90% of renewable heat in industry** and is predominantly used in industries producing biomass waste such as paper and pulp and food. The cement industry in China and the EU is increasing bioenergy consumption using municipal waste.
- Renewable heat can be used to supply both direct and indirect process heat (e.g., hot water or steam generation) and has the **potential to abate up to 120 Mt CO₂ by 2030.**
- In addition to renewable sources discussed, waste **industrial process gases with calorific value can be burnt to generate process heat** in clusters.
- Industrial clusters can collaborate across industries to **leverage technical expertise, existing process infrastructure and waste streams** for the generation of low-carbon heat.

Common Renewable Heat Sources

Bioenergy

- Biomass: Solid fuels such as virgin wood chips and uncontaminated waste wood.
- Biogas: Methane gas produced from biogenic substances in an anaerobic digester.
- Syngas: Gas from pyrolysis or gasification of solid waste or biomass.
- Fuels derived from waste: Solid recovered fuel (SRF), refuse derived fuel (RDF) from treated waste such as municipal solid waste.

Solar thermal: Collection (and concentration) of solar irradiation to generate heat. Technology ranging from flat plate collectors to heliostat tower systems.

Geothermal heat: Utilizing heat from within the earth's crust for industrial processes using technology like ground source heat pumps and hot sedimentary aquifer systems.

Other sources: Renewable electricity and hydrogen are other heat sources explored elsewhere in this report and renewable district heating is applicable, but is not been explored at depth here.

Benefits and Barriers to Renewable Heat in Industrial Clusters

Bioenergy

- ✓ Can supply heat over a wide variety of temperatures
- ✓ Already extensively used in certain industries
- ✓ Opportunities for circular economy and productive waste use
- ✓ Can be used for cogeneration of heat and power
- ✓ Potential for zero or negative fuel cost
- × Low and variable calorific value compared to fossil-based fuels
- × High transport costs and potential raw material availability issues

Solar thermal

- ✓ Zero fuel cost and zero emissions
- × High capital cost for set-up and process integration of CSP
- × CSP dependent on location irradiance and space availability
- × Variable source of heat with expensive storage solutions

Geothermal

- ✓ Zero fuel cost and zero emissions
- ✓ Low footprint above ground level
- ✓ Once developed, can produce heat 24 hours a day
- × High capital cost for set-up and process integration
- × Low achievable temperatures at commercial scale
- × Highly location-dependent

General renewable heat considerations

- Renewable heat can also ease the transition from existing high-temperature heat sources by preheating process streams and provide protection from fossil fuel price volatility
- The most cost-effective renewable heat solution will depend on cluster location, existing infrastructure and raw materials access

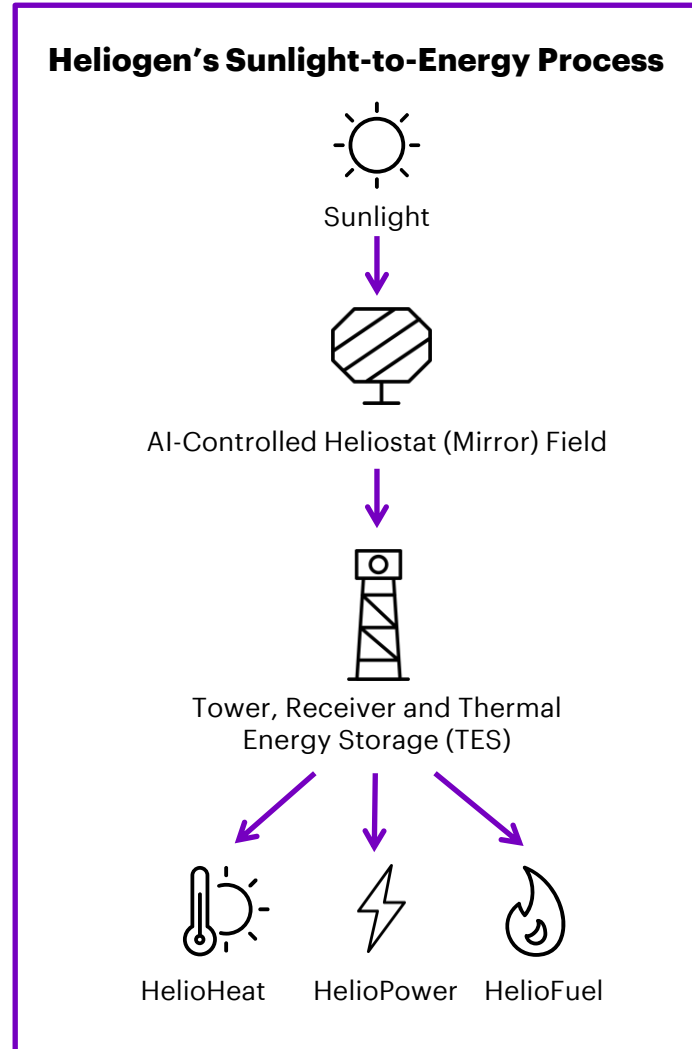
Case study: New Solar Thermal Solutions

New CSP technology from companies such as Heliogen could provide an integrated cost-effective solution for the carbon abatement of heavy industry.

Overview

- Heliogen, a renewable energy technology company with backers including Bill Gates and Patrick Soon-Shiong, can—for the first time in history—cost-effectively concentrate solar energy to achieve ultra-high temperatures (up to 1500°C).
- Heliogen has invented the world’s first Sunlight Refinery™, a green hydrogen and 24/7 electricity plant that captures, concentrates and refines sunlight into cost-effective energy on demand.
- Sunlight refineries harness the power of artificial intelligence (AI), using computer vision and object recognition to precisely align an array of mirrors (heliostats) to reflect sunlight at a single target with unprecedented accuracy.
- Sunlight refineries are built in modular 5 MW_e/13 MW_{th} modules and can be rapidly deployed at scale to generate heat, electricity or hydrogen for heavy industry.

	HelioHeat™	HelioPower™	HelioFuel™
Description	<ul style="list-style-type: none"> • Carbon-free, ultra-high temperature heat that provides an alternative to burning fossil fuels for industrial process heat • Target cost: <delivered natural gas 	<ul style="list-style-type: none"> • Electricity made from concentrated sunlight using thermal energy storage • Target cost: <5¢/kWh 	<ul style="list-style-type: none"> • Renewable fuels like 100% green hydrogen made from concentrated sunlight and electrolysis • Target cost: <\$2/kg
Target Industries	<ul style="list-style-type: none"> • Cement, steel, petrochemicals 	<ul style="list-style-type: none"> • Utilities, mines, data centers, etc. 	<ul style="list-style-type: none"> • Transportation, heavy equipment, chemicals, steel, other industrial uses
Industrial Applications	<ul style="list-style-type: none"> • Calcining, reforming, melting, roasting, sintering, thermal decomposition 	<ul style="list-style-type: none"> • Any industrial use of 24/7 electricity 	<ul style="list-style-type: none"> • Iron ore reduction, chemical feedstocks
Benefits	<ul style="list-style-type: none"> • Reduced fuel costs, reduced GHG emissions, higher margin “green” products 	<ul style="list-style-type: none"> • Reduced fuel costs, reduced GHG emissions, higher margin “green” products 	<ul style="list-style-type: none"> • Reduced fuel costs, reduced GHG emissions, higher margin “green” products



Challenges and Actions for Electrification

Increasing direct electrification of industry will require action to improve cost-competitiveness compared to natural gas.

