

CHALLENGES AND CONSIDERATIONS IN THE ADOPTION OF CARBON
CAPTURE, UTILIZATION AND STORAGE TECHNOLOGIES IN DEVELOPING
COUNTRIES: THE CASE OF TÜRKİYE

by

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ABSTRACT

CHALLENGES AND CONSIDERATIONS IN THE ADOPTION OF CARBON CAPTURE, UTILIZATION AND STORAGE TECHNOLOGIES IN DEVELOPING COUNTRIES: THE CASE OF TÜRKİYE

This thesis examines the complex and often ambiguous landscape of Carbon Capture, Utilization, and Storage (CCUS) technologies in developing nations, amidst the pressing need to accommodate increasing material and energy demand within the decarbonization imperatives put forward by the Paris Agreement. By focusing on Türkiye as a case study, due to its reliance on emission-intensive production and strong trade ties with developed (more particularly European) countries, this thesis aims to bridge knowledge gaps and offer insights into the feasibility and strategic integration of CCUS into national climate and technology policies. By drawing upon the existing literature and insights from national and international experts, it concludes that, while CCUS is not a silver-bullet technology for all greenhouse gas (GHG) mitigation, it holds significant potential as a targeted approach for hard-to-abate sectors such as cement, chemicals, and iron and steel, predominantly found in developing economies, and that successful CCUS integration requires tailored strategies accounting for diverse social, economic, technological, and environmental factors, emphasizing that there's no one-size-fits-all approach. A key finding is the significant deployment disparity between developed and developing countries due to challenges in access to capital, knowledge gaps, and the absence of regulatory frameworks, calling for strengthened international climate policy focused on technology transfer, capacity building, and climate finance, tailored to the specific contexts of developing nations. For Türkiye, integrating CCUS into its net-zero strategies necessitates revised climate and energy policies built on clear governance structures to accelerate CCUS adoption, especially in industrial decarbonization rather than power generation.

ÖZET

GELİŞMEKTE OLAN ÜLKELERDE KARBON YAKALAMA, KULLANMA VE DEPOLAMA TEKNOLOJİLERİNİN BENİMSENMESİNDE KARŞILAŞILAN ZORLUKLARIN VE DİKKAT EDİLMESİ GEREKEN HUSUSLARIN İNCELENMESİ: TÜRKİYE ÖRNEĞİ

Bu tez, Paris Anlaşması'nın ortaya koyduğu karbonsuzlaştırma gereklilikleri çerçevesinde, gelişmekte olan ülkelerdeki artan hammadde ve enerji talebini karşılamak için duyulan acil ihtiyacın paralelinde Karbon Yakalama, Kullanma ve Depolama (KYKD) teknolojilerinin karmaşık ve genellikle belirsiz görünümü incelemektedir. Bu tez, emisyon yoğun üretime olan bağımlılığı ve (özellikle Avrupa'daki) gelişmiş ülkelerle olan güçlü ticari bağları nedeniyle bir vaka çalışması olarak Türkiye'ye odaklanarak, bilgi eksikliklerini kapatmayı ve KYKD'nin fizibilitesi ve ulusal iklim ve teknoloji politikalarına stratejik entegrasyonu hakkında içgörüler sunmayı amaçlamaktadır. Mevcut literatüre ve ulusal ve uluslararası uzmanların görüşlerine dayanarak, KYKD'nin tüm sera gazı (GHG) emisyonlarının azaltımı için genel geçer bir çözüm olmasa da, ağırlıklı olarak gelişmekte olan ekonomilerde bulunan çimento, kimya ve demir-çelik gibi azaltılması zor sektörler için önemli bir potansiyele sahip olduğu ve başarılı bir KYKD entegrasyonunun çeşitli sosyal, ekonomik, teknolojik ve çevresel faktörleri hesaba katan özelleştirilmiş stratejiler gerektirdiği sonucuna varmakta ve herkese uyan tek bir yaklaşım olmadığını vurgulamaktadır. Bulgular, sermayeye erişimdeki zorluklar, bilgi eksiklikleri ve düzenleyici çerçevelerin yokluğu nedeniyle gelişmiş ve gelişmekte olan ülkeler arasındaki önemli yaygınlaştırma eşitsizliğine ve gelişmekte olan ülkelerin özelliklerine göre uyarlanmış teknoloji transferi, kapasite geliştirme ve iklim finansmanı odaklı güçlendirilmiş uluslararası iklim politikası çağrısında bulunmaktadır. Türkiye için, KYKD'yi net sıfır stratejilerine entegre etmek, özellikle enerji üretiminden ziyade endüstriyel dekarbonizasyonda KYKD'nin benimsenmesini hızlandırmak için açık yönetim yapıları üzerine inşa edilmiş ve revize edilmiş iklim ve enerji politikalarını gerektirmektedir.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
BECCS	Bioenergy with Carbon Capture and Storage
BF	Blast Furnace
CapEx	Capital Expenditures
CBAM	Carbon Border Adjustment Mechanisms
CBDR	Common But Differentiated Responsibilities
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization and Storage
CO ₂ -FFI	Carbon Dioxide Emissions from Fossil Fuels and Industry
DRI - EAF	Direct Reduced Iron Electric Arc Furnace
EAF	Electric Arc Furnace
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
ETS	Emission Trading System
EU	European Union
GHG	Greenhouse Gases
HVC	High Value Chemicals
IAMs	Integrated Assessment Models
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
MDB	Multilateral Development Banks
MTPA	Million Tonnes Per Annum
MW	Megawatt
NDC	Nationally Determined Contributions
ODA	Official Development Assistance
OECD	Organization for Economic Co-operation and Development

OpEx	Operational Expenditures
R&D	Research and Development
TENMAK	Turkish Energy, Nuclear and Mineral Research Agency
TRL	Technological Readiness Level
TÜBİTAK	Scientific and Technological Research Council of Türkiye
TÜİK	Turkish Statistical Institute
TWh	Trillion-watt hours
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
WESP	World Economic Situation and Prospects
WRI	World Resources Institute

1. INTRODUCTION

Countries that are parties to the Paris Agreement have been searching for ways to meet their unique Nationally Determined Contributions (NDCs) ever since the agreement's entry into force, to prevent climate change caused by anthropogenic and ever-increasing greenhouse gas (GHG) emissions. However, they face the challenge of reducing greenhouse gas emissions while simultaneously meeting rising energy demands and increasing material consumption due to population growth (Fekete et al., 2021; van Alphen et al., 2010).

Carbon dioxide (CO₂) is more emphasized even though other greenhouse gases have a stronger heat-trapping effect per molecule because CO₂ is more abundant in the atmosphere and has been the primary driver of climate change historically (Intergovernmental Panel on Climate Change (IPCC), 2023c). Additionally, CO₂ stays in the atmosphere much longer than other significant anthropogenic greenhouse gases. While methane (CH₄) lasts about a decade before converting to CO₂, and nitrous oxide (N₂O) remains for about a century, CO₂ can persist for 300 to 1,000 years (National Aeronautics and Space Administration, 2019). Moreover, CO₂ is soluble in water, stable under normal conditions (making it neither explosive nor flammable), yet reactive under specific thermodynamic conditions, serving as a precursor for a wide range of commercial products (North, 2015). The abundance of CO₂, its long atmospheric lifetime, and its unique chemical properties make it an attractive candidate for capture.

Numerous low-carbon or negative-emission technologies are constantly emerging in this pursuit, all of which claim to provide solutions to the challenge of climate mitigation (Nightingale et al., 2020). Although these technologies are purported to utilize the available carbon budget effectively to meet the agreement's 1.5°C, or even 2°C limit, the majority of them either do not work at scale or are not economically feasible (Larkin et al., 2018). Despite their significant potential, these low-carbon or negative-emission climate technologies are also extremely complex to design and deploy on a large scale; this requires substantial financial investments, technical expertise, project management capabilities along with well-designed policy instruments (Malhotra & Schmidt, 2020).

Carbon Capture, Utilization and Storage (CCUS) technologies are one of the most prominent among the technologies that are subject to these discussions, in the last couple of years. While heavily criticised by some, they are at the same time seen as an indispensable solution, especially for the hard-

to-abate¹ industries such as steel, cement, and primary chemical production. Three of four Integrated Assessment Models (IAMs) rely on large scale deployment of Bioenergy with Carbon Capture and Storage (BECCS), a subcategory of CCS technologies, where CO₂ is captured by a biogenic source and converted to biofuels or directly combusted for energy generation purposes (IPCC, 2018). In addition, according to the International Energy Agency (IEA), the cost of climate mitigation is expected to rise by 70% without CCS deployment in the 2020s (IEA, 2009).

Approaching the middle of 2020s, currently most of the existing CCUS facilities are located in the developed countries, mainly in the United States and Northern Europe, with the support of government and EU policies and significant public and private investments (Global CCS Institute, 2024). As a consequence of low Technological Readiness Levels (TRLs) of CCUS Technologies, they are capital-consuming and require risk tolerant investment structures (Bui et al., 2018). Most of the developing countries lack capital, government policies or technological capability to develop and deploy CCUS.

The gap in the regulative environment between the developed and developing countries has been leading to a relocation in manufacturing from developed to developing countries, especially in emission-intensive industries. This is called “carbon leakage” and various measures and policies such as Carbon Border Adjustment Mechanisms (CBAMs) are being implemented at regional and international levels to prevent this phenomenon. However, there are concerns that, in particular, carbon border adjustment mechanisms possess risks for a just transition by placing undue burdens on developing countries (Bednarek, 2023). That is why existing barriers to future CCUS deployment in developing countries where exports primarily rely on emission-intensive products and hard-to-abate industries should be identified, and international policy strategies to facilitate collaboration and coordination across CCUS networks, build technological capacity for R&D, create financial and market incentives for the technology, and provide supportive regulation and sound communication on CCUS is essential (Shirmohammadi et al., 2020).

Inevitably, Türkiye is one of the countries that will be most adversely affected by these burdens if the appropriate policies and supportive mechanisms are not put into place in time (Yetişkin et al., 2023). The EU had a 40.6% share of Türkiye’s total export volume with 103.1 billion dollars in 2022

¹ Hard-to-abate sectors are those where emissions endure due to their essential role in fulfilling basic societal needs, the irreplaceability of their outputs, and the unavoidable process-related CO₂ emissions, as detailed in section 2.2.

and ranks first in total exports (Türkiye Cumhuriyeti Ticaret Bakanlığı, 2023). The European Union Carbon Border Adjustment Mechanism (CBAM) covers 13% of Türkiye's overall exports to the EU (Türkiye Cumhuriyeti Ticaret Bakanlığı, 2022). Additionally, on October 30, the UK Government revealed in an official publication that the national Border Carbon Adjustment Mechanism (UK CBAM) is set to take effect in January 2027 (T.C. Ticaret Bakanlığı, 2024; UK Department for Energy Security & Net Zero, 2023). If applied to the same sectors covered by the EU CBAM iron and steel is among Türkiye's leading exports to the UK (Türkiye Çimento Sanayicileri Birliği, 2023). Considering that many of these sectors prioritized by the CBAM mechanisms are among the ones classified as hard-to-abate, CCUS technologies may offer a way out for Türkiye.

Considering these circumstances, the motive of the study is to identify the genuinely hard-to-abate sectors that are appropriate for the integration of Carbon Capture, Utilization, and Storage (CCUS) technologies, in accordance with the actual climate mitigation efforts and the principles of a just transition. Furthermore, it seeks to address the discrepancy between the geographical concentration of hard-to-abate sectors suitable for CCUS integration and the actual deployment sites of these technologies. Accordingly, the study identifies the challenges faced by developing countries where production and exports primarily rely on emission-intensive and hard-to-abate sectors, and develops recommendations based on successful practices. The case of Türkiye is examined as an example representing these countries, in the light of perceptions of national and international experts and stakeholders, along with available literature.

In that regard, the study includes eight chapters. The following chapter consists of the brief overview of the challenge of decarbonization with its history, and the detailed framing of the “hard-to-abate” phenomenon. Next, in the third chapter, an examination of the value chain of CCUS technologies, and the methods employed in each stage of the value chain are given. In the fourth chapter, the methodology of the study is presented. Chapter five incorporates the current state of CCUS in the world through the analysis of current projects in the pipeline, policies, financing mechanisms, and the best practices in the developing countries, while chapter six examines the case of Türkiye in these same aspects. Chapter seven discusses the implementation of CCUS technologies, with particular attention to financial and policy barriers, and Türkiye's place in each of these areas. The last chapter highlights the main findings and suggests future lines of inquiry for international finance, comparative case studies, and holistic evaluations.

2. THE CHALLENGE OF DECARBONIZATION

While efforts for decarbonization have accelerated after the Paris Agreement, it was not the first attempt to reach a worldwide consensus on the reality of anthropogenic climate change and mobilize countries to act. Since 1994, after the UNFCCC came into force, parties finally recognized the anthropogenic nature of climate change, and agreed on the need for action to reduce greenhouse gas emissions. A year later, the first Conference of the Parties (COP) was held in Berlin. Since then, many of the world leaders have been meeting at the COPs in a different city every year. At COP 3, in 1997, the very first tangible international action, the Kyoto Protocol, was signed. However, it entered into force in 2005. Although there hasn't been an evident decrease in emission levels after the Kyoto Protocol, it has led the way in bringing the topic of lowering greenhouse gas emissions to the attention of the world community and has resulted in several other initiatives on the subject. In the same year, EU Emission Trading System (ETS) was launched, and in 2010, the Green Climate Fund (GCF) was established to support developing countries in their climate mitigation and adaptation efforts.

After the Kyoto Protocol's initial commitment term for emission limitation and reduction ended in 2012, the Doha Amendment was ratified to prolong its provisions. After three years, in 2015, at the COP21 in Paris, 196 parties signed the Paris Agreement, and for the first time, almost all developed and developing countries have shown their interest in collaborating to combat climate change. Since then, although not legally binding, parties are required to submit their nationally determined contributions (NDCs), detailing their strategies for lowering emissions and preparing for climate change (Savaresi, 2016). Afterwards, the EU introduced the European Green Deal in 2019, to decouple resource usage and economic growth in order to make Europe the first continent to achieve climate neutrality by 2050. The EU CBAM was also an extension of the EU Green Deal (Fetting, 2020).

2.1. Global Emissions

According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, global net anthropogenic emissions have consistently increased since 1990, with CO₂ emissions from fossil fuels and industry (CO₂-FFI) accounting for the largest share of this rise, as illustrated in Figure 2.1 (IPCC, 2023c). Based on the latest available data, in 2023, global anthropogenic CO₂ emissions from activities related to fossil fuels and industry amounted to 37.01 Gt, and projections indicate a

1.08 percent rise in 2024, bringing emissions to a new peak of 37.41 Gt. Overall, the global emissions of CO₂ have increased by more than 60 percent since 1990 (Tiseo, 2025).

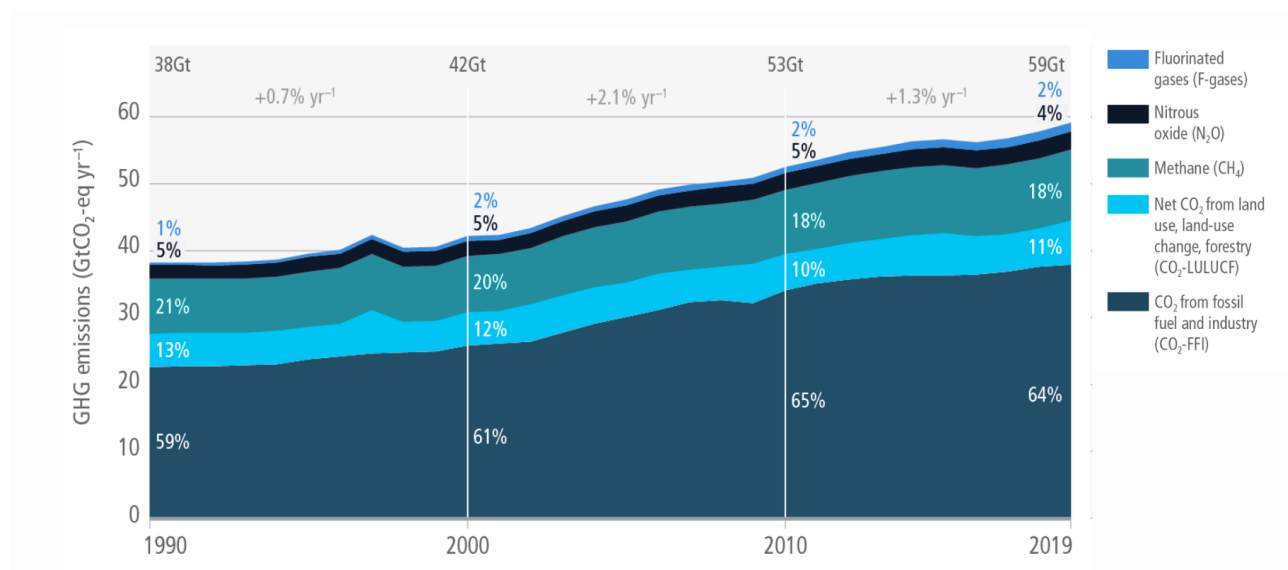


Figure 2.1. Global net anthropogenic emissions by GHG 1990 - 2019 (IPCC, 2023c).

Carbon dioxide emissions from fossil fuel and industry accounts for the 64% of the global greenhouse gas (GHG) emissions. As shown in Figure 2.2, in 2019, GHG emissions by industry subsectors show that the cement sector contributes approximately 8% of global emissions, the metal industry accounts for 16%, and the chemical sector represents 14%. These figures highlight the significant role of hard-to-abate industry subsectors in rising GHG emissions, emphasizing the need for targeted mitigation strategies to reduce emissions in these high-impact industries.

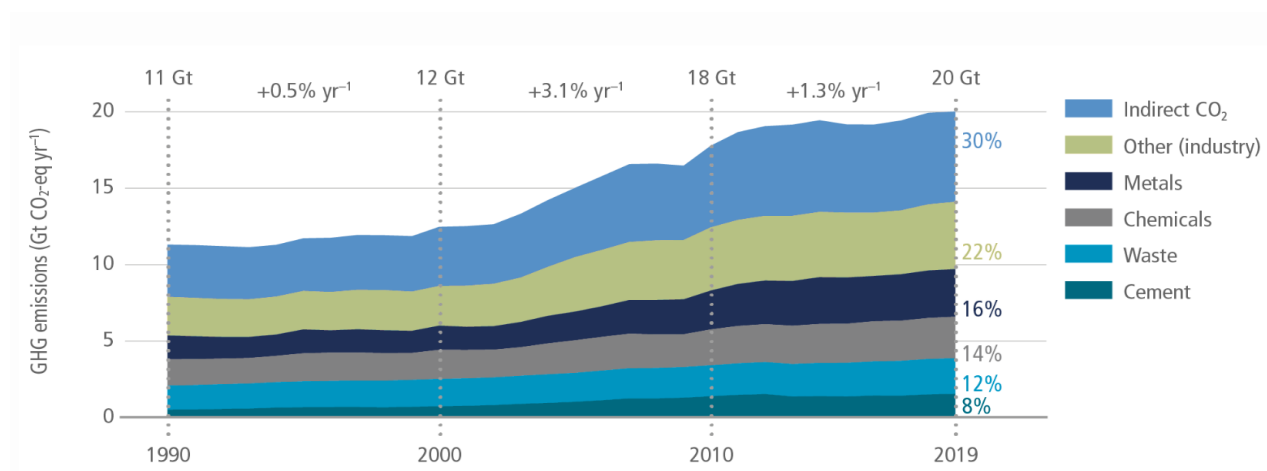


Figure 2.2. Industry global GHG emissions trends by subsectors 1990 - 2019 (IPCC, 2023c).

Reducing GHG emissions at their source is critical to limiting global temperature rise and mitigating the increasingly severe effects of climate change. To achieve this, prioritizing high-emission sectors is a key strategy for effective climate action. However, governments, corporations, and other stakeholders can only devise robust solutions if they have a precise understanding of where emissions originate. This requires a comprehensive approach that maps the connections between different sectors, end uses, and gases, helping to avoid a narrow focus as policymakers formulate their strategies. The diagram in Figure 2.3, created by the World Resources Institute (WRI) and Climate Watch, provides a valuable framework for understanding these emission flows. It visually links emissions across various sectors (left) to their specific end uses (middle) and associated greenhouse gases (right), offering a more integrated perspective on how emissions are generated and distributed.



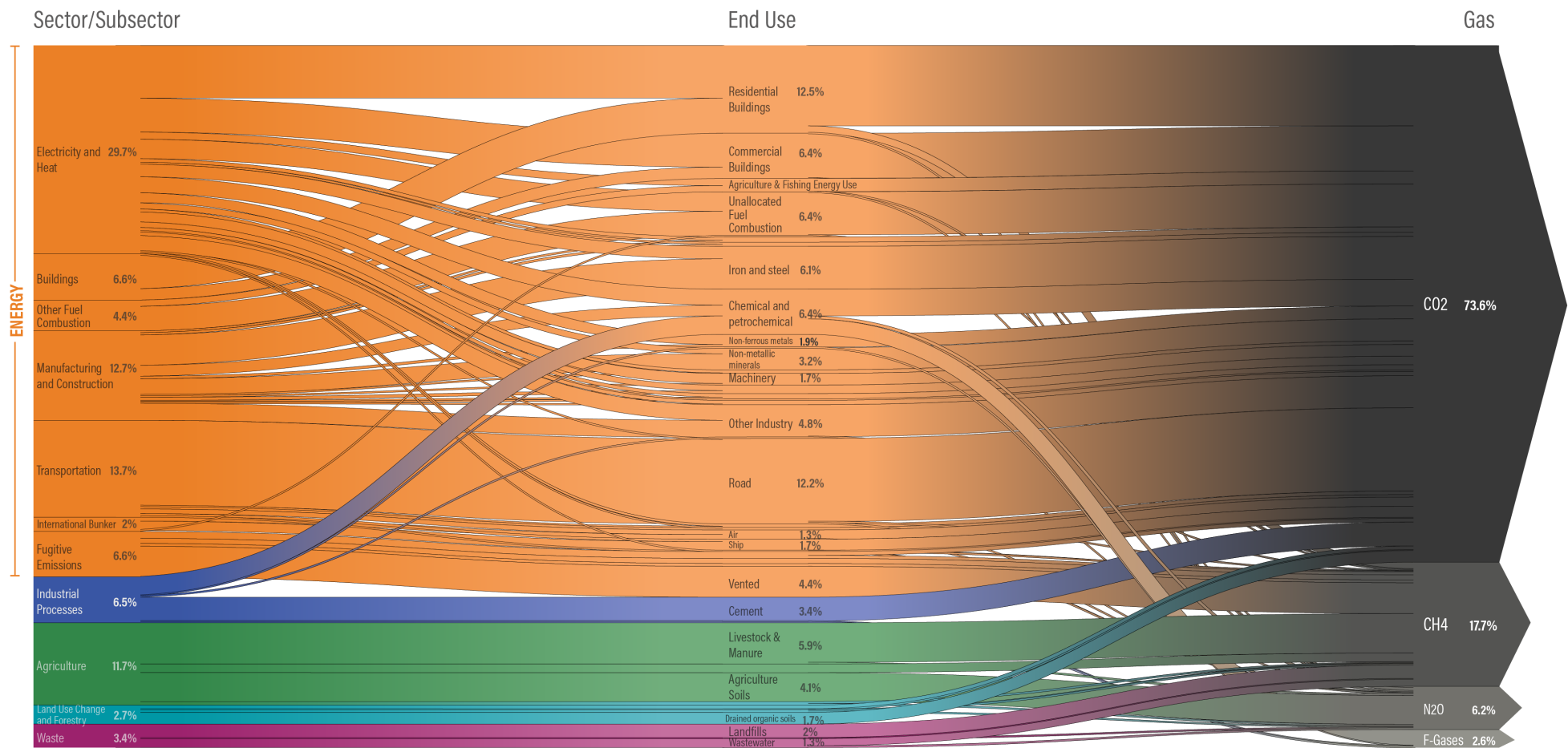


Figure 2.3. Flow of global greenhouse gas emissions in 2021 (Climate Watch & WRI, 2022).

Industry is the fastest-growing source of GHG emissions, with a substantial increase of 225% between 1990 and 2021. However, in contrast to this global trend, the production of key materials in the Group of Seven (G7) has remained relatively stable in the case of chemicals or has experienced a gradual decline in sectors such as steel and cement. As a result, the G7's share of global emissions has not followed the same upward trajectory. This trend is consistent with expectations for mature economies, where demand for industrial materials stabilizes as infrastructure and industrial production reach a more advanced stage. In contrast, developing economies, which are still expanding and modernizing their infrastructure, see a natural increase in material demand. However, attributing this divergence solely to domestic demand is insufficient (International Energy Agency (IEA), 2022a). Figure 2.4. illustrates the net transfer of embodied emissions through trade, with developed countries serving as net importers and regions and developing countries in Asia and the Pacific emerging as significant net exporters. It contrasts CO₂ emissions based on production and consumption by region between 1990 and 2018.

