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Review Article

Cross-regional drivers for CCUS deployment

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Abstract

CO_2 capture, utilization and storage (CCUS) is recognized as a uniquely important option in global efforts to control anthropogenic greenhouse-gas (GHG) emissions. Despite significant progress globally in advancing the maturity of the various component technologies and their assembly into full-chain demonstrations, a gap remains on the path to widespread deployment in many countries. In this paper, we focus on the importance of business models adapted to the unique technical features and sociopolitical drivers in different regions as a necessary component of commercial scale-up and how lessons might be shared across borders. We identify three archetypes for CCUS development—*resource recovery*, *green growth* and *low-carbon grids*—each with different near-term issues that, if addressed, will enhance the prospect of successful commercial deployment. These archetypes provide a framing mechanism that can help to translate experience in one region or context to other locations by clarifying the most important technical issues and policy requirements. Going forward, the archetype framework also provides guidance on how different regions can converge on the most effective use of CCUS as part of global deep-decarbonization efforts over the long term.

Graphical Abstract

Three archetypes for CCUS development - resource recovery, green growth, and low-carbon grids –provide a framing mechanism to translate experience in one region to others by clarifying the most important technical, economic, and policy issues.

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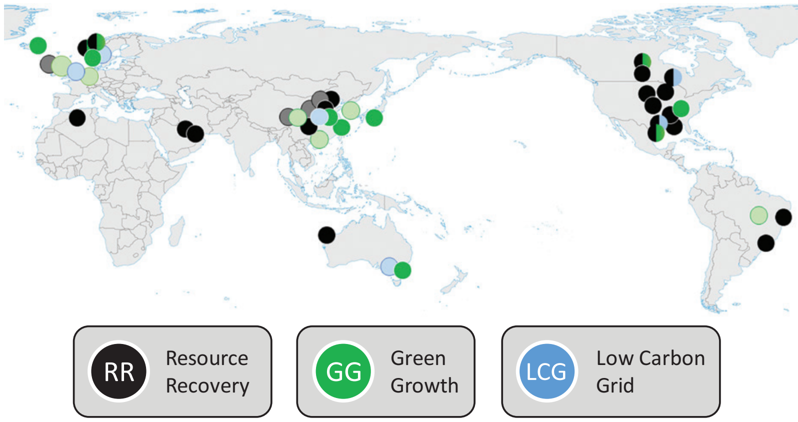

Keywords: CCUS; CO_2; capture; decarbonization; regional; storage; utilization

Introduction

CO_2 capture, utilization and storage (CCUS) is recognized as a uniquely important option in global efforts to control anthropogenic greenhouse-gas emissions. This paper follows a series of publications in Energy & Environmental Science since 2010 on the development and deployment of CO_2 capture and storage (CCS) and its role in meeting climate-change targets [1, 2, 3]. Significant progress has been made globally in advancing the maturity of the various component technologies and their assembly into full-chain demonstrations. However, a gap remains on the path to widespread commercial deployment in many countries.

In this contribution, we focus on the importance of business models adapted to the unique technical features and sociopolitical drivers in different regions as a necessary component of commercial scale-up and how lessons might be shared across borders. We take a broad view of this topic by proposing a framework that accounts for the distinct motivations and value propositions that exist across CCUS projects in different regions. It is our contention that CCUS is now developing owing to three distinct drivers, each with different near-term issues that, if addressed, will enhance the prospects for successful commercial deployment. These archetypal drivers—*resource recovery*, *green growth* and *low-carbon grids*—provide a framing mechanism that can help to translate experience across regions by highlighting the most important technical issues and policy requirements that need to be addressed to move projects forward.

In each of these sections, examples are provided from the experiences of the USA, China, Canada, Norway, the UK, the EU and Australia up to the end of 2019 to more fully illustrate the interplay between different motivations, technical factors and policy implications across archetypes. Particular attention is paid to the USA and China, which currently account for the largest shares of global anthropogenic CO_2 emissions and have distinct differences in their infrastructure bases, market structures and regulatory postures. We extend the traditional scope of CCS to also consider regional impacts on CO_2 capture and utilization (CCU); henceforth, CCS, CCU and CCUS will be used, as appropriate, throughout the text. CO_2 utilization is a rapidly evolving field, with diversity of technical approaches at different levels of maturity. In this paper, we focus primarily on enhanced oil recovery (EOR), since it is the most commercially mature example of utilization and it has the largest body of available information on business models. Other approaches could follow different dynamics as they achieve commercial scale-up, but are still expected to fit into our archetype framework.