Commercial and Technical Challenges to Industry Electrification

Cost-competitiveness: With electricity three times the cost of natural gas, electrification significantly raises operating costs. Competitive global trade and thin profit margins greatly disincentivize increasing production costs, however, the declining cost of renewable electricity, and likely carbon pricing, may reduce this cost differential in the near future.

Capital investment: Transitioning to electric technology could require significant financial outlay to purchase new equipment.

Limited productivity gains: Many electrifiable processes have limited impact on productivity or profitability, the main drivers of technology adoption.

Technical complexity: Electrification of some processes will require complex changes in technology, requiring upskilling of operators and potentially secondary process changes to accommodate new technology.

Process disruption: Replacing process equipment with electric alternatives could cause significant production disruption.

Stranded assets: Electrification could require early retirement of long-life, fossil-based assets—jeopardizing return on investment.

Policy and Industry Actions for Industry Electrification

Carbon pricing: Clear carbon price signals help reduce investment uncertainty and reduce the relative cost of electricity.

Carbon regulations: Consumption-based regulations such as CO₂ footprint requirements for materials in cars and buildings can encourage carbon abatement. CO₂-based tariffs, while complex to implement, can address competition issues that arise from regional asymmetry in net-zero efforts.

Reducing electricity taxation and levies: This will reduce the cost of electricity relative to gas. In Sweden, this led to an electricity and gas price difference half the European average.

Sectoral agreements: International agreements across an industry to reduce emissions will lessen the impact of production cost increases on competitiveness in global trade.

Technology support schemes: These will drive down costs of electrification technologies, incentivize adoption and increase technical expertise.

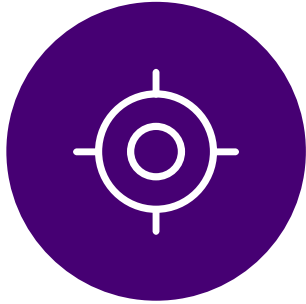
Retrofitting and hybrid technologies: Some technologies allow for gradual transformation by retrofitting existing machines or installing hybrid systems. This allows for minimizing fuel costs by switching between energy vectors.

A detailed view of an industrial hydrogen production facility, showing a complex network of stainless steel pipes, valves, and large cylindrical tanks. The scene is illuminated with a cool blue light, emphasizing the metallic surfaces and the intricate piping system. The perspective is from a low angle, looking down a long, curved pipe that leads into the distance.

Hydrogen

Solution areas to reduce industrial emissions

Hydrogen



Why does Hydrogen Matter?

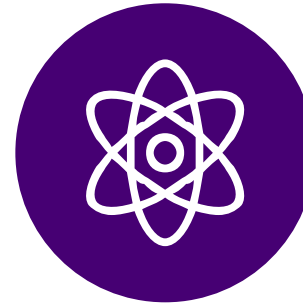
There is growing recognition that hydrogen will be required to reduce industrial emissions and achieve net-zero targets by 2050, with significant investments being announced and the emergence of hydrogen hubs.

Key barrier: Viable storage locations and applications and lack of transport and storage infrastructure



Spotlight Cluster example of Hydrogen: Humber Industrial Cluster

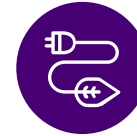
Humber is pursuing a mix of blue and green hydrogen, including hydrogen produced from natural gas through an autothermal reforming plant (ATR) and CCS infrastructure. Green hydrogen is also produced from offshore wind electrolysis using the same infrastructure.



Hydrogen



Produce low-to-zero carbon hydrogen from the most economical source (e.g., blue, green)



Leverage electricity and heat from nearby zero carbon sources (wind, solar, nuclear, biomass)



Use produced hydrogen as an alternative fuel for hard-to-electrify industrial processes, building heating and transport

Areas of exploration in this section

- Hydrogen value chain
- Emergence of hydrogen hubs
- Colors of hydrogen- many sources of zero- (or low-) carbon hydrogen
- Case studies of hydrogen produced from other technologies- solar, nuclear, biomass (in addition to those covered in the Humber which include blue from natural gas and green from offshore wind)

Hydrogen Overview

Hydrogen has significant potential to enable the transition to a clean, zero-carbon economy, particularly where electrification technology is nascent or there are significant process emissions from conversions.

Benefits of Hydrogen

Hydrogen is the most promising technology capable of addressing reducing GHG emissions in hard-to-abate sectors of the economy. It can be used in the following applications:

- **Industry:** In addition to its conventional uses in chemicals and refining industries, hydrogen can be an alternative feedstock in some high-temperature industrial processes that are difficult to electrify.
- **Power:** Hydrogen provides a long-term, large-scale storage solution to support integration of intermittent renewable energy generation and can replace natural gas for power generation or heat.
- **Mobility:** Hydrogen has the potential to be used to derive fuels for long-haul land and maritime shipping as well as aviation.

Barriers and Action to Widespread Deployment of Low/Zero Carbon Hydrogen

- The infrastructure necessary to support a low/zero hydrogen economy consists of transport, storage and distribution stations, and is **extremely costly at present compared to other decarbonization efforts** such as electrification.
- **Cheaper and more abundant renewable energy sources are integral** to scaling low and zero-carbon hydrogen use.
- The lack of proven application at scale to date though large-scale efforts are in planning phases.

Hydrogen's Potential in Industrial Clusters



Industrial clusters can create an **internal market for hydrogen**, where production and consumption are co-located. Therefore, the market can develop without investment in long-distance infrastructure.



Although dedicated renewable capacity is likely to be needed, integrated hydrogen production with wind and solar will **support periods of excess wind and solar generation** providing storage and flexibility to the system.



Potential is greatest where hydrogen can be primarily used as a **feedstock for industrial processes or is an integral part of the reaction/ process**, with an additional option to leverage for secondary applications such as transport fuel and domestic heating.