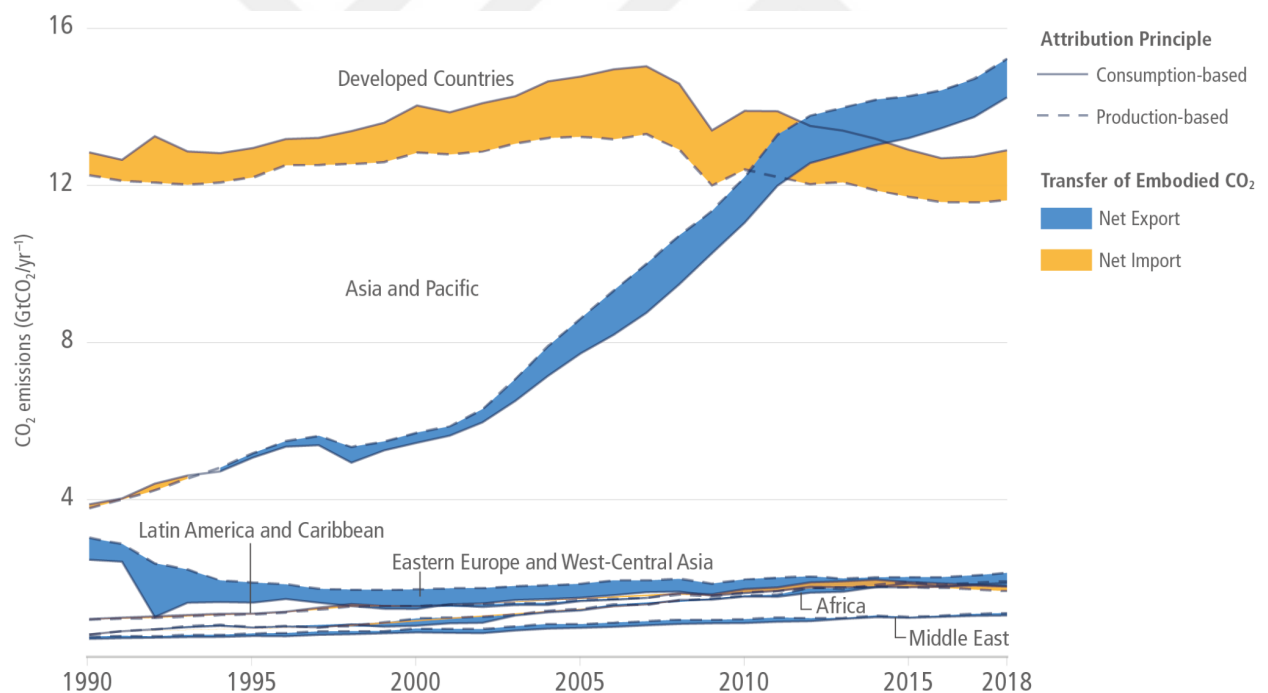


Figure 2.4. Total annual CO₂ emissions by global region based on consumption and production based emissions (IPCC, 2023c)

As economies mature, they often shift away from heavy industries as the primary driver of GDP growth, instead pivoting towards high-value manufacturing or service-based sectors. In this manner, over the past decade, several countries have reduced their production-based emissions, often through outsourcing emissions to other nations, a practice that may ultimately lead to higher global emissions

(Hubacek et al., 2021; IEA, 2022a). In the simplest terms, the regulatory gap between developed and developing countries has contributed to the relocation of manufacturing from developed to developing nations, particularly in emission-intensive industries. This phenomenon, known as "carbon leakage", has prompted the implementation of various measures and policies, such as carbon border adjustment mechanisms at international levels to mitigate its impact. However, there is growing concern that carbon border adjustment mechanisms, particularly those applied uniformly across all countries, could undermine the principle of Common but Differentiated Responsibilities (CBDR) and impede a just transition by imposing disproportionate burdens on developing nations (Bednarek, 2023).

2.2. Decarbonizing Hard-to-Abate Industries

2.2.1. What does “Hard-to-Abate” mean?

The term “hard-to-abate” is often primarily associated with techno-economic constraints in the decarbonization of sectors (Rathi, 2024). While these factors are important, a more comprehensive approach would involve considering the “hard-to-abate” phenomenon from a broader, interdisciplinary perspective, in the context of CCUS. Achieving net-zero emissions, or at least decarbonization, is a complex challenge that requires simultaneous consideration of socio-economic and socio-ecological factors. Any approach that overlooks one or both dimensions fails to address the issue in a holistic manner. In this context, there are several different aspects that make some sectors hard-to-abate:

- **Basic Needs of the Society:** The output products of the hard-to-abate sectors are usually the building blocks of society’s fundamental needs, which makes them essential and impossible to phase out of the market.
- **Irreplaceability:** The manufactured product cannot be substituted under current or projected conditions, as viable alternatives are either unavailable or more costly, or the available alternatives are limited in scope.
- **Industrial Process Emissions:** During industrial processes, CO₂ is emitted either as a by-product of chemical reactions, or through the use of fossil fuels as chemical feedstocks, or for producing high-temperature heat, functioning as reduction agents. As a result, full decarbonization cannot be achieved solely through a transition to clean energy.

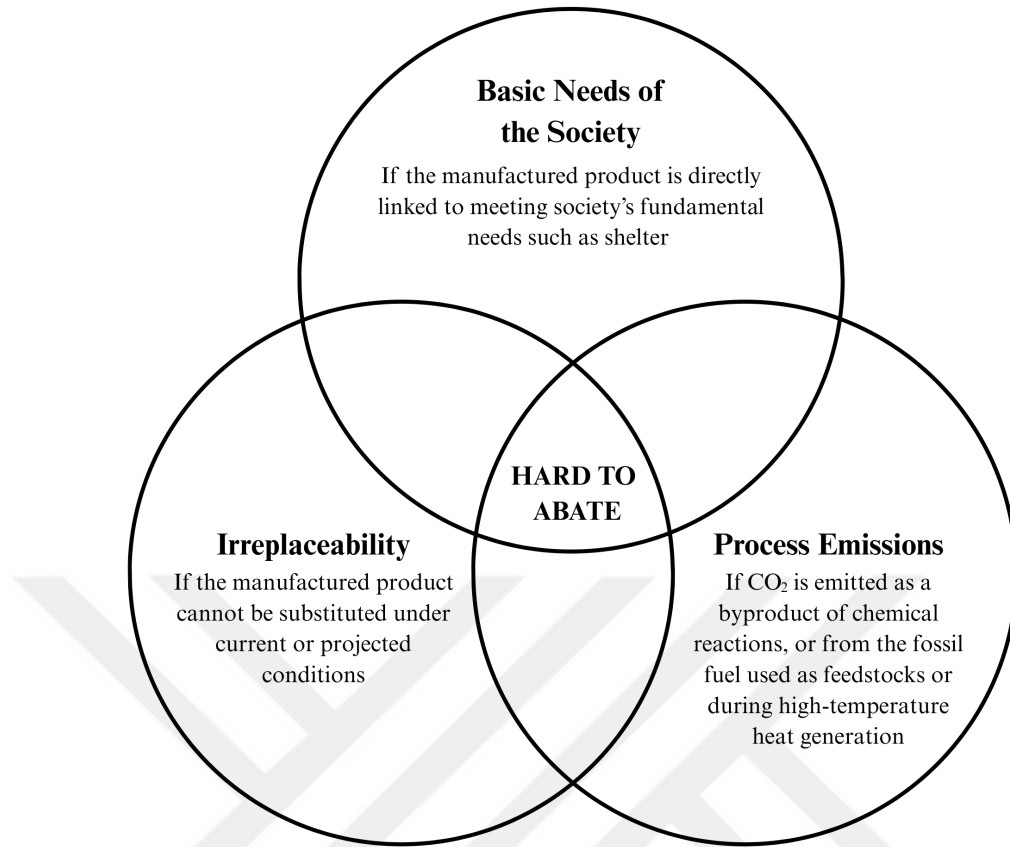


Figure 2.5. A conceptual framework for reframing 'Hard-to-abate' sectors
(Created by the author based on the IEA's definition of heavy industry (IEA, 2022a)).

Considering the factors outlined in Figure 2.5, industries identified by the IEA as “heavy industry sector” (cement, iron and steel, and primary chemical production) can be considered hard-to-abate. The output products of these sectors are essential for meeting the basic living standards of communities. They constitute key materials and goods that are critical to infrastructure, energy, transportation, healthcare, agriculture, and other foundational industries. As the population and wealth increase, the need for heavy sector outputs will inevitably rise. In the last twenty years, the global population has expanded by 25%, and global GDP has doubled. As a result, the need for materials manufactured by heavy industries has surged. Specifically, the demand for steel has increased by roughly 110%, for cement by 140%, and for primary chemicals by 80%. This issue is further exacerbated by the absence of commercially viable technologies to replace the essential materials or the existing industrial processes required to produce them (IEA, 2022a; IEA, 2022c).

In some cases, even when commercially viable alternatives are available, the transition might be more costly. In heavy industry, capital expenditures (CapEx) often significantly surpass operational

expenditures (OpEx), as these sectors often require large-scale infrastructure, and assets, such as machinery and facilities, are capital intensive and long-lived. Retiring or retrofitting existing plants to adopt the latest available technologies may prove financially challenging and, when considering a full life cycle assessment, could fall short of the ideal solution. Furthermore, when plants make the substantial investments required for the transition, these costs are often passed on to the end customers eventually, which can have negative impacts on lower-income households and communities, particularly when the product in question is a basic necessity. On the other hand, these products are generally sold in large volumes, and bulk materials demand uniformity, which complicates efforts to differentiate products for customers willing to pay a premium for low-carbon alternatives (IEA, 2022a). Table 2.1 illustrates the hard-to-abate sector criteria assessment in line with the proposed conceptual framework in Figure 2.5.

Table 2.1. Hard-to-Abate Sector Criteria Assessment

Sector	Basic Need of the Society	Irreplaceability	Process Emissions - Fossil Fuel Consumption		
			Heat/Steam Demand	Feedstock	Process Emissions By-product
Power & Heat Generation	✓	●	✗	✗	✗
Cement	✓	✓	✓	✗	✓
Chemicals	✓	✓	✓	✓	✓
Iron & Steel	✓	✓	✓	✗	✓
Natural Gas	✓	✗	✗	✗	✗

✓ Yes ✗ No ● Case Specific

2.2.2. Hard-to-abate Industries

As illustrated in Table 2.1, key industries associated with Carbon Capture, Utilization, and Storage (CCUS) are evaluated based on five criteria: basic societal need, irreplaceability, demand for heat/steam, utilization of fossil-based feedstocks, and process-related CO₂ emissions as by-products. The Cement, Chemicals, and Iron & Steel sectors fulfill nearly all of these criteria, consequently rendering them difficult to fully decarbonize, a topic discussed in detail below. Conversely, given that the power and heat generation, as well as natural gas sectors, do not satisfy the majority of these criteria, they are not classified as truly hard-to-abate within the context of CCUS. This indicates that

the application of CCUS is region-specific, taking into account the distinct challenges and opportunities pertinent to the locale of the project evaluated.

2.2.2.1. Cement Production. Cement combines with water, sand, and gravel to form concrete, acting as a binder that holds the mixture together. Its production accounted for approximately 3.4% of global greenhouse gas emissions in 2021 and 8% of total industrial emissions in 2019 (Ge et al., 2024; IPCC, 2023b).

The conventional cement manufacturing process consists of the steps shown in the Figure 2.6. Two main steps that make the cement manufacturing process emission-intensive are: fuel combustion to provide kiln heat and the calcination of calcium carbonate. In the kiln, the raw materials are heated up to roughly 1500°C to activate the reaction (Bosoaga et al., 2009).

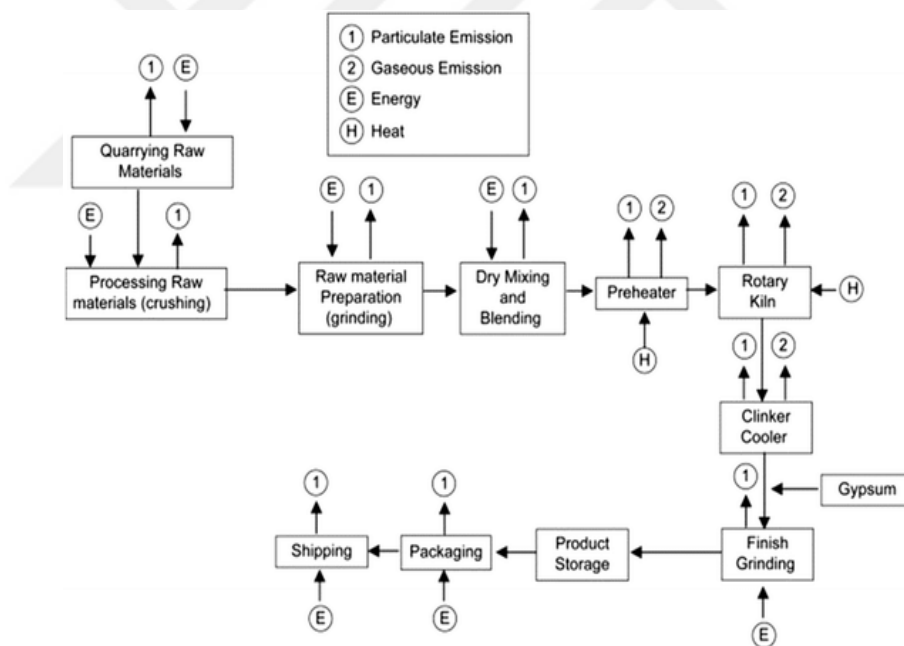


Figure 2.6. Conventional cement production process flow diagram and point sources (Brown et al., 2017).

Limestone is extensively employed as a raw material in conventional cement production due to its cost-effectiveness and widespread geographic distribution, however CO_2 is released as a byproduct of the calcination process of limestone (CaCO_3) into lime (CaO), which is the main chemical reaction of the production process (Bosoaga et al., 2009):



The exhaust gases produced during the cement manufacturing process typically contain 14-33% carbon dioxide (CO₂). Both process-related CO₂ and combustion-related CO₂ can be captured through a single stack, simplifying the overall capture process (U.S. Department of Energy, n.d.). Figure 2.7. outlines the process flow diagram of cement production, integrated with CCUS.

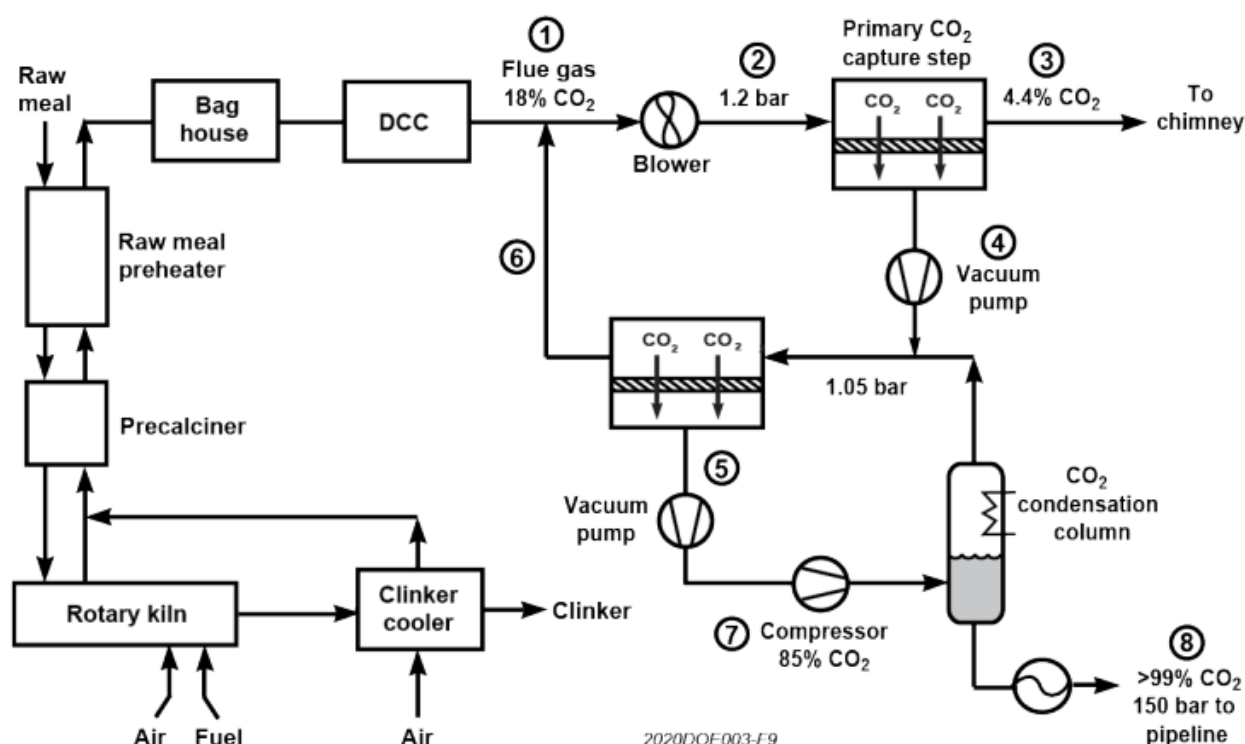
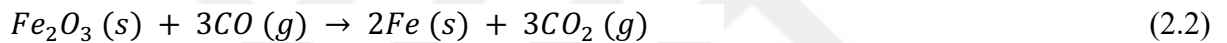


Figure 2.7. Process flow diagram of cement production with CCUS (U.S. Department of Energy, n.d.).

In addition to carbon capture, utilization, and storage (CCUS), the options available for decarbonizing cement production are relatively constrained. These options encompass enhancing energy efficiency, utilizing alternative fuels such as biomass or waste, and substituting limestone with other raw materials, such as calcium silicate rock (Brimstone, n.d.). However, given that cement is fundamental to the construction of buildings and infrastructure, the testing of alternative production methods presents inherent risks, as the material must comply with stringent structural and durability standards. Any failure in this regard could jeopardize the safety of buildings.

2.2.2.2. Iron and Steel Production. Steel is a critical material across numerous sectors, including construction, automotive and other types of vehicles, electrical and mechanical equipment, household appliances, and a wide range of everyday tools. The conventional primary steelmaking process relies on iron ore, and the iron and steel industry accounted for approximately 6.1% of global GHG emissions in 2021 (Ge et al., 2024). The main source of emissions in the iron-steel sector is the dependence on fossil fuels throughout different stages of the production process. CO₂ is emitted during the reduction of iron ore in blast furnaces (BFs), using carbon-based materials like coke, and the transformation of iron into raw steel in basic oxygen furnaces (BOFs) (U.S. DOE National Energy Technology Laboratory, 2014).

A typical iron ore, most commonly Hematite (Fe_2O_3) undergoes reduction primarily through the use of carbon monoxide (CO) as the reducing agent. The simplified chemical reaction for this reduction process occurring in the blast furnaces is as follows (Rippy et al., 2024):



Alternative decarbonization pathways being explored for the sector include electric arc furnaces (EAFs), hydrogen-based direct reduced iron (DRI), biomass and hydrogen injection into blast furnaces (BF), and the electrolysis of iron ore using renewable energy. The choice of technology for these decarbonization strategies, however, varies considerably across regions, driven by factors such as the carbon intensity of the local electricity grid, the availability of biomass for BF use, and the source and production methods of hydrogen (Deloitte, 2023). According to 2022 data from the World Steel Association, the blast furnace (BF) process accounts for approximately 71.1% of global steel production, while the electric arc furnace (EAF) accounts for 28.6%, combining both direct reduced iron-based EAF (DRI-EAF) and scrap-based EAF. The average CO₂ intensity for the BF, DRI-EAF, and scrap-EAF processes are 2.33, 1.37, and 0.68, respectively (World Steel Association, 2024).

As illustrated in Figure 2.8, for the capture of CO₂, the blast furnace gas is targeted because it is the most CO₂-dense stream in the steelmaking process. The CO₂ concentration of BF stack gas is typically around 21%. However, capture can be challenging if not all the blast furnaces are connected to the same flue stack (U.S. Department of Energy, n.d.; U.S. DOE National Energy Technology Laboratory, 2014).

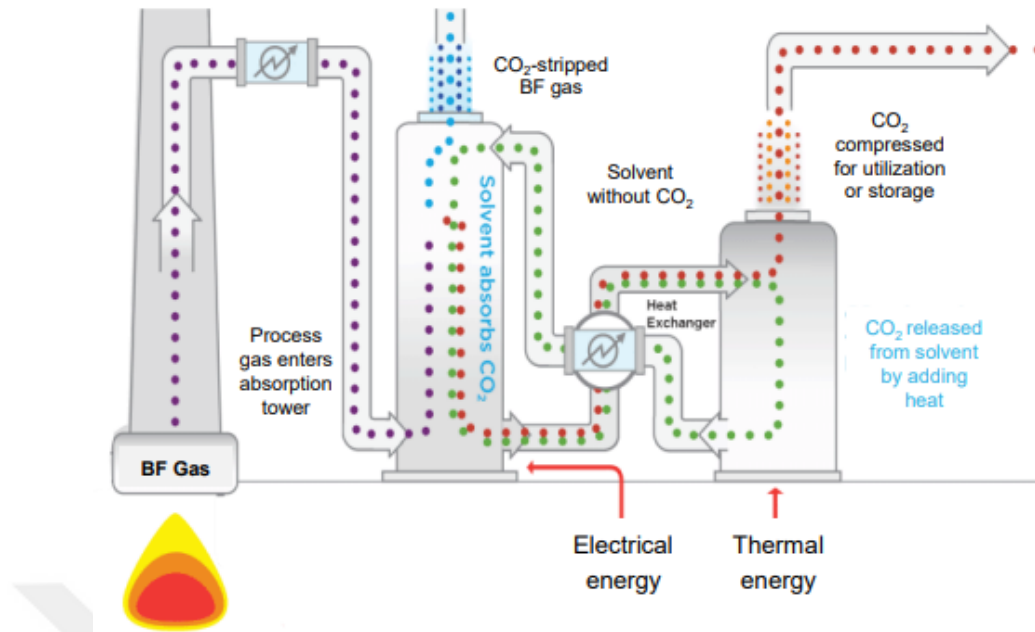


Figure 2.8. Schematic of solvent-based carbon capture from blast furnace-based steel plant (U.S. Department of Energy, n.d.)

The top ten steel-producing countries in 2023, ranked by production capacity, are: China, India, Japan, the United States, Russia, South Korea, Germany, Türkiye, Brazil, and Iran (World Steel Association, 2024). The United States has the lowest CO₂ intensity, largely attributable to the significant deployment of scrap-based Electric Arc Furnace (EAF) technologies (Deloitte, 2023).

2.2.2.3. Chemicals. The production of chemicals like ammonia, methanol, and high-value chemicals (ethylene, propylene, benzene, toluene, xylenes), which are widely utilized in the production of a variety of plastics, often involves fossil fuels, either as a feedstock or energy source, leading to emissions that account for 6.4% of the total emissions and 14% of the emissions resulting from industrial processes (Ge et al., 2024; IPCC, 2023b).

The chemicals industry fulfills all the criteria outlined for the "Hard-to-Abate Sector Criteria Assessment" presented in Table 2.1. This is primarily because the production processes for the majority of chemical products necessitate high-temperature heat and utilize carbon as a feedstock, resulting in CO₂ being emitted as a by-product. Furthermore, as shown in Table 2.2, a significant proportion of the products used in our daily lives are derived from outputs of the chemicals industry.

Table 2.2. Use cases and net-zero pathways for different chemical production processes (created by the author based on (Gabrielli et al., 2023)).

Primary Chemical	Use Cases	Net-Zero Pathways
Ammonia	Urea, other nitrogen fertilizers, direct use, synthetic fibers, plastics, explosives, textiles	-Haber-Bosch Process with CCS -Biomass based-ammonia via gasification or anaerobic digestion -Electrification/Hydrogen
Methanol	Plastics, formaldehyde, fuels, dimethyl, methyl, acetic acid	-Biomass gasification -CCS (Hydrogenation of syngas) -CCU (Direct synthesis from CO ₂ and H ₂)
High Value Chemicals (ethylene, propylene, benzene, toluene, xylenes)	Used as a precursor for most of the plastics (packaging, building and construction, textiles, consumer products, transport, electrical)	-Plastic recycling -Replacement of feedstock with CO ₂ , H ₂ , and biomass - CCU

There are many steps that can be taken to reduce the need for chemicals worldwide. However, alternative technologies at different TRLs for the production of many chemical-based products used to meet society's basic needs are also available, as shown in Figure 2.9. Recycling, replacing feedstocks with biomass, hydrogen/electrification, CCU, and CCS, or the combined technologies are proposed as net-zero pathways for the chemical industry, while each route has its own challenges.

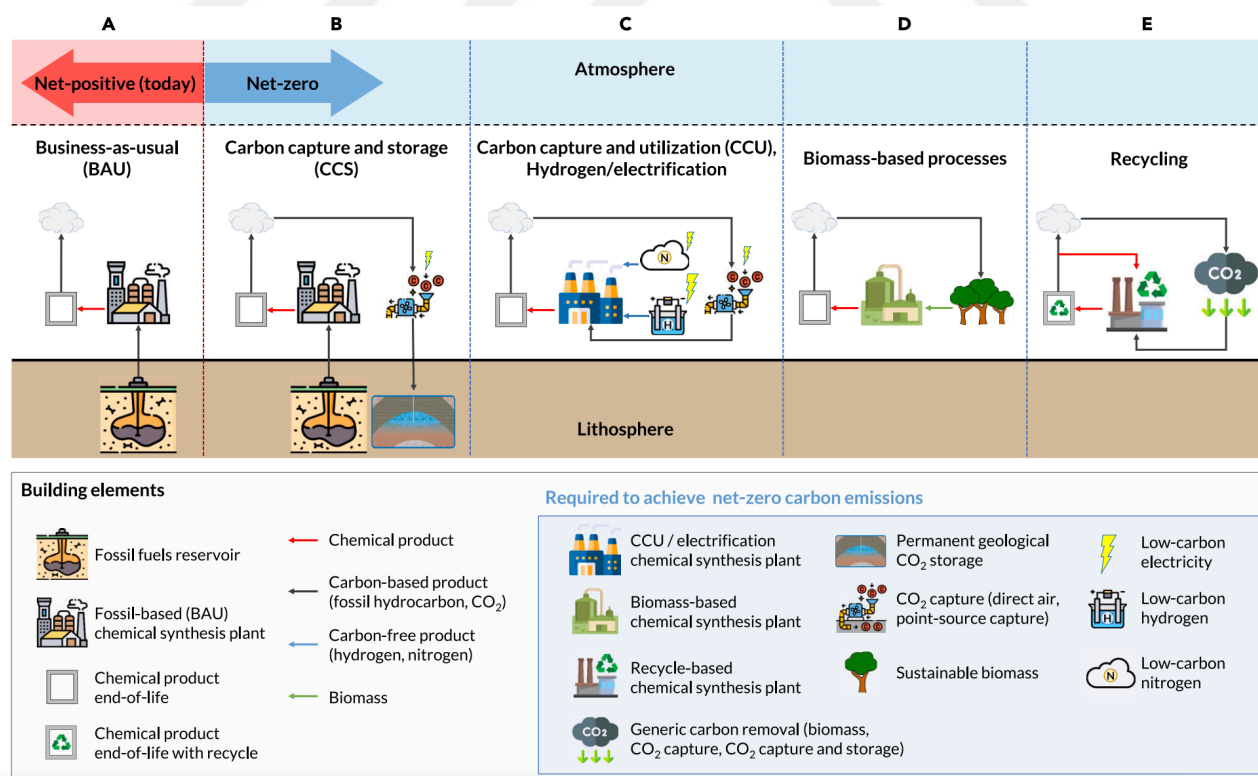


Figure 2.9. Available technology routes for the net-zero chemical industry (Gabrielli et al., 2023).

