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Discussion Paper

Global Demand for Materials for the CCS Industry

A Case Study of Saudi Arabia



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Summary

Carbon capture and storage (CCS) has been identified as a crucial technology to meet ambitious greenhouse gas emission targets, significantly contributing to global net-zero emission targets. Over the past decade, attention toward material requirements for energy transition technologies has intensified, primarily focusing on metals and minerals necessary for renewable energy and electric vehicles. CCS has been on the periphery of this analysis – it has been included in the scope of some analyses of the transition of the energy sector as a whole, but it has received little individual attention. This research addresses this critical gap by conducting an in-depth assessment of materials required for CCS plants, including those involved in capture processes for electricity and non-electricity applications, as well as for transportation and storage infrastructure.

In this paper, we examine the materials required for the deployment of the targeted and projected levels of CCS across the globe and for a case study of the Kingdom of Saudi Arabia (KSA). Aligning with Vision 2030, KSA has set aggressive targets for CCS deployment up to 2035. We examine the materials required for the construction and operation of CCS capture plants on both power generation and industrial plants. We also examine the materials for developing an appropriate carbon dioxide transportation and storage network. In our analysis, we consider both amine and potassium carbonate solvents for chemical absorption-based CO_2 capture based on the most mature systems on the market.

Our analysis highlights significant demand for consumable materials if the projected levels of CCS emerge, such as amines (exceeding 990 million tonnes globally up to 2050, or almost four times the current production level) and potassium carbonate (with demand over 7.5 times the current production levels). Both global and KSA supplies for these materials would need to increase sharply to meet projected demands. Although this may be possible given the availability of feedstock and the historic capacity of the chemical sector to expand, competition with other industrial sectors, particularly for chemicals like potassium carbonate used in fertilizer production, presents potential supply risks.

Most materials that are required for CCS deployment are currently produced in KSA or there is the potential to produce them given the resource availability and the expansion of the mining and processing sectors. This creates high potential for the localization of almost the entire supply chain for CCS deployment in KSA and, given the projected scale of their global deployment, creates potential future export opportunities for the country.

A different challenge may emerge for some of the materials that are needed to produce the corrosion-resistant steel required for the capture equipment and pipelines. Depending on the actual grade of steel employed, this could include metals such as nickel and vanadium, which might face challenging demand environments in view of the potential demand for them from other energy transition technologies, such as electric vehicles and battery storage.

Nevertheless, KSA holds a strategic advantage, as many essential CCS materials are either already domestically produced or could feasibly be produced given the Kingdom's expanding mining and processing sectors. This positions Saudi Arabia favorably to localize much of the CCS supply chain, significantly enhancing its economic resilience and energy security while creating opportunities for future industrial growth. To fully realize this potential,

a set of targeted industrial policy interventions will be essential, including supporting research and development, as well as embedding CCS material localization within the broader industrial and economic diversification agenda of Vision 2030.

Keywords: Carbon Capture and Storage, Material Demand, Localization, Energy Transition

Highlights

- We estimate the material requirements for the deployment of CCS across the world and for a case study of KSA.
- Globally, average annual requirements for potassium carbonate until 2050 are almost 15 million tonnes – over 7.5 times current annual production levels.
- Global average annual requirements for amines are around 40 million tonnes – almost four times the current estimated global annual production.
- CCS in KSA would require, on average, 260 kilotonnes of potassium carbonate annually until 2060 to meet the projected CCS scenario (about 13% of current global production), as well as 585 kilotonnes of amines (about 6% of current global production).
- At a global level, meeting potassium carbonate requirements necessitates rapid scale-up of the industry and risks substitution of inputs such as potash away from other industries, including fertilizer production.
- Overall, materials are likely to be available for CCS deployment within KSA, but some of the alloying elements needed for the proposed steel grades could face challenging demand environments due to high demands from other areas of the energy transition.
- Within KSA, there are, or are likely to be, readily available materials for CCS, which will provide opportunities for creating localized value chains and export opportunities.

1. Introduction

The transition to a new energy and transportation system, as part of a global shift toward net-zero GHG emissions, will require the construction of a range of new infrastructure and equipment over the next three decades (IEA 2021a). This system is projected to consist of considerable renewable electricity generation and electric vehicles, along with a range of other technologies to deal with hard-to-abate sectors, such as steel and cement. Carbon capture and storage (CCS) is one such technology, and it has the potential to play a key role in carbon dioxide mitigation, particularly in hard-to-abate sectors, along with potentially assisting in providing low-carbon baseload electricity generation that can support the intermittency of renewable energy. The technology has been established in the oil and gas and chemical industries for decades in natural gas sweetening and hydrogen and ammonia production, as well as for enhanced oil recovery (Ma et al. 2022). Many countries and organizations have ambitious targets for CCS deployment, including the EU, the UK, Japan, and Saudi Arabia (KSA) (Global CCS Institute 2023).

Despite its anticipated role, CCS still faces several challenges that hinder its deployment on a large scale. A key concern is the energy penalty that is associated with the capture phase, which reduces overall system efficiency and increases fuel consumption. This penalty, combined with the complexity of the additional infrastructure required for capture, compression, transportation, and storage, significantly contributes to the high overall cost of CCS deployment. In addition, material and resource challenges that may arise from scaling up the technology at a global level are also important.

The nature of the technologies being deployed for the energy transition is different from those they are replacing. One critical difference, which has been highlighted by many authors (Moss et al. 2013; Moss et al. 2011), is the more significant material requirements of these new technologies. This material intensity raises possible challenges to the energy transition if there are bottlenecks in supplying the required volumes of materials needed (Ancygier et al. 2023; Schlichenmaier and Naegler 2022). However, it may also bring opportunities in countries that are able to supply the materials or source them effectively and build local manufacturing capacity and supply chains (Hauber 2024). This localization has the potential to create new poles of growth in a range of countries, including in Africa (Barnes et al. 2023; Sustainable Energy for All 2023) and Asia, and especially in Saudi Arabia (Mulligan 2023; PIF 2024).

Much of the literature relating to the material requirements of the energy transition and the potential benefits of localization of production has understandably been focused on renewable energy deployment and the production of electric vehicles. However, the material requirements and potential for developing local supply chains for CCS have received less focus.

CCS offers a pathway to significantly reduce CO_2 emissions in sectors where alternatives are technologically or economically unfeasible. According to the IPCC, hard-to-abate sectors face inherent challenges in terms of decarbonizing due to process-related emissions that cannot be eliminated by simply transitioning to renewable energy.

CCS also allows the production of low-carbon baseload electricity, thus contributing to energy system flexibility (IEAGHG 2012). CCS is recognized as a strategic pillar in the net-zero targets of many countries. The IEA CCUS Database[1] and the GCCSI[2] highlight that over 200 CCS facilities are currently in development or in operation globally, with countries such as the U.S., Canada, Norway, Saudi Arabia, and Australia leading the way. Saudi Arabia, as part of its Circular Carbon Economy (CCE) framework, is leading initiatives to scale-up CCS. The country has set ambitious targets regarding the deployment of CCS in the Kingdom, with one target being to achieve 44 million tonnes per annum of CCS by 2035.

The Kingdom has positioned itself as a global leader in CCS technology as part of Vision 2030[3] and the Circular Carbon Economy (CCE) framework.[4] CCS is recognized as a cornerstone technology in Saudi's strategy to reduce GHG emissions while maintaining economic growth and energy security. The Kingdom's vast hydrocarbon resources, coupled with its extensive experience in energy infrastructure development, pose a unique advantage in scaling CCS technologies across power generation and industrial sectors. The country therefore provides an important case study in CCS development.

Finally, it should be highlighted that CCS also plays a crucial role in addressing equity concerns in the global energy transition. Fossil fuel-reliant developing nations can use CCS to decarbonize their economies while also preserving jobs and industrial capabilities. This ensures that the transition to a low-carbon economy can be achieved justly and ensures socioeconomic stability. Saudi Arabia is building the energy transition into local economy diversification efforts through targets of localizing the manufacture and deployment of the technologies required in the energy sector, with a target of locally producing 75% of these technologies.

This paper integrates research on the material requirements of CCS deployment with existing studies on CCS. It models the demand for materials (including consumables and critical minerals) necessary for projected global deployment of CCS and for a case study of KSA. It then discusses both the global and the KSA demand and supply dynamics, and it extends this analysis to discuss the localization opportunities of the deployment of CCS in the Kingdom.

Section 2 examines the literature surrounding critical minerals, the energy transition, localization, and CCS. Section 3 provides an overview of CCS in the Kingdom, including current projects, plans, and targets. Section 4 provides an outline of the methods toward quantifying material requirements for deploying CCS across the world and for the Kingdom. Section 5 discusses these material requirements and the implications for the localization of supply chains for the materials for CCS within the Kingdom. Section 6 provides a conclusion.

2. Summary of the Literature

Literature focusing on the material requirements of the technologies projected to be needed for the energy transition has evolved rapidly over the last decade. The first set of this literature consists of studies that have examined the material requirements of individual technologies. Seminal work in this area has been conducted by the EU's Joint Research Centre (Moss et al. 2013; Moss et al. 2011). These studies have outlined the various material requirements for a wide range of technologies, giving an estimation (kg or tonne per unit of capacity) for these technologies.

CCS is covered in Moss et al. (2011), addressing its use in electricity power plants. Crude estimations are made for the material requirements of the capture plant and the pipeline infrastructure based on existing gas generation plants, and two types of steel, API X65 and API X100, are highlighted for potential use in CCS infrastructure.

The reviewed studies collectively highlight the material-intensive nature of CCS technologies, with steel, concrete, and chemicals such as ammonia and solvents forming the core requirements. These materials are critical for constructing capture units, pipelines, and storage facilities, as well as maintaining operational efficiency. The studies highlight that while CCS offers substantial CO_2 mitigation potential, its lifecycle material impacts present challenges that require innovative solutions in material efficiency, recycling, and decarbonization of supply chains to achieve sustainable deployment at scale. Our paper contributes to this literature by extending these studies and scaling them up to the scenario level at global and KSA levels.

A second set of studies has grown out of this earlier identification of the material intensities of technologies. This literature has moved from examining the material requirements of individual technologies (Moss et al. 2013; Moss et al. 2011) to projecting the total material requirements from the installation of all the technologies needed for the energy transition as a whole. A branch of this literature has emerged from international agencies such as the IEA (2021a), the World Bank (Hund et al. 2020; The World Bank Group 2017), IRENA (Gielen and Papa 2021) and the Energy Transitions Commission (Energy Transitions Commission 2023). These studies have examined the material requirements of different future energy scenarios based on different levels of ambition, different technological scopes, and different underlying assumptions on a range of parameters, such as recycling rates. These studies have different types of coverage of CCS, depending on the role that it plays in the underlying emissions abatement scenarios on which they are based. Further academic studies have examined the same question (Tokimatsu et al. 2018; Watari et al. 2019; Wang et al. 2023; Bandpey, Rahimpour, and Kraslawski 2024), and they are summarized in Appendix 1 and Table 1.

Table 1. Review of key LCA and material requirement studies relating to CCS.

Reference	Focus area	Key findings as they relate to CCS and materials
LCA and material intensity studies		
Tahara, Kojima, and Inaba (1997)	CO_2 payback from renewable and fossil-fuel based systems	CCS plant level requirements are for steel and concrete, along with aluminum and amines
Spath and Mann (2000)	LCA of blue hydrogen (inc. CCS)	Steel, concrete, and chemicals identified as key requirements for CCS infrastructure
Odeh and Cockerill (2007)	LCA of power plants with and without CCS	Material requirements are largest for steel, concrete, and solvents
Koornneef et al. (2008)	LCA of CCS for coal plants	Significant steel and concrete required at a plant-level, and highlights the importance of ammonia and other chemicals
Moss et al. (2011)	Material intensity of technologies	Material requirements for capture plant and pipeline infrastructure
Singh et al. (2015)	LCA of CCS for coal plants	Higher steel, copper, and chemical requirements in CCS equipped plants
Kalt et al. (2022)	Material requirements of global electricity pathways	Importance of steel, concrete, and copper for CCS deployment
Cao, Chen, and Xiang (2024)	LCA of ultra-supercritical coal with and without CCS	Steel and concrete are the main requirements along with solvents and other chemicals
Material requirements studies		
Tokimatsu et al. (2018)	Covers CCS used in electricity sector	Vanadium and nickel flagged as distinctly critical
Watari et al. (2019)	Includes CCS for coal, gas, and biomass for electricity generation as per ETP scenario	Future energy scenarios will increase total material requirements
Hund et al. (2020)	Includes CCS for coal and gas electricity generation as per ETP scenario	Highlights material differences between scenarios with CCS from IEA and those without from IRENA
Gielen and Papa (2021)	No CCS Coverage	N/A
IEA (2021b)	No CCS Coverage	N/A
Energy Transitions Commission (2023)	Estimates amine demand for CCS and DAC	Discusses the need for chemical industry scale-up to meet CCS demands
Wang et al. (2023)	Covers CCS for coal, gas, and biomass	Includes emissions from production of materials
Bandpey, Rahimpour, and Kraslawski (2024)	Includes CCS for gas and coal in electricity	Highlights the role of CCS in mitigating critical mineral demand in net zero scenarios

The growing literature that has examined total material requirements has had different types of coverage of the deployment of CCS, from not including any to varying coverages across the electricity generation sector. This literature has highlighted that CCS could increase the criticality of some minerals, such as vanadium and nickel, while also increasing the demand for chemicals, such as amines. Our study extends this literature by looking at a broader deployment of CCS, which includes both industrial and electricity sector applications while capturing requirements for both structural materials, such as steel and concrete, and consumables, such as potassium carbonate and amines.