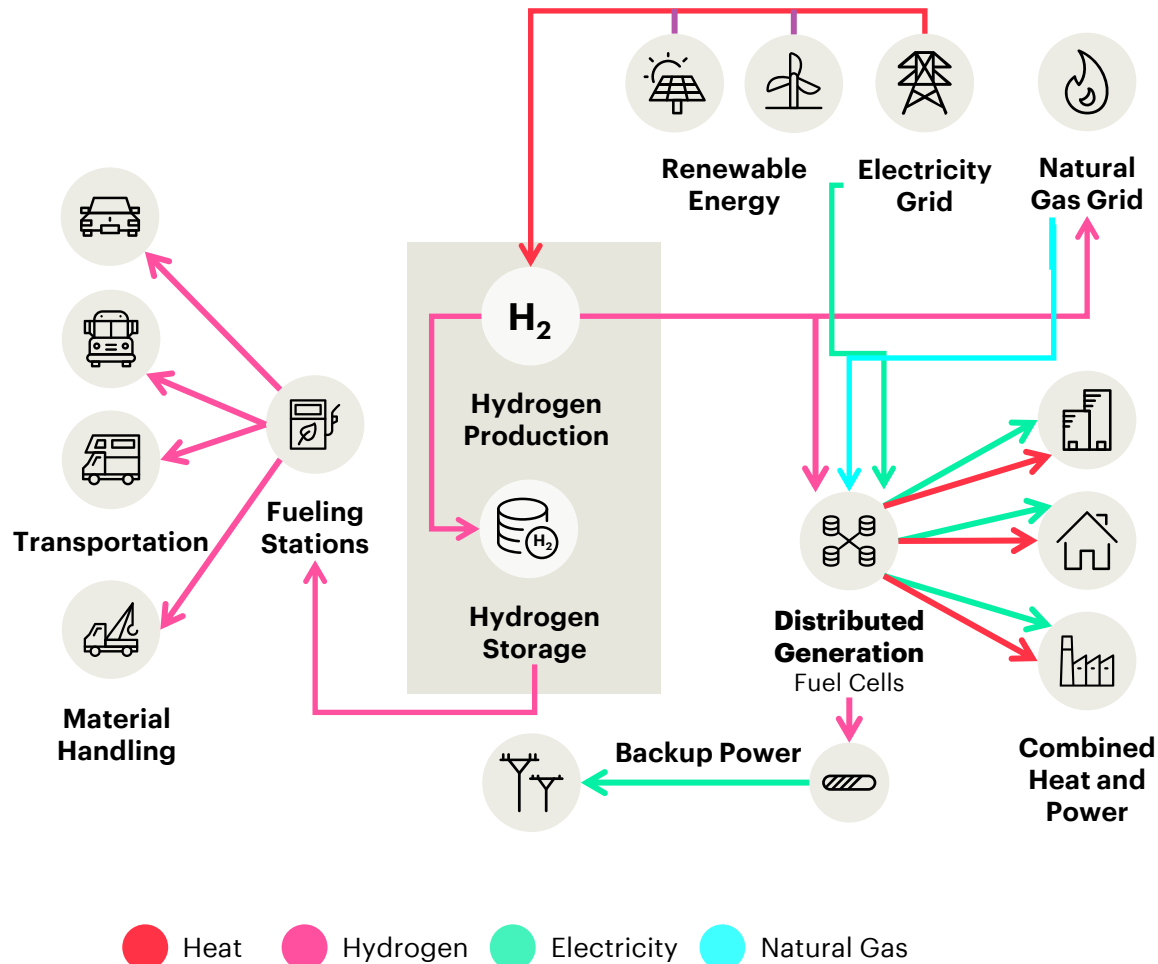


Stored hydrogen can be used as an **energy source** for a variety of sectors during disruptions to the energy system.

Emergence of Hydrogen Hubs

Hydrogen Hubs bring together industry, local businesses and other local stakeholders to develop and deploy hydrogen projects to meet energy and transportation needs of the local community.

Overview of Hydrogen Hubs (Illustrative)



Global Examples (Not Exhaustive)



Australia

Asian Renewable Energy Hub

- The Asian Renewable Energy Hub is a large-scale clean energy hub based in Western Australia.
- It is expected to utilize 20+ GW of wind and solar capacity to produce green hydrogen for domestic and export consumption.



China

Datong Hydrogen Hub

- Datong, the coal capital of China, is transforming into a hydrogen hub by supporting the rollout of hydrogen fuel cells for transport and the creation of a hydrogen energy industrial park.



Spain

Green Hysland

- The Green Hysland project in Mallorca will create a green hydrogen ecosystem in the Balearic Islands.
- It will generate, distribute, and use at least 300 metric tonnes of renewable hydrogen per year, produced from solar sources.



UK

Tees Valley Transport Hub

- Tees Valley is set to host the UK's first hydrogen transport hub, with a hydrogen-powered mainline train trail.
- The project will explore how green hydrogen could power buses, rail, maritime, and aviation transport.










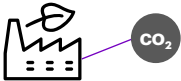







Oman

Sohar Port

- Oman's Sohar Port, partnering with the Port of Rotterdam, will be one of the Middle East's first green hydrogen hubs, powered by 3.5 GW of solar.
- Hydrogen will be stored for later use for industrial and transport purposes.

Colors of Hydrogen

Several key factors determine the hydrogen type that is most suitable to a particular industrial cluster.

Type	Production Process	Energy Input	Emissions Intensity	Pros and Cons
	Electrolysis 	 Wind or Solar	Zero carbon as feedstock electricity is powered by renewable sources such as wind, solar and hydro	<ul style="list-style-type: none"> + Zero-carbon production of pure hydrogen + Pure hydrogen can be used in fuel cells for transport applications + Opportunity to integrate into gas networks, long-term storage for electricity - CapEx-intensive due to large-scale renewables needed to feed electrolyzers - Geographical constraint due to resource requirement - Scale: Largest electrolyzer is currently 10 MW with 20 MW projects underway
	Electrolysis 	 Nuclear	Zero carbon as feedstock electricity is powered by nuclear energy	<ul style="list-style-type: none"> + Production of hydrogen using zero-carbon dispatchable power + High-purity hydrogen can be used for industrial processes + Low-carbon hydrogen production via electrolysis or combining with gas and CCS to provide heat in SMR - CapEx-intensive unless using small modular reactors
	Gasification with CCS 	 Biomass	Low intensity, with potential for negative CO ₂ emissions if byproducts of gasification process are captured and stored	<ul style="list-style-type: none"> + Low-carbon hydrogen or even negative emissions if paired with CCS - CapEx-intensive due to CCS infrastructure requirement - Potential concerns on environmental sustainability of biomass production - Geographical constraint due to availability of feedstock resource
	Autothermal reforming (ATR) and/or steam methane reforming (SMR) with CCS 	 Natural Gas	Low intensity as CO ₂ emissions from feedstock gas are captured and stored	<ul style="list-style-type: none"> + Low carbon due to CCS + Intermediate solution to exploit low gas prices - CapEx-intensive due to CCS infrastructure requirement - Exposure to natural gas price fluctuations - Scale requirement on demand side (i.e., outside of clusters in domestic heating)
	Autothermal reforming (ATR) and/or steam methane reforming (SMR) 	 Natural Gas	High Intensity with CO ₂ released into atmosphere	<ul style="list-style-type: none"> + Less need for additional infrastructure + Hydrogen can be used for industrial processes - Carbon-intensive - Exposure to natural gas price fluctuations









Note: Classification of colors of hydrogen is not fixed and is subject to some variation depending on sources

Case study: Puertollano Green Hydrogen

Iberdrola, in partnership with Fertiberia, plans to place Spain at the forefront of the green hydrogen economy of Europe.