3. CARBON CAPTURE, UTILIZATION AND STORAGE TECHNOLOGIES

Rather than referring to a single technology, CCUS is an umbrella term covering various combinations of different carbon dioxide capture, utilization, and/or storage technologies. The CCUS value chain is given in Figure 3.1, with a detailed overview of each stage provided in Table 3.1.

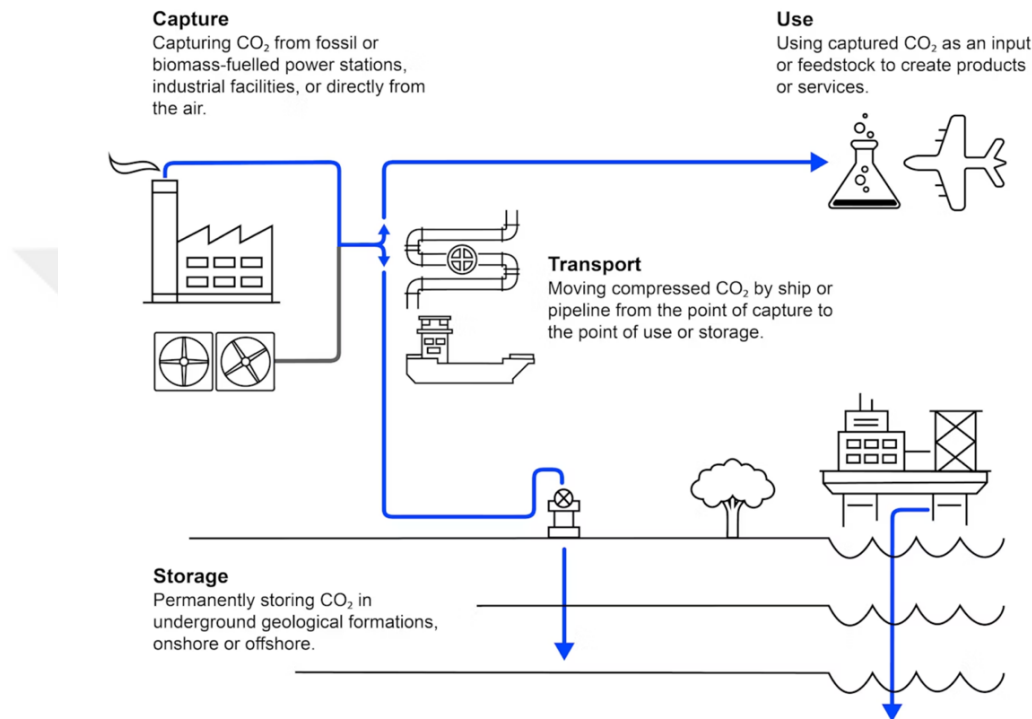


Figure 3.1. What is CCUS? (International Energy Agency, 2021)

Table 3.1. CCUS technologies overview (created by the author using (Carbon Capture, Utilization, and Storage: Handbook for Policymakers, 2024; REC,2023))

Capture	Transportation	Utilization	Storage
• Direct Air Capture • Point Source Capture ○ Post- Combustion Capture ○ Pre-Combustion Capture ○ Oxy-Fuel Combustion ○ Membrane Separation ○ Cryogenic Distillation ○ Pressure Swing Adsorption (PSA) ○ Calcium Looping ○ Chemical Looping	• Railway • Trucks • Ships • Pipeline	• Concentrated CO₂ • Fuels • Construction Materials • Chemicals	• Depleted Oil and Gas Reservoirs • Deep Saline Aquifers • Minerals (Basaltic & Ultramafic Formations)

Although CCUS has gained increased attention recently, the concept itself is not new. In fact, most of the techniques that now enable the separation of CO₂ from several industrial streams were originally developed for different industrial applications. Likewise, underground CO₂ injection was initially employed for Enhanced Oil Recovery (EOR) and Enhanced Gas Recovery (EGR) purposes by pressurizing the depleted oil and gas reservoirs, ultimately increasing the yield of hydrocarbon extraction; however, it has been repurposed to store CO₂ underground permanently. Moreover, novel technologies are also being developed, such as electrochemical conversion and advanced mineralization processes, which aim to broaden the scope and effectiveness of CCUS beyond its conventional applications (Ma et al., 2022). Figure 3.2 illustrates the historical development of CCUS technologies, emphasizing the major milestones.



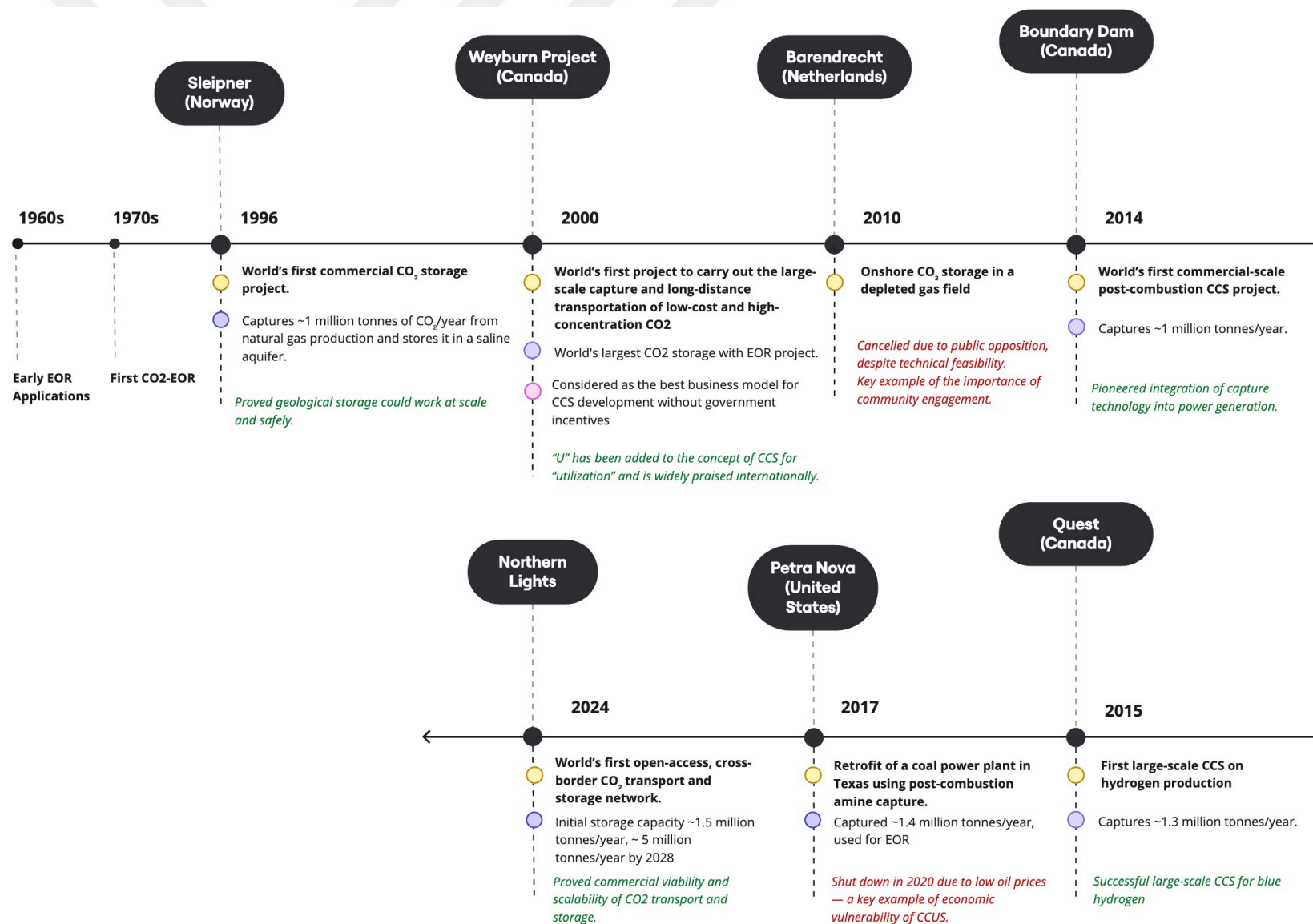


Figure 3.2. CCUS Timeline (created by the author using (Bahar, 2023; Georgiou, 2020; Ma et al., 2022; Northern Lights, 2024)

3.1. Capture

In the context of CCUS, capture refers to capturing CO₂ from point sources, such as industrial facilities or fossil or biomass-fueled power plants, before it reaches the atmosphere. Carbon capture techniques for industrial processes began in the 1930s, utilizing chemical absorption with amine-based solvents in natural gas sweetening (Global CCS Institute, 2021). Since that time, a range of physical and chemical processes has emerged. Currently, various methods, each at different technological readiness levels (TRL), are employed depending on the point source. Table 3.2 shows the TRLs of each capture method in 2020 and 2024.

Table 3.2. CO₂ capture technologies commercially available or under development (Global CCS Institute, 2025).

CATEGORY	TECHNOLOGY	2020 TRL ASSESSMENT	2024 TRL ASSESSMENT	DETAILS
Chemical Absorption	Amine based Solvents	9	9	Widely used in fertilizer, soda ash, natural gas processing plants, e.g., Sleipner, Snøhvit, and used in Boundary Dam
Chemical Absorption	Hot Potassium Carbonate (HPC)	9	9	Fertilizer plants, e.g., Enid Fertilizer
Chemical Absorption	Sterically hindered amine	6-9	6-9	Demonstration to commercial plants, depending on technology provider
Chemical Absorption	Carboxylic Acid based solvent	6-7	6-7	Pilot tests to demonstration plant feasibility studies
Chemical Absorption	Chilled Ammonia Process	6-7	6-7	Pilot tests to demonstration plant feasibility studies
Chemical Absorption	Phase change Solvents	5-6	6-7	DMX™ Demonstration
Chemical Absorption	Water-Lean Solvent	4-7	6-7	Pilot test and commercial scale FEED studies: Gerald Gentleman Station carbon capture plant, the Jinjie pilot plant
Chemical Absorption	Amino Acid based solvent/Precipitating Solvents	4-5	4-5	Lab test to conceptual studies
Chemical Absorption	Ionic Liquids	4-5	4-5	Pilot tests
Chemical Absorption	Encapsulated solvents	2-3	2-3	Lab tests
Chemical Absorption	Physical Solvents	9	9	Widely used in natural gas processing, coal gasification plants; e.g., Val Verde, Shute Creek, Century Plant, Coffeyville Gasification, Great Plains Synfuels Plant, Lost Cabin Gas plant
Chemical Absorption	Enzyme Catalysed Absorption	6	7-8	Commercial demonstration facility in Quebec

CATEGORY	TECHNOLOGY	2020 TRL ASSESSMENT	2024 TRL ASSESSMENT	DETAILS
Solid Adsorbent	Pressure Swing Adsorption/Vacuum Swing Adsorption	9	9	Port Arthur SMR VPSA
Solid Adsorbent	Temperature Swing Adsorption	9	9	Kern River Pilot
Solid Adsorbent	Sorbent-Enhanced Water Gas Shift	5-7	6-7	Pilot tests, e.g., STEPWISE
Solid Adsorbent	Electrochemically Mediated Adsorption	5	5	Lab testing
Solid Adsorbent	Gas separation membranes for natural gas processing	2-3	2-3	Santos Basin Pre-Salt Oil Field CCS
Solid Adsorbent	Polymeric Membranes	9	9	FEED studies for large pilots
Solid Adsorbent	Electrochemical membrane integrated with Molten Carbonate Fuel Cells	7	7	Large pilots at Plant Barry, demonstration plant in South Korea
Solid Adsorbent	Polymeric Membranes / Cryogenic Separation Hybrid	7	8	Demonstration plants and pilot studies
Solid Adsorbent	Polymeric Membranes/Solvent Hybrid	7	6-8	Conceptual studies
Solid Adsorbent	Room Temperature Ionic Liquid (RTIL) Membrane	6	4	Lab testing
Solid Looping	Calcium Looping (CaL)	6-7	6-8	STRATOS plant in Texas (0.5 Mtpa) is under construction
Solid Looping	Chemical Looping Combustion	5-6	5-6	Pilot test at ALSTOM's existing Multipurpose Test Facility (3 MWth) and at a technical university in Germany
Solid Looping	Allam-Fetvedt Cycle	6-7	6-7	50 MW demonstration plant in La Porte
Solid Looping	Lime Processing Kilns	6-7	6-7	Leilac-1, with Leilac 2 under development
Inherent Capture	Electrodialysis of Oceanwater	6	6-7	Ongoing field trials
Cryogenic Separation	Cryogenic Distillation	9	9	Deployed on various projects around the world

There are numerous plant-specific and material-specific considerations to take into account when selecting an appropriate capture method. These considerations include the location of the plant, the type of facility, the volume of the outlet stream, the purity, the temperature and pressure of the stream, the availability of water supply, the level of degradation of the materials utilized in the capture technique, as well as whether the plant represents a new build or a retrofit, among other factors (*Carbon Capture, Utilization, and Storage: Handbook for Policymakers, 2024*). The capturable point sources across sectors, along with key flue gas properties, are summarized in Table 3.3.

Table 3.3. CO₂ characteristics in typical industrial flue gas streams (Bains, Psarras & Wilcox 2017; Global CCS Institute 2015; IEAGHG 1999; Grantham Institute 2014, as cited in Global CCS Institute, 2021).

INDUSTRY	POINT SOURCE	CO ₂ PARTIAL PRESSURE (WET) (kPa)	GAS STREAM PRESSURE (kPa)	INHERENT CO ₂ CAPTURE
Power	Natural gas combined cycle (NGCC) power plant	3.8 - 4.6	Atmospheric***	No
Power	Coal fired-power plant	12.2 - 14.2	Atmospheric***	No
Power	Biomass/waste-fired power plant	10.1 - 12.2	Atmospheric***	No
Power / Industrial Heat	Natural gas-fired power and/or heat plant (Open Cycle)	4.1 - 8.1	Atmospheric***	No
Power / Industrial Heat	fluid catalytic cracking	10.1 - 14.2	Atmospheric***	No
Petroleum Refining / Petrochemicals	Process heater	8.1 - 10.1	Atmospheric***	No
Petroleum Refining / Petrochemicals	Ethylene production steam cracking	7.1 - 12.2	Atmospheric***	No
Petroleum Refining / Petrochemicals	Steam methane reforming hydrogen production	300 - 480	Atmospheric***	No
Cement	Ethylene oxide production	> 92	Atmospheric***	Yes
Cement	Kiln flue gas	~ 18	Atmospheric***	No
Pulp and paper	Pre-calciner	20 - 30	Atmospheric***	No
Iron & Steel	Lime kiln	~ 16	Atmospheric***	No
Iron & Steel	COREX smelting reduction process	32 - 35	Atmospheric***	No
Iron & Steel	Hot Stove	24 - 28	Atmospheric***	No
Iron & Steel	Lime calcining	71 - 8.1	Atmospheric***	No
Aluminium	Sinter plant	3.7 - 4.2	Atmospheric***	No
Aluminium	Aluminium smelter	0.8 - 1.1	Atmospheric***	No
Fertiliser	Coal gasification syngas	750 - 2500	3000 - 6000	Yes*
Fertiliser	Natural gas reforming syngas	300 - 1200	2000 - 3000	Yes*
Natural gas processing	Natural gas processing	Varies, up to 5000	900 - 8200	Yes, acid gas removal
Bioethanol	Ethanol fermentation	> 85	Atmospheric***	**

*CO₂ from syngas stream is captured for downstream urea production.

**Only dehydration and compression required

***Standard atmospheric pressure is 101.3 kPa, which is close to the average air pressure at sea level. However, atmospheric pressure does vary by location and altitude.

Although it might vary greatly depending on the point source, capture technique, and plant specifications, capture is generally considered the costliest stage in the CCUS value chain. Each facility's design specifications affect the cost of capture, including the partial pressure of the CO₂ stream, the percentage of CO₂ captured, stream pretreatment, capture technique, and cooling or heating needs, as listed in Table 3.4.

Table 3.4 Factors affecting the cost of capture (created by the author based on (Global CCS Institute, 2025)).

Factor	Description
Partial Pressure of CO ₂	Higher partial pressures are more favorable. Inlet streams with higher partial pressures and concentrations require less energy and equipment to capture.
Pretreatment	Contaminants can harm certain types of capture techniques (e.g., fouling, solvent degradation). Therefore, contaminants (e.g., NO _x , SO _x) should be removed from the inlet streams before they enter the capture plant.
Plant Scale	Because of economies of scale, as the plant scale and total volume of CO ₂ capture increase, the unit cost of capture tends to decrease.
Capture Technique	There are plenty of different methods to separate CO ₂ from the inlet streams; they all have distinct and case-specific advantages and disadvantages, as listed above.
Capture Percentage	Although capturing up to 99% of the carbon dioxide is technically feasible, there is a trade-off between capturing high percentages and the energy required. So, 90% is mostly accepted as the optimal percentage in FEED studies.
Temperature	Capture plants might generate significant amounts of heat, and the level of cooling needed depends on the plant's location.

3.2. Transportation

The point source where the CO₂ is captured from is mostly not in the exact location as the storage, so the transportation of CO₂ from the source to the injection point, or in some cases where the CO₂ will be utilized, is required. Since the CO₂ captured from the plants is approximately at atmospheric pressures (~ 101.3 kPa), and in most cases saturated with water vapor, the stream must be compressed and dehydrated before transportation. Also, compression increases the pressure and temperature, so additional cooling is required in most cases to keep the stream's temperature and volume within reasonable limits. However, the selection of the transportation method also depends on many other factors, such as geography, ports, existing pipeline and railway infrastructure of the region, and land use regulations (Global CCS Institute, 2025). The methods of transposition and their TRLs are listed in Table 3.5.

Table 3.5. CO₂ transportation modes (created by the author based on (Carbon Capture, Utilization, and Storage: Handbook for Policymakers, 2024; Global CCS Institute, 2021; IEA, 2023a)).

Technology	TRL	Notes
Pipelines	10	CO ₂ pipelines have been extensively used for EOR, and more recently for dedicated storage, with around 9,500 km deployed.
Shipping	6-7	Low-volume CO ₂ vessels are operating around the world at median pressure (15 bar) for the food industry. The first 7,500 m ³ and medium pressure (19 bar) ship operating was built for the Northern Lights project in November, 2024. Higher volume ships (e.g. 40,000-70,000 m ³) operating at lower pressure (7 bar) are currently at prototype scale.
Rail	6-7	The Morecambe Net Zero Cluster in the United Kingdom plans to transport CO ₂ from the Peak cluster via rail.
Trucks	9	Transporting CO ₂ by truck is commonly employed for short-distance, small-volume shipments. This method typically utilizes cryogenic tankers or pressurized containers. Additionally, it necessitates facilities for loading and unloading the CO ₂ onto and off the trucks.

3.3. Utilization

Carbon serves as the fundamental building block of numerous materials utilized in our daily lives. Rather than perceiving CO₂ as a mere waste product, it can be transformed into valuable feedstocks. Furthermore, carbon utilization presents a viable alternative to storage, particularly in countries where incentives for storage are limited (e.g., most developing countries based on current projections). This transformation into marketable products can generate revenue streams for various projects. CO₂ can be converted into either long-lived product, representing a durable storage pathway, or short-lived products, aligning with a circular economy pathway. However, the effective utilization of CO₂ may necessitate extensive infrastructure, including capture, purification, dehydration, transportation, and conversion, depending on the specific point source of the CO₂, as elaborated in the “Capture” section. The Life Cycle Assessment (LCA) of the entire process is crucial in determining whether capturing carbon dioxide for utilization is worthwhile. The National Academies of Sciences, Engineering, and Medicine published a comprehensive study on the utilization of CO₂ into different products through different processes, such as chemical conversion, biological conversion, mineralization, and hybrid processes. Figure 3.3 shows the summary of the feedstocks, processes, product classes, and services for CO₂ utilization.

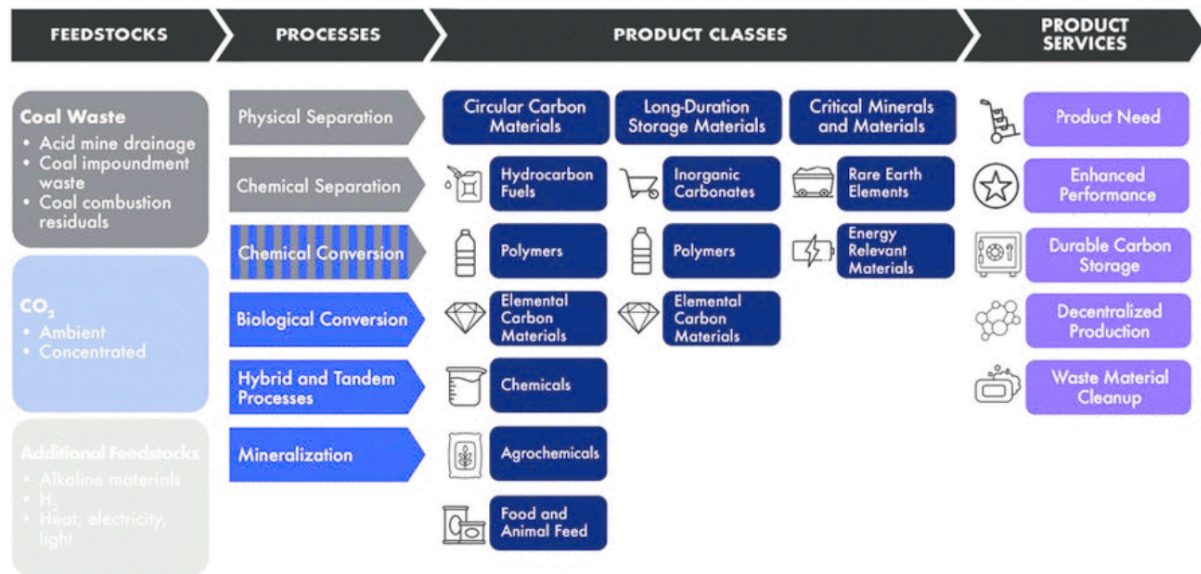


Figure 3.3 CO₂ utilization pathways (National Academies of Sciences, Engineering, and Medicine, 2023).

Another key point regarding the utilization is prioritizing long-duration storage materials. The research on the utilization of CO₂ for marketable products has increased, primarily in the construction sector, while the technologies are still maturing. Various commercial efforts exist, especially on mineral carbonation, and currently, the carbonation of conventional concrete possesses the greatest potential for CO₂ avoidance. Furthermore, the carbonate minerals also have applications in various industries such as pharmaceuticals, paper and pulp, and agriculture. However, most of these applications are not well-suited for long term storage (Woodall et al., 2019).

3.4. Storage

Although utilization represents a viable alternative, it is essential that the majority of CO₂ be injected underground for permanent storage to support long-term mitigation efforts (*Carbon Capture, Utilization, and Storage: Handbook for Policymakers*, 2024). Various methods and formations are currently used or being tested for dissolved CO₂ injections, such as deep saline formations, depleted oil and gas reservoirs, and basaltic and ultramafic formations. Deep saline formations are the most widely proposed globally because they have the highest technological maturity and encounter less public backlash (“Not in my backyard” phenomenon). Depleted oil reservoirs are also favored due to existing infrastructure from the history of enhanced oil recovery (EOR) and enhanced gas recovery (EGR), and even countries with no CCUS traction already know where the reservoirs are located.

Moreover, dissolved CO₂ injections into basaltic and ultramafic formations are promising, following the demonstrations by Carbfix in Iceland. The types of storage and the motivations for storage across countries exhibit significant variation, influenced by the presence of complementary policies, the domestic capabilities of each country regarding different storage types, and the sectors that influence the national economy. In countries such as Norway, where supportive policies are robust, mechanisms like the carbon tax enhance the motivation for storage. Conversely, in certain countries, Enhanced Oil Recovery (EOR), which is not regarded as a legitimate strategy for climate mitigation, is prioritized based on its potential to create a revenue stream. Table 3.6 shows a summary of these storage methods.

Table 3.6. Geological storage types (created by the author (IEA, 2023; Kelemen et al., 2019)).

Storage Type	Storage Mechanism	TRL	Stage – Example	Key Advantage
Deep Saline Formations	Structural + Solubility	9	Most widely proposed globally, CO ₂ injection in saline aquifers has been successfully demonstrated over the past two decades with many operational large-scale first-of-a-kind projects around the world (e.g. Sleipner in Norway, Quest in Canada).	Abundant, No Commercial Resource Conflict
Depleted Oil & Gas Reservoirs	Structural (Proven Trap)	7-8	Used in North America & North Sea, the first injection of CO ₂ within depleted fields has been completed in 2023 during the pilot phase of Project Greensand in the Danish North Sea.	Known Seal Integrity, Existing Infrastructure
Dissolved CO ₂ Injections (Basaltic & Ultramafic Formations)	Mineral Carbonation	5	Aqueous injections, where CO ₂ is dissolved in water and injected into mafic igneous rocks, have been demonstrated by Carbfix in Iceland. In Oman, two pilots have been conducted injecting CO ₂ dissolved in rainwater into peridotite formations for accelerated mineralization and sequestration of CO ₂ .	Permanent Mineral Storage Potential

While various options exist globally for CO₂ sequestration, geological formations are unevenly distributed across regions, as shown in Figure 3.4 and Figure 3.5. This may exacerbate regional disparities, emphasizing the necessity for cross-border collaboration.