A critical narrative that has emerged within the literature regarding the low-carbon transition concerns the (local) economic benefits that could emerge. The narrative of "green jobs" associated with the construction and deployment of low-carbon technologies has been much discussed in the literature (Kozar and Sulich 2023; Dell'Anna 2021). Much of this discussion has been in the context of supply chains for renewable power (Zhou et al. 2022; Sooriyaarachchi et al. 2015), but a small policy-related literature has been emerging in the UK regarding the linkages between CCS and employment (Turner et al. 2023; Turner, Alabi, and Race 2019).

A key component of the "green jobs" economic development argument is the ability (and, indeed, the economic imperative in terms of creating domestic employment) to localize large segments of upstream supply chains for low-carbon energy technologies. This includes the manufacturing of the specific equipment involved as well as the extraction and processing of the materials required. The localization of renewable energy supply chains has been discussed in the context of Asia (Hauber 2024) and, more specifically, China (Quitzow, Huenteler, and Asmussen 2017), with the latter being especially successful in this regard. However, the move toward localization has not always been smooth, and the case of South Africa, for example, has been highlighted as having encountered several failures around its industrial policy (Morris et al. 2022, 2020). Within a KSA context, there has been much policy discussion and emerging academic literature examining the opportunities for localization and economic benefits, mainly in the context of renewable energy (Almarshoud and Adam 2021; Mulligan 2023).

In this paper, we extend this literature on localization, critical minerals, and material requirements by first examining what the material requirements of the proposed deployment of CCS both across the globe and within the Kingdom are likely to be, and then discussing options and opportunities for localization for each key material and, in turn, for local economic development.

3. Overview of CCS in KSA

CCS is vital to KSA's efforts to decarbonize hard-to-abate sectors, such as electricity, cement, steel, and petrochemicals, which collectively contribute significantly to the country's carbon footprint. Given the reliance on fossil fuels for power generation and industrial processes, CCS offers a pragmatic solution to achieving emissions reductions while continuing to leverage the Kingdom's energy resources. Additionally, CCS plays a crucial role in supporting the Kingdom's commitment to global climate agreements, such as the Paris Agreement, by facilitating the reduction of CO_2 emissions without undermining its energy-intensive industrial base.

KSA has implemented several high-profile CCS projects to showcase its leadership in carbon management. Notable initiatives include the Uthmaniyah CO_2 Enhanced Oil Recovery (EOR) project, which captures approximately 800,000 tonnes of CO_2 annually for injection into oil fields to enhance recovery while sequestering CO_2 underground.[5] This project highlights the dual benefits of CCS in reducing emissions and supporting hydrocarbon production.

Another major initiative is the Jubail Industrial City project, which integrates CCS with hydrogen production to generate low-carbon hydrogen for domestic use and export.[6] This initiative aligns with KSA's ambitions to become a global hydrogen leader while leveraging CCS to produce blue hydrogen sustainably. Moreover, research institutions like King Abdullah Petroleum Studies and Research Center (KAPSARC) and Saudi Aramco are actively exploring advanced CCS technologies and pathways to optimize energy efficiency and reduce costs.

KSA's CCE framework underscores the importance of CCS in achieving carbon neutrality through the "four-Rs" – reduce, reuse, recycle, and remove. CCS technologies complement other strategies, such as renewable energy expansion and energy efficiency measures, by addressing residual emissions from industries that are challenging to decarbonize. The integration of CCS with other carbon management technologies, such as direct air capture (DAC) and bioenergy with CCS (BECCS), further demonstrates the Kingdom's commitment to comprehensive climate solutions.

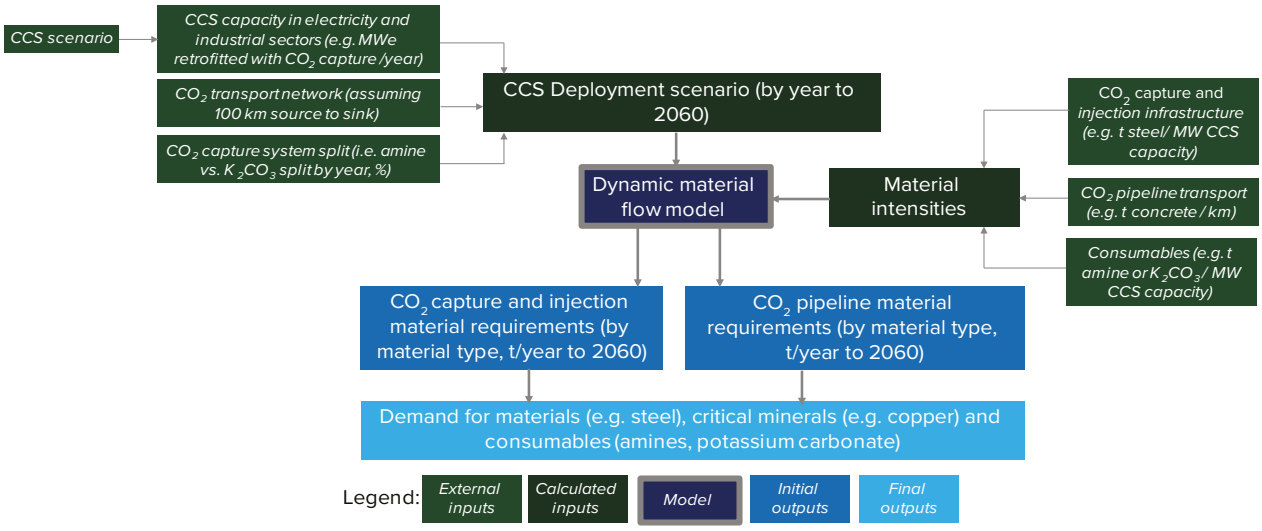
While KSA has made significant progress in CCS deployment, challenges remain, including the high costs associated with capture, transport, and storage infrastructure, as well as the energy penalty incurred during CO_2 capture. However, the Kingdom's access to low-cost energy and its established expertise in large-scale infrastructure development provide opportunities to overcome these barriers. International collaborations and partnerships with organizations such as the Global CCS Institute are also helping KSA to address technical and financial challenges while also contributing to the global knowledge base on CCS. Further details on storage capacity and costs in KSA are presented in Appendix 2.

4. Methods

The overall approach for estimating material requirements is shown in Figure 1. To estimate the material requirements for both the deployment of CCS across the world and for the case study of KSA, a dynamic material flow model was utilized that allowed for the total (and annual) material requirements to be projected under a range of scenarios. The model is based on previous literature (Hund et al. 2020; Moreira and Laing 2022; Deetman et al. 2021; Carrara et al. 2020) and tracks, on a mass basis, the materials needed for the construction and operation of CCS infrastructure, encompassing new capacities and retirements along with degradation rates of consumables.

It has key elements that we will discuss in turn. It estimates the material requirements for CCS in terms of the input materials required for construction and operation, as well as for the primary material requirements (i.e., the amount that needs to come from virgin extraction or production), and it contextualizes these requirements in terms of the current global and domestic production (where data exists).

Figure 1. Overall approach.



Source: Authors.

4.1 Global and KSA CCS Deployment Scenarios

A critical input is the scenario for the deployment of CCS across the globe and within the Kingdom. The scenarios make projections for the deployment of CCS in four categories:

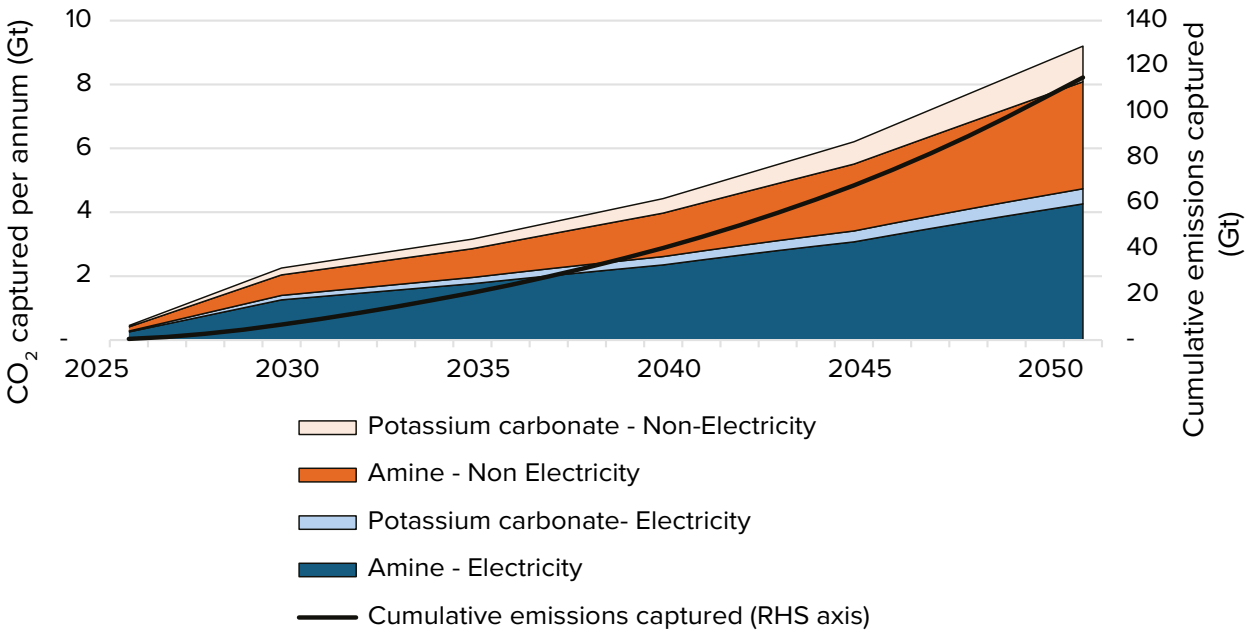
- CCS for electricity
  - Amines
  - Potassium carbonate
- CCS for non-electricity (e.g. steel, petrochemicals, cement)
  - Amines
  - Potassium carbonate

Several CO_2 capture systems can be deployed, including chemical and physical absorption, pressure and temperature swing adsorption, and membrane systems and cryogenic CO_2 separation and capture. For this analysis, though, we focused on chemical absorption technology for CO_2 capture, as it is currently the most established and conventional approach. This reflects the fact that chemical absorption systems, particularly liquid solvent-based approaches such as amine scrubbing and aqueous carbonate systems, are the most established and widely deployed at commercial scale. According to the Bloomberg NEF CCUS Project Database, as of December 2024, liquid absorption accounts for approximately 89.7% of current operational capture capacity globally, while membrane and solid adsorption systems make up 10.2% and less than 0.1%, respectively. These alternative systems, while useful for smaller applications such as hydrogen production, are not yet scalable for large industrial emitters like power plants, cement kilns, and refineries.

Under chemical absorption systems, amines and potassium carbonates are the most common solvents with systems already in commercial deployment, mainly in hydrogen and ammonia production, ethylene oxide, and other chemical processes, and for natural gas sweetening as part of natural gas processing.

The global CCS projections are based on the IEA Net Zero Emissions by 2050 Scenario of 1.7 Gt/y by 2030 and 7.7 Gt/y by 2050 (Figure 2), and they are limited to a 2050 timeframe.[7]

Figure 2. Projected global deployment of CCS up to 2050.

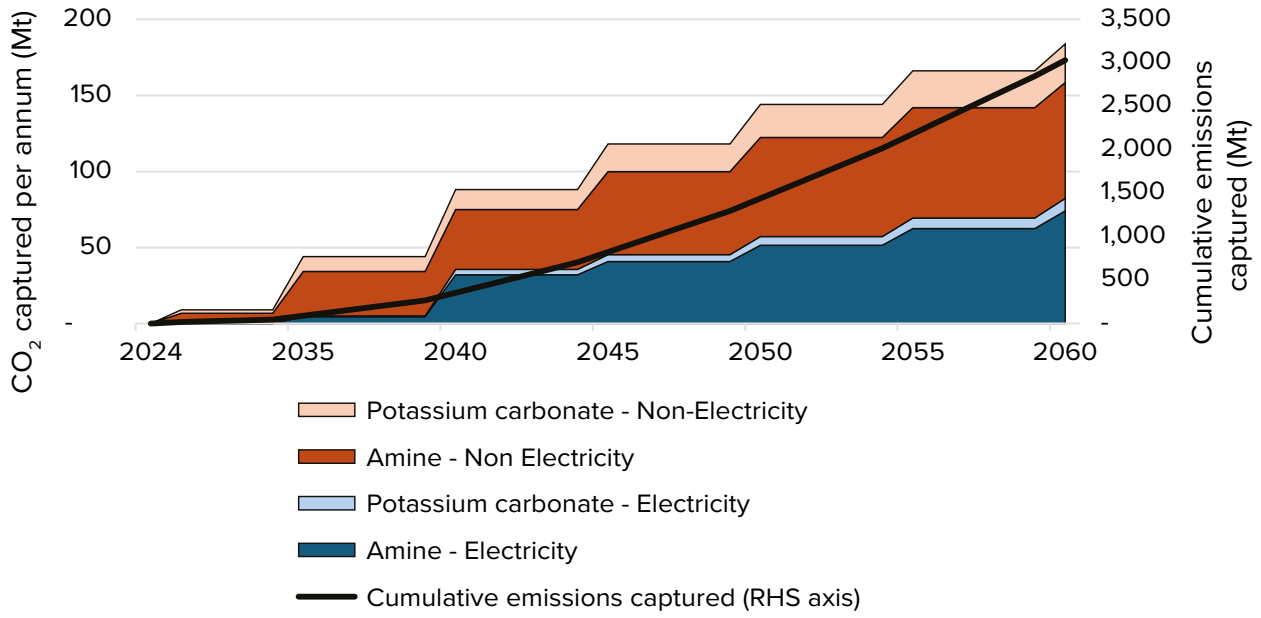


Source: Authors' estimation.