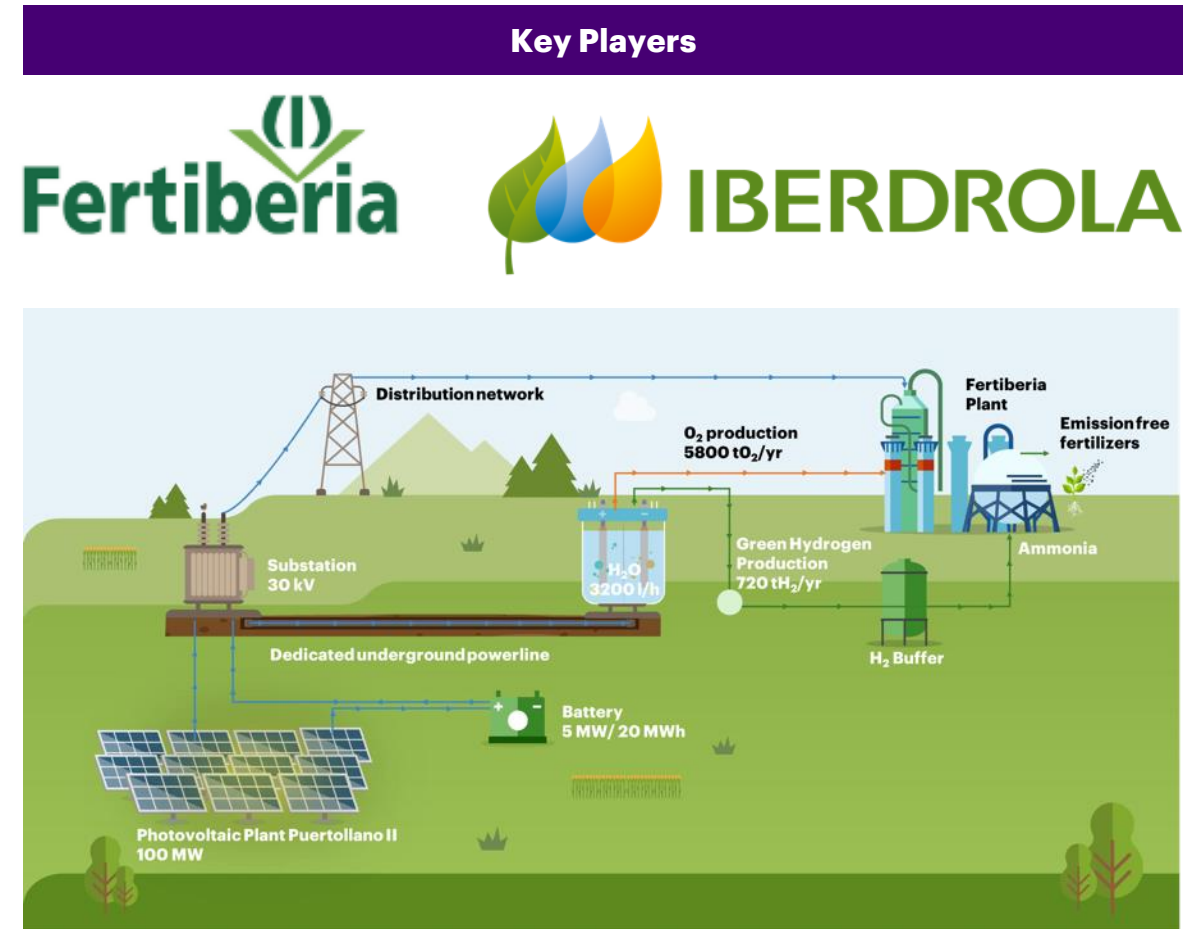
Current Project

- Iberdrola has launched what will be the largest plant producing green hydrogen by 2021, in partnership with Fertiberia, for industrial use in Europe.
- Iberdrola will supply solar PV electricity to be used in an electrolyzer supplied by Nel, that will provide green H₂ to be used in Fertiberia's fertilizer production plant.
- Fertiberia will modify its plant to use green hydrogen to manufacture green fertilizers, significantly reducing natural gas requirements and emissions at the plant.

 Located in Puertollano, Spain	 Planned buildout of 100 MW solar	 Expected completion by 2021
 Electrolyzer capacity of 20 MW	 Investment cost of €150m	 Battery Storage capacity of 20 MWh
 Expected to add 150 new jobs	 Annual CO₂ savings of 39,000 tonnes	

Future Pipeline

- Iberdrola and Fertiberia plan to expand the Green Hydrogen project and develop 800 MW of electrolysis capacity.
- The hydrogen development would cover 25% of Spain's national target of 4 GW and is expected to create 4,000 jobs and use more than 500 local suppliers.
- The projects are set to be completed in phases between 2023 and 2027, with an expected investment cost of €1.8 billion.



Case study: Majorca Green Hydrogen

Power-2-Green Hydrogen will be the first flagship project in Southern Europe and will create a "green hydrogen ecosystem" in the Balearic Islands. The project will generate, distribute and utilize renewable hydrogen produced from solar energy.

Project Context

- The Power-2-Green Hydrogen project aims to **pioneer a solution for island GHG emissions reduction and industrial reconversion** in the island of Majorca, Spain.
- Power-2-Green Hydrogen is planned as a **revitalization project for the Balearic town of Lloseta**, which has been significantly impacted by the end of cement production, a major employer in the area.

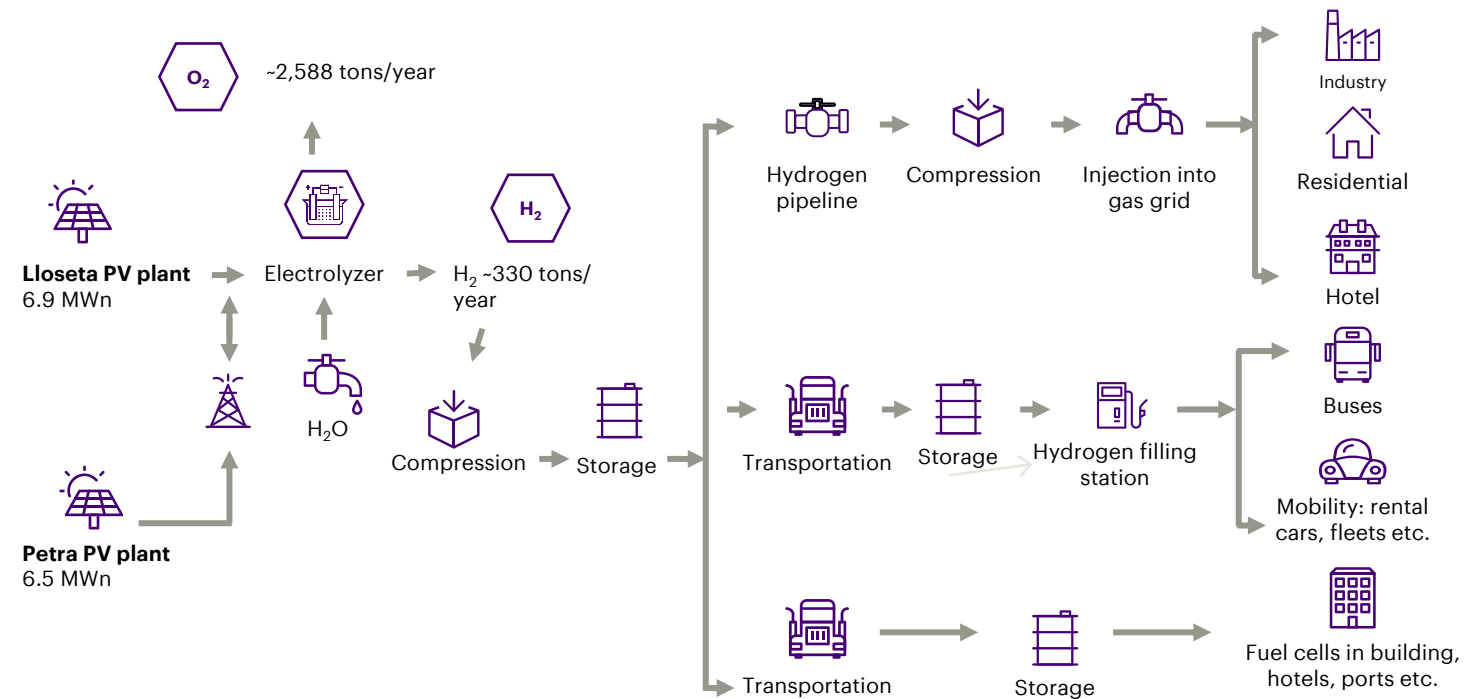
Project Overview

- The project consists of **two solar PV plants making up > 13 MW** of combined generation capacity and a **2.5MW PEM electrolyzer**.
- The output from the electrolyzer will support multiple end-use applications:
 - Powering part of the island's **public transportation fleet**.
 - Green hydrogen **injected into the gas grid** to supply industrial parks.
 - As **back-up energy** for buildings (public buildings, ports, hotels, etc.)
- The project will generate at least **330 tonnes** of hydrogen per year and is expected to **reduce CO₂ emissions** in Majorca by over **20,700 tonnes per year**.
- Power-2-Green Hydrogen is expected to contribute substantially to local GDP and **create jobs during the construction** (expected to commence in 2021) and O&M phases.
- The project was awarded a **€10 million grant** by the Fuel Cells and Hydrogen Joint Undertaking (FCHJU), making it the second-largest grant awarded by FCHJU to a green hydrogen project, and the largest grant offered to a Mediterranean country. In addition to this grant, the project has also received **public funding from** Institute for Diversification and Saving of Energy (IDAE).
- The renewable origin of the hydrogen will be traced by **ACCIONA's GreenH2chain®**, the world's first platform based on blockchain technology that guarantees the renewable origin of green hydrogen.