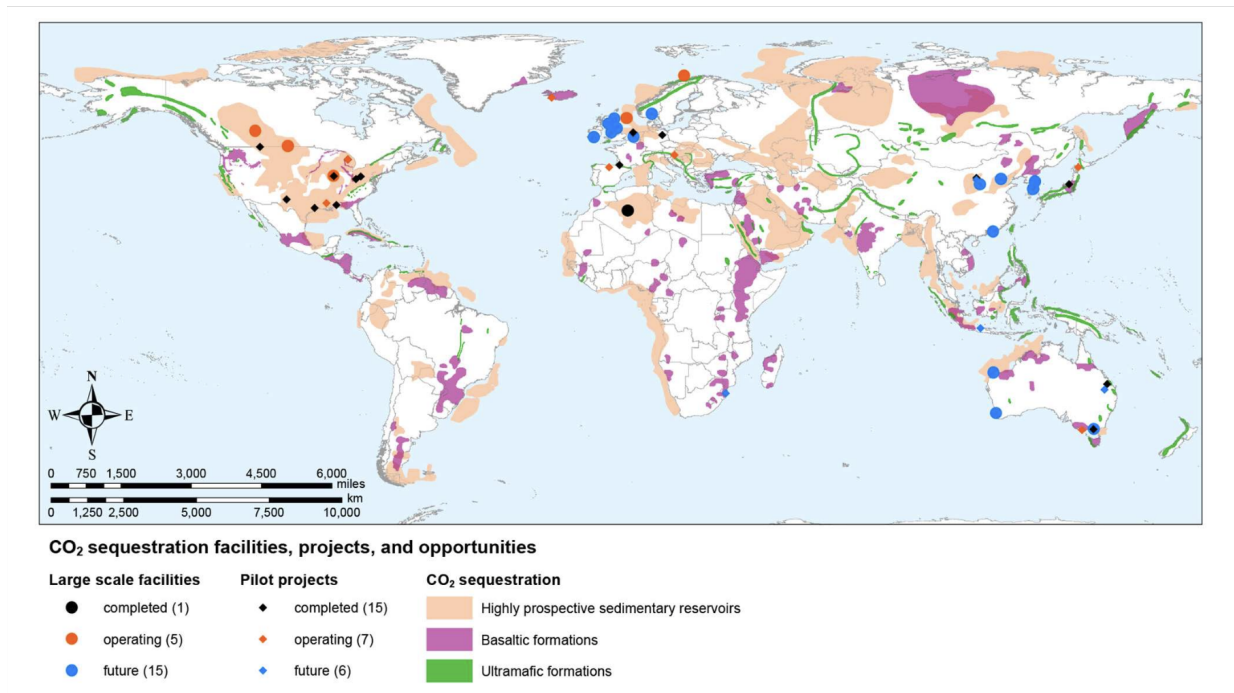


Figure 3.4. Global storage potentials (sedimentary reservoirs, basaltic and ultramafic formations) (Kelemen et al., 2019).

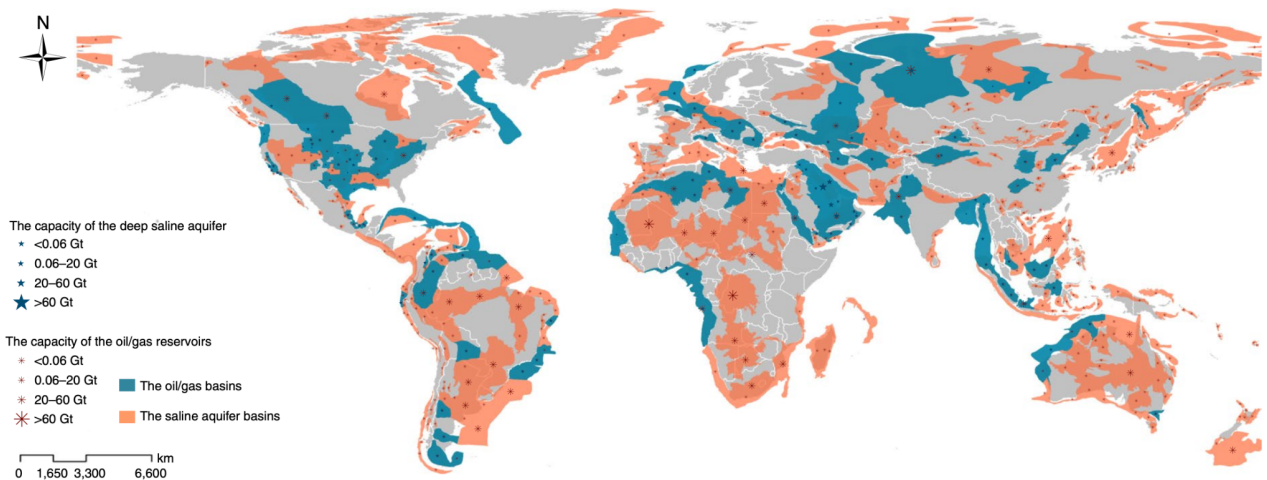


Figure 3.5 Global storage potentials (oil/gas reservoirs & saline aquifers)(Wei et al., 2021).

While there exists a consensus that geological sequestration should be prioritized for the most effective climate mitigation, Kelemen et al. (2019) elucidate ex-situ carbon mineralization options for regions where prospective geological formations are limited or where concentrated CO₂ sources are not in close proximity to geological formations. However, the risk of side environmental effects of employing these methods must be considered.

Table 3.7. Details of industrial and municipal wastes regarding the quantities produced per year, the potential CO₂ uptake per year, and the cost of the method (Kelemen et al., 2019).

Industrial and Municipal Wastes	Production (Gtwaste/yr)	Conditions of Carbon Mineralization	Uptake (MtCO ₂ /yr)	Cost (\$)
Steel and blast furnace slag	0.17–0.5	- High temperature and pressure - Reaction with purified CO ₂ or CO ₂ -saturated water ± Various pretreatment steps	2–100	75–100
Cement waste	0.42–2.1		1–300	Probably steel slag cost divided by ratio of weight fraction CO ₂ for steel slag to this commodity
Construction and demolition waste	1.4–5.8		100–600	~150
Municipal solid wastes	1.3		4–160	
Coal ash	0.4–0.6		0.2–90	
Red mud, wastes from Al extraction	0.12		0.01–6	
Total CO ₂ uptake			~100–1,250	

The most important part regarding the storage is ensuring the engagement with the communities in the regions or locations in close proximity to the storage sites, especially regarding the risks associated with the leakage of injected carbon as well as the other geomechanical risks. The Barendrecht project, which was aiming to inject CO₂ in a depleted gas field in the Netherlands, is a good example of the importance of community engagement, since the project had to be cancelled due to public concerns about the possibility of damaging homes, and also a decrease in the property value (*Carbon Capture, Utilization, and Storage: Handbook for Policymakers*, 2024).

4. METHODOLOGY

This section outlines the methodologies employed by this thesis. The research adopts a multimethod approach, comprising four steps: content analysis, data analysis, interviews, and case studies. Initially, technical and academic papers, industry reports, policy briefs, and guidelines from both international and local authorities are examined to attain a comprehensive understanding of CCUS technologies, their effectiveness and deployment strategies, as well as current and prospective policies and financing mechanisms, thereby identifying existing gaps.

Secondly, the Global CCS Institute has provided a comprehensive list of all facilities worldwide as of February 2025, including the following data breakdowns for each facility: facility name, network, status, facility category, operational year, country, region, facility type, industry, capture type, capture source, transportation type, and storage code. The data for the facilities are analyzed by project stage, country classification, sectors, and storage or utilization pathways through RStudio to outline the current state of CCUS in the world. Accordingly, the figures in section 5.1 are developed. (See Appendix D for RStudio code used in this analysis). Countries classified as “Least developed” and “Developing” are labeled as “developing” and the other categories are labeled as “developed” according to WESP 2025 report (United Nations, 2025) to determine the disparity between two country groups (See Appendix A).

After, 12 semi-structured in-depth interviews with international and local stakeholders, experts, innovators, founders, investors, and potential users of these technologies were conducted to provide valuable insights into the perceptions, motivations, needs, and challenges in the field (See Appendix C for interviewee list). Given the researcher's network in the United States, European Union, and Türkiye, the recruitment process began by leveraging existing professional connections. This approach provided access to key stakeholders and facilitated initial outreach. As the interviews progressed, snowball sampling was employed, where initial participants recommended other relevant stakeholders who contributed valuable perspectives. These interviews were used to gather the perspectives of different stakeholder groups in both developed and developing countries, allowing for an exploration of the successes and failures in advanced regions, as well as a deeper understanding of the barriers and needs of stakeholders in developing countries. All the questions prepared for the different stakeholder groups to interview were sent to interviewees before the interviews. The interviews were conducted based on the participant's location and preference. They took place face-to-face, or via an online platform, depending on what is most convenient for the interviewer and the

interviewee. The participant consent form was emailed to the participant prior to the interview in either case, and the interview proceeded once consent is confirmed. With the participant's permission, the interviews were audio recorded for transcription purposes.

Lastly, a case study to provide insights on the current status of CCUS in Türkiye, promising storage sites, sectors to focus on, and recommendations for the region were developed, as a representation of developing and emerging economies.



5. THE STATE OF CCUS IN THE WORLD

5.1. Current projects in the pipeline

Data on commercial, pilot, and demonstration facilities were obtained from the CO₂RE database of the Global CCS Institute, and countries were classified as Least Developed, Developing, Economies in Transition, or Developed according to the World Economic Situation and Prospects 2025 country classification (See Appendix A) (United Nations, 2025). The dataset was subsequently analyzed using RStudio to generate in-depth, data-driven insights.

As we approach the mid-2020s, there are currently 130 CCS facilities in operation with a total capture capacity of approximately 85.4 MTPA CO₂, 54 facilities under construction with an estimated capacity of about 90.5 MTPA CO₂, and 706 facilities in various stages of development (early development, advanced development, or announced) with a combined disclosed capacity exceeding 1,084 MTPA CO₂, with the latest announced operational start date extending to 2032. Approximately 62 pilot and demonstration projects have been completed, further contributing to the advancement and commercialization of CCS technologies. Most existing CCUS facilities are concentrated in developed countries, particularly in the United States and Northern Europe, supported by robust government policies, EU initiatives, and substantial public and private investments. (Global CCS Institute, 2025).

As illustrated in Figure 5.1, significant disparities exist across all stages of facility maturity between developed and developing economies. Notably, some joint projects involve partnerships between two or more countries, and these are analyzed separately. This disparity is expected to grow, as indicated by the distribution of planned projects by country development stage.

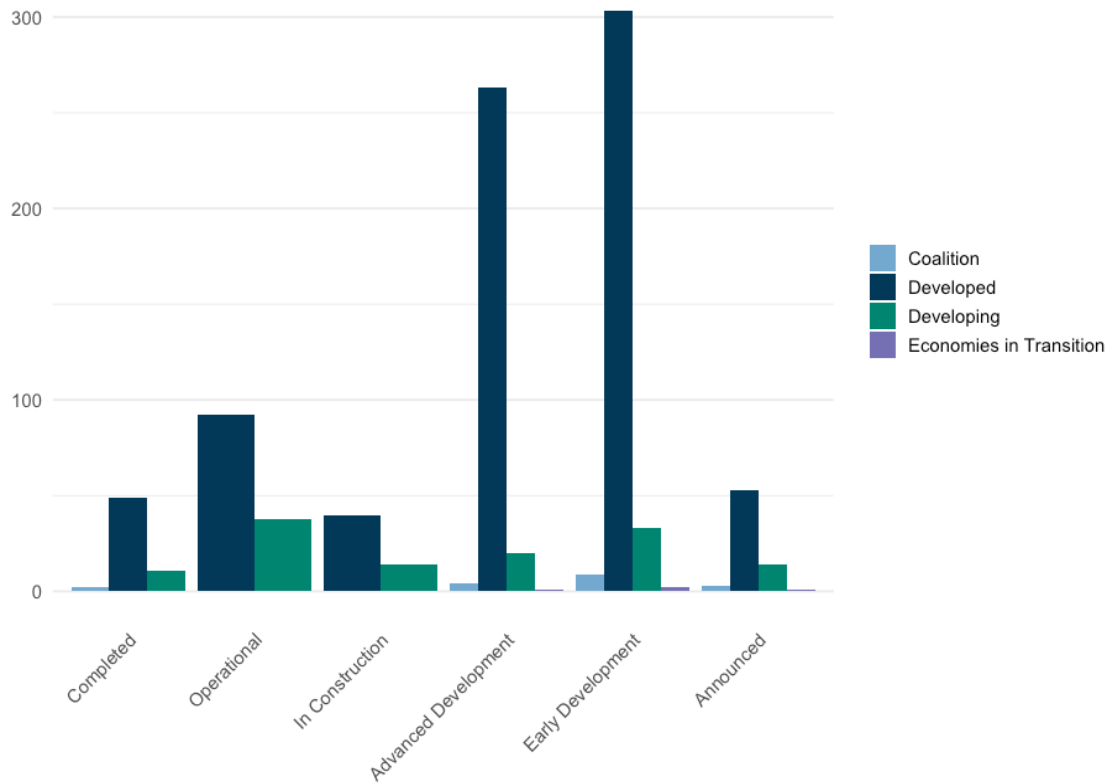


Figure 5.1. Number of projects in the pipeline by project stage and country classification (based on data from CO₂RE Facilities Data (Global CCS Institute, 2025)).

Across all stages of development, the global distribution of carbon capture and storage (CCS) facilities reveals stark inequalities. Based on current projections, of the 957 facilities worldwide, 815 are expected to be located in developed countries and 120 in developing countries, with developing countries accounting for only 12.5% of the total. Additionally, there are 4 projects located in Russia, classified as a transition economy, and 18 joint projects involving collaboration between two or more countries, labeled as “Coalition”.

To provide a clearer understanding of the global distribution of facilities, a bubble map (Figure 5.2) has been developed. In this map, the size of each bubble corresponds to the number of facilities in the respective region, while the color of the bubbles represents the development stages of the countries where the facilities are located. The United States, United Kingdom, Canada, China, and Norway lead in the number of CCS projects, with 370, 92, 82, 46, and 35 projects in their pipeline, respectively. Compared to the data presented in the Global Status of CCS 2024 Report by the Global CCS Institute, the top five countries remain unchanged, although China has overtaken Norway in project count. Regarding developing countries, there are 22 countries with at least one project in their pipelines, with China and Indonesia standing out as outliers, having 46 and 20 projects, respectively. This marks a promising increase compared to only 9 countries with projects in 2024, indicating growing engagement in developing countries in CCUS space.

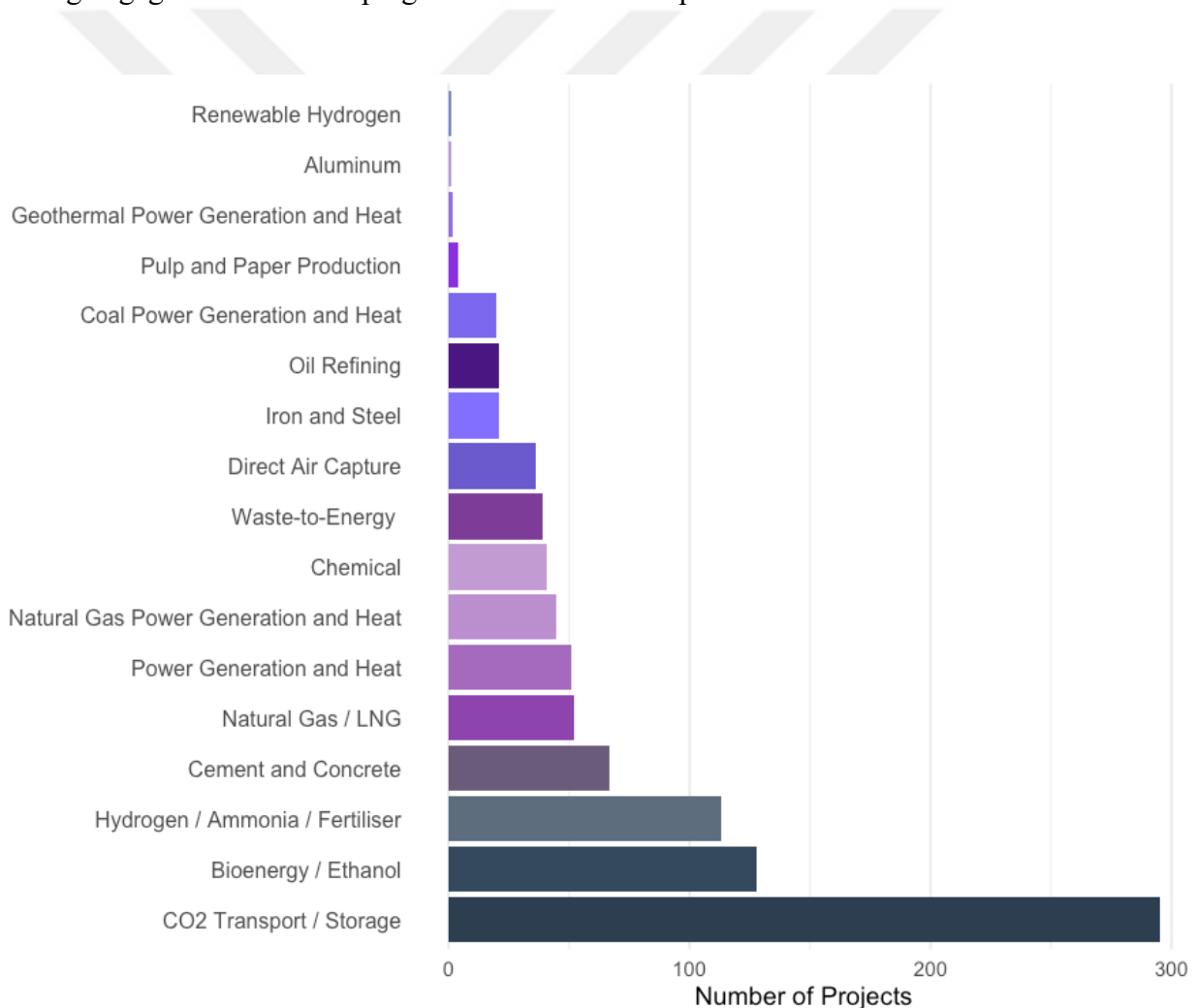


Figure 5.3. Facilities distribution by industry (world) (based on data from CO₂RE Facilities Data (Global CCS Institute, 2025)).

Figure 5.3 illustrates the distribution of CCUS facilities by industrial sector, offering insight into which sectors are at the forefront of current deployment trends. CO₂ transport and storage projects comprise the largest share, consistent with their cross-cutting, sector-independent role in the CCS value chain. Their prominence also suggests ongoing investment in essential infrastructure, indicating a strategic effort to build the capacity required for large-scale implementation in the near future. While this study centers on point source carbon capture, Direct Air Capture is nevertheless included in the analysis to enable meaningful comparison across technologies, given its notable presence, with a greater number of projects than some hard-to-abate sectors where CCUS deployment is expected, such as the iron and steel industry.

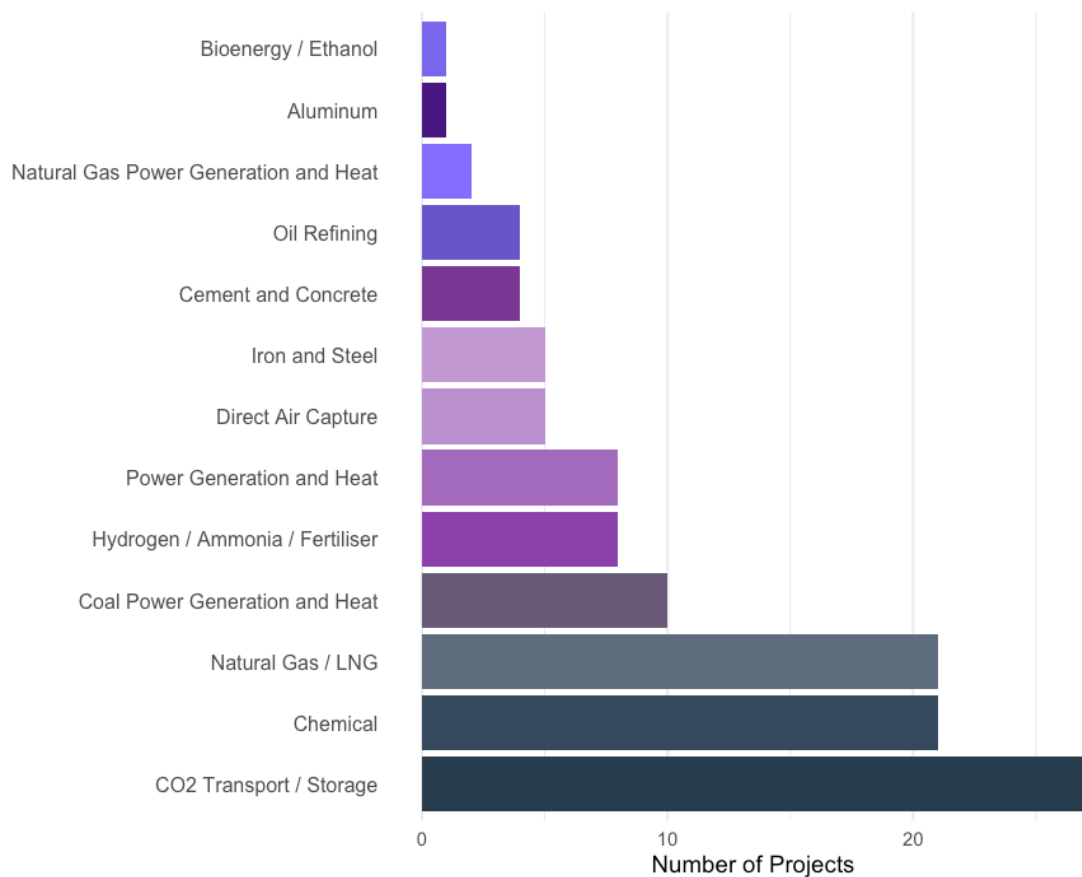


Figure 5.4. Facilities distribution by industry (developing countries) (based on data from CO₂RE Facilities Data (Global CCS Institute, 2025)).

However, when the analysis is limited to projects in developing countries, three dominant sectors emerge: Chemicals, Natural Gas/LNG, and Coal Power Generation and Heat, as illustrated in Figure 5.4. This reflects the fact that developing economies tend to rely more heavily on fossil fuels for energy and power generation, and typically have younger, emission-intensive infrastructure compared to developed countries. Many of these nations are also major producers of heavy industrial

goods, with carbon leakage happening over decades, and contributing significantly to emissions in these regions. As carbon capture technologies in real hard-to-abate sectors continue to mature, greater emphasis should be placed on deploying them in hard-to-abate sectors.

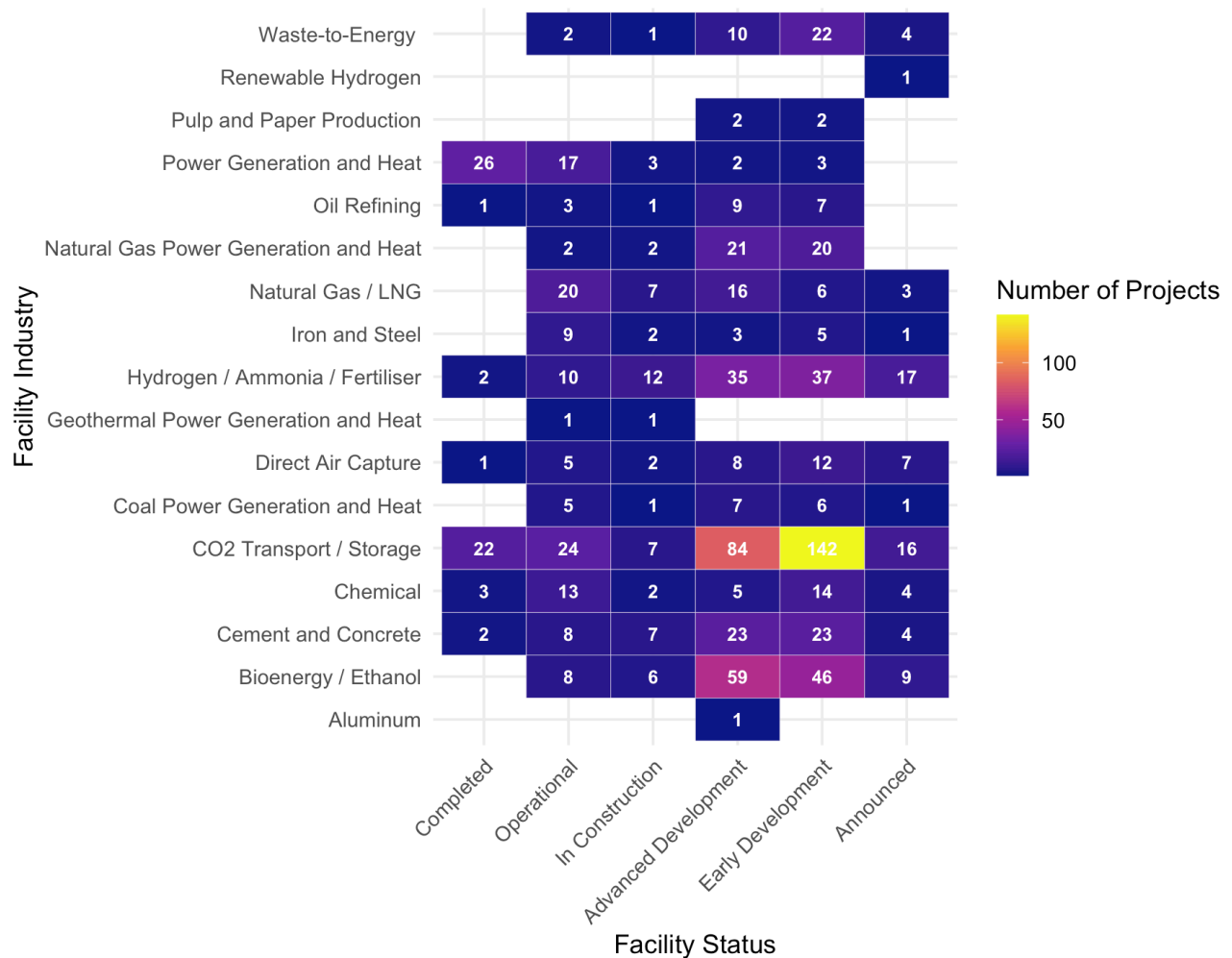


Figure 5.5. Sector dominance by project stage (based on data from CO₂RE Facilities Data (Global CCS Institute, 2025)).