The baseline scenario for CCS growth in KSA is primarily based on an "NDC Continued" scenario, which applies emissions constraints, in addition to the "Current Policy" scenario, which includes no CCS, to achieve an emissions reduction of 278 $MtCO_{2eq}$ in the Kingdom by 2030 relative to a "No Policy" scenario, as reported by Kamboj et al. (2024) (Figure 3). The KSA scenario continues until 2060.

Under its Vision 2030 commitments, KSA has already pledged to achieve 9 Mt/y of CCS capacity between 2027 and 2030 (Phase I) and 44 Mt/y by 2035. Starting with the current 0.8 Mt/y (Uthmaniyah CCS project) in 2025, the model assumes a conservative increase to 3 Mt/y in 2030 (90% on industrial sites) and 35 Mt/y in 2035 (60% in the power sector and 40% in industry). This is then extrapolated to 145 Mt/y CCS by 2060 (57% in the power sector) (Table 2).

Figure 3. Projected deployment of CCS within KSA up to 2060.



Source: Authors' estimation.

Table 2. Projected CCS deployment within KSA up to 2060 (Mt/y).

	2025	2030	2035	2040	2045	2050	2055	2060
Electricity	0.0	0.1	21.4	35.6	45.3	57.2	69.4	82.3
Non-electricity	0.8	2.7	13.7	31.2	43.4	52.5	58.8	62.3
Total	0.8	3	35	67	89	110	128	145

** Source: Adapted from Kamboj et al. (2024).*

4.2 Selecting Types of CO_2 Capture Technology: Amines vs. Carbonate Systems

As highlighted, amine and potassium carbonate-based CO_2 capture solvents are both well-established technologies, yet their long-term deployment in future CCS plants depends not only on their efficiency but also on their stability and degradation mechanisms. For this analysis, the projected CCS capacity for power generation and industrial sectors from 2025 to 2060 is further divided into amine-based CO_2 capture systems (e.g., Econamine FG Plus process by Fluor Corporation, the KM carbon dioxide recovery process by Mitsubishi Heavy Industry (MHI)) and potassium carbonate-based CO_2 capture systems (e.g., the Benfield Process by Honeywell UOP,[8] or Shell Global Solutions).[9] (We outline the details and the justification of this division for both the globe and KSA in Appendix 3.)

To examine the impact of increasing the capture of some of the market by potassium carbonate-based capture systems, especially in the industrial sectors, we also analyze a more potassium-carbonate intensive scenario (High K_2CO_3). We assume a baseline division between amine-based and potassium carbonate solvent systems based on our expert judgment and a review of the literature, as well as recent datasets on emerging CCS applications. In the base scenario, amine systems account for 90% of CO_2 capture in the electricity sector and 75% in industrial sectors, with potassium carbonate systems representing the remaining 10% and 25%, respectively. While both solvent systems are widely deployed in established CO_2 removal applications, particularly in hydrogen production, amine-based systems remain the technology of choice for full-scale CCS, as reflected in the proliferation of commercial technology providers and project announcements over the past two decades.

The higher assumed share of potassium carbonate in industry reflects its suitability for higher-pressure applications, as demonstrated by the deployment of over 700 UOP potassium carbonate-based units (Benfield process) worldwide (Honeywell 2024), particularly in the hydrogen and gas processing sectors. However, the use of potassium carbonate systems in power generation and energy-intensive industrial sectors, such as cement and iron and steel, remains less advanced compared to amine-based systems, which dominate among the announced CCS projects due to their greater commercial maturity and operational track record.

Notably, the CATACARB process, a potassium carbonate-based system, has been selected for the planned Stockholm Exergi Bioenergy with CCS project in Sweden, signaling potential future uptake in both power and industrial applications (see CATACARB n.d.).

We also explore an alternative scenario with a greater uptake of potassium carbonate systems, reaching 30% in the electricity sector and 60% in industrial sectors. This reflects a plausible shift driven by potassium carbonate's favorable thermal stability and potential cost advantages, particularly in industrial contexts. Additional data on the technology split is given in Appendix 3.

4.3 Transportation Assumptions

The material requirements for CO_2 pipeline construction across the globe and in KSA (e.g., steel, concrete) depend on the length, diameter and wall thickness of pipeline, which, in turn, depends on the volumes transported. An approximation methodology for both the world and the KSA case study is used in this paper to estimate the diameter, thickness, and steel requirements for the pipeline, and this is outlined in Appendix 3.

Our methodology is based on fluid mechanics equations applied to a reference case of 1 Mt/y CO_2 transported over 100 km, from which pipeline diameter and wall thickness were calculated based on the assumptions and methodology described in detail in Appendix 3. These parameters were used to estimate the steel volume required per unit length, incorporating standard assumptions such as design pressure, carbon steel strength, and steel density.

Global and national material requirements were then scaled proportionally based on total CCS capacity in each case, using the reference pipeline segment (1 Mt CO_2/y transport for 100 km) as a base unit. A detailed step-by-step of the calculation procedure used is provided in Appendix 3.

4.4 Material Intensities

The second key input is the material intensities of different components of key CCS infrastructure. The material intensities can be split into three main areas: capture and injection infrastructure, pipelines for transportation, and consumables (i.e., amines and potassium carbonates).[10]

For the first area, the models draw on estimates from the literature (chiefly Koornneef et al. 2008, but also Moss et al. 2011, Spath and Mann 2000, and Tahara et al. 1997). The focus of this literature is on steel and the related alloying elements needed for the capture infrastructure, along with concrete and ancillary elements such as copper. Further assumptions regarding steel intensity and grade are outlined in Appendix 3. The same intensities are assumed for CCS deployment across the world and in KSA, with the functional unit being tonnes of CO_2 captured.

4.5 Ancillary Assumptions

Further assumptions were made regarding the lifetime of the CCS infrastructure, inclusive of the pipelines (25 years for all infrastructure) and the material recycling rates (based on Graedel et al. 2011). Global production for the majority of materials was based on the USGS (2024a).

5. Overall Material Requirements for CCS and Localization Potential

In this section, we show the material requirements for CCS deployment across the globe, followed by the requirements for our case study of KSA. It should be noted that, as discussed above, the global projections extend to 2050, while those for KSA extend to 2060.

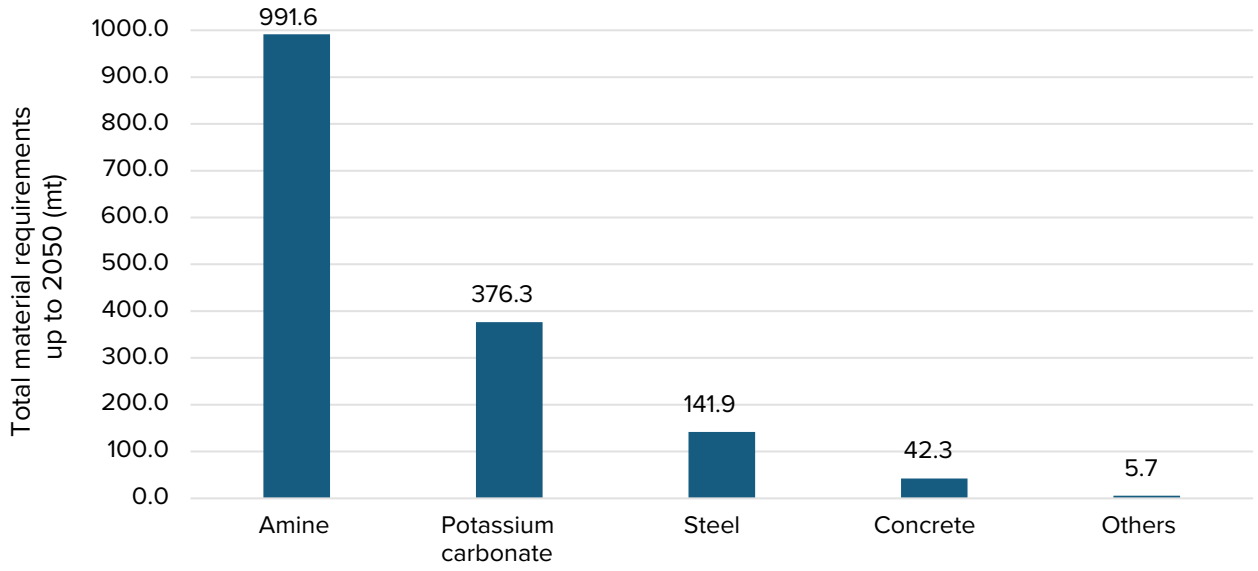
5.1 Global Material Requirements

The largest material requirement for deployment of CCS by volume (Figure 4) is for amines (64%), followed by potassium carbonate (24%) and steel (9%). Total global demand for amines for CCS up to 2050 is greater than 990 million tonnes, with approximately 375 million tonnes of potassium carbonate. Steel requirements are approximately 150 million tonnes.

The highest relative demands (compared to current global production levels) are for consumables – especially potassium carbonate, with annual average requirements at almost 750% of current production levels (although there is potential for production to expand rapidly – see Section 5.6), and for amines with annual requirements at almost 400% of the current annual production estimates. Should greater deployment of potassium carbonate emerge as per our High K_2CO_3 scenario, amine global demand falls to approximately 270% of current production levels, but demand for potassium carbonate increases markedly – to almost 20 times current production levels (Figure 5). Relative requirements for minerals are lower, with average molybdenum requirements at 2.8% of current global production, followed by niobium at 2.4% and vanadium at 2.0%.

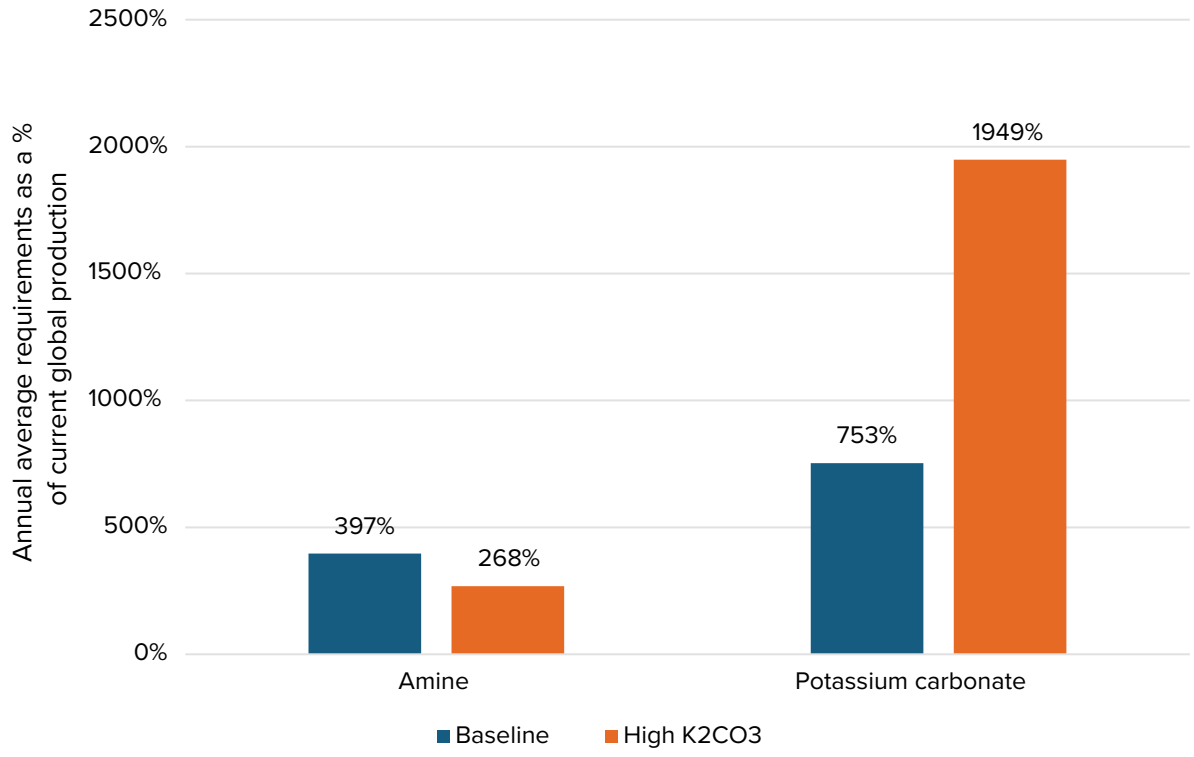
However, given the nature of CCS deployment, which is unlikely to be linear (i.e., with large developments happening in a few years), this demand may not be evenly distributed over time. We therefore examine not just the annual average but also the largest annual requirement and how that compares with current production levels. When this metric is examined, the share of global production increases, with potassium carbonate reaching almost 11 times current production levels, amines at 630%, and metals such as molybdenum at 4%, niobium at 3.5%, and vanadium at 2.9%. These market shares indicate that there could be challenges in meeting some of the projected demand levels for chemicals if supply does not respond accordingly or if competing demands for these materials are also increasing. We examine these issues more in relation to steel, concrete, amines, and potassium carbonate in Section 5, and in relation to other materials in Appendix 4.