Key Partners



Power-2-Green Hydrogen Layout

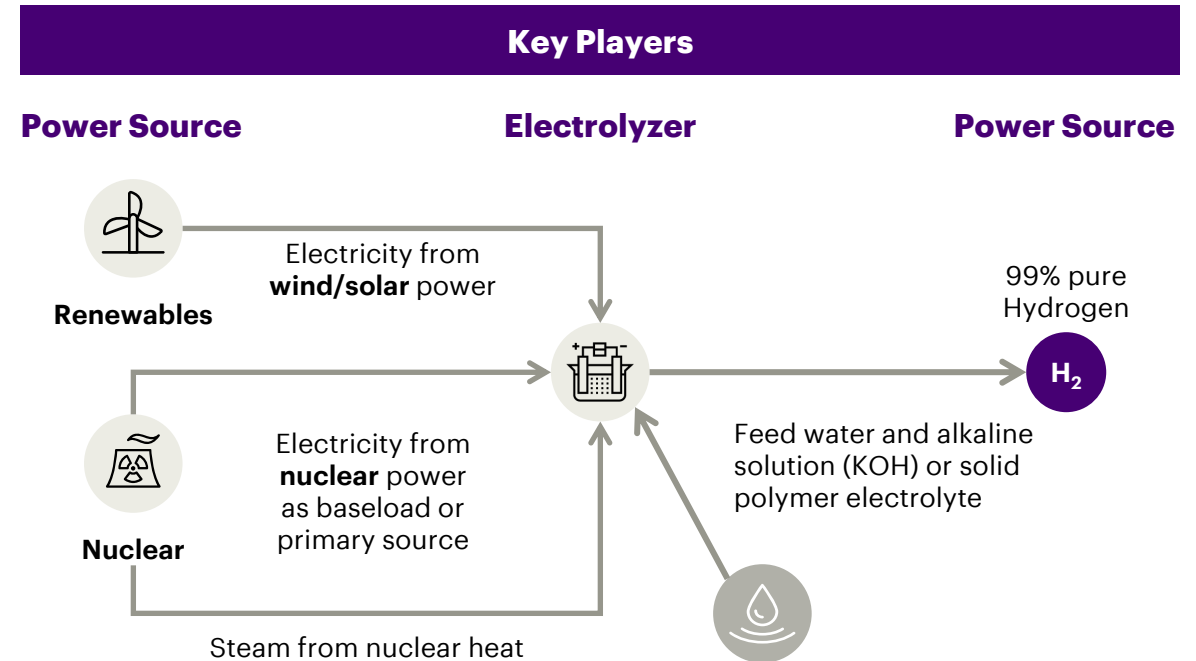


Hydrogen Production from Nuclear

Nuclear energy can play an important role in the production of hydrogen through either electrolysis or steam methane reforming by providing zero-carbon electricity and/or heat.

Considerations for Nuclear Energy to Hydrogen

- Nuclear energy's **high-capacity factor** and **non-intermittent** profile compared to other renewable sources such as wind and solar make it an efficient source of power for **zero-carbon hydrogen production**, either as **the primary source** of electricity or as **baseload power** for intermittent sources.
- Nuclear energy can provide **heat from its reactor**, supplementing some natural gas during **production of gray hydrogen** and thereby **reducing its carbon intensity**.
- Heat from nuclear can be used in **high-temperature steam electrolysis (HTSE) to produce hydrogen**. Based on early indications in Germany, this is expected to reduce cost by 10% due to lower electricity requirement at high temperatures.
- **Advanced modular reactors (AMR)** can potentially produce hydrogen more efficiently, as it produces less waste and higher temperature heat.
- **Small modular reactors (SMR)** could provide an effective, economic solution for hydrogen production in remote areas with limited grid access.
- Given the reluctance to co-locate hydrogen production plants with nuclear reactors, realizing benefits of hydrogen production via nuclear energy is more influenced **by economics of heat transport infrastructure and demand willingness** than technological breakthroughs. For example, heat has been transported approximately 80 km via pipes in Russia.

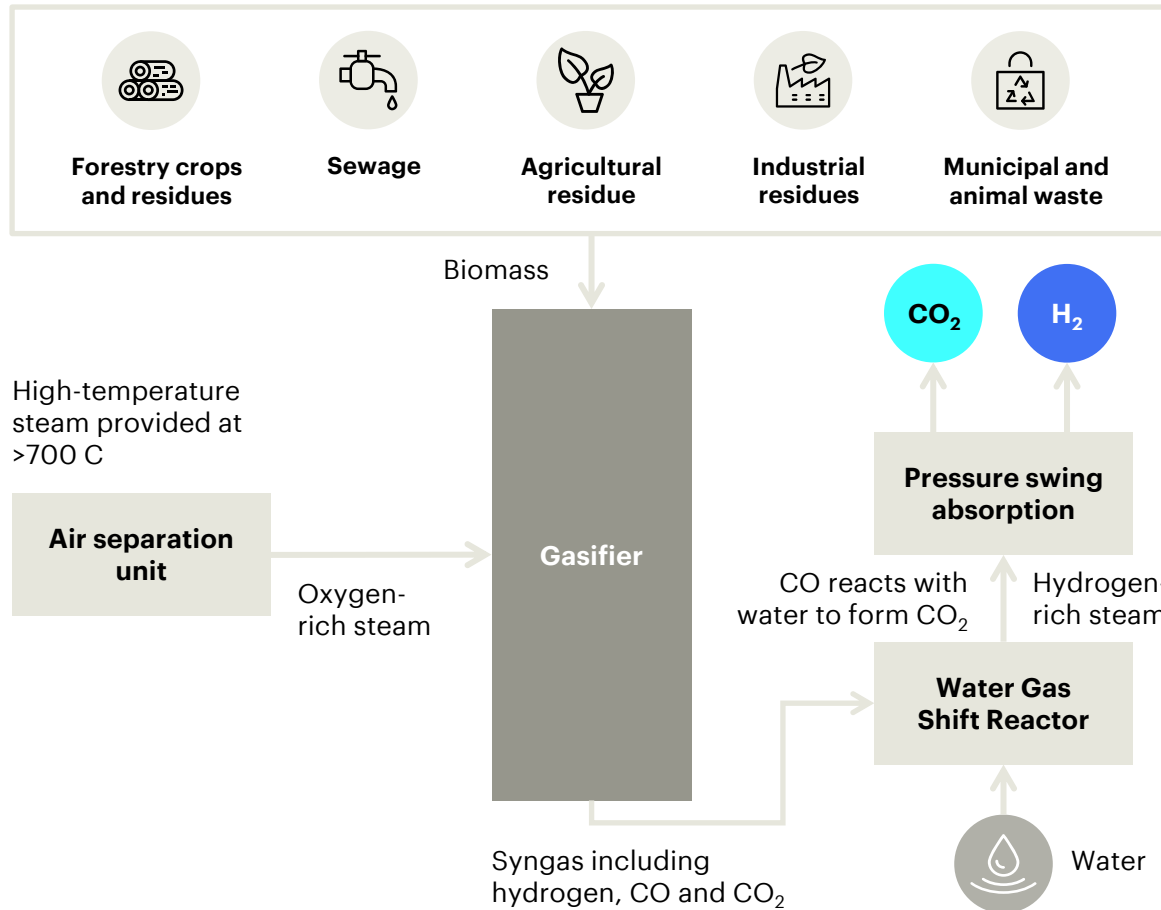


- **Low-temperature electrolysis** is used to split water molecules using an electrical current to produce high purity hydrogen and oxygen.
- **High-temperature steam electrolysis (HTSE)** uses both heat and electricity, thereby reducing the total electrical energy demand by approximately 30%.
- HTSE requires that the solid oxide electrolyte be connected to both a heat and electrical source, therefore **nuclear plants**, in particular those of the fourth generation, could provide the electricity and heat.