This paper is divided into four parts. First, we introduce the three archetypes and describe them in detail. Second, we review regional differences in installed infrastructure, regulatory policies and market structures relevant to CCUS around the world and show how these factors can influence the direction of individual projects and the overall ecosystem, but that the core archetypes remain readily recognizable. Third, we consider technical imperatives across archetypes and the impact these can have on technology development in different regions. Finally, we propose specific paths forward for each of the archetypes. For the near term, we suggest priorities focused on establishing distinct aspects of the commercial viability of CCUS. Longer term, we show how all three archetypes can converge towards a common goal of global deep decarbonization, but evolve towards this state along different pathways.

1 Perspective on the development of CCUS

1.1 Archetypes for CCUS development

Fig. 1 summarizes the three archetypes. *Resource recovery* (RR) focuses on the management of carbon in the production of hydrocarbon resources, primarily the disposition of CO_2 from natural-gas extraction and the use of CO_2 in EOR operations. *Green growth* (GG) prioritizes CO_2 reductions in support of climate action, using CCUS to reduce the carbon

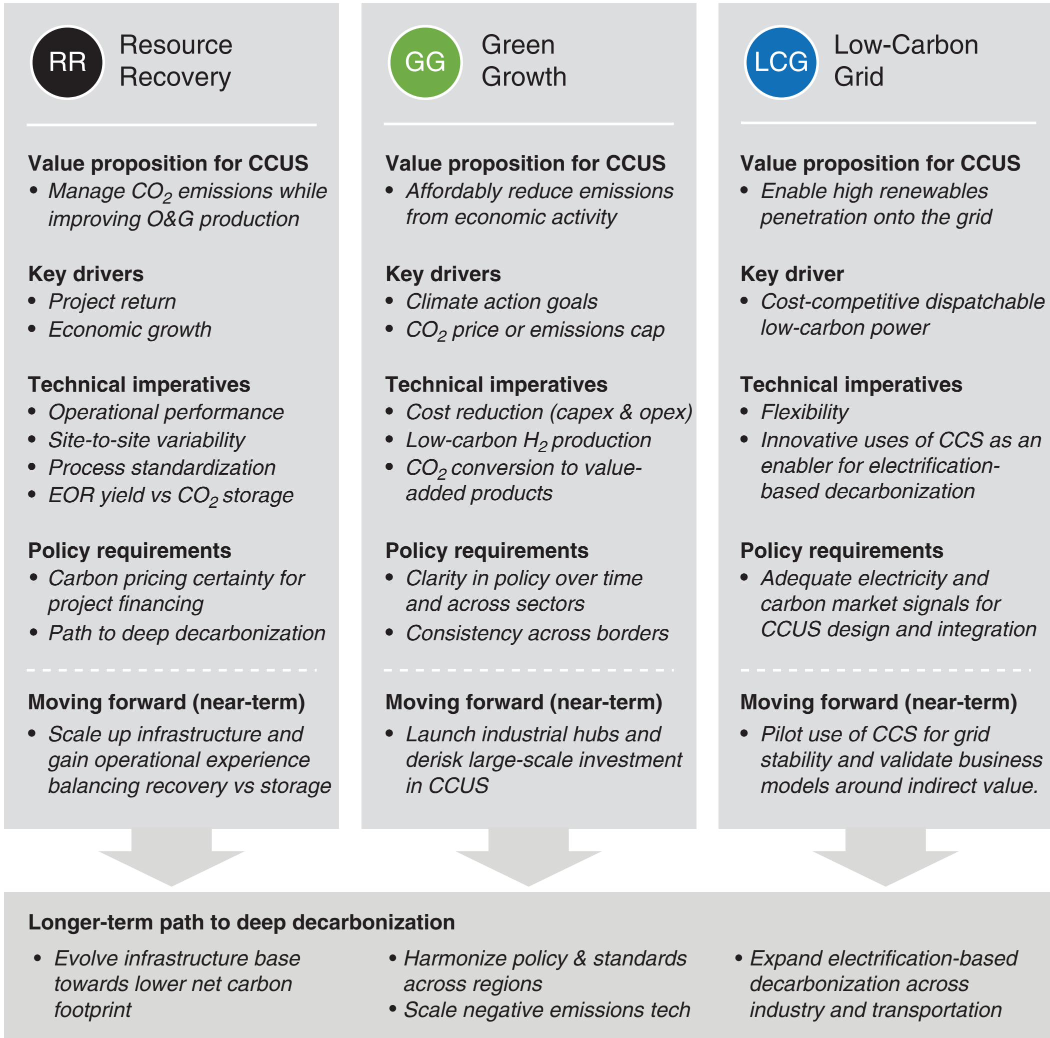

Fig. 1: Archetypes for CCUS development

footprint of economic activity. *Low-carbon grid* (LCG) development emphasizes the value of CCUS as an alternative (or complement) to grid-scale energy storage in enabling a lower-cost and more stable grid with high renewables penetration that can be used to drive decarbonization through widespread electrification.