Figure 4. Cumulative global material demands for CCS up to 2050 to meet projected scenario.



Source: Authors' estimation.

Figure 5. Annual average requirements up to 2050 for consumables for projected global CCS deployment as a % of current global production.

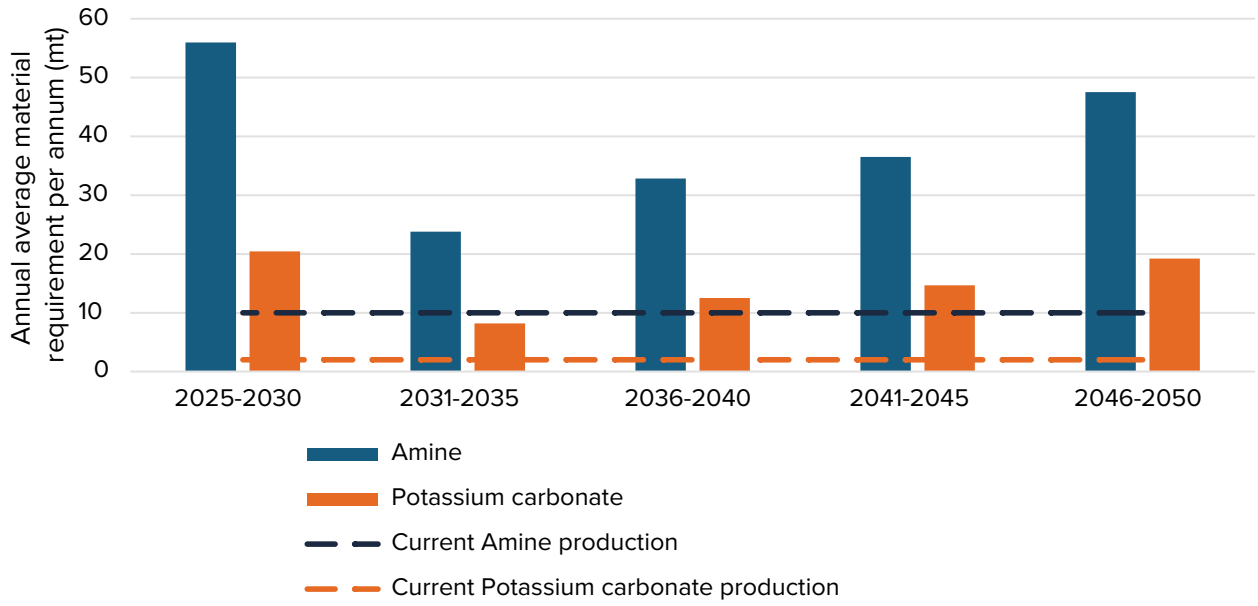


Source: Authors' estimation.

The annual average requirements for consumables for CCS are shown in more detail in Figure 6. Demand for both potassium carbonate and amines occurs not only with the construction of the capture infrastructure but also on an ongoing basis, depending on the level of existing capacity and the degradation of these active chemicals.

The requirements are largest in the late 2020s for both amines and potassium carbonate, which aligns with a projected wave of expansion of CCS facilities. However, due to the need for replenishment of consumables, demand continues at a steady rate through 2050, even though the expansion of facilities occurs at a slower pace.

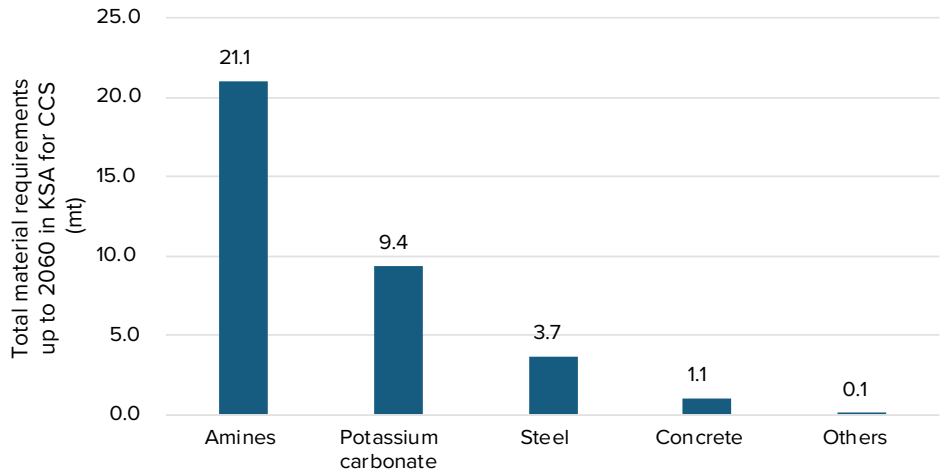
Figure 6. Annual average requirements up to 2050 by time-slice for consumables for projected global CCS deployment.



5.2 KSA Material Requirements

The largest material requirement for the deployment of CCS in KSA mirrors that of the global situation, with the greatest needs for potassium carbonate and amines, followed by steel (Figure 7). KSA would need over 23 million tonnes of potassium carbonate and over 13 million tonnes of amines up to 2060 in order to meet the projected CCS scenario, with peaks at almost eight times the average annual requirement,[11] along with over 3.5 million tonnes of steel – the latter predominantly for use in pipelines for transporting CO_2 to injection and storage sites. The next largest material by volume is concrete – again, predominantly for pipelines. Other materials, such as alloying elements, including nickel, niobium, and vanadium, make up the rest of the materials.

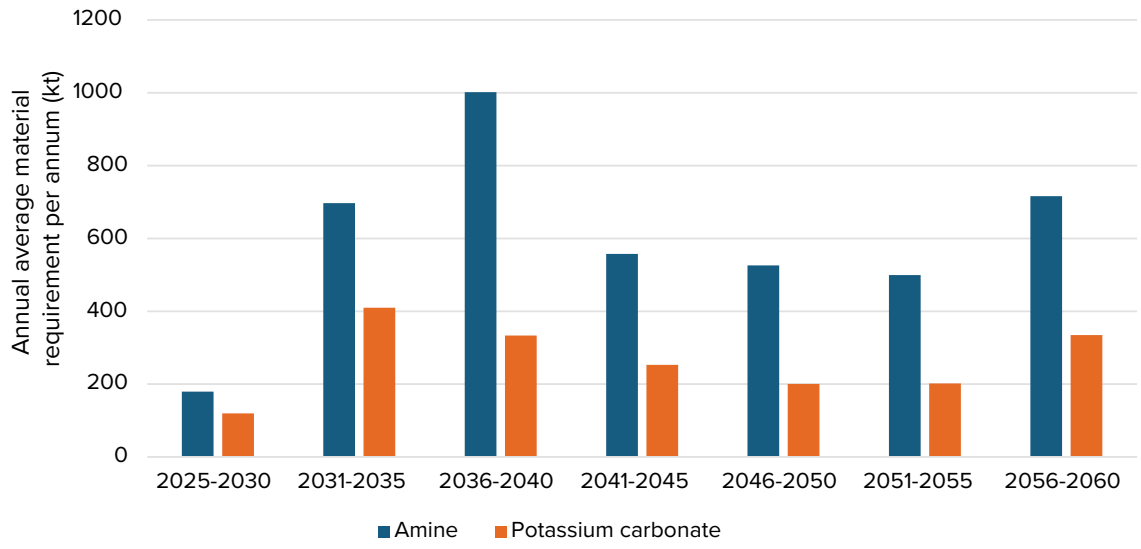
Figure 7. Cumulative material requirements for the KSA CCS Deployment scenario up to 2060.



Source: Authors' estimation.

Comparing these figures to the current estimated global production shows that the Kingdom would require an average of 13% of the current global annual potassium carbonate production and about 6% of the current global amine production to achieve the 2060 CCS scenario. The move to a high K_2CO_3 scenario increases potassium carbonate demand to almost a third of the current global production, with amine requirements falling to 4% of the current production levels. The requirements for other materials are much lower, with steel at 0.005% of global production, molybdenum at 0.05%, and vanadium and niobium at 0.04%. Annual requirements for consumables mirror similar trends globally, but with slightly later peaks in the 2030s for amines and potassium carbonate (Figure 8).

Figure 8. Average annual requirements for consumables for CCS deployment scenario in KSA up to 2060.



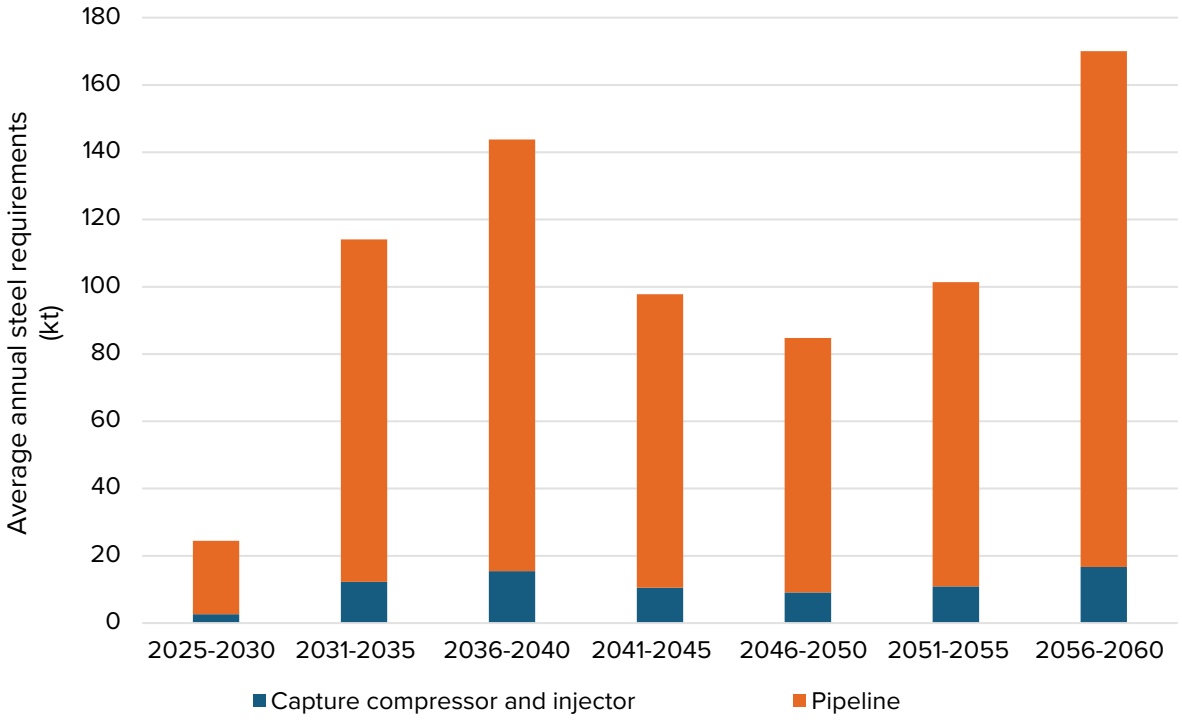
Source: Authors' estimation.

In the subsections below, we discuss the specific requirements for four key materials for CCS deployment (steel, concrete, amines, and potassium carbonate), their production and demand context, and the prospects for localization of production within KSA. (Similar analysis for other materials is given in Appendix 4.)

5.3 Steel

Steel is a vital component for the development of CCS infrastructure. It is needed in all phases of operation from the capture infrastructure to the compressors and the injector facilities. The greatest requirement is in the pipeline infrastructure (approximately 89%) both globally and in KSA (Figure 9). Changes to assumptions regarding the structure of the transport network therefore have key implications for the steel requirements for CCS.

Figure 9. Steel required for construction of CCS infrastructure in KSA up to 2060 by stage.



Source: Authors' estimation.

To deploy the global scenario requires 141.9 million tonnes of steel up to 2050, with an annual average of 5.7 million tonnes and an annual maximum of 8.1 million tonnes. The production of this steel would require energy of 120 PJ per annum – approximately the same amount as total annual energy consumption of Estonia.[12] Capital costs of approximately US$3.3 billion would be required to build sufficient electric arc furnace capacity to supply this steel.[13] To deploy the projected scenario for KSA, approximately 3.7 million tonnes of steel are estimated to be required up to 2060. This equates to an annual average of 103 kt per annum (requiring over 2 PJ in energy), but with a maximum requirement of 850 kt per annum.

Although this tonnage is large, the requirements are still small compared to the global market, or, indeed, even compared to KSA's current production capacity. Annual average global requirements for steel from CCS account for just 0.3% of the current global production (or 0.7% of the ex-China market). KSA produced approximately

9,940 kt of steel in 2023, rising 21% from 2019 production levels (World Steel 2024).[14] This accounted for 0.53% of the total global production in 2023, rising slightly from the 2019 level of 0.44% (World Steel 2024). This production capacity, which may be expanded given the investments in the industry, is comfortably sufficient to meet the requirements of the projected deployment of CCS in the Kingdom. The total requirements for steel up to 2060 in the base case account for just 37% of current annual capacity, and, therefore, just 1.2% of annual production. Thus, even with increases in demand from other components of the economy, assuming that the correct grades of steel are available, there is potential for 100% localization of the steel requirements for the deployment of CCS in the Kingdom.