To explore how sectoral engagement shifts across stages of project maturity, a heatmap is developed to visualize the distribution of CCS projects by industry and facility status, as illustrated in Figure 5.5. The results indicate significant planned expansion in the CO₂ transport and storage infrastructure, with most of the projects in their early and advanced development stages. Bioenergy/Ethanol, and Hydrogen/Ammonia/Fertiliser also emerge as sectors of interest, showing a promising trajectory with a concentration of projects in advanced and early development stages, driven largely by the United States, which accounts for approximately 77% of “Bioenergy/Ethanol” projects, and 48% of “Hydrogen/Ammonia/Fertiliser” projects. These sectors are followed by

“Cement and Concrete”, “Natural Gas Power Generation and Heat”, and “Natural Gas/LNG” respectively. Sectors like “Renewable Hydrogen”, “Aluminum”, “Pulp and Paper Production”, and “Geothermal Power Generation and Heat” show minimal project activity. Notably, Power Generation and Heat is the only sector that displays a consistent downward trend across project stages. However, it is important to note that coal and natural gas power plants are classified under separate industry categories in this analysis.

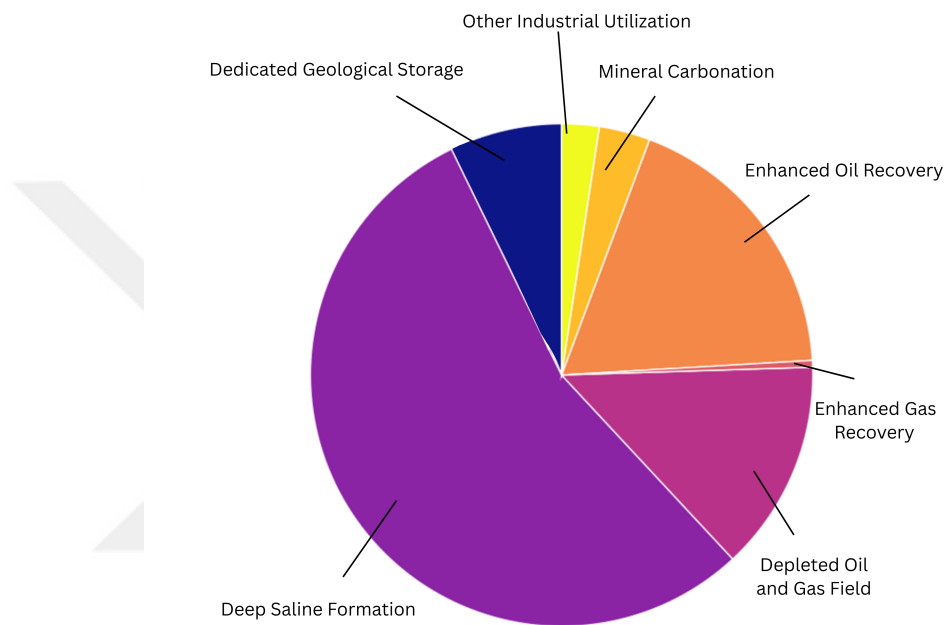


Figure 5.6. Project distribution by storage/utilization pathway (based on data from CO₂RE Facilities Data (Global CCS Institute, 2025)).

The pie chart in Figure 5.6 illustrates the distribution of CCS projects by storage or utilization pathway, showing a clear dominance of deep saline formations. Depleted oil and gas fields and enhanced oil recovery also represent significant shares, while alternative pathways such as mineral carbonation and industrial utilization remain limited due to their lower TRL levels.

5.2. Policies

There is no singular approach to policy tools or international frameworks for the development, deployment, and regulation of Carbon Capture, Utilization, and Storage (CCUS) technologies, as this process consists of various steps and a distinct set of technologies employed at each stage. At the international level, some existing frameworks were amended to include CCS, or new directives were

adopted specifically for CCS. These frameworks also guide the nation-level policies and strategies. Table 5.1 shows the list of international and multilateral frameworks relevant to CCS.

Table 5.1. Key international and multilateral legal instruments relevant to CCS projects (European Commission, n.d-a.; UNFCCC, 2015; UNFCCC, 2012)

Framework	Year	Description
London Convention	1972	It is the convention on the prevention of marine pollution by dumping of wastes and other matter, to protect the marine environment from anthropogenic activities. In 2006, Annex I is amended to the convention to allow and regulate CO ₂ injections in the geological formations under the seabed and set criteria.
United Nations Convention on the Law of the Sea	1982	The United Nations Convention on the Law of the Sea (UNCLOS) delineates the boundaries of various maritime zones, including internal waters, territorial waters, archipelagic waters, contiguous zones, exclusive economic zones (EEZs), and the continental shelf.
Basel Convention	1989	The convention regulates the trans-boundary movements of hazardous waste.
The European Union (EU) CCS Directive	2009	The first comprehensive legal framework for the management of environmental risks related to CCS, to ensure the safe deployment of CCS across EU member states.
UNFCCC and Paris Agreement	2015	Although the agreement does not explicitly mention CCUS, it is the most comprehensive agreement on climate mitigation, and it supports and facilitates the use of technologies for climate change mitigation efforts, through Nationally Determined Contributions (NDCs), international cooperation and technology transfer and financing mechanisms, and carbon markets.
Net Zero Industry Act (NZIA)	2024	Aims to establish a union market for CO ₂ storage by increasing the storage site availability and support projects within EU. Sets and EU-wide target of 50 MTPA CO ₂ injection by 2030.

According to the International Energy Agency (IEA), the policy tools to be implemented depend on the approaches categorized as incentive-based or penalty-based (often referred to as "Carrot or Stick"), shared cost allocation, and full control, contingent upon the level of intervention that the government is willing to undertake. The level of intervention is a spectrum, rather than a selection; and is affected by institutional, economic, and political factors. Moreover, where a government want to stand in the spectrum might change as the CCUS market matures, and as these institutional, economic, and political factors change over time (e.g. election cycles, recession) (IEA, 2023). Figure 5.7 illustrates the positioning of various pioneer countries in the CCUS space along the spectrum.

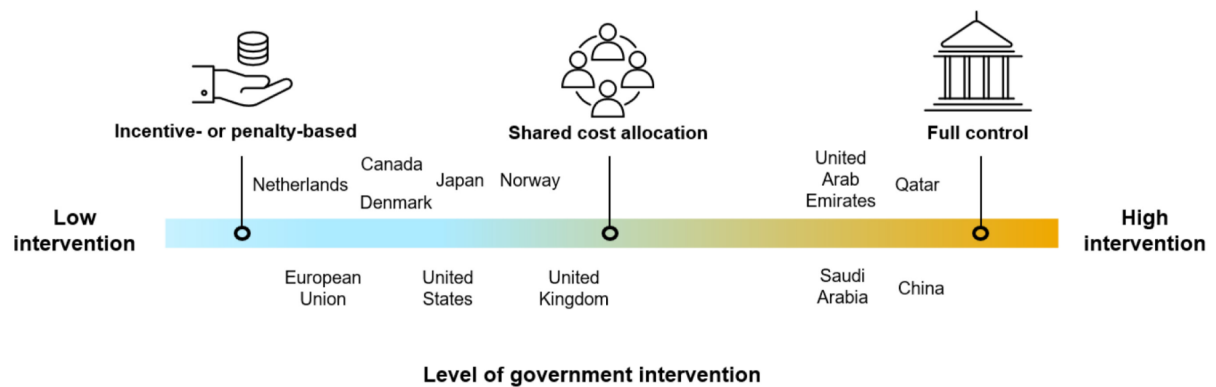


Figure 5.7. Spectrum of existing approaches to building a commercial market for CCUS (IEA, 2023).

In the spectrum, incentive or penalty-based approaches lie in the low intervention part, giving more flexibility to the private sector. Still, their investment decisions are influenced by incentives (e.g. grants, tax credits) for specific technologies that the government prioritized, or through penalties (e.g., taxes, fees) for noncompliance. However, these incentive mechanisms should be designed carefully to ensure they meet the objectives of the policies. In the high intervention part of the spectrum lies the full control approach, in which the government takes more responsibility and ownership through state-owned enterprises to finance and operate projects (IEA, 2023).

While the shared cost allocation method lies in between, the efforts are shared between private and public companies. This approach is mostly adopted when there is a high capital need with uncertain revenue streams. So, the risk and cost are allocated between public and private sector. As it is the case for grid infrastructure, it is seen as a good fit for the CO₂ Transport and Storage infrastructure (IEA, 2023).

Table 5.2 provides a list of policy tools designed to address various challenges faced in the research, development, and deployment of CCUS technologies. The policy tools a country may employ depend on where it seeks to position itself along the spectrum of intervention. Specifically for the storage assessments in emerging market and developing economies (EMDEs), the IEA has developed a checklist, as presented in Table 5.3.

Table 5.2. Policy tools for CCUS (IEA, 2023).

Challenge	Policy Categories to Address Challenge	Specific Policy Tools
Economic Viability	Cost reduction measures Regulation of industrial activities Revenue support International collaboration	Grants Tax Credits Loan Support State-Owned Enterprises Carbon Pricing and Leakage Policy Public Procurement Low-emissions Mandates (Carbon) Contracts-for-Difference Regulated Asset Base Emerging Market and Developing Economy Considerations Concessional Finance, Sustainable Debt Multilateral Funding Instruments
Lead Times	Enabling legislation and rules	One-stop shop for permitting Clear permit approval timelines Internal regulatory capacity Precompetitive resource assessments Data sharing and transparency requirements Community engagement requirements
The Innovation Gap	Cost reduction measures International collaboration	RD&D Platforms for international co-operation Foreign direct investment for technology co-development
Project Complexity	Enabling legislation and rules Strategic signalling International collaboration	Long-term storage liability, Competitive solicitations for CCUS hubs, One-off backstop agreements for first movers, London Protocol specifications, Definition of high-quality removals, Robust measurement, Reporting and verification mechanisms

Table 5.3. IEA's checklist for emerging market and developing economies (EMDEs) for CO₂ storage resource assessment (IEA, 2022b).

Step	Description
1. National CCUS Focal Point	- Assess whether CO₂ storage resources fall under the mandate of any agency or agencies. - Identify and nominate an organisation or agency to serve as a national CCUS focal point. - Consider engaging the national geological survey or equivalent.
2. International Support	Consider engaging international expertise and support to assist with the process, such as the IEA, IEAGHG and World Bank.
3. CO₂ Storage Assessment Project Team	- Determine which agency should co-ordinate/be involved in the resource assessment process. - Define a project team to reanalyse existing geological data with the goal of identifying CO₂ storage resources. - Decide which internationally recognised storage assessment methodology should be used.
4. Leverage National Human Capacity	Initiate discussion on CO₂ storage with stakeholders who may be able to assist in the assessment process, such as oil and gas companies, local universities and research centres with subsurface expertise, and other government agencies.
5. Data	- Identify owners and custodians of geological data, which may be government agencies, private-sector companies, research organisations, etc. - Gather as much existing relevant geological data as possible and make it publicly available whenever possible.
6. CO₂ Storage Assessment	- Assess the collated data. As a part of assessment, clearly define the methodology and assumptions that were used. - Make assessment results publicly available whenever possible.
7. Next Steps	- Determine if there are specific resources that should be targeted at further assessment. - Outline priorities for future CO₂ storage-related work and consider defining a CCUS deployment work programme.

5.3. Financing

In the context of emerging climate technologies, investors encounter a variety of risks; therefore, particularly during the initial phases of research and development, it is imperative to implement risk-tolerant financing mechanisms. Table 5.4 summarizes different types of risks.

Table 5.4. Types of risk for climate technology investments (Yale Center for Business and the Environment, n.d.)

Risk	Definition
Funding Risk	The risk associated with a potential shortfall in capital runway in relation to reaching the next milestone of technology development, or the stage at which market traction is achieved, is a matter of concern.
Impact Risk	The challenges associated with defining and measuring impact, both qualitatively and quantitatively, as well as the unforeseen repercussions related to technology, necessitate careful consideration.
Technology Risk	The potential for technological development to fall short in achieving adequate performance or efficiency outcomes, alongside a lack of commercially proven solutions, is a significant concern.
Market Risk	The absence of a clearly defined market essential for the sale of products or services, coupled with the risks entailed in the simultaneous development of the market alongside the technology, presents significant challenges.
Regulatory Risk	The risks associated with a business model, market, or deployment reliance (whether positive or negative) on the regulatory framework or policy.
Scaling Risk	The uncertainty and complexity associated with the scaling of technology, along with the demands for and interdependencies with emerging forms of capabilities and resources.

The extent to which various categories of risks predominate differs at distinct phases of the research, demonstration, and deployment processes. Consequently, the level of risk tolerance varies, as do the required financing mechanisms across different stages of the technology. Figure 5.8 illustrates the categories of capital sources utilized throughout various stages in a broader context of climate solutions.

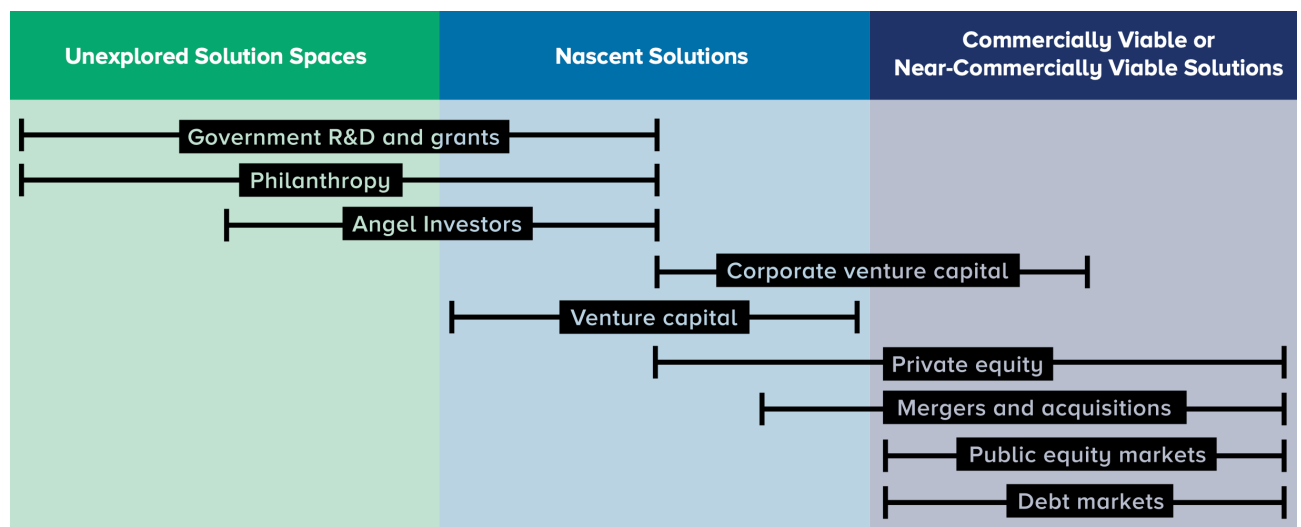


Figure 5.8. Funding sources across climate technology development stages (Yale Center for Business and the Environment, n.d.).

Research and development require significant amounts of continuous funding for many years to make progress on the Technology Readiness Level (TRL), considering that R&D of hardware technologies requires physical experimental set-ups consisting of materials, equipment, and computational devices, experienced human capital (mostly engineers), and physical space (Malhotra & Schmidt, 2020). The substantial capital requirements and extended research and development timelines increase the risk for investors. Consequently, more risk-tolerant capital sources, such as government research and development grants, philanthropic funds, and high net worth individuals, play a significant role during the research and development phase. Once the technology is deemed commercially viable, venture capital and private equity facilitate its market introduction. Moreover, the technology should be underpinned by market incentive policies to foster sustained private investments. However, technologies often encounter challenges in securing funding and become trapped in the demonstration and pre-commercialization stage, commonly referred to as the “valley of death”. This predicament arises when innovations surpass the capacity of early financing sources but are not adequately advanced for later funding sources. Proof of Concept (PoC) pipelines, corporate venture capital (CVC), and public-private partnerships (PPP) could represent promising pathways to address this issue.

Corporate Venture Capital (CVC) can be regarded as a promising avenue for both supplying the necessary financial resources and creating a proof of concept (PoC) pipeline for demonstrating the technology within the value chain of the investor company. However, industries where Carbon Capture, Utilization, and Storage (CCUS) is expected to be predominantly applied, such as cement and iron and steel, operate in significantly more traditional manners; thus, the establishment of CVCs in these sectors remains limited.

Furthermore, innovation ecosystems in developed nations exhibit a greater level of advancement compared to those in developing nations. This advancement is attributable to the collaborative efforts of both the private and public sectors, including state incubators, national laboratories, angel investors, venture capitalists, and private equity firms. Besides, the absence of regulations that establish pricing or limitations on CO₂ emissions, along with the insufficient policies aimed at providing government grants or incentivizing the private sector in developing countries, is notable (Global CCS Institute, 2024). Consequently, this situation imposes a burden on developing nations, highlighting the necessity for international climate policy and financing intervention.

Table 5.5 summarizes international mechanisms for climate financing in developing countries. The Green Climate Fund (GCF) and Multilateral Development Banks (MDBs) are noted for their potential to fund Carbon Capture, Utilization, and Storage (CCUS) infrastructure development, as well as feasibility projects. However, considering that some of the Carbon Capture and Storage (CCS) funds provided by Multilateral Development Banks (MDBs), such as the World Bank and the Asian Development Bank, have come to an end, there exists a current gap in financial assistance for developing countries. Furthermore, if implemented effectively, carbon credits have the capacity to generate revenue streams for Carbon Capture and Storage (CCS) business models.

Table 5.5. International mechanisms for climate financing in developing countries (Global CCS Institute, 2024).

Mechanism	Description
Green Climate Fund (GCF)	GCF is the world's largest body for the climate finance in developing countries. The GCF funded its first CCS project in Trinidad and Tobago.
Multilateral Developments Banks (MDBs)	MDBs are established to ease the financial burdens in developing countries, consisting of members from both developed and developing countries. The biggest MDB is World Bank, and the other 4 major MDBs can be listed as the African Development Bank (AfDB), the Asian Development Bank (ADB), the European Bank for Reconstruction and Development (EBRD) and the Inter-American Development Bank.
Carbon Credits	The Article 6 under Paris Agreement provides a mechanism for UN Carbon Crediting to allow nations meet their NDCs. If implemented effectively, high-quality carbon credits have the potential to create revenue streams for the CCS business models.

5.4. Best practices in developing countries

At present, the developing countries with the highest number of projects in the pipeline are China, Indonesia, and India, with respective project counts of 46, 20, and 8. In Asia Pacific and India, CCUS is of strategic importance, considering the region's reliance on relatively younger coal-fired power plants, and cement, iron and steel, chemical industry, and the growing infrastructure dependent on fossil fuels. Also, due to limited storage sites in neighboring countries such as Japan, Singapore, and South Korea, countries like Indonesia and Malaysia are developing their cross-border CCS value chains to prepare to import CO₂ for storage in their territories. A substantial portion of the developments in Asia can be attributed to the support of the Asian Development Bank and the commitment of governments to undertake measures aimed at constructing Carbon Capture, Utilization, and Storage (CCUS) value chains through the implementation of requisite policies and regulatory frameworks (Global CCS Institute, 2024).

Table 5.6. Best practices in developing countries (created by the author based on (IEA, 2022c)).

Practice	Type	Supporter	Year/Period	Activity
Asian Development Bank CCS Fund	Financing	Multi-partner Trust Fund	2009-2022	Supported Storage Resource Assessments, CCUS Piloting and Demonstration in Southeast Asia and China
The World Bank CCS Trust Fund	Financing	United Kingdom and Norway	2009-2023	Allocated USD 55M+ in Botswana, Egypt, Jordan, Mexico, Nigeria, and South Africa
Indonesia Center for Excellence for CCS and CCUS	R&D	Indonesia University Center of Excellences Program and the Ministry of Research, Technology, and Higher Education	2017	- Deliver a co-ordinated programme of CCUS research. - Pilot CCUS in Indonesia and identify opportunities for CCUS deployment. - Formulate policies, strategies and regulations that support implementation. - Develop effective communication on CCUS. - Provide educational and informational materials on CCUS.
Atlas on Geologic Storage of Carbon Dioxide in South Africa	R&D	Prepared by the Council of Geosciences and the Petroleum Agency of South Africa	2010	The agencies used existing data from seismic surveys and historic drill cores to estimate the on and offshore storage potential of each resource type

Table 5.6. shows the current best practices in developing countries, highlight the importance of MDBs, as well as the country-led initiatives. As also discussed under the financing section, Asian Development Bank CCS Fund and the World Bank CCS Trust Fund have significantly supported the CCS efforts in the developing countries. The World Bank CCS Trust Fund has allocated more than USD 55M in developing countries like South Africa, Egypt, Nigeria, Mexico, Jordan, and Botswana. Also, the ADB CCS Fund has facilitated the storage assessments and CCUS Piloting and Demonstration efforts in Southeast Asia and China. In Southeast Asia, Indonesia stands out among the developing countries in the world, since the country has developed comprehensive CCS legal and regulatory frameworks, and signed cross-border memorandums of understanding (MoUs), to be able to receive CO₂ from nearby countries like Singapore, as well as manage domestic emissions. Along with the regulatory frameworks, the country also established incentive mechanisms such as tax incentives, allowances for storage operators, and the basis of carbon pricing for CCS activity. Indonesia was also one of the co-sponsor governments of the Carbon Management Challenge (CMC), along with the UK, the U.S, Canada, and Brazil (Global CCS Institute, 2025a).

6. THE CASE OF TÜRKİYE

The Republic of Türkiye, commonly referred to as Türkiye, is a developing country situated in Anatolia, positioned between the Middle East and Southeastern Europe. The Republic of Türkiye holds several significant international memberships and statuses, as listed in Table 6.1, which indicate its geopolitical, economic, and strategic position. The country ratified the Paris Agreement in 2021.

Table 6.1. International memberships of Türkiye.

Organization	Status	Year
United Nations (UN)	Founding Member	Since 1945
Organisation for Economic Co-operation and Development (OECD)	Founding Member	Since 1960
European Union (EU)	Candidate	Since 1999
World Trade Organization (WTO)	Founding Member	Since 1995
G20	Member	Since 1999
World Bank Group	Member	Since 1947
International Monetary Fund (IMF)	Member	Since 1947
European Bank for Reconstruction and Development (EBRD)	Member	The EBRD has been investing in Türkiye since 2009.
Black Sea Economic Cooperation (BSEC)	Founding Member	Since 1992

Note. Table is created citing (*BSEC - Black Sea Economic Cooperation*, n.d.; *G-20 / Republic of Türkiye Ministry of Foreign Affairs*, n.d.; *Member Countries*, n.d.; *Republic of Türkiye and the IMF*, n.d.; *Türkiye*, n.d.; *European Commission*, n.d -b; *WTO | Türkiye - Member Information*, n.d.; *United Nations*, n.d.)

6.1. Challenge of Decarbonisation for Türkiye

Türkiye was the last G20 country ratifying the agreement in 2021, despite having signed it in 2016. The rationale for this positioning derives from Türkiye's classification among developed nations in the context of categorizing the parties to the agreement. On April 28, 2021, Türkiye submitted a proposal to amend Annex I of the convention, thereby indicating that the country bears minimal responsibility, is classified as a developing country by international organizations, such as the World Bank, the International Monetary Fund (IMF), the United Nations (UN), and Organization

for Economic Co-operation and Development (OECD) and is consequently eligible to receive Official Development Assistance (ODA) (UNFCCC, 2021). Subsequently, the convention resolved to amend the list in Annex I. Ultimately, while it submits Nationally Determined Contributions (NDCs), the country is also eligible to benefit from climate finance and is not obliged to provide assistance in the areas of climate finance or technology transfer (Batmaz & Sisman-Aydin, 2025).

In 2015, Türkiye established a target to reduce emissions by 2030. This target was subsequently revised in 2023 to a more ambitious 41%, effectively doubling the original target. Additionally, the country aims to reach net-zero emissions by 2053. However, this updated target has been deemed critically insufficient and misaligned with the 1.5°C climate scenario (Climate Action Tracker, n.d.).

On top of the responsibilities coming from the Paris Agreement, it's worthwhile to say that the main driver for the efforts on decarbonization in Türkiye is the EU CBAM mechanism, which plans to impose tariffs on imported goods at the border. According to Türkiye Cumhuriyeti Ticaret Bakanlığı (2022), the EU ranks first in terms of total exports and holds a 40.6% part of the country's total export volume, with 103.1 billion dollars. 13% of Türkiye's total exports to the EU are covered by the EU CBAM (Türkiye Cumhuriyeti Ticaret Bakanlığı, 2022) In addition, the UK government announced that the UK CBAM will go into force in January 2027 (T.C. Ticaret Bakanlığı, 2024; UK Department for Energy Security & Net Zero, 2023). Iron and steel is among Türkiye's top exports to the UK, if applied to the same industries covered by the EU CBAM (Türkiye Çimento Sanayicileri Birliği, 2023).

6.2. Greenhouse Gas Inventory

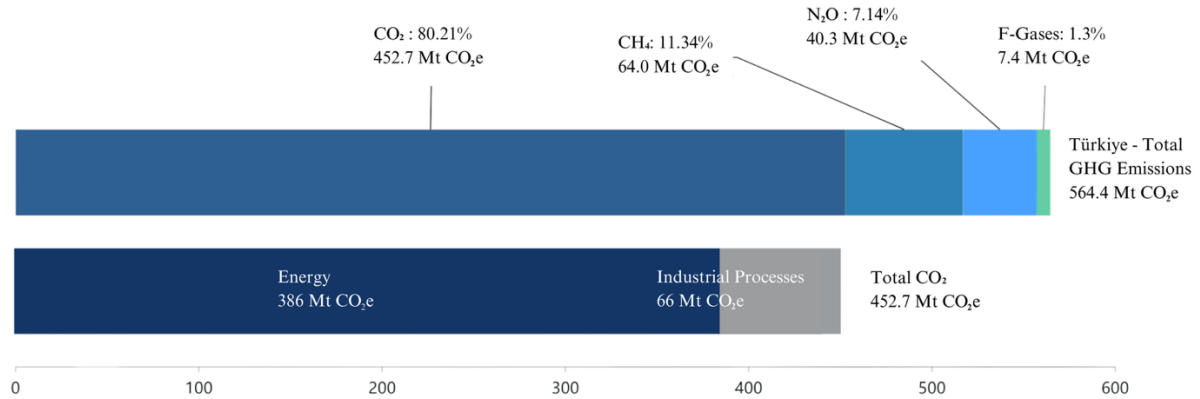


Figure 6.1. Greenhouse gas emissions of Türkiye by source (Turkish Statistical Institute (TÜİK), 2024, as cited in Kaynak, Çevre ve İklim Derneği (REC), 2024).