Divergent value propositions across these models lead to different drivers, technical imperatives, policy requirements and trajectories. Development under an RR model is driven by the value of the produced hydrocarbons, leading to a technical focus on process performance and reliability. An important caveat for this development model is its sensitivity to the price of oil and natural gas. By way of example, EOR commenced in the USA in 1973, well before any other country, then stagnated in 1986 when the price of oil collapsed, before recovering and then steadily growing from <40 CO_2-EOR projects in 1986 to >100 projects in 2010 [4]. EOR has now become more widespread with 375 projects underway around the world in the United Arab Emirates (UAE), Malaysia, Saudi Arabia, India, China, Columbia and Ecuador, of which approximately 40% are CO_2-EOR projects, with the proportion growing. An increasing share of the CO_2 used in these projects is anthropogenic, captured from industrial sources or power plants, rather than 'mined' CO_2 produced from natural sources for the purpose of EOR; both Petra Nova and Boundary Dam projects provide CO_2 for EOR. The other major example is natural-gas production. Separation of co-produced CO_2 is necessary to meet natural-gas purity specifications; government policies around CO_2 have led to large commercial CCS projects in Norway (Sleipner, with CO_2 stored to reduce the carbon-tax burden) and Australia (Gorgon, with CO_2 stored to meet state regulations). In the near term, efforts under the RR archetype are necessarily focused on profitable operations and scale is achieved through increasing the number projects. Technical advances that can reduce risk (e.g. standardization) and policy certainty are the keys to progress. Given the emissions implications of additional hydrocarbon production, an important question for the RR model is its compatibility with longer-term deep-decarbonization targets (e.g. net-zero carbon emissions by 2030 in Norway, by 2045 in California and by 2050 in the UK and France).

Since this model, to date, has been the most successful in terms of actual infrastructure deployment, it can be a vital bridge to net-zero scenarios. The primary strategic pivot for the RR model will be evolution towards the use of its infrastructure to accommodate zero- and negative-emissions activities [5–7]. Active and growing interest in understanding the technical requirements of optimizing CO_2 retention in the reservoir (as opposed to exclusively oil productivity) in EOR operations is a step in this direction and could eventually lead to net negative CO_2 [8–11].

Under the GG archetype, CO_2 is considered a pollutant and CCUS provides a way to reduce emissions in response to government regulations (e.g. carbon pricing, or hard caps on emissions, or renewable portfolio standards) or social pressure. Since emissions reduction through CCUS requires significant capital investment, the corresponding commercial and technical imperative is to de-risk CCUS projects by demonstrating their feasibility through successful large-scale projects and continuing to reduce costs. From this perspective, capture from concentrated industrial sources is a promising starting point and a number of countries are pursuing industrial CCS hubs (including five projects in the USA, UK, Norway, the Netherlands and China as part of the Oil and Gas Climate Initiative (OGCI)'s recently announced KickStarter programme) [12]. There is growing interest in converting CO_2 into value-added products [13–16]. The idea of revenue offsets from low-carbon products is enticing and work is under way to prove the technical and commercial viability of these approaches. Policy-wise, GG requires a clear and stable landscape because regulations impact how projects are de-risked, which, in turn, also affects which emerging business models will become most viable. The GG archetype is aligned with deep decarbonization and the primary longer-term objectives are harmonizing policies to allow effective international collaboration as countries converge on net-zero targets and integrating negative-emissions technologies (NETs) at the large scale to address difficult-to-decarbonize segments of industry and transportation (viz. aviation) in the most affordable manner.

Hydrogen production is an especially interesting use case given its value as a direct product and as a feedstock for a range of chemical and industrial processes, and how amenable conventional steam methane reforming (SMR) and coal gasification (CG) are to CO_2 capture. Over the past decade, a slate of projects around the world have established the feasibility of low-carbon H_2 production using CCS (e.g. Port Arthur in the USA, Quest in Canada, Repsol in Spain, Shenhua Ordos in China, Tomakomai in Japan) and the number of announced initiatives going forward (e.g. the OGCI KickStarter projects, the UK Acorn project and the Australia CarbonNet project) attests to its strategic value to decarbonization efforts [12, 17–24]. While hydrogen-production projects have features that are found in all three archetypes (viz. H_2 use in hydrocarbon refining for RR, low-carbon H_2 production motivated by decarbonization initiatives, H_2 production as a means of chemical energy storage for LCG), we categorize it as GG for the purposes of this discussion. This is because the underlying drivers for H_2-CCS projects align most strongly with GG, making it the most relevant filter for translating learning across regions.