The production of steel is a crucial provider of employment, and a gross value added to countries across the world. Using the average ratio of production to jobs from the steel industry in the EU,[15] the production of the steel that is needed for the deployment of CCS in KSA, if it was all produced domestically, could support 230 jobs directly, rising to over 1,925 if indirect and induced jobs are included at the same rate as they are projected to occur within the EU (EUROFER 2023). If the maximum annual requirements are considered, producing that level of steel per annum would support 1,900 jobs per annum, rising to 16,000 if indirect and induced impacts are considered (although it is unlikely that all of these would occur domestically). Gross value added from the annual average production would be approximately US$40 million per annum, rising to US$250 million per annum if indirect and induced impacts are included (assuming the same GVA and multipliers as assumed in EUROFER (2023). This would rise to US$150 million per annum if a maximum production capacity is put in place, rising to US$900 million with indirect and induced impacts (again, with the caveat that not all of this is likely to remain in KSA). Globally, the annual average steel requirement for CCS could support approximately 12,800 jobs directly, rising to 107,000 if indirect and induced impacts are included (assuming the same multipliers as above). Gross value added is projected at approximately US$1 billion per annum, rising to US$6 billion with indirect and induced impacts.

The requirements for steel for CCS deployment in KSA are moderate compared to current production levels, and are well within scope for full localization, assuming that the appropriate grades of steel are available on the local market. Furthermore, the global steel demands for CCS are also within the global ability to supply, but they do offer opportunities in terms of value and jobs should there be the opportunity to meet this global demand with competitive exports.

5.4 Concrete

Similar to steel, concrete is needed across all aspects of CCS deployment from the capture infrastructure to the pipelines. However, the balance for concrete requirements is different, with two-thirds needed in the capture, compressor, and injector infrastructure compared to one-third for the pipeline infrastructure. At a global level, CCS deployment would require 42.2 million tonnes in total up to 2050, equating to 1.7 million tonnes per annum, with a peak requirement of 2.4 million tonnes. These numbers are relatively small compared to the global cement production of approximately 4 billion tonnes,[16] and they should thus be comfortably within the global ability to supply. The requirements for concrete for CCS deployment in KSA equate to approximately 1 million tonnes up to 2060 – an annual average of 30 kt per annum, with a peak demand of approximately 240 kt per annum. KSA's production of cement in 2023 equated to 49.2 million tonnes, with domestic sales slightly smaller at 47.3 million tonnes.

The average annual requirement for CCS deployment of 30 kt of concrete, or approximately 5 kt of cement, thus represents only a very small share of the total annual production, and, even with increasing demand for concrete with wider economic development, it should be feasible to meet demands for CCS using localized production.

5.5 Amines

The use of amines is a key component of the wide deployment of CCS in KSA and beyond. A number of different amines may be utilized in CCS, including ethanolamines (such as monoethanolamines), diethanolamines, or methyldiethanolamines (Luis 2016), and propanolamines (such as diisopropanolamines) (Shao and Stangeland 2009). The nature of the use of the amines in CCS means that the demand for the product from CCS is annual – with a greater demand at the construction of CCS equipment, and with residual demand in the intervening years to replace amines that are lost to the system.

Ethanolamines are produced by treating ethylene oxide with ammonia, while propanolamines are based on the combination of propylene oxide (from propane) and ammonia. Ethylene is predominantly produced in steam crackers from hydrocarbons (Chen et al. 2024), while propylene is produced either from steam cracking or as a by-product of refining operations, specifically fluid catalytic cracking (Akah and Al-Ghrami 2015). Ammonia is predominantly produced from steam reforming via the Haber-Bosch process.

Ethylene and propylene oxide are widely produced in KSA by companies such as Sadara. Ammonia is also widely produced in the country, with 3% of the total global production equating to 4 million tonnes (USGS 2024e). In addition to the capacity to produce the precursor ingredients, there is also a capacity to produce the amines themselves in the Kingdom with plants that produce both amines.[17] Indeed, the development of future productive capacity has been identified as a crucial area for future investment in the Kingdom.[18]

Globally, 991 million tonnes would be needed for CCS deployment up to 2050, which is an annual average of 39.6 million tonnes, with a peak capacity of 62.9 million tonnes. These global requirements indicate that, should the CCS scenario be achieved, there would have to be a scale-up of global amine production. However, given the global production of the precursor ingredients, it is likely that this is within the scale of potential expansion for the industry. The energy required for this production of amines would be approximately 140 PJ per annum, the majority of which would be for heat.

The requirements for amines for CCS deployment in KSA are projected at an annual average of 585 kt per annum (with an energy requirement of approximately 2.1 PJ per annum), with a peak requirement of 4.8 mt per annum. Total needs up to 2060 equate to 21 million tonnes, inclusive of what is required to replenish degraded materials. Localizing the requirements for amines for CCS deployment in KSA is likely to be highly feasible, and it could offer export opportunities for the country.

5.6 Potassium Carbonate

As an alternative to amines, some CCS may utilize potassium carbonate to capture CO_2 (Smith et al. 2014; Borhani et al. 2015). Potassium carbonate is produced using potash, which is widely mined across the world, with Canada and China representing almost 50% of the global production (USGS 2024b). Potash is predominantly used for fertilizer production, accounting for 86% of the approximately 45 million tonnes produced annually (European Commission 2022b). There are considerable global resources and reserves, which are sufficient to meet current demand levels for decades (USGS 2024b).

Global potassium carbonate production is approximately 2 million tonnes (ChemAnalyst 2023), but it could be scaled up if required given the scale of global potash production, although it does risk diverting potash away from fertilizer production.

Globally, requirements are 15 million tonnes per annum, with a peak at 22.7 million tonnes, and a total requirement of 376 million tonnes up to 2050. These global requirements are approximately 7.5 times higher than the current production levels (rising to almost 20 times in the high K_2CO_3 scenario), and they indicate that global production would need to sharply increase in order to meet demands. This expansion is technically possible, and other reports have highlighted that it is likely to be within the ability of the global chemicals industry given the relatively simple production process (Energy Transitions Commission 2023). However, the greatest risk could be substituting potash input away from fertilizer production, with both real and perceived impacts on food markets and global food security. Rising potash requirements to meet potassium carbonate demands for CCS would lead to rising potash and, therefore, rising fertilizer prices, at least in the short term as potash production capacity increases. This would create risks regarding global food security, and also around the perception of CCS. Should there be widespread utilization of other technologies that may require potassium carbonate, such as direct air capture (DAC), these risks could be even greater. The total energy requirements to produce the potassium carbonate required would be approximately 53 PJ per annum.

Potassium carbonate requirements in KSA for CCS up to 2060 are projected at 9.3 mt, which is an annual average of 260kt per annum (requiring 0.9 PJ per annum). These requirements equate to 13% of current global production, rising to 33% in the high K_2CO_3 scenario.

Within the region, potash is produced in Jordan by Arab Potash, which produced 1,800 kt in 2023, accounting for 4.6% of the global supply. This supply could help to

meet the KSA CCS deployment, and agreements are in place with Ma'aden in the Kingdom and Arab Potash that focus on specialized products and fertilizers, but greater production is likely to be required in order to meet both fertilizer production and CCS deployment (Argaam 2022). There is also potential for domestic potash production (Hains et al. 2016). Given the timelines to develop production capacity, the potential to meet local demands for CCS for potassium carbonate is low in the short term, but it could increase in the long term if local potash production emerges.

The potential challenges related to meeting the requirements from CCS deployment of solvent production suggest that research and development is needed in relation to both improving the performance of existing chemicals and the development of new alternatives. Emerging next-generation solvents, including advanced amine formulations, amino acid salts, and phase-change solvents, may offer lower degradation rates, reduced energy penalties, and lower volumetric demand, potentially reducing supply chain pressure. However, the safety, costs, environmental performance, and technical parameters of such new solvents will need to be verified.

5.7 Localization Opportunities

KSA has identified a key target of localizing 75% of the value of the energy sector by 2030 (Saudi Gazette 2022). For CCS, this would involve localizing key components such as the production of the pipelines, the capture infrastructure, the injectors, and the replacement consumables like amines and potassium carbonate. This would require sourcing and securing sufficient critical minerals and materials to produce this equipment (and materials such as steel). The previous section discussed local current and future potential for extracting or producing those materials. The potential for domestic production and CCS material requirements is summarized in Table 3.

Table 3. Total material requirements for CCS deployment globally and in KSA cumulatively ranked from highest to lowest, and current status from production domestically.

Material	Total KSA material requirements up to 2060 (kt)	Total global material requirements up to 2050 (kt)	Current annual global production (kt)	Domestic production potential
Amines	21,067	991,610	10,000[19]	Currently produced
Potassium carbonate	9,384	376,340	2,000[20]	Potential for production (via regional partners)
Steel	3,706	141,873	1,900,000	Currently produced
Concrete	1,091	42,277	34,000,000	Currently produced
Manganese	50	1,922	20,000	No current production
Nickel	39	1,518	3,700	No current production
Chromium	29	1,169	47,000	No current production
Copper	17	666	27,000	Currently produced (extracted but not refined)
Molybdenum	4.7	182	260	No current production
Titanium	3.6	141	320	Currently produced (processed but not mined)

Table 3. Continued.

Niobium	1.3	51	110	Potential for production
Vanadium	1.3	51	100	Potential for production
Cobalt	0.1	3.8	290	No current production
Aluminum	0.1	5.3	72,000	Currently produced

Source: Authors' estimation.

Table 3 highlights that the localization potential for the materials required for the deployment of the proposed level of CCS in the Kingdom is high. For the materials with the greatest absolute requirements, there is already sufficient domestic production capacity (with potential exceptions for specialist grades of steel). For others with relatively niche demand in potentially tight global markets, such as niobium and vanadium, there is the potential for local production through conventional or unconventional approaches. There is not sufficient demand from CCS itself to justify such local production of these materials; however, as they also face potential rises in demand from the energy transition more broadly, it could transpire that material demand from CCS plays a role in higher levels of material demand from the energy transition as a whole.

Realizing the global potential of CCS and also the economic localization opportunities will require action at both global and country-level scales. Globally targeted R&D, technology demonstrations, and materials foresight to reduce future bottlenecks and support the required CCS scalability are all required. At the KSA level, priority should be given to supporting research and development programs at universities and research centers across the Kingdom, with a particular focus on advancing next-generation solvents to alleviate pressure on amine and potassium carbonate supply chains. In parallel, strategies to position KSA as a regional leader in CCS material manufacturing should be actively promoted. Embedding CCS material localization within the broader Vision 2030 industrial and economic diversification agenda, especially across the chemicals, metals, and advanced manufacturing sectors, could unlock significant value and establish the Kingdom as a hub for low-carbon industrial innovation.

6. Conclusion

This paper has examined the material requirements for the projected deployment of CCS in KSA and globally, highlighting the key materials needed for the capture, transport, and storage infrastructure. The findings indicate that the greatest material demand is expected for consumables – amine solvents (cumulatively, over 670 million tonnes globally up to 2050, with average annual requirements at almost four times current annual global supply) and potassium carbonate (over 375 million tonnes globally up to 2050, with annual requirements at 7.5 times current annual supply, and rising to 20 times in the high K_2CO_3 scenario). Significant steel (over 140 million tonnes globally up to 2050) and concrete (over 40 million tonnes) will be required for infrastructure.

These findings suggest that global production capacity is likely to be sufficient to meet demand for most of the materials required, but that production of specific chemicals will need to scale-up rapidly, with challenges in terms of competition with other sources of demand, such as fertilizers. Alloying elements for corrosion-resistant steel (niobium, nickel, vanadium) will also face broader energy transition demand challenges. The scale of requirements for chemicals such as amines and potassium carbonate means that the scale-up of CCS will depend not only on scaling current material supply chains but also on improving the performance of the chemicals, and, in addition, developing new, next-generation solvents with improved efficiency and reduced environmental impacts.

This study has expanded on the existing literature by estimating both global and local CCS material needs, and by exploring Saudi Arabia's local supply chain potential. Material demand estimates rely on assumptions regarding CCS deployment, steel grades, and capture technology assumptions. Pipeline length for CO_2 transport is also a major uncertainty, favoring optimized networks over single pipelines in order to reduce material demand and costs, especially for critical alloys. Most of the required materials for KSA's CCS goals are potentially locally available, offering localization and export opportunities if technical and cost barriers are overcome.

The limitations of the study include the historic nature of material intensity data for CCS equipment, which highlights the need for updated figures from current projects as well as analysis of steel grades. Future research should explore various deployment and transportation scenarios in order to analyze material requirements, potential bottlenecks, localization opportunities, and investment potential, along with comparisons between the material requirements of different types of energy scenarios, such as CCS versus renewable-intensive deployments.

Endnotes

1 https://www.iea.org/data-and-statistics/data-product/ccus-projects-database.

2 https://www.globalccsinstitute.com/resources/global-status-report/.

3 https://www.sgi.gov.sa/about-sgi/sgi-targets/reduce-carbon-emissions/.

4 https://www.moenergy.gov.sa/en/OurPrograms/Sustainability/CircularEconomy/Pages/default.aspx.

5 https://fossil.energy.gov/archives/cslf/Projects/Uthmaniyah.html.

6 https://www.aramco.com/en/what-we-do/energy-innovation/advancing-energy-solutions/carbon-capture-utilization-and-storage.

7 https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage.