As visualized in Figure 6.1, in 2021, Türkiye's total greenhouse gases accounted for 564.4 MTCO₂e, representing an increase of 40.4 Mt, or 7.7%, in comparison to the emissions level recorded in 2020 and a rise of 157.1% relative to the 1990 levels. The contribution of CO₂ accounted for 80.21% among all GHG emissions, and the highest portion of the emissions resulted from the energy sector with 85.2% (386 MtCO₂e), while 14.5% (66 MtCO₂e) originated from IPPU (Industrial Processes and Product Use). However, the combustion of fossil fuels for the purpose of industrial processes is accounted for within energy metrics. In other words, the Industrial Processes and Product Use (IPPU) category exclusively encompasses emissions originating from these industrial processes, excluding the emissions arising from the combustion of fossil fuels utilized to generate energy for the processes (Turkish Statistical Institute (TÜİK), 2024).

In 2023, Türkiye ranked 14th in the world in terms of territorial CO₂ emissions (CO₂ emissions that are attributed to the territories where they are physically located.), and 8th among all developing countries, as presented in Figure 6.2. When this ranking is broken down by sector, the country ranked 6th among all countries in the world in emissions from the cement sector (Global Carbon Atlas, 2023).

Territorial (MtCO₂)

Rank	Country	MtCO ₂
1	China	11903
2	United States of America	4911
3	India	3062
4	Russian Federation	1816
5	Japan	989
6	Iran	818
7	Saudi Arabia	736
8	Indonesia	733
9	Germany	596
10	South Korea	577
11	Canada	549
12	Brazil	487
13	Mexico	483
14	Turkey	432
15	South Africa	402
16	Australia	383
17	Vietnam	335

Figure 6.2. Ranking of territorial emissions of countries (Global Carbon Atlas, 2023).

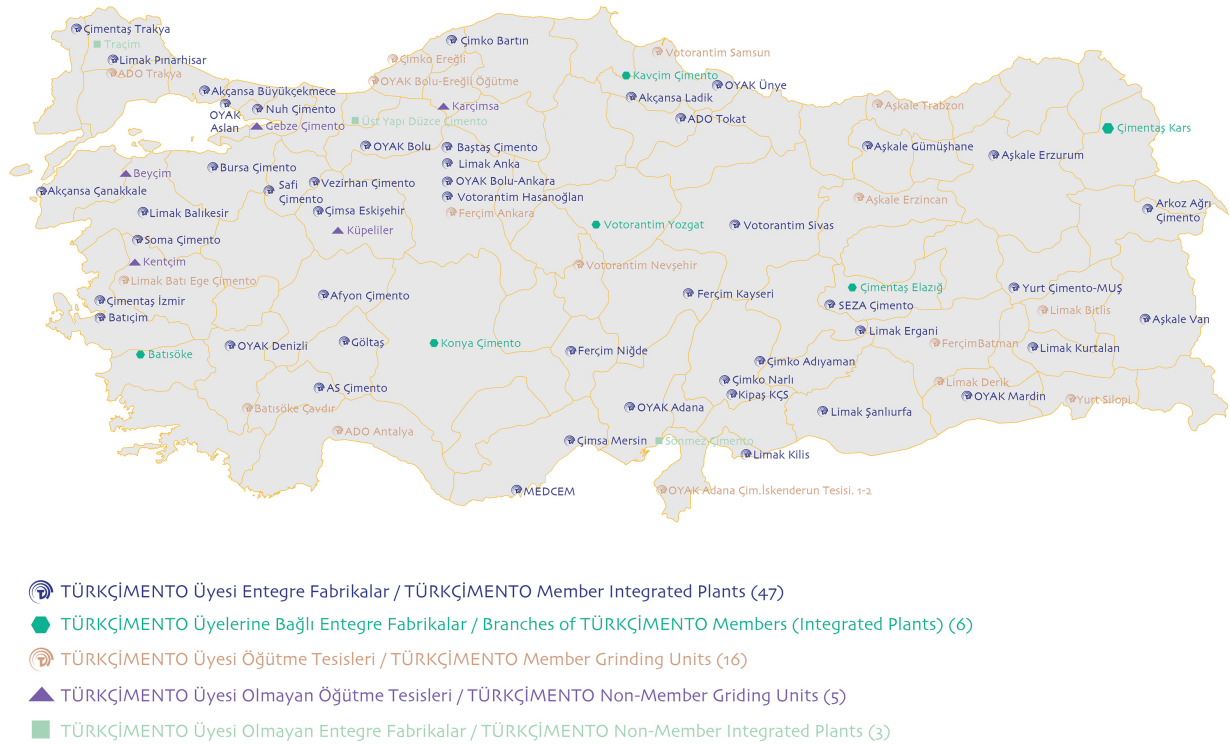
6.3. Industrial Emissions and the State of Carbon Capture Potential

Cement, lime, iron, steel, and other industrial applications utilizing carbonates, have been identified as primary sources of carbon dioxide emissions in the Turkish Greenhouse Gas Inventory (1990 – 2021). Specifically, the production of cement, and iron and steel constituted 7.8% and 2.1% of the total national greenhouse gas emissions (LULUCF), respectively. There is currently no active commercial capture in Türkiye. This section will discuss process emissions in four main hard-to-abate sectors and the potential for carbon capture in these sectors (Turkish Statistical Institute (TÜİK), 2024).

6.3.1. Cement

Türkiye ranked 5th among the leading cement-producing countries in the world, and 1st in Europe in 2025 with a production volume of 79 Mt (*Cement Production by Country 2025*, 2025). Thereafter, the mineral industry accounted for 67.4% of the emissions from the IPPU sector, with 87.4% of CO₂ emissions within the mineral industry attributed to cement production, and an

additional 5.4% originating from lime production, which is primarily utilized in the cement sector, in 2021. Additionally, fuel combustion emissions from the non-metallic minerals sector constitute a share of 49.4% within all manufacturing industries; however, the specific share of cement emissions remains undisclosed (Turkish Statistical Institute (TÜİK), 2024). Cement production is geographically spread across the country, making centralized solutions like shared infrastructure or pipeline networks difficult, as mapped in Figure 6.2.



Bu harita TÜRKCİMENTO tarafından hazırlanmıştır.
This map designed by Turkish Cement Manufacturers' Association (TÜRKCİMENTO)
Güncellenme Tarihi/ Updated on 29.05.2025

Figure 6.3. Map of cement plants in Türkiye (Turkish Cement Manufacturer's Association, 2025).

As previously discussed, heating the kiln requires elevated temperatures, thereby making the procedure considerably energy intensive. Subsequently, the majority of carbon dioxide emissions are generated from the kilns during clinker production. In Türkiye, coal, petroleum coke, and lignite are the predominant energy sources for the kilns. Also, some cement plants hold a waste incineration license granted by the Ministry of Environment, Urbanization, and Climate Change. These plants utilize waste as alternative fuels and as raw materials. The types of waste co-incinerated under the license include waste plastics, used tires, waste oils, industrial sludge, tank bottom sludge, and sewage sludge, among others (Turkish Statistical Institute (TÜİK), 2024). The emissions resulting from the cement and clinker production is shown in Figure 6.3.

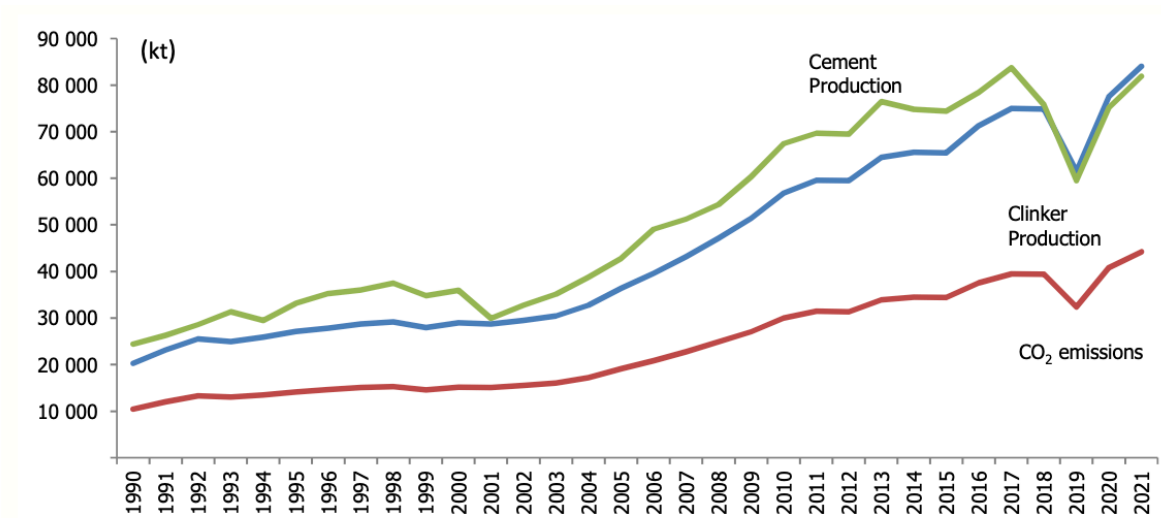


Figure 6.4. Cement and clinker production emissions of Türkiye (Turkish Statistical Institute (TÜİK), 2024).

Türkiye started cement production in 1911 and became a cement exporter in 1978. All cement companies in the country are privately owned. The production is distributed all over the country due to the high transportation costs of cement. While most of the cement and clinker produced is utilized domestically for construction, approximately 19.3% of the total cement production is exported. The United States alone accounts for 46.7% of the total cement exports, while nearly 8.3% is exported to the European Union. Regarding clinker production, exports constituted 5.4%, with the European Union and the United States holding respective shares of 48.6% and 6.6% of the total exports (Global Cement, 2013; Turkish Cement Manufacturer's Association, 2024).

6.3.2. Iron and Steel

Türkiye ranked 9th among the major steel-producing countries in the world as of 2024, with a production volume of 36.9 million tonnes, and accounts for the 6.7% of the total exports in the country (Turkish Steel, 2023; World Steel, 2025). In 2021, the metal industry constituted 17.2% of the total emissions from the IPPU sector, with the predominant share of emissions, amounting to 92.3%, arising from iron and steel production. Additionally, an extra 5.8 MtCO₂e is derived from fuel combustion for energy purposes, which constitutes 8.8% of the emissions resulting from fuel combustion in the manufacturing sector. The production volume of iron and steel increased 71.5% between 1990 and 2021, which was primarily responsible for a 69.4% rise in emissions from the metal industry during the same period (Turkish Statistical Institute (TÜİK), 2024).

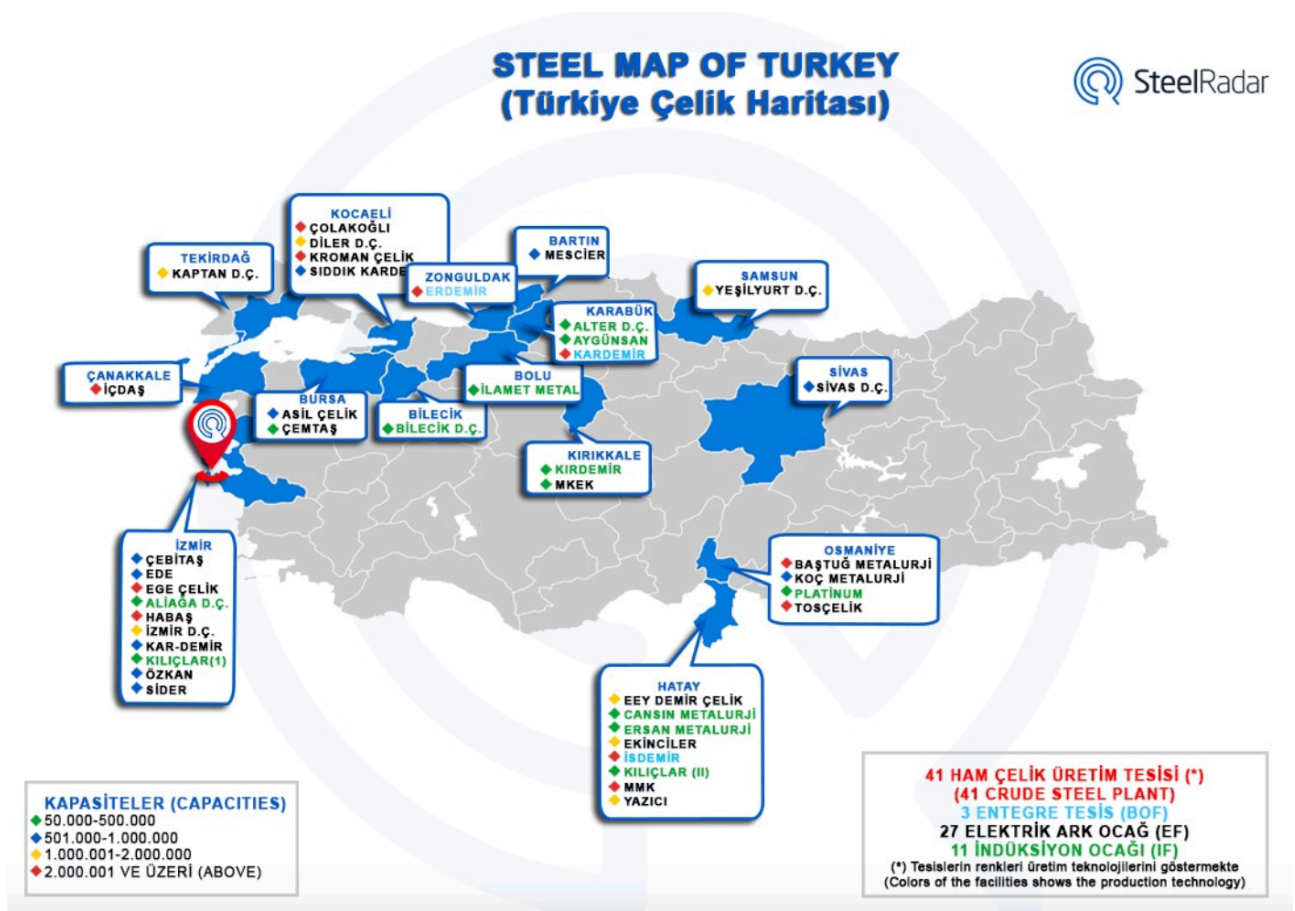


Figure 6.5. Map of iron and steel plants in Türkiye (Steel Radar, 2023).

In Türkiye, currently, there are three integrated iron and steel production plants, producing primary steel. Also, by technology, 27 electric arc furnace mill plants (EAF) producing secondary steel, 11 induction furnace plants, and 3 basic oxygen furnaces (BOF), as shown in Figure 6.4. However, there is no direct reduced iron (DRI) production in Türkiye. Additionally, there exists one plant producing pellet iron to meet the iron demands of the integrated steel plants. All integrated steel plants in Türkiye recycle the exhaust gases from the BF's and BOFs for combustion, with the purpose of heating the coke ovens, generating high-pressure steam, and preheating the air for the blast furnace (Turkish Statistical Institute (TÜİK), 2024). The production volumes and the resulting emissions of BOF and EAF steel production between 1990 and 2021 are shown in Figure 6.5.

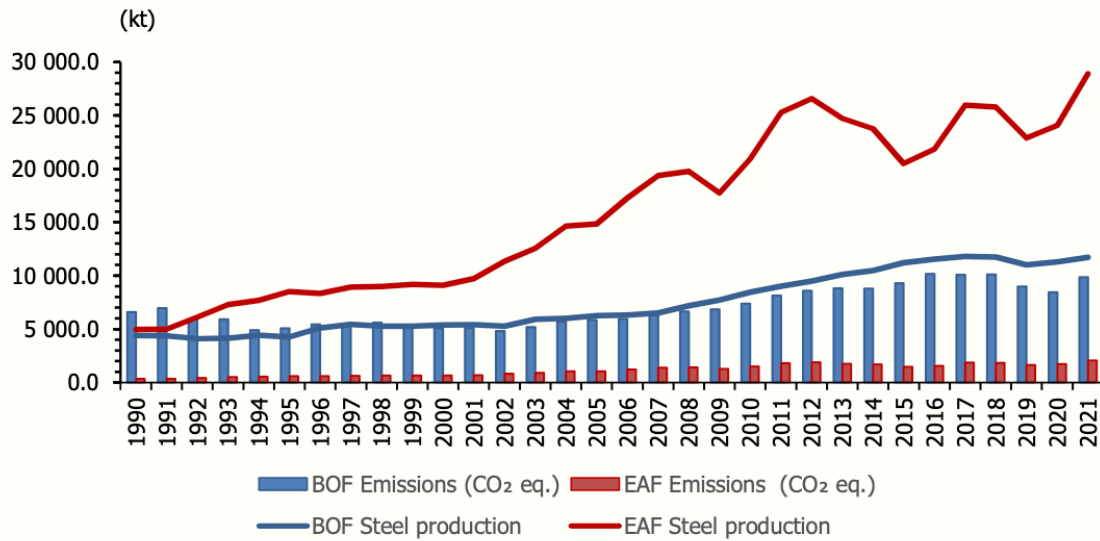


Figure 6.6. Iron and steel emissions in Türkiye (Turkish Statistical Institute (TÜİK), 2024).

All steel companies in the country are privately owned, and it's the fifth-largest contributor to the economy. In 2023, Türkiye exported 4.5 million tons to the European Union, making 31% of the total steel exports, followed by Middle Eastern countries with 22.8%. Moreover, taking into account the export shares of the automobile and electronics industries, which stand at 15.8% and 7.3% respectively, the embedded emissions should also be kept in mind (Turkish Steel, 2023).

6.3.3. Chemicals

In 2021, chemicals accounted for 5.5% of the emissions from IPPU, contributing 0.7% to the total greenhouse gas (GHG) emissions. Between 1990 and 2021, total emissions attributed to the chemical industry increased by 154%. A significant portion of the carbon dioxide (CO₂) emissions originated from nitric acid production (48.9%), followed by ammonia production (36.0%), soda ash production (14.87%), carbide production (0.21%), and the production of petrochemicals and carbon black (0.03%), in that order (Turkish Statistical Institute (TÜİK), 2024).

In Türkiye, natural gas functions as the primary feedstock for ammonia production in Turkish production facilities. Carbon dioxide (CO₂) is generated during the reforming of natural gas to extract hydrogen, which subsequently reacts with nitrogen to synthesize ammonia. The country is home to three ammonia plants. Among these, IGSAS stands out as it produces urea by utilizing CO₂ gas as a feedstock, achieved by separating CO₂ from the syngas during the ammonia production process (Turkish Statistical Institute (TÜİK), 2024).

6.3.4. Power and Heat Generation

According to TEİAŞ (Türkiye Elektrik İletim A.Ş.), the total installed capacity is 118.185,3 MW as of March 2025 (TEİAŞ, 2025). Total annual electric energy generation is 88,4 TWh, with 87,3 TWh consumed domestically, 1,3 TWh exported, and 0,1 TWh imported. In 2023 data, as illustrated in Figure 6.6, the grid mainly was from coal (36%), followed by natural gas (21%), hydro (19.6%), wind (10.4%), geothermal, biofuels, waste, and other sources (IEA, 2023b). As of 2022, the grid emission factor of Türkiye was 0.442 tCO₂e/MWh (T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2024). This value can be considered moderate compared to other developing countries; yet still necessitates efforts to transition away from fossil fuels, particularly given that Türkiye has the potential to meet the 95% of its total energy demand by 2050 using only renewable sources (excluding nuclear). Moreover, Türkiye lacks natural gas, oil, and gas reserves, yet it is abundant in renewable energy resources, which makes it energy-dependent on external fossil energy sources (Cekinir et al., 2022).

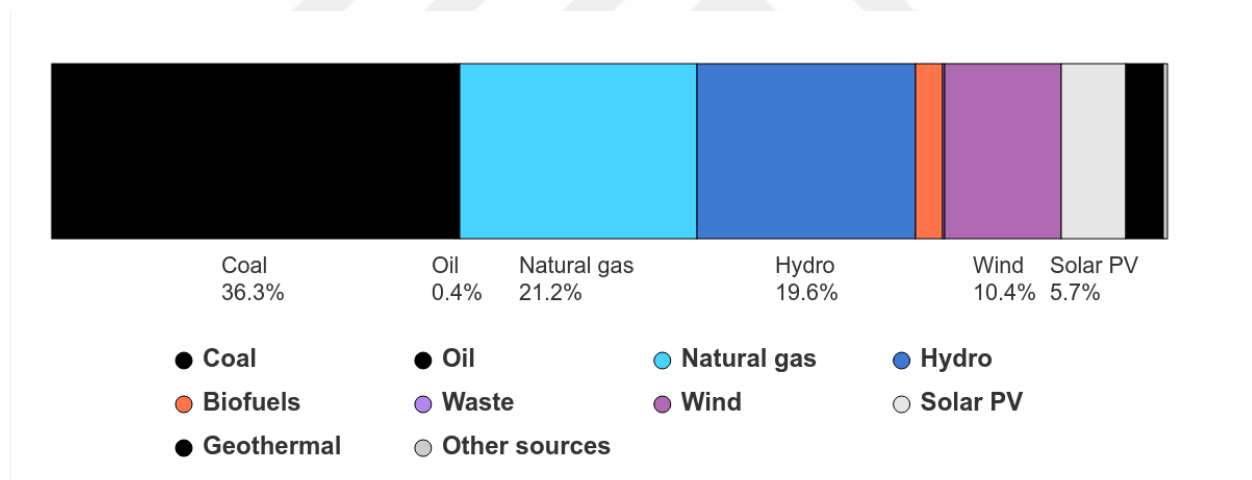


Figure 6.7. Electricity generation in Türkiye (IEA, 2023b).

In the context of the nation's 2053 grid decarbonization strategy, the proportion of renewable energy sources, particularly solar and wind, is anticipated to rise (T.C. Çevre, Şehircilik, ve İklim Değişikliği Bakanlığı İklim Değişikliği Başkanlığı, 2021). This development occurs concurrently with the ongoing construction of two nuclear power plants, a matter that has generated controversy regarding community engagement, especially considering the protests that have been held against the construction of the Akkuyu Nuclear Plant. Nevertheless, the construction is still in progress, despite the associated risks, and concerns of the local community (Uysal, 2024).

6.4. Storage Potential in Türkiye

Since 1986, Türkiye has developed expertise in Enhanced Oil Recovery (EOR); however, there has been no significant progress regarding geological storage. The initial study concerning the identification of potential CO₂ storage sites was conducted by the Middle East Technical University (METU) Petroleum Research Center, supported by TÜBİTAK. The study reveals that there exists a total of over 120 small oil and gas fields, with nearly all of these fields in Türkiye located in the Southeastern Anatolia region, as shown in Figure 6.7. Furthermore, owing to their limited capacity, the known oil and gas reservoirs can accommodate only the CO₂ emissions generated by small industrial sites (Enerji Verimliliği ve Çevre Dairesi Başkanlığı, 2019).

According to another study led by the Ministry of Environment, Urbanisation and Climate Change and METU Petroleum Research Center, a total of 108.7 MtCO₂ storage capacity was found in depleted reservoirs in Adıyaman, Batman, and Trakya. Given the lack of incentive mechanisms related to storage, the prioritization of Enhanced Oil Recovery (EOR) is anticipated. However, EOR does not qualify as a genuine mitigation strategy (Kaynak, Çevre ve İklim Derneği (REC), 2024).

Models also predict significant potential in deep saline formations across the Black Sea and parts of the Mediterranean, as well as basaltic and ultramafic formations throughout the region. However, further detailed studies by the government authorities are needed to assess the characteristics and suitability of these storage sites (Kelemen et al., 2019; Wei et al., 2021).



Figure 6.8. Oil and gas fields in Türkiye (Kaynak, Çevre ve İklim Derneği (REC), 2024).

The Turkish Petroleum Law provisions on managing and utilizing oil reservoirs for underground storage. These provisions require that an oil field must be fully depleted and approved by the competent authorities before it can be used for storage. A field can be subjected to both oil production and storage, as well as other energy-related activities. However, the legislation permits the use of carbon dioxide produced in oil fields exclusively for Enhanced Oil Recovery (EOR); there are currently no regulations governing the use of CO₂ originating from industrial facilities, or other storage types such as mineral carbonation and injection into deep saline formations. Furthermore, regarding the transportation of carbon dioxide (CO₂) to designated storage sites, it should be noted that there is currently no specific provision made by the Directorate of Petroleum Transportation by Pipelines (BOTAŞ) for either CO₂ or flue gas. Also, the industrial zones are mainly located in the north west of Türkiye, while the known storage sites are in the south east, which is expected to increase the transportation cost for the CO₂ to be stored. (Kaynak, Çevre ve İklim Derneği (REC), 2024).

6.5. Policies

As a candidate country, Türkiye follows EU climate policies, especially after the establishment of the EU Carbon Border Adjustment Mechanism (CBAM). The draft of the climate law was submitted to Parliament in February 2025; however, it was subsequently retracted in response to public backlash and criticisms regarding the prioritization of corporate interests over genuine ecological protection. The initial draft of the climate law encompassed both direct and indirect support for Carbon Capture, Utilization, and Storage (CCUS) by fostering technological self-sufficiency and promoting clean technologies. It aimed to confer upon the Directorate of Climate Change the authority to monitor advancements, collaborate with relevant institutions, guide research and development (R&D) efforts, and establish research centers, marking a foundational step toward implementation. In addition to these direct mechanisms, complementary strategies were proposed, including a national Emission Trading System (ETS), the enhancement of climate finance, the promotion of a circular economy, as well as the imposition of administrative sanctions and enforcement measures. The draft is anticipated to undergo review by various committees prior to its resubmission. Meanwhile, government officials have stated that they are advancing with the preparations, which include a national carbon offsets registry for Article 6.2, assuming that the law will eventually pass (Stefanini, 2025). However, a bipartisan climate law consistent with the principles of a just transition is essential.