Hydrogen Production from Biomass

Biomass can be used as an input to produce viable hydrogen for industrial processes, with several countries and groups around the world exploring this hydrogen production method.

Considerations for Nuclear Energy to Hydrogen



Global Examples



Australia

- Hazer is seeking to build a \$15.8 million, 100-tonne per annum facility by 2021 to demonstrate its hydrogen production technology, converting biomethane from sewage to renewable hydrogen.
- Hazer group has received €6 million in funding from the Australian Renewable Energy Agency (ARENA) for development of green hydrogen from biomass.



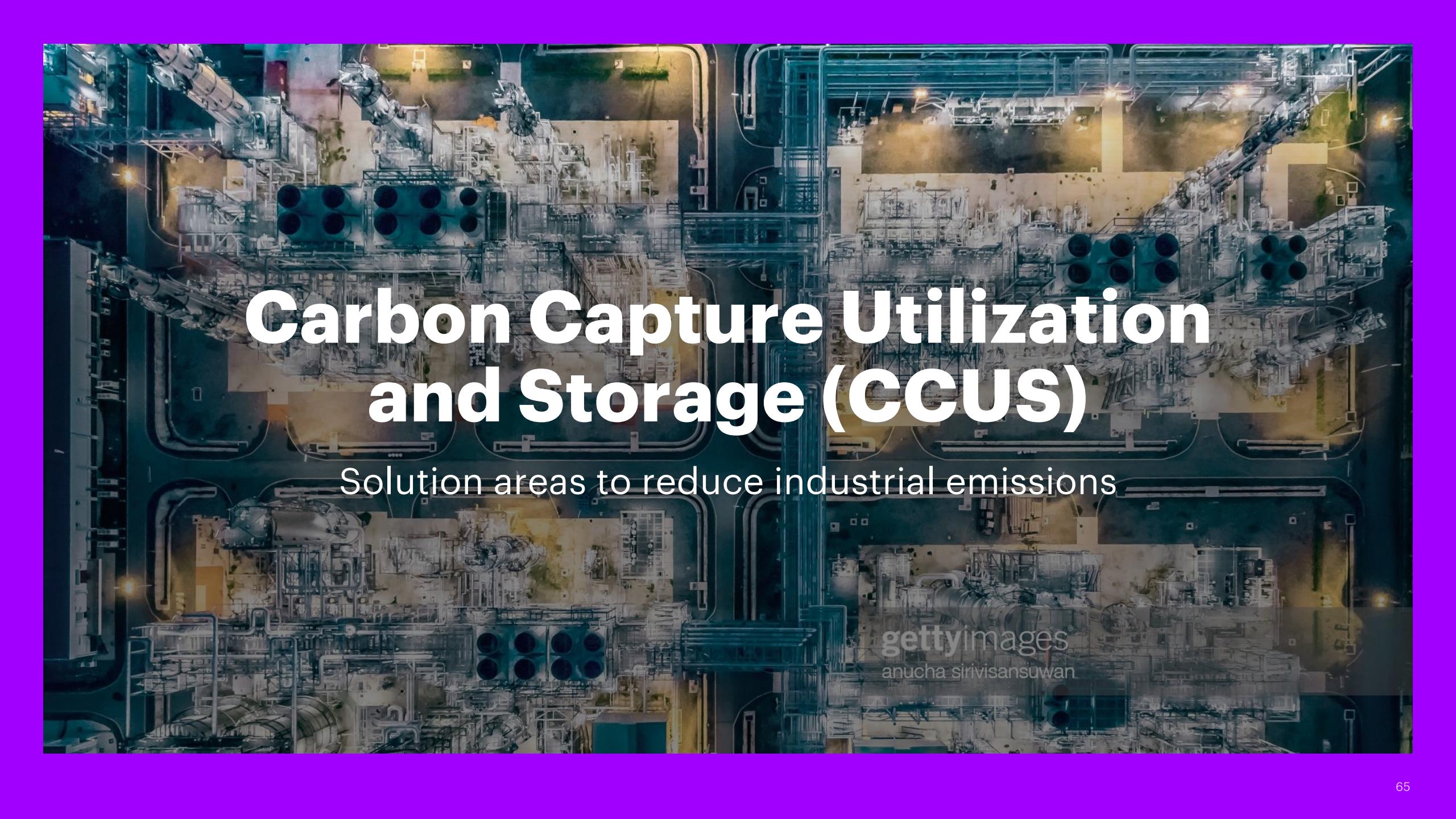
India

- Indian Oil Corp. (IOC) has signed an agreement with the Indian Institute of Science to develop and demonstrate biomass gasification-based hydrogen generation technology.
- The goal is to produce fuel-cell-grade hydrogen at an affordable price to be used in fuel cell buses as part of IOC's larger aspiration to usher in hydrogen economy for India.
- IOC has submitted an expression of interest (EOI) to procure 15 hydrogen fuel cell buses for mass transport.



EU

- The BIONICO project (€3.4 million project cost) is assembling a pilot plant to convert biogas directly into hydrogen using a novel reactor concept at its core.
- The plant will be the first example of a biogas-to-hydrogen plant based on membrane reactor technology installed and is expected to produce 100 kg of hydrogen daily.



Carbon Capture Utilization and Storage (CCUS)

Solution areas to reduce industrial emissions

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Carbon Capture, Utilization and Storage (CCUS)



Why does CCUS matter?

CCS, where suitable infrastructure exists, is emerging as a promising opportunity for heavy industry, with CCS hubs emerging. However, the economics of CCU are still a challenge.

Key barrier: Viable storage locations and applications and lack of transport and storage infrastructure



Spotlight Cluster example of CCUS: Humber Industrial Cluster

Humber is planning CCS infrastructure (transport via pipeline and storage) to be shared across cluster entities and treated as a regulated asset base—an innovative method of shared funding and proposals.