8 https://uop.honeywell.com/en/equipment-and-aftermarket-services/aftermarket/gas-processing/spare-parts-consumables-and-services.

9 https://www.shell.com/business-customers/catalysts-technologies/licensed-technologies/emissions-standards/tail-gas-treatment-unit/cansolv-co$_2$.html.

10 The requirements for activated carbon and sodium hydroxide were also considered (with more information in Appendix 3) but were deemed too small to have major impacts.

11 The peaks are partly due to the lumpy nature of CCS deployment, which the scenario may overestimate.

12 Based on 2022 average energy intensity of steel production.

13 This is based on capital cost estimates per tonne of capacity in Benavides et al. (2024).

14 The production of steel is from both public and private companies in the Kingdom. In 2023, the Public Investment Fund (PIF) procured the previously SABIC-owned Saudi Iron and Steel Company (Hadeed), with the previously private AlRajhi Steel Industries Company also being brought into the new umbrella company to create a new national steel champion.

15 EU multipliers are used in the absence of Saudi-specific data. They may however misrepresent what is likely to be the employment impact, which will be dependent on local circumstances and the types of technology utilized for steel manufacture.

16 https://gccassociation.org/concretefuture/cement-concrete-around-the-world/.

17 https://www.sadara.com/News?NewsArticle=Sadara+announces+startup+of+its+Amines+Facility.

18 https://www.investsaudi.sa/medias/Ethyl-Amines-EA.pdf?context=bWFzdGVyfHBvcnRhbC1tZWRpYXw1MDU3MDZ8YXBwbGljYXRpb24vcGRmfHBvcnRhbC1tZWRpYS9oNGlvaDQ5Lzg5MDk1OTM0MTE2MTQucGRmfDlkMWNkMTVhMWZmZmYyOTY0NmIzZWRhOWY2NDcxZmM3N2E4NWZkM2U3YWNiMDcwNjBlNDM3N2I2MzhlNGMzOTg.

19 There is a lack of data on global amine production. The estimate here is based on market size estimates from Forbes and amine prices from Alibaba. It should be noted that there is considerable variation in estimates of both of these variables, and total production data should therefore be seen as an approximation.

20 There is a lack of data on global potassium carbonate production. The estimate here is based on data from ChemAnalyst (2023).

21 https://projectblue.com/blue/news-analysis/142/vanadium:-plans-to-construct-and-operate-a-metals-supercentre-in-saudi-arabia. https://www.shell-amg.com/supercenter.html. https://investsaudi.sa/medias/VANADIUM.pdf?context=bWFzdGVyfHBvcnRhbC1tZWRpYXw1NzU1MDZ8YXBwbGljYXRpb24vcGRmfHBvcnRhbC1tZWRpYS9oODUvaDIyLzg5MDk2MDEwNzkzMjYucGRmfDQ5ZjM1ODc5MWM0NzU5MGNhZTdhNTBjYjllODc0MWY3Mzc3MWFhZDI4NjhiZmRmOTY3MTExOGZmYzAxYjNlNzQ.

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Appendix

Appendix 1: Detailed Literature Review

LCA Studies

Singh et al. (2015) deployed LCA methodologies to assess the material requirements for CCS-equipped coal power plants. Their findings showed that while CCS reduces CO_2 emissions by up to 83%, it increases material use significantly. The study estimated a 60% increase in steel consumption, a 20% increase in copper consumption, and a 400% rise in the use of ammonia and other chemicals for CCS operations. These material intensities highlight the need for optimized designs and supply chain strategies to mitigate the environmental impacts of scaling CCS technologies. The detailed analysis also revealed that steel is extensively used for constructing CO_2 pipelines and capture equipment, while concrete forms the foundation of CCS infrastructure. Chemicals like ammonia, used for CO_2 capture, represent a substantial operational input that must be sourced sustainably. The study emphasizes the importance of balancing the material and environmental trade-offs associated with CCS by prioritizing innovations in material efficiency, recycling, and alternative supply chain approaches.

Kalt et al. (2022) analyzed global electricity pathways to 2050, focusing on their material requirements and greenhouse gas (GHG) emissions. The study highlighted that scenarios aligned with the 1.5°C climate target demand significantly higher material inputs due to the increased deployment of renewable energy systems, grid infrastructure, and CCS. The authors emphasized the importance of decarbonizing material production processes, as upstream emissions from materials such as steel and concrete could constitute a substantial fraction of the remaining carbon budget. The study underscores the need for integrated approaches that consider both technological deployment and the material supply chains required to support them. The material requirements for CCS include bulk materials, such as steel for pipelines and equipment, concrete for infrastructure and foundations, and aluminum for auxiliary systems. The study also pointed out the importance of critical minerals like copper, which is used in integrating power systems and infrastructure. These demands highlight the challenges of scaling CCS in a sustainable manner, particularly when considering the emissions and energy required for material production. The authors advocate for strategies to decarbonize material manufacturing and optimize material efficiency to reduce environmental trade-offs.

For power plants with CCS, the existing literature indicates that bulk material requirements are up to twice as high as those of the corresponding conventional power plants (without CCS). Based on Singh et al. (2015), Volkart et al. (2013), Luderer et al. (2015), and Cormos and Agachi (2012), the paper assumes that the material intensities, including infrastructure for the transport and injection of CO_2, are at least 50% and up to 100% higher than those of the conventional power plants without CCS.

Koornneef et al. (2008) conducted an LCA of pulverized coal power plants with post-combustion CCS, evaluating environmental impacts across capture, transport, and storage phases. The study finds that while CCS reduces greenhouse gas emissions by up to 78%, it introduces environmental trade-offs, such as increased toxicity, eutrophication, and ozone depletion. These impacts arise from the additional energy and resource consumption required for CCS operations, and from emissions of ammonia and other byproducts. Koornneef et al. (2008) emphasize that while CCS is crucial for decarbonizing fossil-fuel-based power systems, its deployment must be carefully managed to minimize unintended environmental consequences. The material requirements identified in this study include significant quantities of steel and concrete for constructing capture units, pipelines, and storage facilities. Ammonia and other chemicals are essential for CO_2 capture processes, contributing to both direct material consumption and indirect emissions during their production. The energy penalty associated with CCS increases the demand for fuel inputs, indirectly influencing upstream material extraction and processing. Koornneef et al. (2008) suggest innovations in material design and recycling to reduce these requirements and enhance the environmental sustainability of CCS.

Tahara et al. (1997) evaluated the CO_2 payback times for various power plants, comparing renewable and fossil fuel-based systems, and they found that renewable energy plants, such as photovoltaics and ocean thermal energy conversion systems, achieve significantly shorter CO_2 payback times compared to fossil fuel power plants. For CCS-equipped fossil fuel plants, the study emphasizes the need to balance CO_2 mitigation benefits with the environmental costs associated with material use, construction, and operational energy inputs. The material requirements for CCS in fossil fuel plants are substantial, with steel and concrete accounting for the majority of inputs during construction, and aluminum is also highlighted as a material used in auxiliary systems, while chemicals like amines play a role in the capture process. Tahara et al. (1997) also stress that minimizing the environmental footprint of these materials through lifecycle assessments and recycling is critical for maximizing the sustainability of CCS technologies.

Spath and Mann (2000) provided a life-cycle assessment of hydrogen production via natural gas steam reforming, including CCS as a mitigation option, identifying that while CCS reduces GHG emissions significantly, the process incurs high material and energy demands. Most emissions arise from plant operations, with additional contributions from natural gas extraction and distribution, and Spath and Mann (2000) suggest that while CCS is an effective emissions reduction strategy, its scalability depends on improving lifecycle efficiencies and reducing upstream material impacts. The material requirements for CCS in hydrogen production, meanwhile, are dominated by steel for reformers, pressure vessels, and pipelines, and concrete is also extensively used in constructing plant foundations and infrastructure. Chemical inputs, including solvents for CO_2 capture, contribute to ongoing material consumption, requiring sustainable sourcing and efficient use. Spath and Mann (2000) highlight the need for lifecycle strategies to optimize material use and to enhance the environmental performance of CCS-equipped hydrogen systems.

Odeh and Cockerill (2007) have provided a comparative analysis of life cycle GHG emissions for power plants with and without CCS, including technologies such as supercritical pulverized coal, integrated gasification combined cycle (IGCC), and natural gas combined cycle (NGCC). Their study demonstrates that CCS achieves significant reductions in lifecycle GHG emissions – ranging from 75% to 84% – but also results in higher emissions of pollutants such as NOx and NH3, which lead to eutrophication and acidification, and their findings underscore the trade-offs associated with CCS technologies, which provide substantial climate benefits, but which require careful management of broader environmental impacts. Material requirements for CCS in Odeh and Cockerill (2007) are dominated by steel and concrete, which are essential for building CO_2 capture systems, compressors, and pipelines, and solvents and other capture chemicals are also highlighted as significant material inputs, with regular replenishment required to maintain capture efficiency. The authors emphasize that these material demands amplify the life cycle impacts of CCS, and they recommend further research into reducing the intensity of materials used, as well as recycling strategies to minimize waste.

Cao, Chen, and Xiang (2024) performed an LCA comparing six emerging post-combustion carbon capture technologies in an ultra-supercritical coal-fired power plant, evaluating the environmental impacts of monoethanolamine (MEA), aqueous ammonia, pressure swing adsorption (PSA), temperature swing adsorption (TSA), membrane separation, and calcium looping technologies, and the authors highlight that CCS implementation can reduce GHG emissions by 49%-75%, with calcium looping offering the highest reduction (75%). However, CCS also increases environmental impacts in categories like eutrophication, human toxicity, and water consumption. For instance, the particulate matter formation potential (PMFP) is reduced by 47%-83% across the technologies, while water consumption increases for most cases, except for calcium looping. Calcium looping emerges as the most environmentally favorable technology due to its ability to recover heat and retain higher power efficiency. Membrane systems and aqueous ammonia follow in terms of GHG mitigation and minimized environmental trade-offs. Conversely, chemical absorption technology (via amines) and adsorption technologies show higher environmental impacts due to their intensive energy requirements and chemical waste. The study underscores the need for balancing emission reductions with broader environmental considerations to ensure the sustainability of CCS systems.

Cao, Chen, and Xiang (2024) also found that material demands for the six post-combustion technologies are substantial and vary based on technology. Steel and concrete dominate the infrastructure requirements for CO_2 capture, compression, and transport units. Calcium looping requires additional materials like limestone and calcination equipment, although it minimizes solvent and water use. Membrane separation, while advantageous for its smaller footprint, has a shorter material lifespan, with membranes

typically requiring replacement every five years due to chemical degradation. MEA and ammonia technologies are characterized by high chemical consumption, necessitating regular replenishment of solvents.

In addition, the study by Cao, Chen, and Xiang (2024) highlighted the energy penalties associated with these material demands. For example, adsorption technologies have the highest energy consumption, driven by adsorbent regeneration requirements, which indirectly amplify the material throughput in power plant operations. The study emphasized the importance of innovative materials and design efficiencies to mitigate these challenges, making CCS deployment more viable and environmentally sustainable.

Material Requirement Studies

In terms of international organizations, the IEA (2021b) does not include any role for CCS in the STEPS and SDS scenarios that underpin its material analysis, and it thus does not include CCS material implications in its study. The same is true for the similar IRENA study (Gielen and Papa 2021). The World Bank (Hund et al. 2020) does include CCS as it relies on the earlier IEA ETP scenarios – reporting material requirements for CCS use in coal and gas. The ETC extends such analysis by including a brief discussion of the role of chemicals in the deployment of CCS (Energy Transitions Commission 2023).

Beyond international organizations, similar studies have been published in the academic literature. Tokimatsu et al. (2018) examined material requirements under two scenarios using their own global model, and included CCS within this, examining material demand for vanadium, niobium, and nickel for use in the steel required, and they highlight that vanadium is deemed “distinctly critical” by 2100, partly for its projected use in CCS (that they utilize for electricity generation using gas, coal, and biomass), along with flagging the importance of nickel for use across a range of technologies. Watari et al. (2019) conducted a similar study using the IEA’s ETP scenario that included CCS, utilizing the material intensities for CCS from Moss et al. (2011) and focusing on the steel required. Studies using similar assumptions have also been conducted at a global level by Deetman et al. (2018) and de Koning et al. (2018) using material intensities from Moss et al. (2011) and Van der Giesen (2008).

Wang et al. (2023) have also conducted a global study of material demand, extending it to include the emissions associated with producing the required materials, covering 15 materials (including concrete), and they include CCS for coal, gas, and biomass but do not include downstream pipeline infrastructure, utilizing material intensities from a wide range of historical studies (Tahara, Kojima, and Inaba 1997; Spath and Mann 2000; White and Kulcinski 2000; Albers et al. 1976; El-Bassioni 1980).

In modeling the material demands from a wide range of technologies including CCS for gas and coal, Bandpey, Rahimpour, and Kraslawski (2024) have considered a wide range of scenarios from the IEA and IRENA, and they cover steel, aluminum, copper, chromium, manganese, nickel, and molybdenum, utilizing material intensities from Koornneef et al. (2008), Wang et al. (2023), and Simon (2023).

Beyond CCS, several studies have examined the material implications of individual technologies (or a small group of technologies). The material implications of wind deployment have been examined by authors such as Verma, Paul, and Haque (2022), who modeled the implications for India, and Farina and Anctil (2022), who examined the material requirements of the deployment of the technology for the U.S. and the globe. The global implications of offshore wind have also been examined by Li et al. (2022), and the material requirements of hydrogen deployment have been studied by Moreira and Laing (2022).