While the draft climate law mentions Carbon Capture, Utilization, and Storage (CCUS), there is currently no regulation specifically addressing the capture, transportation, and geological storage of carbon, except the injection of CO₂ for Enhanced Oil Recovery (EOR) purposes. Furthermore, no governmental bodies have been appointed to oversee these matters as of yet. The Regulation on Environmental Impact Assessment regulates the procedures and principles to be followed in the EIA process and includes special provisions for carbon capture and geological storage projects. The technical safety and environmental regulations for crude oil and natural gas pipeline facilities operated by the General Directorate of Petroleum Transportation by Pipelines (BOTAŞ) do not include specific provisions on flue gas/carbon dioxide transport (Kaynak, Çevre ve İklim Derneği (REC), 2024).

In 2022, Turkish Energy, Nuclear and Mineral Research Agency (TENMAK) has started a project to create a roadmap for the CCUS strategies, the report was expected to be published by 2024, however it is not published yet. However, during the meetings by the Directorate of Climate Change on February 20th, 2025, CCUS is considered a key strategy for the unavoidable emissions in the energy sector within the scope of the 2024–2030 Climate Mitigation Strategy as an NDC Implementation Tool. In this regard, a CCUS Roadmap to reduce carbon intensity in power generation was discussed as a strategy. Furthermore, the roadmap is anticipated to encompass the integration of Carbon Capture, Utilization, and Storage (CCUS) technologies into industrial applications, particularly in the Cement, Iron, and Steel sectors over the long term. Moreover, CCUS is projected to serve as a fundamental strategy for the cement industry following 2040. Ongoing efforts to align with EU CCS Directive (2009/31/EC) via IPA III was also discussed (İklim Değişikliği Başkanlığı, 2025).

Türkiye must address the regulatory and commercial barriers to CCUS implementation in the first place. The country lacks experience with financial mechanisms related to the proper operation, closure, and post-closure monitoring of CCUS facilities. Additionally, there are no existing market incentives, such as carbon pricing or carbon taxes. Since Türkiye currently does not have a carbon trading mechanism, potential CO₂ reductions achieved through CCUS are not rewarded. Apart from Enhanced Oil Recovery (EOR) applications that facilitate additional production, operators who choose geological storage of CO₂ do not have access to benefits like carbon trading or tax incentives. If CCUS were included in a future carbon trading system, these reductions could be valued through

carbon pricing. In short, the absence of carbon markets or taxes is a key barrier to the development of CCUS facilities in Türkiye (Kaynak, Çevre ve İklim Derneği (REC), 2024).

Resource, Energy, and Climate (REC) Türkiye has conducted a survey involving various stakeholders. Consequently, there is a limited understanding and a lack of consensus among these stakeholders regarding the definition and implementation of "delegation of authority" as outlined in the relevant directive for the regulation of activities, particularly concerning the identification and management of prospective geological storage sites. Furthermore, more than 70% of survey participants believe that Türkiye lacks the technical capacity to research, develop, and deploy these technologies. Public awareness and social acceptance of Carbon Capture, Utilization, and Storage (CCUS) are also critical factors affecting its deployment, particularly considering that Türkiye is a highly earthquake-prone region, traumatized by past events (Kaynak, Çevre ve İklim Derneği (REC), 2024).

6.6. Financing

Current research and development projects are primarily financed through European Union grants, including the EU ACT (Accelerating Carbon Capture and Storage Technologies) and EU Horizon, in addition to TÜBİTAK grants. Additionally, TENMAK launched a CCUS Technologies R&D Incentives Call aimed at advancing R&D technologies, in collaboration with public and private institutions, to elevate the TRLs from 4 to 8. However, the maximum cap for the grant (50 million Turkish Lira) is not considered realistic for Carbon Capture, Utilization, and Storage (CCUS) research. There are also R&D efforts by companies, especially in the cement sector, as stated by the Turkish Cement Manufacturers Association (TürkÇimento) (Turkish Cement Manufacturer's Association, n.d.).

Türkiye's Industrial Decarbonization Investment Platform (TIDIP) was launched in November 2024, by the Government of Türkiye, in partnership with the World Bank Group institutions, International Bank for Reconstruction and Development (IBRD) and International Finance Corporation (IFC), and the European Bank for Reconstruction and Development (EBRD). The objective of the TIDIP is to promote the low-carbon transition of Türkiye within industrial sectors, including iron and steel, aluminum production, cement, and fertilizers. It aims to deploy \$5 billion in investments by 2030, while no specific technologies have been stated for support (World Bank, 2024). In addition, SAYEM Green Transformation call under Türkiye Green Industry project, managed by

World Bank and TÜBİTAK – TEYDEB, aims to deploy \$450 million, with a cap for 300 million ₺ per project (TÜBİTAK, n.d.).

6.7. Current Efforts

The majority of the disclosed projects and activities pertain to research and development (R&D), pilot and demonstration projects, as well as strategy and road mapping within the current situation. Carbon Capture, Utilization, and Storage (CCUS) is primarily under consideration among cement industry stakeholders, as there are limited alternatives available to decarbonize the sector (Turkish Cement Manufacturer's Association, n.d.). However, the same motivation is not presently observed among Iron and Steel producers, except 2 R&D projects by TÜBİTAK. Furthermore, most projects concentrate on utilization, as the total storage capacity has not yet been determined, and the necessary regulations have not yet been established. Disclosed efforts are summarized in Table 5.2.

Table 6.2. List of projects on CCUS in Türkiye.

Project	Partner	Project Type	Scope	Year/ Period	Notes
Ar-Ge Teşvikleri KYKD Teknolojileri Çağrısı (CCUS Technologies R&D Incentives Call)	Turkish Energy, Nuclear and Mineral Research Agency (TENMAK)	R&D Incentive	- Capture (95%+ efficiency, 1 T/day) - Utilization (High efficiency, low-cost, modular conversion to fuels, chemicals, carbonates) - Storage (>1 T/day, modular to reservoir scale, efficient, low cost)	2023	Objective: Developing commercializable CO₂ capture, utilization, and storage technologies. Amount: 50M€≤ Requirement: Public-Private Collaboration between institutions, universities, and industry, and projects must be completed within 36 months. Target: Advancing Technology Readiness Level (TRL) from 4 to 8 Criteria: High efficiency, low cost, modular, compact, and environmentally friendly materials. Focus: R&D and innovation leading to tools, products, methods, systems, and production techniques.
Ulusal Karbondioksit Tutma ve Değerlendirme Teknolojileri Yol Haritası (National Carbon Dioxide Capture and Utilization Technologies Roadmap)	Turkish Energy, Nuclear and Mineral Research Agency (TENMAK) & Ministry of Energy and Natural Resources	Strategy	-Capture - Utilization - Storage		- CCUS is considered as a key strategy for the unavoidable emissions in energy sector within the scope of 2024–2030 Climate Mitigation Strategy (NDC Implementation Tool). - A CCUS Roadmap to reduce carbon intensity in power generation. - A CCUS Roadmap for the integration of CCUS to industrial applications (Cement, Iron & Steel), CCUS is expected to be a key strategy for the cement sector after 2040. - Ongoing efforts to align with EU CCS Directive (2009/31/EC) via IPA III.
Pilot CO ₂ Capture Plant	Scientific and Technological Research Council of Turkey Marmara Research Center (TÜBİTAK MAM)	Pilot & Demonstration	- Capture (Absorption)		- 2 Pilot capture plants
Karbondioksitten Sentetik Doğal Gaz Üretimi Projesi (Synthetic Natural Gas Production from Carbon Dioxide Project)	TENMAK (Turkish Energy, Nuclear and Mineral Research Agency)	R&D	-Utilization		1- Design and installation of fuel production process and reactor system -Evaluation of alternative reactor geometries and modeling studies -Design of process and reactor system -Installation of process and reactor system 2- Development of catalyst for synthetic natural gas production from carbon dioxide -Catalyst synthesis and characterization -Catalyst preparation for semi-pilot scale system -Catalyst Performance/optimization

Project	Partner	Project Type	Scope	Year/ Period	Notes
Karbondioksitin Metanole Dönüştürülmesi ile Enerji Depolanması Projesi (Energy Storage Project by Converting Carbon Dioxide to Methanol)	TÜBİTAK (İkili İşbirliği Programı-1071)	R&D	-Utilization		Catalytic conversion of carbon dioxide (CO ₂) to methanol for energy storage using "waste H ₂ " The project aims to: - Store surplus hydrogen energy in high value-added chemicals (methanol), - Develop CO ₂ hydrogenation technologies, - Help protect the environment by not allowing industrial CO ₂ emissions during these processes, - Expand the product range and achieve chemical integration by producing new compounds with methanol production.
ACT LOUISE: Efficient Low-Cost CO₂ Capture from Waste-Derived Fuels Using Chemical Looping Combustion	EU ACT (Accelerating CCS Technologies) Project - 18 Partners from Germany, Norway, Greece and Türkiye (TÜBİTAK MAM, SOCAR, ERDEMİR)	R&D	- Capture	2021-2023	Feasibility: Technically feasible, good KPIs at high temperatures Corrosion risk: Linked to low-temp fluctuations; more tests needed Demo plant: 10 MWth layout and cost estimate developed Economics: Lower OPEX than amine systems; limited for WtE retrofits Profitability: CCS more profitable than CCU under various scenarios LCA findings: Better climate performance than amine systems; CO ₂ storage preferred over CCU fuels
PYRAGRAF-Decentralized Pyrolytic Conversion of Agriculture and Forestry Wastes Towards Local Circular Value Chains and Sustainability	EU HORIZON Project - TÜBİTAK MAM, Ankara University and 20 other partners - Test Fields: Portugal, Germany, Türkiye (Kilis, Haymana)	R&D	- Utilization	2023 - 2027	Total Cost: €6.48M (€6.13M funded by EU) Objective of the project: Establishment of a solar powered mobile pyrolysis unit at TRL 7 level to demonstrate the conversion of agricultural and biomass wastes into value added products (biochar, wood vinegar, liquid fuel) - Field trials of biochar and wood vinegar samples produced in the mobile pyrolysis unit in collaboration with local stakeholders in Portugal, Germany and Turkey - Evaluation of the utilization potential of gaseous and liquid fuel from pyrolysis unit

Project	Partner	Project Type	Scope	Year/ Period	Notes
EU HORIZON Project					
SUSTEPS Sustainable, Secure and Competitive Energy Through Scaling Up Advanced Biofuel Generation - EU Horizon Project	- Coordinator: TÜBİTAK - TÜBİTAK MAM, Boğaziçi University and 11 other partners from Morocco, Brazil, Germany, France, Denmark, Netherlands, Ireland, Switzerland, and Canada	R&D	-Capture - Utilization	2023 - 2027	Total Cost: €3M (Entirely funded by EU) SUSTEPS project objectives: - Improve knowledge on algae-based biofuel systems and accelerate scaling - Develop and validate a cost-effective biorefinery concept - Produce sustainable biofuel from non-food/feed microalgae - Use CO ₂ from high-emission facilities and nutrient-rich wastewater - Integrate green hydrogen for fuel upgrading - Valorize side streams through value-added chemicals - Support international collaboration and best practices - Accelerate scaling up of algae-based sustainable biofuels globally
Geothermal Emission Control Project (GECO)	Middle East Technical University (METU) & Zorlu Enerji Elektrik Üretim, and other 15 public-private partners from France, Italy, Spain, Norway, Türkiye, Germany, UK and Iceland	Pilot and Demonstration	- - Utilization	Capture 2018 - 2023	Total Cost: €18M (€15.6M funded by EU) GECO is an innovative project aiming at providing clean geothermal energy with a lower cost. It builds upon the success of the recently completed CARBFIX project. Has 4 demo sites in Türkiye (Kızıldere, Denizli), Iceland, and Germany. - Operator: Zorlu Energy (concession since 2008) - Facilities: Kızıldere-I (15 MWe, 1984), Kızıldere-II (80 MWe, 2013), Kızıldere-III (165 MWe, 2018) - CO ₂ Use: ~1/3 of non-condensable gases (NCG) from Kızıldere-II sent to Linde for commercial CO ₂ processing - GECO Goal: Reduce CO ₂ emissions, enhance green geothermal production, and support reservoir sustainability - Among the demo plants, the projects in Iceland and Türkiye (Kızıldere) were found to be economically viable, with the Levelized Cost of Stored Carbon (LCOS) ranging from €19 to €63 per ton, and an average of €40 per ton for Kızıldere.
Carbon Capture, Utilization and Storage (CCUS) and Carbon Dioxide Removal (CDR) Solutions with the Potential to Create Economic Value” Deep Dive Report	Technology Development Foundation of Türkiye (TTGV)	Analysis	-Capture - Utilization - Storage	2025	The report analyzes developments in Türkiye and globally, and covers critical aspects such as technology applications, policy frameworks and carbon markets in detail with contributions of 75 sector experts and organizations. This deep dive report, approached from a techno-economic perspective, evaluates the potential of CCUS technologies and CDR solutions in decarbonization strategies, their feasibility, and their capacity to support innovative business models. This summary report of the study, aims to be a guide and a strategic resource for our country to benefit from these technologies at the highest level.

Project	Partner	Project Type	Scope	Year/ Period	Notes
Türkiye'de Termik Santraller ve Sanayi Tesislerinden Gelen Karbondioksit Emisyonu Envanterinin Çıkartılması ve Karbondioksitin Yeraltı Jeolojik Ortamlarda Depolanma Potansiyelinin Belirlenmesi (Assessment of CO₂ Emissions from Thermal and Industrial Plants in Türkiye and Evaluation of Underground Geological Storage Potential)	TÜBİTAK KAMAG 106G110 Project Coordinating Institutions: Middle East Technical University, Petroleum Research Center (METU PAL), Turkish Petroleum Corporation (TPAO) Project Client Institutions: Ministry of Energy and Natural Resources, General Directorate of Energy Affairs	R&D	-Capture - Storage	2009	The primary goal of the project was to determine whether suitable underground structures exist in Türkiye for CO ₂ storage and to assess the storage capacity of selected sites. The secondary objective was to model and analyze, both geologically and numerically, the injection and storage of CO ₂ at a selected site, along with an economic feasibility analysis. The project was carried out in six main phases: - Identification of major CO ₂ -emitting facilities (thermal power plants, refineries, cement factories, iron and steel plants) and collection of annual fuel data. - Calculation of CO ₂ emissions using the IPCC Tier 1 method based on fuel consumption. - Investigation of potential storage structures in Türkiye (oil and gas fields, deep aquifers, soda caves), and modeling of CO ₂ injection and storage in a selected structure. - Technical and economic feasibility analysis of transporting captured CO ₂ (assumed to be separated via capture technologies) to the selected site via tanker or pipeline.
					- The project explores microalgae-based bio-jet fuel as a sustainable alternative, using non-food biomass that doesn't rely on fertile land or freshwater. - It aims to develop fuel from locally adaptable microalgae under integrated biorefinery conditions with the help of selective catalytic processes. Four species were cultivated in tubular photobioreactors and open pond systems. - The prototype fuel from one specie showed strong performance, though it did not meet three ASTM parameters under Annex-7, and Turkish Airlines (THY) engine tests and flight trials were postponed. - Nevertheless, the project successfully produced a pre-blending bio-jet fuel, marking an important milestone toward sustainable aviation fuel development.
Mikroalg Tabanlı Sürdürülebilir Biyo-Jet Yakıtı Projesi (Mikro-Jet) Microalgae Based Sustainable Bio-Jet Fuel Project (Micro-Jet)	TÜBİTAK & Boğaziçi University	R&D	-Capture - Utilization	2020-2023	

Note. Table is created citing (ACT Louise, 2024; Bahar, 2023; CORDIS, European Commission, n.d; GECO, n.d.; Haznedaroğlu and Tezel, 2023; Okandan et al., 2011; TENMAK, 2023; Türkiye Teknoloji Geliştirme Vakfı, 2025)

7. DISCUSSION AND POLICY IMPLICATIONS

Since CCUS technologies promise to decarbonize hard-to-abate sectors where limited mitigation pathways are available, efforts to develop and deploy CCUS technologies have gained momentum in recent years as the urgency to meet global climate mitigation targets intensifies. However, the capital-intensive and technologically complex nature of these technologies has led to a dominance by the developed countries in technology deployment, even though the majority of the production in hard-to-abate sectors is in developing countries. While countries like the United States, the United Kingdom, and Canada have already deployed commercial-scale projects for years, the majority of the projects in developing countries are either in the research, development, and demonstration phase or have no traction at all.

Efforts in developed countries are driven by robust environmental and climate regulations, policies for direct governmental support, incentives for the private sector, and the establishment of public-private partnerships. Furthermore, the established climate technology ecosystems in these countries complement the efforts and assist in bridging the gaps in the transition from research to commercialization. As a carbon utilization startup founder in the United States has stated during the interviews, *“Federal grants supported us in the early stages of developing our technology, and in the later phases we were able to secure venture capital investment thanks to the strength of the climate tech ecosystem in the U.S.”*(Interviewee 6, 2025).

As in every other field, developing countries are either following or being forced to follow the footsteps of the developed countries. Cross-border mechanisms, especially carbon border adjustment mechanisms, aim to both mobilize the developing countries to act on global mitigation efforts and to regain the competitive advantage of companies in their own countries by regulating imports with customs tariffs. Nevertheless, there are also concerns that uniformly applied CBAMs might impose disproportionate burdens on the developing countries. If not designed well, these mechanisms might impede the Common but Differentiated Responsibilities (CBDR) principle affirmed under the Paris Agreement. Global climate mitigation should not solely rely on punitive measures; it must also encompass actions that facilitate collective global efforts.

Despite its significant shortcomings in practical application, which are extensively discussed annually at the Conference of Parties (COP), the Paris Agreement delineates the obligations of

developed countries that are parties to the agreement to assist developing and least developed nations in their climate mitigation and adaptation efforts across various dimensions, thereby ensuring collective global action. In the context of CCUS, the biggest challenge for the deployment in developing countries, financing, must be addressed through more ambitious international climate finance mechanisms, especially for the countries supplying hard-to-abate sector outputs to the world.

Although there had been efforts by the Global Climate Fund, and some Multilateral Development Banks (MDBs) such as the World Bank CCS Trust Fund and Asian Development Bank CCS Fund, there is currently a gap in financing for the developing countries after the funds have closed. Other than the dedicated funds, the Official Development Assistance (ODA) might also be an alternative for the ODA recipient countries. However, many emerging economies can not access grants easily for CCS projects due to the limitations on the use of ODA (Interviewee 5, 2025). For a collaborative global mitigation strategy, international climate financing mechanisms under the Paris Agreement must be strengthened, and the targets must be more ambitious for the countries supplying hard-to-abate sector products to the world.

Besides, as stated by a CCUS expert during the interviews, *“The most successful approach is making sure it is a country-led initiative, rather than an outside entity like an MDB or another government coming in and saying, ‘You need to do this.’”* (Interviewee 5, 2025). This is the point at which the responsibilities of governments in developing countries become significant. Many countries are waiting for climate finance as if they are waiting for a savior, but in the meantime, they need to take some steps up front to qualify for this support. The governments should ensure that they establish their strategies to meet their Nationally Determined Contributions (NDCs) in alignment with their regional challenges and opportunities, determine how CCUS can play a role in this strategy, and subsequently establish clear market mechanisms, policies, and regulations.

This brings us to another question about how CCUS should be positioned in the governments’ decarbonization strategies. In the previous chapters, the phenomenon of “hard-to-abate” is discussed in detail, and cement, iron and steel, and the chemical industry are found truly hard-to-abate in the context of CCUS. However, the hard-to-abate status of certain sectors, such as power generation, is determined to be case-specific. While developed countries are en route to successfully transition to a decarbonized energy mix, many developing countries remain reliant on fossil fuels, particularly coal, to fulfill their energy demands. While not inherently hard-to-abate, factors such as the age of thermal power plants, the state of the nation's domestic fossil reserves and their contribution to the national

economy, and the geographical potential for renewable energy sources may justify the application of CCUS in the power sector under specific circumstances. This shows the need for region or country-specific strategies for CCUS deployment.

Accordingly, a country-specific case study on Türkiye has been developed, given its strong trade ties with developed countries, particularly in emission-intensive sectors such as cement, and iron and steel. Despite Türkiye's considerable potential for both carbon capture and geological storage, the country is already late to step in the CCUS space. There are currently no commercial scale CCUS projects in the pipeline. Since 2022, the Turkish Energy, Nuclear and Mining Research Agency (TENMAK) has been leading the development of a national CCUS roadmap. In parallel, reports published by TTGV and REC Türkiye have assessed the country's technical and policy readiness. Existing R&D and pilot-scale initiatives are primarily supported through joint projects funded by the European Union and by TÜBİTAK, in collaboration with universities and the private sector. Additionally, a dedicated CCUS working group operates under the Directorate of Climate Change, reflecting growing institutional engagement in the field. However, the meeting notes published by the working group state that Türkiye will prioritize the power generation sector for the CCUS integration in the short term. In contrast, the cement, iron, and steel sectors will be positioned in the long term. Given that Türkiye possesses abundant renewable energy potential, particularly in wind, hydro, and solar sources, yet concurrently serves as a coal importer, it is imperative that industrial decarbonization be regarded as the primary focus for the integration of Carbon Capture, Utilization, and Storage (CCUS).

From the perspective of the private sector in the country, while some sectors like petrochemicals and cement have shown limited CCUS engagement and interest, the iron and steel sector is largely absent from these conversations. Currently, hydrogen receives much more attention than CCUS in the iron and steel sector. The lack of interest can be attributed to the lack of government intervention, as a trade union representative emphasized during the interviews, *“There is no clear strategy or regulatory framework, and even companies interested in investing in CCUS wouldn't know which authority to approach for permitting. Expecting the private sector to drive CCUS deployment in Türkiye is akin to expecting them to build tram lines; these infrastructure-scale investments require strong public-private collaboration.”* (Interviewee 9, 2025).

As stated, no matter which sector the country prioritizes, Türkiye still does not have a national CCUS strategy and clear governance structure other than the meeting notes published by the working

group. Moreover, the withdrawal of the climate law which proposed the establishment of complementary mechanisms like emission trading system, climate finance and green investments; limits the further establishment of a national carbon market. In order to advance, Türkiye should first revise its draft climate law to establish a robust carbon market that derisks the investments through complementary mechanisms. Spontaneously, The Government of Türkiye should assign the responsible bodies for the offshore and onshore storage resource assessment, transportation infrastructure, permitting processes, community engagement and awareness, and formulate necessary policies, regulations, and strategies.



8. CONCLUSION AND FURTHER RESEARCH

This thesis aimed at exploring the currently complex and vague body of knowledge surrounding the deployment of Carbon Capture, Utilization, and Storage (CCUS) technologies in developing nations, a critical issue given the increasing material and energy demands of these societies. It focused on Türkiye as a case study due to its unique profile of being heavily reliant on emission-intensive production and having strong trade ties with developed countries, especially Europe. As such, this thesis aimed to bridge the existing knowledge gap and offer insights into the feasibility and strategic integration of CCUS in countries' climate and technology policies. This investigation, drawing upon the literature and the perceptions of national and international experts, stakeholders, concludes that while CCUS cannot (and should not) be used a solution for all greenhouse gas (GHG) mitigation efforts (especially power production), it nonetheless holds significant potential as a targeted solution for truly hard-to-abate sectors like cement, chemicals, and iron and steel—industries predominantly concentrated in developing economies.

My findings show that the integration of CCUS technologies is contingent upon a multifaceted array of social, economic, technological, and environmental considerations, and hence, there is no one-size-fits-all approach for all countries. Critically, any CCUS strategy and policy must be specifically designed to prevent its misuse as a mechanism for perpetuating existing business practices or delaying more substantial, systemic climate mitigation efforts, particularly where alternative, more efficient pathways are readily available. The main utility of CCUS lies in its capacity to address emissions from industrial processes where direct electrification or other abatement methods are technically or economically unfeasible.

One of the main conclusions coming out of this research is the significant deployment gap between developed and developing countries. Addressing this disparity is not merely an issue of equity but a prerequisite for achieving collective global climate mitigation. Developing nations, often characterized by growing industrial sectors and limited access to advanced technologies and financial resources, face significant barriers to CCUS adoption. These challenges include, but are not limited to, access to capital, knowledge gaps regarding the technical and operational aspects of CCUS, and the absence of regulatory frameworks essential for the establishment of viable CCUS value chains. Without robust regulatory clarity, investors are hesitant, and project developments are slower. Therefore, for CCUS to meaningfully contribute to global decarbonization efforts, particularly in

developing countries, there must be a coordinated effort for strengthening of international climate policy for technology transfer, capacity building, and climate finance. These policies should be designed with an understanding of the specific socio-economic and technological contexts of developing nations. This includes exploring innovative financing mechanisms that de-risk CCUS projects in these regions and facilitating collaborative research and development initiatives.

Integrating CCUS into Türkiye's net-zero strategies, as highlighted in this study, necessitates a tailored approach that leverages its strong trade ties and industrial base, while simultaneously addressing its unique domestic challenges through supportive policy and investment. Despite considerable geological storage potential, Türkiye lags in CCUS adoption, with no commercial-scale projects currently underway. While national efforts to develop a CCUS roadmap and assess readiness are emerging, notably through TENMAK and other organizations, the prevailing focus is on integrating CCUS into the power generation sector in the short term, deferring industrial applications to the long term. This prioritization is counterintuitive, considering Türkiye's substantial renewable energy potential and its reliance on coal imports, making industrial decarbonization a more logical primary focus for CCUS. Furthermore, private sector engagement in CCUS, particularly within the iron and steel industry, remains limited, largely due to the absence of clear government strategy, regulatory frameworks, and designated authorities for permitting. Lastly, the withdrawal of a proposed climate law that would have established crucial mechanisms like an emissions trading system, further complicates the development of a national carbon market, and hence potential incentives to adopt CCUS. Türkiye urgently needs to revise its climate law to establish a robust carbon market, alongside defining clear governance structures and assigning responsibilities for storage assessment, infrastructure, permitting, and public engagement.

Finally, this study advocates for a pragmatic and strategic integration of CCUS, particularly within hard-to-abate sectors where its impact can be most profound. Further research could examine how current and prospective international climate policy and financing mechanisms can be optimized to better support developing countries for collective global climate action with just transition principles and ensuring actual mitigation efforts. Furthermore, there exists the opportunity to explore how trade-related pressures may be leveraged to encourage more ambitious actions in countries that are lagging in their climate commitments. Such pressures can serve as incentives for alignment, rather than relying on punitive measures that may exacerbate existing disparities. Additionally, comparative analyses of best practices from other developing countries, such as Indonesia, could provide valuable insights into the development of effective strategies for reforming national policy frameworks and

attracting international financing. Moreover, integrated modeling approaches that incorporate both socio-ecological and techno-economic dimensions could be utilized to evaluate the cost-effectiveness and mitigation outcomes of CCUS technologies in comparison to alternative decarbonization pathways, particularly within the key industrial sectors of Türkiye, considering various policy and economic scenarios.