Carbon Capture, Utilization and Storage (CCUS)



Capture carbon from energy and hydrogen production



Use captured carbon for industrial and manufacturing processes



Store carbon underground where feasible

Areas of exploration in this section

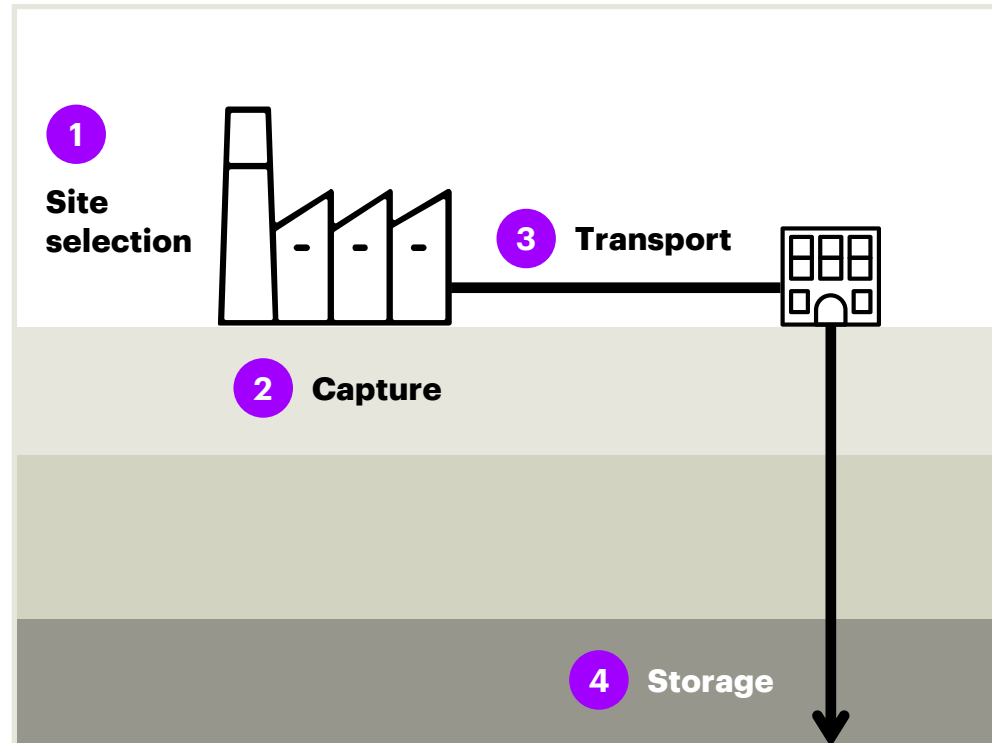
- Emergence of CCS hubs
- Feasibility and barriers of CCS
- CCU (utilization)—emerging uses and barriers that need to be overcome

Overview of CCUS

CCUS technology requires scale but can permanently store carbon or recycle it for reuse.

1 Site selection
Carbon capture and purification plants are ideally situated near heavy industry, to further reduce costs down the value chain. However, in some cases, pipelines may connect emissions from industry to CCUS plants over far distances.

2 Capture
CO₂ gas from industrial processes is captured and separated from other by-products into a “dense phase” or liquid-like state. Emissions can be captured pre- or post-combustion. The most common separation tactic is amine absorption.



3 Transport
CO₂ is then usually dehydrated and compressed to prepare for transport. It is usually transported via pipelines operating at a pressure that enables the CO₂ to remain in a dense phase. It can also be moved via rail, truck or ship.

4 Storage
Compressed CO₂ is injected and stored in deep saline formations or depleted oil and natural gas reservoirs for permanent, safe storage.

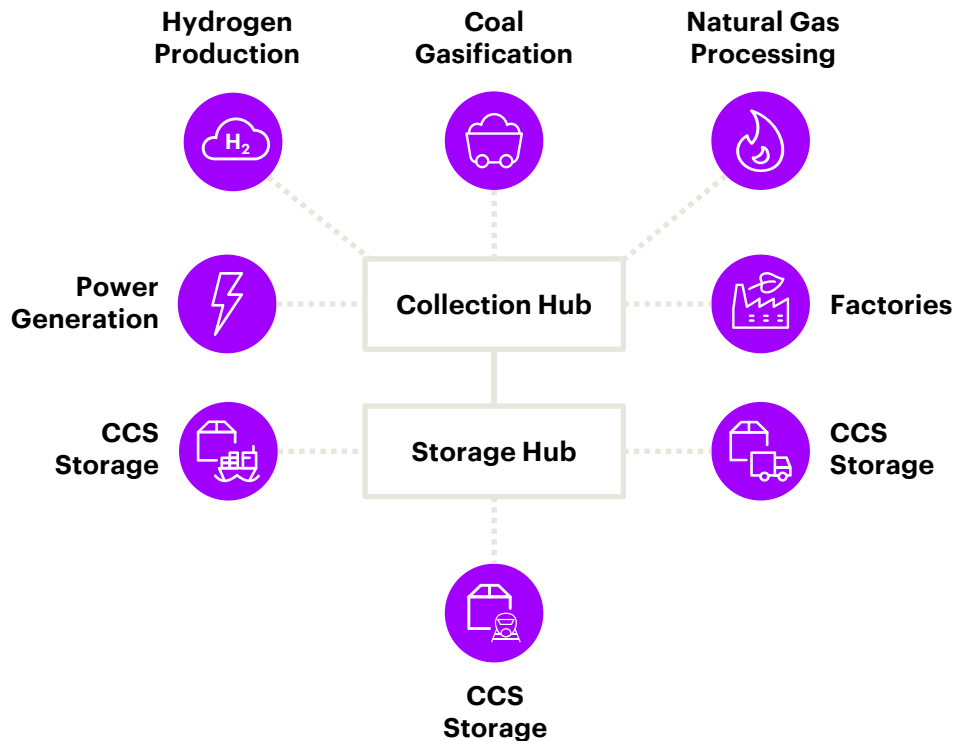
Carbon utilization

It is possible to use captured CO₂ for energy processes. Uses include enhanced oil recovery (EOR), the manufacture of fuels or use as a raw material for a variety of industries (such as beverages and cement). It is estimated that the utilization rate for captured carbon is only 1%, but this could increase with further market and technology development and investment.

Emergence of CCS Hubs

CCS hubs bring together shared infrastructure, emissions and storage availability from local industrial players and surrounding geography to reduce overall emissions and store and utilize carbon.

Overview of CCS Hubs



Global Examples



China

China North West Project

- The China North-West CCS hub is aiming to capture and store CO₂ from the hydrogen production units of refineries in surrounding areas.
- Potential emitters include cement, chemical and the power sector.
- The project is currently still in the demonstration phase but is expected to reduce more than 3 Mt CO₂ per year by 2030.



Norway

Longship Project

- Norway's Longship Project has three main components contributing to a CCS infrastructure: (1) Carbon capture at the Heidelberg cement factory in southern Norway, (2) Carbon capture at Fortum Oslo Varme's waste incineration facility Oslo and (3) the Northern Lights project, which will transport and store carbon offshore in the North Sea.
- The project is expected to capture 400,000 MtCO₂ and cost \$2.7 billion.



U.S.

Gulf of Mexico

- In the U.S., Texas and Louisiana (which border the Gulf of Mexico) are both exploring options to scale CCS infrastructure.
- It is estimated that CO₂ storage capacity in the Gulf of Mexico area exceeds 30Gt based on depleted hydrocarbon and saline reservoirs.
- U.S. federal incentives such as the 45Q tax incentive can support CCS hub development.

Carbon Capture and Storage Overview

To help meet climate change mitigation requirements, an estimated 2,000 large-scale CCS facilities must be deployed by 2040. There are currently 26 in operation, three under construction and 34 in development stages globally, according to the Global CCS Institute.

Increasing Feasibility of CCS

- To accelerate CCS development, **policies that increase demand and improve financials** will be needed. **National tax credits** for carbon sequestration, such as the Section 45Q tax incentive in the U.S, or **tax programs** such as the EU Carbon Border Tax, can help to **improve the price of carbon**.
- Facilities that are on the path to success have been underpinned **by favorable commercial conditions and supportive government policies and funding**. For example, the UK government provided £200 million in funding to industrial clusters at Humber and Teesside to help develop their CCS technology, and the EU provided a £9 million subsidy to the Port of Antwerp for CCS.
- Industrial clusters are ideal locations** for implementing CCS, as **costs across the value chain can be driven down due to scale**. Heavy industries in shared locations can transport emitted CO₂ via a single capture, transport and storage system that is nearby, ultimately reducing transportation and cost barriers and increasing economies of scale. Further, industrial clusters offer commercial synergies that reduce the risk of investment.