Beyond these global studies, an emerging cluster of literature has started to examine the material requirements of the energy transition at a national level. Lee et al. (2024) have analyzed the requirements for wind and solar PV deployment for a basket of 15 materials for the U.S. Studies have also emerged examining the material requirements in China for the energy transition across a basket of technologies, with some studies including CCS (Wei et al. 2022) and some excluding it (Elshkaki and Shen 2019). Chadha and Sivamani (2021) have examined the material requirements of the energy transition in India, but they also do not include CCS.

Appendix 2: Storage Capacity and Costs of CCS

One of the key areas for accelerating CCS deployment in the Kingdom is understanding the country's CO_2 storage capacity. A recent study (Ye et al. 2023) has evaluated the geological CO_2 storage potential in Saudi Arabia, assessing 17 sedimentary basins using the CO_2-SCREEN tool. The Eastern Arabian Basin and Interior Homocline-Central Arch have been identified as the most promising storage sites, while Western Saudi Arabia offers a limited capacity, except for the Umm Luj, Yanbu, and Jeddah basins. At the 50th percentile uncertainty, estimated effective storage capacities are ~432 Gt CO_2 in deep saline aquifers, ~5 Gt in future depleted oil reservoirs, and ~9 Gt in non-associated gas reservoirs. The study by Ye et al. (2023) follows Carbon Sequestration Leadership Forum (CSLF) guidelines, incorporating technical, geological, and engineering constraints but excluding socioeconomic and regulatory factors, and it highlights the need for further prospect-level evaluations, including drilling, monitoring, and injectivity performance assessments, in order to refine CO_2 storage planning and support Saudi Arabia's net-zero strategy.

Understanding the costs of CCS in KSA is also an important research topic. A recent study (Rowaihy et al. 2025) has evaluated the cost of carbon capture in Saudi Arabia's energy and industrial sectors using a Marginal Abatement Cost Curve (MACC) approach, estimating an average CO_2 capture cost of \$69/tCO_2, with ammonia production being the most cost-efficient at \$11/tCO_2 due to high-purity CO_2 streams, while smaller-scale operations face costs up to \$189/tCO_2. The Eastern region is identified as a prime location for cost-effective deployment, benefiting from economies of scale and a planned CCS hub in Jubail, and the analysis highlights how CO_2 concentration, plant size, and economies of scale influence capture feasibility, with low-cost opportunities in ammonia, refineries, and large industrial clusters. Rowaihy et al. (2025) recommend prioritizing low-cost capture options while tailoring policies and investments to regional and sector-specific conditions to accelerate KSA's path to net-zero emissions by 2060.

Appendix 3: Methodological Details

Amine and Potassium Carbonate Assumptions

Amine degradation occurs due to thermal and oxidative stress, leading to the formation of heat-stable salts, ammonia emissions, and corrosive byproducts that impact solvent longevity and increase operational costs. Similarly, potassium carbonate solutions suffer from degradation due to solvent precipitation, CO_2-induced bicarbonate formation, and interactions with impurities, which can lead to reduced absorption efficiency and higher maintenance requirements. While amine-based systems require frequent solvent reclamation and anti-oxidation strategies, potassium carbonate systems demand strict impurity management and process optimization to minimize performance losses.

Each of the two technologies is preferable depending on a particular set of operational conditions. For example, potassium carbonate systems are superior for CO_2 at higher flue gas pressure, while amine systems operate better at atmospheric pressures. It is expected that both amine and carbonate systems will be deployed in the future for CO_2 capture depending on the composition of flue gas and the type of industry, with the selection of the right system conducted on a case-by-case basis.

Table A1. Projected split between amine and potassium carbonate systems.

Data point		Type of CO_2 capture system (chemical absorption)	
		Amine systems	Potassium carbonate systems
Base scenario – Share in global and Saudi CO_2 capture capacity (see (1) in Notes below)	Electricity sector	90%	10%
	Industrial sectors	75%	25%
High $K2CO_3$ scenario – Share in global and Saudi CO_2 capture capacity	Electricity sector	70%	30%
	Industrial sectors	40%	60%
Initial demand of solvent for a 1 Mt/y CO_2 capture plant – tonnes/y, tonne (see (2) in Notes below)	Electricity sector	158,000	318,840
	Industrial sectors	158,000	318,840
Annual loss (solvent make-up demand) as % of initial demand (see (3) in Notes below) – tonne/year	Electricity sector	1,500	536
	Industrial sectors	1,500	536
Reduction of initial and annual demand every 10 years (due to technological innovation) (see (4) in Notes below)		80%	80%

Notes: (1.) Existing Benfield systems by UOP (carbonate-based) have a high share of existing industrial applications in the chemical industry (mainly CO_2 removal for hydrogen and other chemical production). Measuring by the number of existing commercial systems, amine CO_2 capture is expected to capture a higher proportion of the power sector, while potassium carbonate may continue to capture a high proportion of CO_2 capture deployment in industrial applications. (2) Initial demand is filled into the system as the commissioning phase, and is considered as part of the capital investment. Amine systems have a higher demand because of their lower CO_2 loading capacity (0.3-0.5 mol CO_2/mol solvent for amines and 1 mol CO_2/mol solvent for potassium carbonate). (3) Amine data taken from amine-based post-combustion CO_2 capture by IECM (2019). Amines have higher degradation rates than carbonate systems, so their make-up requirements are also higher (Kothandaraman 2010). (4) A reduction in requirements is expected due to the development of new solvents and catalysts, which will help improve the reaction kinetics.

For our analysis, this differentiation will help us to estimate the need for critical minerals and the materials associated with each of the two solvents. The split is based on the specific operational and economic advantages of each capture technology in different sectors. The assumed split is shown in Table A1. The following paragraphs provide the justification for our assumptions and estimates.

Additional material requirements for amine systems include:

- Sodium hydroxide: Used for amine reclamation for heat-stable salts in the amine reclaimer (0.13 kg CO_2 per tonne of CO_2 captured).
- Activated carbon: Used for the removal of long chained/cyclic polymeric compounds formed from the degenerated MEA (0.075 kg activated carbon bed per tonne of CO_2 captured).

In KSA, the future power generation sector is expected to rely heavily on natural gas-fired power plants rather than other types of fuels as part of the energy transition strategy. Amine-based CO_2 capture is the preferred and widely adopted technology for retrofitting combustion systems operating at atmospheric pressure (due to amine high CO_2 selectivity at low pressures), and so a higher ratio of 90% is chosen (Rochelle 2009). It is expected that in the future, there may be gasification systems in the power sector (e.g., waste or bioenergy gasification). In this case, operation occurs at higher pressures, which enhances the functioning of carbonate systems for CO_2 capture (Figueroa et al. 2008), and so carbonate systems are expected to be more suitable. Given that this in the High $K2CO_3$ scenario, a share of 30% for carbonate systems is selected.

The industrial sector includes cement, steel, refining, and chemical processing, where CO_2 is often produced under higher pressure conditions, making potassium carbonate-based capture relatively more favorable than in power generation (Feron 2010). Potassium carbonate absorption is more effective at higher temperatures and pressures, making it well-suited for industries like steel production and hydrogen production, where CO_2 is captured from high-pressure syngas streams. However, amine-based capture still plays a significant role (70%), particularly in lower-pressure applications, such as cement plants and industrial boilers, where flue gases are similar to those in the power sector. Given these conditions, the industrial sector's CCS capacity is assumed to be 75% amine-based and 25% potassium carbonate-based in order to reflect technological suitability and operational efficiency. However, to capture the greater potential for carbonate systems in industry in the High $K2CO_3$ scenario, a share of 60% is chosen for potassium carbonate.

It should be noted that both amine and potassium carbonate technology for CO_2 capture are well established and have been deployed heavily for many decades in hydrogen production and natural gas sweetening plants, but amine-based CO_2 capture is currently the widely proposed post-combustion capture technology for retrofitting gas-fired power plants and lower-pressure industrial applications. Potassium carbonate-based absorption technology is more efficient at high pressures, and it is commonly used in hydrogen production, ammonia synthesis, and syngas processing. The industrial sector in KSA includes high-pressure processes (e.g., refining, chemical synthesis, and gasification-based hydrogen production), making potassium carbonate-based capture more relevant.

Using these assumptions, the total CCS capacity projections are split proportionally into amine-based and potassium carbonate-based systems for each time period from 2025 to 2060, ensuring that technology selection aligns with expected industry developments. For the global scenarios, the same split of technology is assumed as for KSA.

Transport Assumptions

Assumptions regarding transportation of CO_2 and related pipelines are as follows:

1. It is assumed that to satisfy the total CCS capacity in a given year, several CO_2 capture plants, each with a capacity of 1 Mt/y, are constructed.
2. This study does not define specific locations of the 1 Mt/y plants, and instead assumes that a single source-to-sink pipeline is constructed.
3. It is assumed that most plants constructed (70%) are 100 km from sink, while the rest are 200 km from sink (30%).
4. The diameter of a single pipe is estimated based on a CO_2 flow rate of 1Mt/y (31.7 kg/s), a target flow velocity of 1.5 m/s, and an assumed CO_2 density of 700 kg/m3 (supercritical fluid).

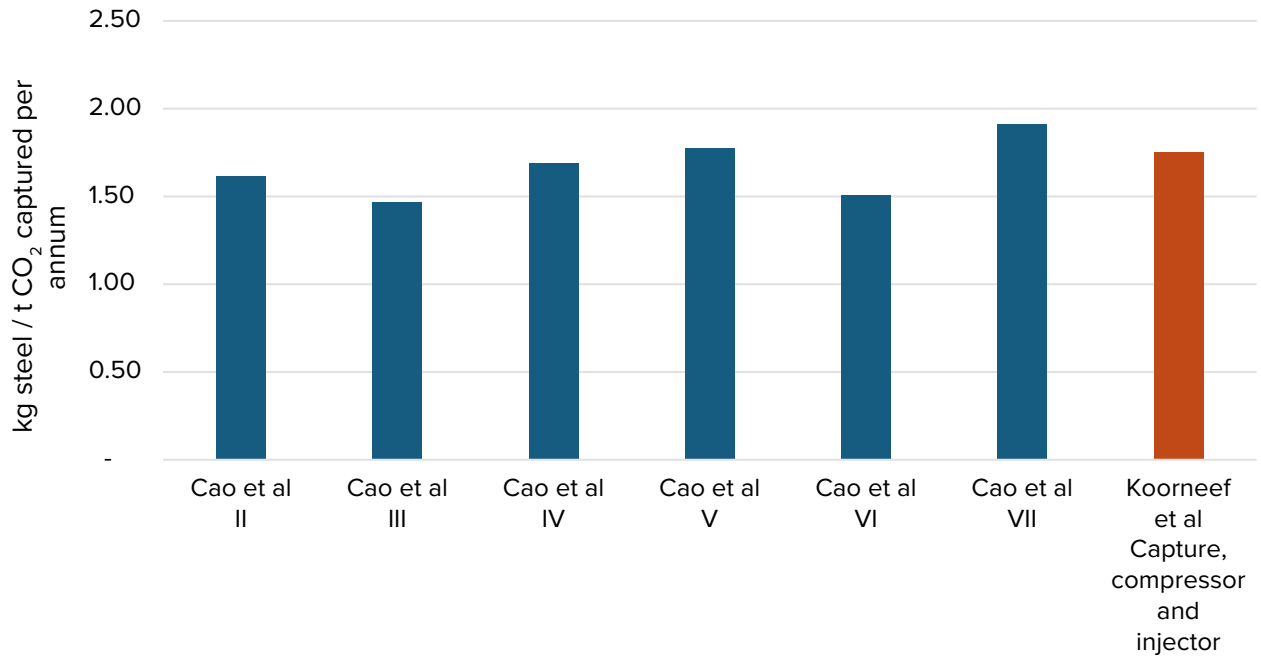
5. A pipe diameter of 19.6 cm is estimated.
6. An assumed carbon steel pipe (strength of 450 MPa), a pressure of 15 MPa in pipeline, a safety factor of 0.72, and a required pipeline thickness of 4.5 mm are estimated.
7. Based on a density of steel of 7850 kg/m^3, a mass of steel of 112 tonne /km is estimated.
8. For a 1 Mt/y CO_2 capture plant transporting 1 Mt/y CO_2 for 100 km for storage, the total steel required is 11,200 tonnes (11.2 kilotonnes). The total amount required in a given year is estimated based on what CCS capacity is deployed for a given year. This means that the amount of steel needed increases linearly with capacity.

In reality, the increase in steel requirements will not be linear because several CO_2 capture plants will share the same CO_2 transmission network, albeit CO_2 distribution pipelines will still be required. The assumptions above, and the linear increase of material requirements with CCS capacity, are thought to be sufficient for the purposes of this work.

Steel Assumptions

One of the most important materials for CCS deployment is steel, which is required for the capture equipment, compressor, injector, and pipeline infrastructure. However, the estimates for how much steel is required for this infrastructure vary, with most of the literature focusing on the infrastructure at plant level (i.e., capture) rather than downstream (i.e., pipelines). Much of the literature focuses on estimating plant-level material requirements for CCS infrastructure to be attached to coal or gas-fired power plants. This creates challenges in estimating material requirements on a larger scale. Figure A1 shows the variation in steel required per unit of emissions captured per annum from the reported plant from six different CCS specifications for coal-fired power plants in Cao, Chen, and Xiang (2024), along with the study from Koornneef et al. (2008). This highlights that although there is a range of material requirements, there is also a general consensus in the literature regarding the steel that is required per unit of capacity.