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APPENDIX A:

Table A.1. Developed Economies (United Nations, 2025).

Developed Economies

European Union	Europe New EU Member States	Other Europe	Other countries	Major developed economies (G7)
Austria	Bulgaria	Iceland	Australia	Canada
Belgium	Croatia	Norway	Canada	Japan
Denmark	Cyprus	Switzerland	Japan	France
Finland	Czechia	United Kingdom	New Zealand	Germany
France	Estonia		United States	Italy
Germany	Hungary			United Kingdom
Greece	Latvia			United States
Ireland	Lithuania			
Italy	Malta			
Luxembourg	Poland			
Netherlands	Romania			
Portugal	Slovakia			
Spain	Slovenia			
Sweden				
Sweden				

Table A.2. Economies in Transition (United Nations, 2025).

Economies in Transition

South-Eastern Europe	Commonwealth of Independent States and Georgia	
Albania	Armenia	Republic of Moldova
Bosnia and Herzegovina	Azerbaijan	Russian Federation
Montenegro	Belarus	Tajikistan
Serbia	Georgia	Turkmenistan
North Macedonia	Kazakhstan	Ukraine
	Kyrgyzstan	Uzbekistan

Table A.3. Developing Economies by Region: Africa (United Nations, 2025).

Developing Economies by Region – Africa

North Africa	Central Africa	East Africa	Southern Africa	West Africa
Algeria	Cameroon	Burundi	Angola	Benin
Egypt	Central African Republic	Comoros	Botswana	Burkina Faso
Libya	Chad	Democratic Republic of the Congo	Eswatini	Cabo Verde
Mauritania	Congo	Djibouti	Lesotho	Côte d'Ivoire
Morocco	Gabon	Eritrea	Malawi	Gambia
Sudan	Equatorial Guinea	Ethiopia	Mauritius	Ghana
Tunisia	Sao Tome and Principe	Kenya	Mozambique	Guinea
		Madagascar	Namibia	Guinea-Bissau
		Rwanda		Liberia
		Somalia		Mali
		South Sudan		Niger
		Uganda		Nigeria
		United Republic of Tanzania		Senegal
				Sierra Leone
				Togo

Table A.4. Developing Economies by Region: Asia (United Nations, 2025).

Developing Economies by Region – Asia

East Asia	South Asia	Western Asia
Brunei Darussalam	Afghanistan	Bahrain
Cambodia	Bangladesh	Iraq
China	Bhutan	Israel
Democratic People's Republic of Korea (North Korea)	India	Jordan
Fiji	Iran (Islamic Republic of)	Kuwait
Hong Kong SAR	Maldives	Lebanon
Indonesia	Nepal	Oman
Kiribati	Pakistan	Qatar
Lao People's Democratic Republic	Sri Lanka	Saudi Arabia
Malaysia		State of Palestine
Mongolia		Syrian Arab Republic
Myanmar		Türkiye
Papua New Guinea		United Arab Emirates
Philippines		Yemen
Samoa		
Singapore		
Taiwan Province of China		
Thailand		
Timor Leste		
Vanuatu		
Viet Nam		

Table A.5. Developing Economies by Region: Latin America and Caribbean (United Nations, 2025).

Developing Economies by Region - Latin America and Caribbean

Caribbean	Mexico and Central America	South America
Bahamas	Costa Rica	Argentina
Barbados	El Salvador	Bolivia (Plurinational State of)
Belize	Guatemala	Brazil
Cuba	Honduras	Chile
Dominican Republic	Mexico	Colombia
Guyana	Nicaragua	Ecuador
Haiti	Panama	Paraguay
Jamaica		Peru
Trinidad and Tobago		Uruguay
		Venezuela (Bolivarian Republic of)

Table A.6. Least Developed Countries (United Nations, 2025).

Least Developed Countries*

Africa		East Asia
Angola	Madagascar	Cambodia
Benin	Malawi	Kiribati
Burkina Faso	Mali	Lao People's Democratic Republic
Burundi	Mauritania	Myanmar
Central African Republic	Mozambique	Samoa
Chad	Niger	Solomon Islands
Comoros	Rwanda	Tuvalu
Democratic Republic of the Congo	Senegal	
Djibouti	Sierra Leone	
Equatorial Guinea	Somalia	
Eritrea	South Sudan	
Ethiopia	Sudan	
Gambia	Togo	
Guinea	Uganda	
Guinea-Bissau	United Republic of Tanzania	
Lesotho	Zambia	
Liberia		
South Asia	Western Asia	Latin America and Caribbean
Afghanistan	Yemen	Haiti
Bangladesh		
Nepal		

* Not included in the WESP discussion because of insufficient data.

* [By the end of 2024, eight countries had left the list. Botswana was the first to leave, in 1994. The next to exit was Cabo Verde \(2007\), followed by Maldives \(2011\), Samoa \(2014\), Equatorial Guinea \(2017\), Vanuatu \(2021\), Bhutan \(2023\), and São Tomé and Príncipe \(2024\).](#)

APPENDIX B:

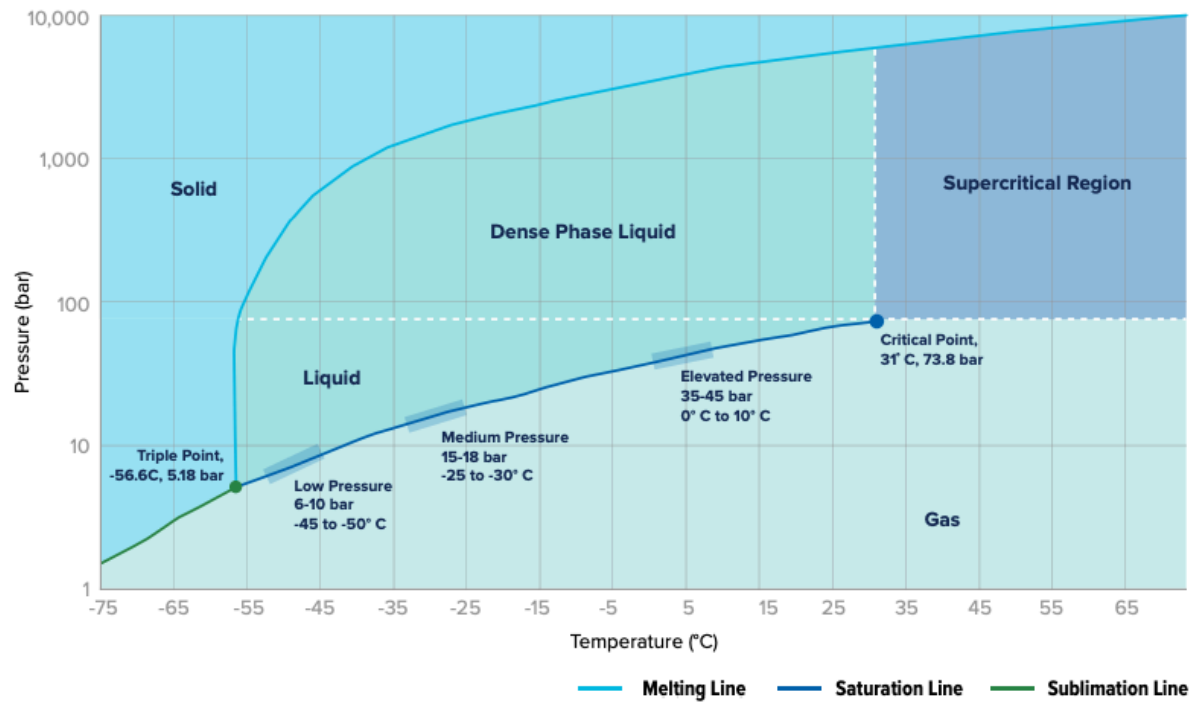


Figure B.1. CO₂ Phase Diagram (Global CCS Institute, 2025a).

APPENDIX C:

Table C.1. Interviewee List

Interviewee	Category	Date	Discussed topics
Interviewee 1	Non-Profit	2.Apr.25	EU Policies
Interviewee 2	Non-Profit	21.Apr.25	Feasibility, Financing
Interviewee 3	Industrial Carbon Management Consultant	22.Apr.25	Feasibility, Financing, The Case of Türkiye
Interviewee 4	Investor	25.Apr.25	Financing
Interviewee 5	CCUS Consultant	28.Apr.25	Policies and Regulatory Frameworks, Climate Finance
Interviewee 6	CCU Technology Developer	1.May.25	Technology Development and Financing in Developed Countries, Feasibility
Interviewee 7	CCU Technology Developer	5.May.25	Technology Development and Financing in Developing Countries
Interviewee 8	Non-Profit	7.May.25	EU Policies, Just Transition
Interviewee 9	Non-Profit	8.May.25	Sector Engagement in Türkiye
Interviewee 10	Technology Transfer Expert	13.May.25	Technology Transfer and Commercialization in Türkiye
Interviewee 11	Decarbonization Advisor	14.May.25	Carbon Credits, Policies in Türkiye
Interviewee 12	Non-Profit	15.May.25	Sector Engagement in Türkiye

APPENDIX D:

```
#####
##### setup
#####

library(tidyverse)
library(readxl)
library(janitor)
library(writexl)
library(ggplot2)
library(maps)
library(countrycode)
library(dplyr)

setwd("/Users/zisanozdemir/Desktop/FacilitiesData")

#####
##### Load Data
#####

facility_data <- read_excel("CO2RE Facilities Date Feb 2025 - Zisan.xlsx", sheet = "Feb 2025")

#rename col

facility_data <- facility_data %>%
  clean_names()

facility_data <- facility_data %>%
  rename("country"="facility_country")

facility_data <- facility_data %>%
  mutate(country = case_when(
    country == "United States" ~ "USA",
    TRUE ~ country
```

```
))
```

```
colnames(facility_data)
```

```
options(digits = 2, scipen = 999)
```

```
# Read the countries classification file
```

```
classification_data <- read_excel("countries_classification.xlsx") #WESP 2025
```

```
classification_data <- classification_data %>%
```

```
  rename("country"="Country")
```

```
#Data Cleaning
```

```
classification_data <- classification_data %>%
```

```
  clean_names()
```

```
classification_data <- classification_data %>%
```

```
  mutate(country = case_when(
    country == "United States" ~ "USA",
    country == "Russian Federation" ~ "Russia",
    country == "Republic of Korea" ~ "South Korea",
    TRUE ~ country
  ))
```

```
classification_data <- classification_data %>%
```

```
  mutate(classification = case_when(
    country == "South Korea" ~ "Developed",
    TRUE ~ classification
  ))
```

```
facility_data <- facility_data %>%
```

```
  left_join(classification_data, by = "country")
```

```
facility_data <- facility_data %>%
  mutate(classification = if_else(is.na(classification), "Coalition", classification))
```

```
facility_data <- facility_data %>%
  mutate(classification = case_when(
    country == "Timor-Leste" ~ "Developing",
    country == "Russia" ~ "Economies in Transition",
    TRUE ~ classification # leave everything else unchanged
  ))
```

```
#write_xlsx(facility_data, "/Users/zisanozdemir/Desktop/FacilitiesData/facility_data_cleaned.xlsx")
```

```
facility_data_active <- facility_data %>%
  filter(facility_status != "Cancelled")
```

```
facility_data_cancelled <- facility_data %>%
  filter(facility_status == "Cancelled")
```

```
#write_xlsx(facility_data_cancelled,
"/Users/zisanozdemir/Desktop/FacilitiesData/facilities_cancelled.xlsx")
```

```
# First find all removed projects
```

```
removed_projects <- facility_data %>%
  anti_join(facility_data_active, by = "facility_name")
```

```
# Then keep only those that are NOT Cancelled
```

```
weird_removed_projects <- removed_projects %>%
  filter(is.na(facility_status) | facility_status != "Cancelled")
```

```
projects_restored <- weird_removed_projects %>%
  filter(facility_name %in% projects_to_restore)
```

```
facility_data_active <- bind_rows(facility_data_active, projects_restored)
```

```
#write_xlsx(facility_data_active,
"/Users/zisanozdemir/Desktop/FacilitiesData/facility_data_active.xlsx")
```

```
#Coalition
```

```
coalition_projects <- facility_data_active %>%
filter(classification == "Coalition")
```

```
#write_xlsx(coalition_projects,
"/Users/zisanozdemir/Desktop/FacilitiesData/coalition_projects.xlsx")
```

```
#####
##### Analysis
#####
```

```
#number of facilities and total capacity by country classification
```

```
agg_data <- facility_data_active %>%
  group_by(classification) %>%
  summarise(no_of_facilities = n(),
            total_capacity = sum(facility_capture_capacity, na.rm = T))
```

```
country_data <- facility_data_active %>%
```

```
  group_by(country) %>%
  summarise(sum = n())
```

```
#number of facilities and total capacity by facility status
```

```
facility_status_summary <- facility_data_active %>%
```

```
  group_by(facility_status) %>%
  summarise(
    Number_of_Facilities = n(),
    Total_Capture_Capacity = sum(facility_capture_capacity, na.rm = TRUE)
```

```

) %>%
  arrange(desc(Number_of_Facilities))

#number of facilities and total capacity by facility status
facility_summary_table <- facility_data_active %>%
  group_by(classification, facility_status) %>%
  summarise(
    Number_of_Facilities = n(),
    Total_Capture_Capacity = sum(facility_capture_capacity, na.rm = TRUE)
  ) %>%
  arrange(desc(Number_of_Facilities))

#Projects in developing countries

developing_country_projects <- facility_data_active %>%
  filter(classification == "Developing")

developing_country_count <- developing_country_projects %>%
  distinct(country) %>%
  count()

developing_country_count

# 2. Group and count the number of projects per country
developing_country_project_counts <- developing_country_projects %>%
  group_by(country) %>%
  summarise(Number_of_Projects = n()) %>%
  arrange(desc(Number_of_Projects))

# Filter only for Bioethanol and Fertilizer projects
bioenergy_data <- facility_data_active %>%
  filter(`facility_industry` %in% c("Bioenergy / Ethanol"))

# Filter only for Bioethanol and Fertilizer projects

```

```

fertilizer_data <- facility_data_active %>%
  filter(`facility_industry` %in% c("Hydrogen / Ammonia / Fertiliser"))

bioenergy_fertilizer_country_wide <- facility_data_active %>%
  filter(`facility_industry` %in% c("Bioenergy / Ethanol", "Hydrogen / Ammonia / Fertiliser"))
%>%
  group_by(country, `facility_industry`) %>%
  summarise(Number_of_Projects = n(), .groups = "drop") %>%
  pivot_wider(
    names_from = `facility_industry`,
    values_from = Number_of_Projects,
    values_fill = 0 # fill missing with 0
  ) %>%
  arrange(desc('Bioenergy / Ethanol'), desc('Hydrogen / Ammonia / Fertiliser'))

facility_data_active %>%
  distinct(`facility_industry`) %>%
  arrange(`facility_industry`)

#write_xlsx(facility_status_summary,
"/Users/zisanozdemir/Desktop/FacilitiesData/facility_status_summary.xlsx")

#####
##### Plots
#####

# Filter out NA classifications
facility_summary_table_clean <- facility_summary_table %>%
  filter(!is.na(facility_status))

# Set the correct x axis order
facility_summary_table_clean <- facility_summary_table_clean %>%
  mutate(facility_status = factor(facility_status, levels = c(

```

```

    "Completed", "Operational", "In Construction", "Advanced Development", "Early Development",
    "Announced"
  )))

```

```
library(ggplot2)
```

```

ggplot(facility_summary_table_clean, aes(x = facility_status, y = Number_of_Facilities, fill =
classification)) +
  geom_bar(stat = "identity", position = "dodge") +
  labs(
    title = "Facility Count by Development Status and Country Classification",
    x = NULL,
    y = NULL,
    fill = NULL
  ) +
  scale_fill_manual(values = c(
    "Economies in Transition" = "#7570b3",
    "Developing" = "#018571",
    "Developed" = "#023858",
    "Coalition" = "#74a9cf"
  )) +
  theme_minimal(base_size = 14) +
  theme(
    plot.title = element_text(hjust = 0.5, face = "bold", size = 16),
    axis.text.x = element_text(angle = 45, hjust = 1),
    panel.grid.major.x = element_blank()
  )

```

```
#Industry Pie Chart
```

```

facility_storage_pie <- facility_data_active %>%
  filter(
    !`facility_storage_code` %in% c("N/A", "Not Specified", "Under Evaluation", "Various"),
    !is.na(`facility_storage_code`)
  )

```

)

```
storage_summary <- facility_storage_pie %>%
  group_by(`facility_storage_code`) %>%
  summarise(Number_of_Projects = n()) %>%
  arrange(desc(Number_of_Projects))
```

```
library(ggrepel)
```

```
library(ggplot2)
```

```
ggplot(storage_summary, aes(x = "", y = Number_of_Projects, fill = `facility_storage_code`)) +
  geom_col(width = 1, color = "white") +
  coord_polar(theta = "y") +
  scale_fill_viridis_d(option = "C") + # or use your custom navy-lavender palette
  labs(
    title = "Project Distribution by Storage Code",
    x = NULL,
    y = NULL,
    fill = "Storage Code"
  ) +
  theme_void() +
  theme(
    plot.title = element_text(hjust = 0.5, face = "bold", size = 16),
    legend.position = "right",
    legend.title = element_text(size = 12),
    legend.text = element_text(size = 10)
  )
```

#Sectors over time:

```
facility_sector_status_summary <- facility_data_active %>%
  filter(!`facility_industry` %in% c("N/A", "Research and Development", "Under Evaluation", "Not
Specified", "Under Evaluation", "Various", "NA"),
```

```

!is.na(facility_status),
!is.na(`facility_industry`)) %>%
group_by(facility_status, `facility_industry`) %>%
summarise(Number_of_Projects = n(), .groups = "drop")

#Set custom order
facility_sector_status_summary <- facility_sector_status_summary %>%
mutate(facility_status = factor(facility_status, levels = c(
  "Completed",
  "Operational",
  "In Construction",
  "Advanced Development",
  "Early Development",
  "Announced"
)))

library(ggplot2)

ggplot(facility_sector_status_summary, aes(x = facility_status, y = `facility_industry`, fill =
Number_of_Projects)) +
  geom_tile(color = "white") +
  geom_text(aes(label = Number_of_Projects), color = "white", size = 3.5, fontface = "bold") +
  scale_fill_viridis_c(option = "C") +
  labs(
    title = "Heatmap: Sector Dominance by Project Stage",
    x = "Facility Status",
    y = "Facility Industry",
    fill = "Number of Projects"
  ) +
  theme_minimal(base_size = 14) +
  theme(
    plot.title = element_text(hjust = 0.5, face = "bold"),
    axis.text.x = element_text(angle = 45, hjust = 1)
  )

```

#Heat Map by Year - Cumulative

```

facility_operational <- facility_data_active %>%
  filter(facility_status == "Operational") %>%
  filter(!is.na(`facility_year_operational`), !is.na(`facility_industry`))

facility_operational <- facility_operational %>%
  mutate(`facility_year_operational` = as.integer(`facility_year_operational`))

# Get all combinations of industry and year
all_years <- min(facility_operational$`facility_year_operational`, na.rm =
TRUE):max(facility_operational$`facility_year_operational`, na.rm = TRUE)

expanded_data <- facility_operational %>%
  group_by(`facility_industry`, `facility_year_operational`) %>%
  summarise(new_projects = n(), .groups = "drop") %>%
  complete(
    `facility_industry`,
    `facility_year_operational` = all_years,
    fill = list(new_projects = 0)
  ) %>%
  arrange(`facility_industry`, `facility_year_operational`)

cumulative_data <- expanded_data %>%
  group_by(`facility_industry`) %>%
  mutate(cumulative_projects = cumsum(new_projects)) %>%
  ungroup()

library(ggplot2)

ggplot(cumulative_data, aes(
  x = `facility_year_operational`,

```

```

y = `facility_industry`,
fill = cumulative_projects
)) +
geom_tile(color = "white") +
scale_fill_gradient(low = "#001f3f", high = "#66c2a5") +
labs(
  title = "Cumulative Operational Projects by Industry and Year",
  x = "Operational Year",
  y = "Facility Industry",
  fill = "Cumulative Projects"
) +
theme_minimal(base_size = 14) +
theme(
  axis.text.x = element_text(angle = 45, hjust = 1),
  plot.title = element_text(hjust = 0.5, face = "bold")
)

write_xlsx(developing_country_project_counts, "developing_country_project_counts.xlsx")

# library(dplyr)
# library(ggplot2)
# library(ggrepel)

## Prepare filtered summary
# facility_data_pie <- developing_country_projects %>%
#   filter(!`facility_industry` %in% c("Research and Development", "N/A", "NA", "Under
#   Evaluation")) %>%
#   filter(!is.na(`facility_industry`))
#
# facility_industry_summary <- facility_data_pie %>%
#   group_by(`facility_industry`) %>%
#   summarise(Number_of_Projects = n()) %>%
#   mutate(Percentage = Number_of_Projects / sum(Number_of_Projects) * 100)
#

```

```

# facility_industry_summary <- facility_data_pie %>%
#   group_by(`facility_industry`) %>%
#   summarise(Number_of_Projects = n())
#
# custom_navy_lavender_palette <- c(
#   "#2c3e50", # dark navy
#   "#34495e", # navy grey
#   "#5d6d7e", # soft navy
#   "#6c5b7b", # muted lavender
#   "#8e44ad", # purple
#   "#a569bd", # soft purple
#   "#bb8fce", # lavender light
#   "#c39bd3", # very light lavender
#   "#7d3c98", # deep violet
#   "#6a5acd", # slate blue
#   "#836fff", # lighter slate blue
#   "#4b0082", # deep indigo
#   "#7b68ee", # medium slate blue
#   "#8a2be2", # blue violet
#   "#9370db", # medium purple
#   "#b39ddb", # soft lilac
#   "#7986cb", # blue grey
#   "#5c6bc0" # stronger blue
# )
#
# library(ggplot2)
#
# # Sort industries from most to least
# facility_industry_summary <- facility_industry_summary %>%
#   arrange(desc(Number_of_Projects)) %>%
#   mutate(`facility_industry` = factor(`facility_industry`, levels = `facility_industry`))
#
# # Plot

```

```

# ggplot(facility_industry_summary, aes(x = Number_of_Projects, y = `facility_industry`, fill =
`facility_industry`)) +
#   geom_col() +
#   labs(
#     title = "Number of Projects by Facility Industry",
#     x = "Number of Projects",
#     y = NULL,
#     fill = NULL
#   ) +
#   scale_fill_manual(values = custom_navy_lavender_palette) + # use your custom colors
#   theme_minimal(base_size = 14) +
#   theme(
#     plot.title = element_text(hjust = 0.5, face = "bold", size = 16),
#     legend.position = "none",
#     axis.text.y = element_text(size = 12),
#     panel.grid.major.y = element_blank()
#   )

# library(ggplot2)
#
# # Sort industries by size
# facility_industry_summary <- facility_industry_summary %>%
#   arrange(desc(Percentage)) %>%
#   mutate(`facility_industry` = factor(`facility_industry`, levels = `facility_industry`))
#
# ggplot(facility_industry_summary, aes(x = Percentage, y = `facility_industry`, fill =
`facility_industry`)) +
#   geom_col() +
#   labs(
#     title = "Project Distribution by Facility Industry",
#     x = "Percentage of Projects",
#     y = NULL,
#     fill = NULL
#   ) +

```

```

# scale_fill_manual(values = custom_navy_lavender_palette)
# theme_minimal(base_size = 14) +
# theme(
#   plot.title = element_text(hjust = 0.5, face = "bold", size = 16),
#   axis.text.y = element_text(size = 12),
#   panel.grid.major.y = element_blank()
# )

#write_xlsx(facility_industry_summary,
"/Users/zisanozdemir/Desktop/FacilitiesData/facility_industry_summary.xlsx")

#
## Set custom colors
# custom_colors <- c(
#   "#6a5acd", "#836fff", "#4b0082", "#8a2be2", "#7b68ee", "#9370db"
# )
#
## 3. Plot
# ggplot(facility_industry_summary, aes(x = "", y = Percentage, fill = `facility_industry`)) +
#   geom_col(width = 1, color = "white") +
#   coord_polar(theta = "y") +
#   geom_text_repel(
#     aes(label = paste0(round(Percentage, 1), "%")),
#     show.legend = FALSE,
#     color = "black",
#     size = 4,
#     segment.color = "grey30",
#     segment.size = 0.5,
#     nudge_x = 1
#   ) +
#   scale_fill_viridis_d(option = "C") + # Viridis option C: bluish-purplish tones
#   labs(
#     title = "Project Distribution by Facility Industry",
#     x = NULL,

```

```

# y = NULL,
# fill = "Facility Industry"
# ) +
# theme_void() +
# theme(
# plot.title = element_text(hjust = 0.5, face = "bold", size = 16),
# legend.position = "right",
# legend.title = element_text(size = 12),
# legend.text = element_text(size = 10)
# )
#

# check

#

# # Define the list
# countries_to_check <- c(
# "South Korea", "Czech Republic", "South Sudan", "Sudan", "Sierra Leone", "Eswatini", "South
Africa", "Zambia", "Zimbabwe", "Cambodia", "Kiribati", "Mongolia", "Bahamas", "Yemen",
"Lesotho", "Mauritania", "Mozambique"
# )
#

# # See if any facilities exist
# facility_data_active %>%
# filter(country %in% countries_to_check) %>%
# select(`facility_name`, country, facility_status)
#

# see only distinct countries
# facility_data_active %>%
# filter(country %in% countries_to_check) %>%
# distinct(country)

# library(ggplot2)
#

```

```
# ggplot(facility_summary_table, aes(x = classification, y = Number_of_Facilities, fill =  
facility_status)) +  
#   geom_bar(stat = "identity", position = "dodge") +  
#   labs(  
#     title = "Facility Status by Classification",  
#     x = "Classification",  
#     y = "Number of Facilities",  
#     fill = "Facility Status"  
#   ) +  
#   theme_minimal(base_size = 14)
```