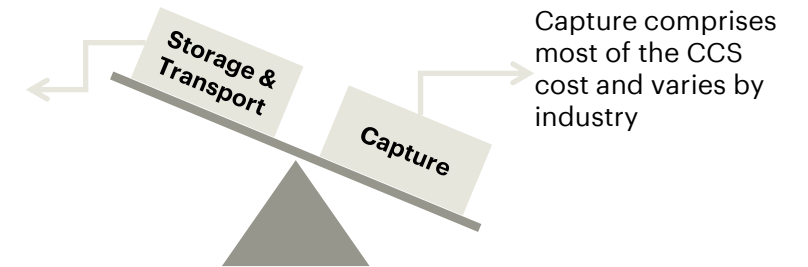
Barriers to CCS Adoption

- Cost:** The equipment and energy needed during the capture phase accounts for the greatest cost. Capture costs can span a wide range depending on the sector (see chart to the right), but cement, petroleum refining, iron and steel are the most expensive, at more than \$100 per tonne in some instances. Transport and storage are cheaper than capture costs, usually around \$30/tonne of CO₂. The Carbon Capture & Storage Association estimates that the total cost of CCS can be reduced to \$40-\$57 per tonne through technological advancements.
- Investor Weariness:** Due to the nascency of CCS, some investors view the technology as a financial risk. There is also the possibility that certain projects could become stranded assets. Therefore, fewer investments are made into CCS and higher premiums are imposed.
- Transportation:** To safely transport condensed CO₂, pipelines must be specially designed and pressurized. Existing oil and gas pipelines must be renovated accordingly.
- Geological Factors:** Pipelines must connect to the appropriate storage site, which can make CCS more difficult and expensive to implement in areas without nearby geological reservoirs.

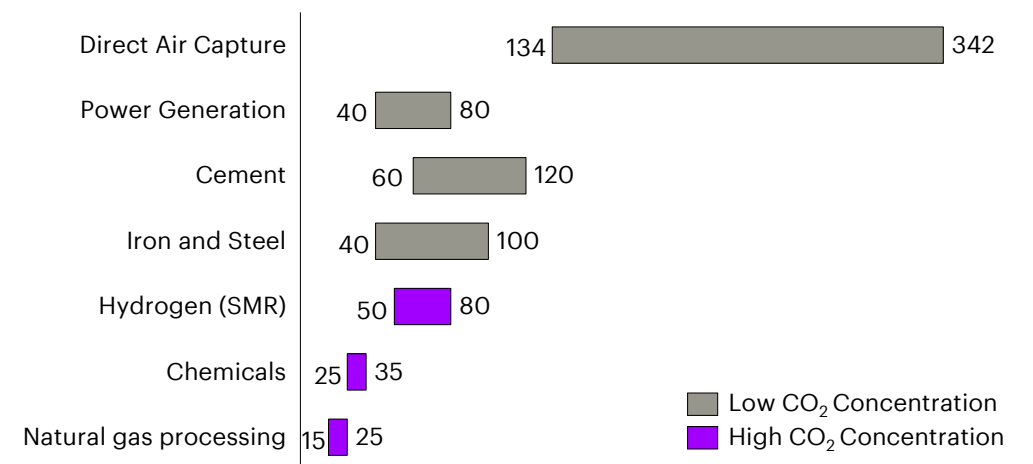
Note: "Chemicals" in the above chart refers specifically to ethylene oxide, bioethanol and ammonia.

Market Segment Costs Range for Carbon Capture

Storage and transport are estimated at \$30-\$40/tonne of CO₂



CO₂ Capture Cost by Industry (\$/tonne)



Carbon Capture and Utilization Pathways

Captured carbon can be used in a variety of ways. Enhanced oil recovery is currently the most advanced method, but technological advancements and cost-efficiency measures can help advance usage in other applications to reach a larger scale.

Circularity of CO₂ in Oil and Gas

- **Enhanced Oil Recovery (EOR):** EOR involves injecting CO₂ into reservoir rock of an existing oil or gas field to recover increased oil and natural gas. The injected CO₂ trades places with the released oil and is permanently stored in minute pore spaces. CO₂ can also be injected into unmineable coal deposits and basalts. Studies show that oil produced from existing fields using EOR with captured CO₂ have 63% fewer emissions.
- **CO₂ Fracking:** As a relatively less environmentally intensive process than hydraulic fracking, CO₂ fracking would replace and/or reduce water used during the process. Additionally, the CO₂ injected would be trapped underground and removed from the atmosphere.

Biological Conversion

- This process uses biological pathways to convert CO₂ and other products into **biomass, chemicals, and fuels**.
- Both photosynthetic and non-photosynthetic processes can convert CO₂ into desired products.

Carbonation and Cement

- Inorganic reactions are used to **transform gaseous CO₂ into solid carbonates** for building use, industrial water residue, and nanoparticles. Strong potential in **cement production and green construction**.

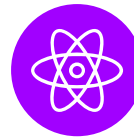
Electrochemical and Photochemical

- Electrons and protons are used to activate CO₂ to create products. The **electrochemical pathway uses electricity from renewable sources** to power the reaction, whereas **the photochemical path uses sunlight** convert CO₂ and water into solar fuels.

Thermochemical

- High-temperature reactions with CO₂ are used to **produce useful hydrocarbons**. CO₂ can be used as a feedstock, a co-reactant or a mild oxidant. Carbon monoxide is one of the primary products created from the reaction.
- Hydrogen is a major input and catalyst in the thermochemical use case, so it is important that there is a renewable and clean source of hydrogen available.

Barriers to Scale



The primary factor that limits the growth of carbon utilization is the **lack of locally available, affordable CO₂** that can be delivered at a price below that of the project itself.



Technology maturation in this area is needed to help bridge the gap between lab concept and commercially viable scale.



The conversion of CO₂ to chemicals, fuels and materials requires significant energy. Therefore, **cost and efficiency improvements** are essential to increasing CCU adoption.



Carbon utilization pathways can have **negative indirect impacts**, so it is crucial to consider the environmental impact of the full life cycle of utilization strategies to confirm emissions are reduced permanently.

CCS Example: Port of Rotterdam

The Port of Rotterdam CO₂ Transport Hub and Offshore Storage Project (Porthos) will transport CO₂ from industry in the Port of Rotterdam in the Netherlands and store it in empty gas fields in the North Sea. It is currently still in preparation and planning stages.



Carbon capture

A **shared pipeline** will run through heavy-industry refineries and hydrogen producers in the Rotterdam Port area and will transport CO₂ to a **compressor station**.



Transport and storage

Pressurized CO₂ will be sent from the compressor station to an **offshore platform** via pipeline and pumped into empty gas fields that are more than 3 km beneath the **North Sea seabed**.



Emissions reduction

It is expected that the project will be able to store approximately **2.5 Mt of CO₂ per year**, equivalent to **10% of the total emissions** produced by Rotterdam's industrial sector.



Cost and investment

The European Commission has proposed awarding **£102 million in funding** to the Porthos project, out of a **total expected investment of £450 to £550 million**.



Project partners

Four companies—**Air Liquids, Air Products, ExxonMobil, and Shell**—have agreed to supply CO₂. The transport and storage will be supported by the Port of Rotterdam Authority, Gasunie and EBN.



Timeline

Porthos has started with the **FEED phase as well as the SDE++ grant**. The final investment decision is expected in early-2022 and the **first storage will occur by end of 2024**.



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