Figure A1. Estimates of steel requirements for CCS infrastructure (excluding pipelines).



Source: Cao, Chen, and Xiang (2024); Koornneef et al. (2008).

Steel is not a singular product – it occurs in different forms and in different grades with different types proposed for use in CCS infrastructure (Moss et al. 2011), including API X65 (Hashemi 2011) and API X100 (Nafisi et al. 2012). These different grades of steel have different ratios of alloying elements, such as nickel, manganese, chromium, vanadium, and niobium, which give different properties in resisting corrosion. Corrosion in CCS may come from a range of different sources that require different properties in the steel needed in injection and pipeline infrastructure (Craig et al. 2023).

In this study, we assume that the steel required is predominantly API X65, but we vary this to highlight the implications for requirements for alloying elements.

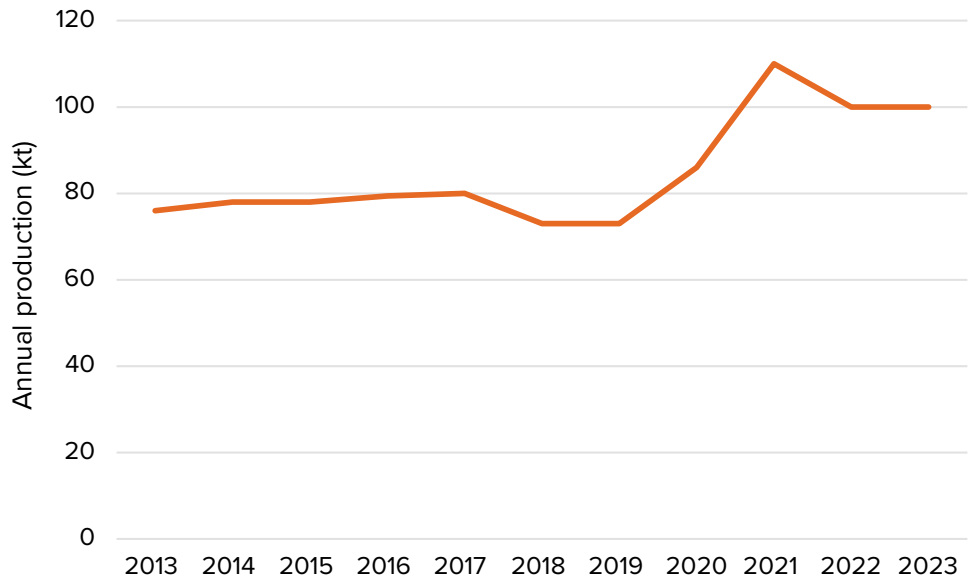
Appendix 4: Additional Results

Vanadium

Vanadium is an important alloying element in a range of steel grades, with potential for use in various components of CCS. The vast majority of the 100,000 tonnes produced annually is used in steel production (93%), with half used in high-strength low-alloy steel (HSLA) (European Commission 2023b). Vanadium occurs in a range of ores and materials, including bauxite and crude oil, and also in carnotite, which is mined for uranium. Vanadium production occurs predominantly in China, which accounts for 66% of the mined production, followed by Russia (19%) and South Africa (6%), but Australia holds the world's largest reserves (45% of the global total) (USGS 2024c).

Vanadium could play a crucial role in the energy transition beyond its role in steel. Vanadium redox flow batteries could play vital roles in stationary storage to support intermittency issues with renewables, for example. Under the IEA's Stated Policies Scenario, vanadium use in battery storage is projected to reach 139 kt in 2040, and is projected to reach 219 kt under the Sustainable Development Scenario (IEA 2021b). This scale of demand eclipses current production and is far beyond its use in current and projected steel production. Vanadium production has increased by 31% in the last decade (Figure A2), with global reserves increasing 36% in the same period. However, should demand for storage meet projections, production would have to increase much more rapidly.

Figure A2. Annual global production of vanadium, 2013-2023.



Source: USGS (2024b).

Current vanadium reserves are large and are sufficient to meet current annual production levels for over 250 years, and, thus, even if demand increases, the question that arises is not one of total reserve availability but more of ensuring that there is sufficient production capacity available in order to meet future requirements. Indeed, the growing demands for vanadium, especially in scenarios where there is widespread global deployment of vanadium redox flow batteries, are projected to cause growing shortages through the 2030s, and especially in the 2040s (Sverdrup and Olafsdottir 2023; Rodby et al. 2023).

The use of vanadium in CCS in KSA is projected at a total of 0.8 kt up until 2060 at an annual average of 23 tonnes per annum, but with a peak demand of 256 tonnes. Globally, demand for vanadium from CCS deployment is projected to be 50kt up until 2050 at an annual average of 2 kt per annum, and up to a peak demand of 2.96 kt per annum. This is approximately 2% of the current global production, but this needs to be seen in the context of potentially growing global demand from steel use generally and also from potential deployment of vanadium redox flow batteries.

It may be possible to reduce the requirements of vanadium by switching between different grades of steel. For example, Moss et al. (2011) highlight both API X65 and API X100 grades as having potential for use in CCS infrastructure, with the latter not requiring vanadium as an alloying element. Thus, should some, or all, of the steel utilized in pipeline infrastructure for CCS be less vanadium-intensive, overall vanadium demand will fall. It is likely that a mix of steel grades will be utilized, and, therefore, that the amount of vanadium demand may be less than is projected here given a full utilization of API X65 steel.

An option to increase the annual production capacity of vanadium is to utilize non-conventional resources. Vanadium occurs in high concentrations in carbon black waste – a waste product from oil refining. Recovering this to provide a future vanadium supply for use in steels for CCS or otherwise is both technically possible (Zhan et al. 2018) and economically viable, at least on paper (Zhan et al. 2019). In addition, extracting ferro-vanadium (which can be used in the types of steels needed for CCS) from spent catalysts used in heavy oil refining is also possible. Given the large refinery output in the Kingdom, there is great potential to domestically produce the vanadium required for the steel in the deployment of a CCS pipeline network in the country. This potential has started to be realized with the movement toward developing such a recovery capacity, along with future opportunities being promoted.[21] This avenue for vanadium production therefore makes it feasible, at least in theory, to meet the material requirements for vanadium from the deployment of CCS through localized production.

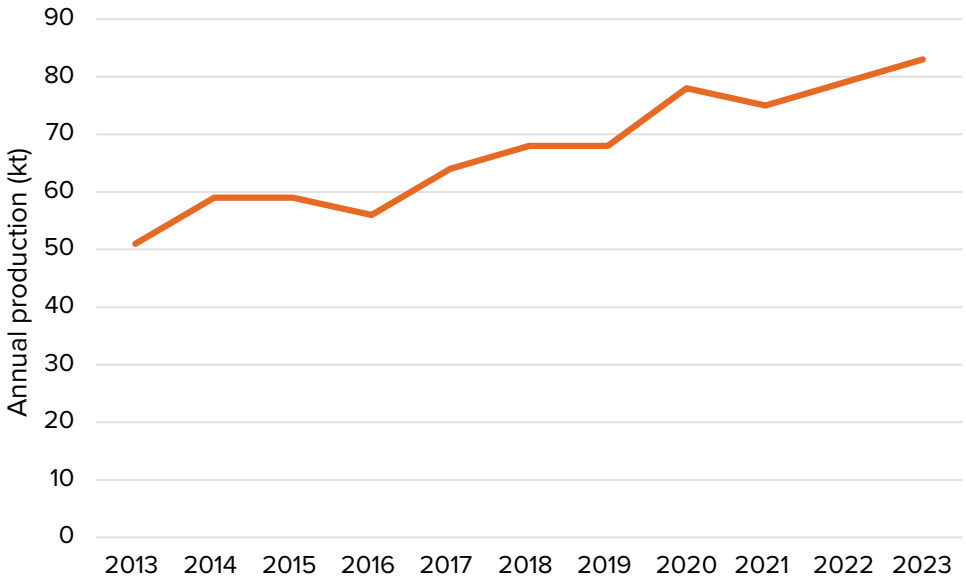
Niobium

Niobium is, like vanadium, a key element in the alloying of various grades of steel that are projected to be used in CCS manufacture. Almost all (91%) niobium is used in steel – in construction (40%), automobiles (24%) and oil and gas (16%), along with also being used to produce stainless steel (11%) (European Commission 2022a).

Niobium requirements for CCS deployment in KSA are projected at 0.65 kt up to 2060, with an annual average of 18 tonnes per annum, and with peak demand requirements of 200 tonnes per annum. At a global level, CCS requirements would total 39 kt up to 2050, or 1.6 kt per annum on average, and with peak demand of 2.3 kt. Similar to vanadium, these requirements equate to approximately 2% of the current global production.

Niobium production is heavily concentrated in Brazil, which has over 90% of the current global mined production (USGS 2024d) and 88% of the refined production (RMIS). Canada represents the vast majority of the remainder (8%), with very small levels of production from DRC, Russia, and Rwanda. Current reserves of niobium are large, and they are sufficient to meet over 200 years of current production levels. However, the potential supply risks of the near total monopoly position of Brazilian production have been highlighted (Silveira and Resende 2020). Similarly to vanadium, recent production has increased in line with increasing global demands, growing 41% since 2015 (Figure A3).

Figure A3. Annual global production of niobium, 2013-2023.



Source: USGS (2024a).

Similar to vanadium, niobium demand could increase with the energy transition due to its role in high-strength low-alloy steel (Omar and Veiga 2021). Future growth rates for niobium demand are projected at between 4% and 6% per annum (Bakry, Li, and Zeng 2023), although this could change dramatically, as it could be utilized as an anode in lithium-ion batteries for electric vehicles (Xie et al. 2023; Aghamohammadi, Hassanzadeh, and Eslami-Farsani 2022).

Saudi Arabia has potential for future niobium production. Resources within the Kingdom are valued at between US$38 to US$41 billion (Ministry of Industry and Mineral Resources 2022), and between 1.05 and 1.14 million tonnes at current prices, which is equal to 6% of the current identified global reserves (USGS 2024d), or about 12.5 times the current global production levels.

However, there are challenges in entering what is a very small global market with substantial market power. An entry into the market may face price challenges either through the large increase in supply (e.g., from moving from two to three mines globally) or from market manipulation from existing players to avoid new entry (i.e., increasing production to reduce prices). If these challenges can be overcome, it is feasible that niobium requirements for CCS deployment can be met through local production.

Other Materials

A small range of other materials are required for CCS deployment in KSA (and globally). These are predominantly alloying elements that are required to produce the particular grades of steel projected for use in capture and pipeline infrastructure. The materials include manganese, nickel, chromium, molybdenum, titanium, copper, aluminum, and cobalt. The requirements of these materials are small at both the KSA level and for the global deployment of CCS, with the highest relative requirements being for molybdenum (accounting for 0.05% of the current market for KSA deployment of CCS, and rising to 2.8% for global CCS deployment), followed by titanium and nickel (0.03% for KSA for both materials, and 1.69% and 1.71%, respectively, for global CCS deployment).

There are no major challenges with supplying the quantity of materials required for CCS deployment at either a KSA level or a global one, but the requirements of some of these materials across the projected transition to a low-carbon energy system should also be considered. This is especially the case for nickel, which could play a key role in some of the different chemistries of cathodes that are being used in lithium-ion batteries for electric vehicles.

About the Authors



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Dr. Timothy Laing is a Senior Fellow at KAPSARC specializing in critical minerals, with expertise in environmental, natural resource, and development economics. He has held academic positions at the University of Brighton, the University of Cambridge, the London School of Economics and Political Science, and the University of the West Indies. Timothy has worked as an independent consultant for organizations including the World Bank, Climate Strategies, the International Council on Mining and Metals, and Conservation International. His work has addressed mining policy, carbon markets, the EU Emissions Trading System (EU ETS), and REDD+. He has published research on topics such as critical minerals, natural resource management, artisanal and large-scale mining, international carbon market mechanisms, and the EU ETS. Timothy earned his Ph.D. from the London School of Economics and Political Science. He holds an M.A. in Development Economics from the University of Sussex and a B.A. in Economics from the University of Nottingham.



Naser Odeh

Naser Odeh is a Principal Fellow at KAPSARC and a leading expert on carbon dioxide removals (CDRs) and carbon capture, utilization, and storage (CCUS). Naser has more than 20 years of experience in consultancy and academia in the United Kingdom, where he has worked closely with the private sector and with governments across the region. As Head of CCUS and Bioenergy in his previous role, he led several industrial decarbonization projects, supporting clients in developing net-zero strategies. He also led the conceptualization and development of BIOCCUS, a community-scale, biomass pyrolysis-based cogeneration technology integrating biochar production with CCUS. This system was funded by the UK government. Naser holds a B.Sc. in Chemical Engineering from the University of Kentucky and a Ph.D. in Energy and Environmental Engineering from Edinburgh Napier University.

About the Project

The importance of critical minerals in deploying energy transition technologies has gained increasing recognition in recent years. As Saudi Arabia advances its plans to integrate renewable energy and low-carbon transportation into its future energy system, understanding the interactions between technologies and critical minerals is essential. With ambitions to scale up mining, a key question is how best to utilize these resources to support the Kingdom's strategic goals. This project aims to develop literature that is relevant both to Saudi Arabia and the global community in these areas.

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