The LCG archetype is based on the idea that dispatchable power from CCS-equipped power plants can be an important enabler for a low-carbon electricity grid with high levels of variable renewable energy (VRE). The power sector is decarbonized by a combination of direct reductions from CCS operations and indirect reductions arising from increased wind and solar generation. Under this development model, CCS lowers the overall system costs by reducing the need to overbuild infrastructure for reliability [25–27]. The most important technical imperative is flexibility, since power dispatch from CCS-equipped facilities must respond to grid dynamics. This is a multifaceted problem and modelling studies have explored how to profitably operate individual plants in liberalized electricity markets in the UK, Western Europe, Australia and the USA [28–31]. Among the archetypes, LCGs are the least mature in terms of actual practice. First steps have been taken in incorporating low-carbon fossil power with CCS onto the grid as baseload generation and understanding the technical challenges of the flexibility of CO_2 capture in support of renewables integration onto the grid [32, 33]. Near-term priorities include extending business models (e.g. capacity payments) to properly assign the value of grid services provided by CCS-equipped plants, understanding flexible CCS in regulated markets (e.g. China) and conducting field demonstrations with grid-integrated plants. As decarbonization efforts progress, the overlap between GG and LCG archetypes is likely to increase as CCUS makes both direct and indirect contributions to the integrated effort to reduce global emissions. For countries with net-zero targets, the level of capture will need to approach 100% or the use of biomass co-firing or supplemental capture from NETs will be needed to eliminate emissions on a life-cycle-accounting basis.

The key contribution of this paper is to integrate these archetypes into a useful framework for appreciating the differing motivations for development efforts to date and also for developing more focused and effective strategies for advancing CCUS in different parts of the world. As we will see in the next section, different projects within a single region might follow different archetypes; parsing them in this manner can help to clarify what experiences are most transferable and provide insight into why one project might be successful while another (nearby) project may fail. In addition, the archetype framework can also highlight under-recognized opportunities for targeted technology development or policy action.

1.2 CCUS deployment: regional variations

Fig. 2 presents a graphical overview of selected CCUS research, demonstrations and commercial projects from

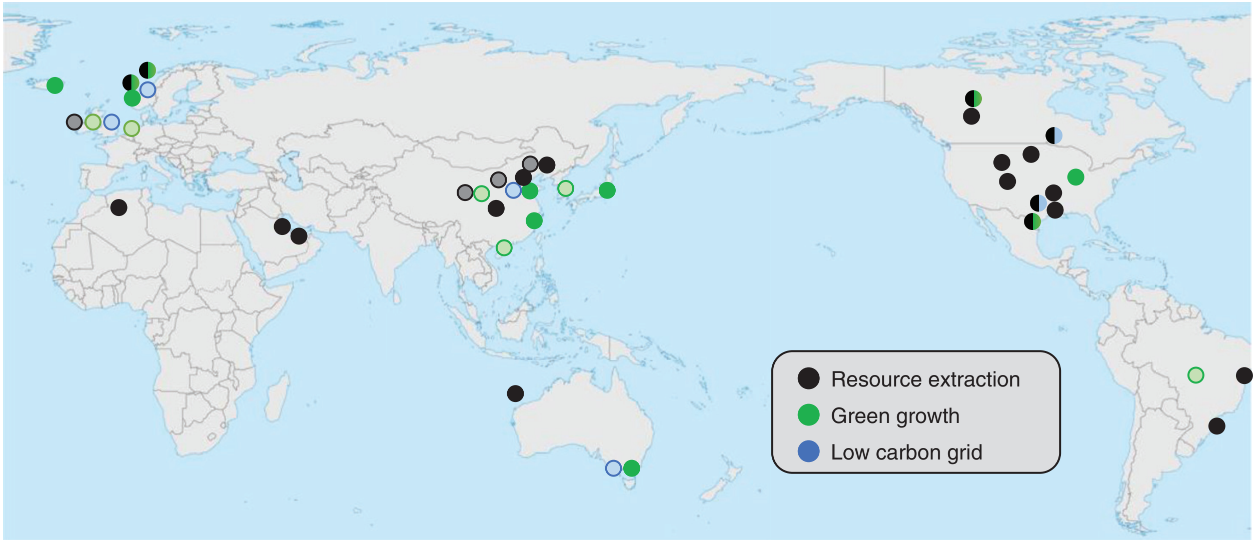

Fig. 2: Overview of CCUS projects and significant R&D pilots by archetypes

the past 40 years, with the goal of illustrating where different archetypes have been used. (See Table 3 and accompanying discussion for more details.) The light shading of some circles indicates notable research and development (R&D) activity (including pilots). The narratives included in this section are intended to be illustrative rather than exhaustive; the examples here were selected to illustrate how the archetypes can coexist in different countries.

The USA has been a pivotal player in the historical development of CCUS and, despite its current mixed political outlook on climate action, continues to be a leader in investment and innovation [7, 34]. As such, the US experience has strongly influenced both R&D and project development around the world. The origins of CCUS in the USA are tied to the RR archetype, under which the core capabilities for large-scale deployment were established. This includes solvent-based separation technology for capture from the chemical industry, pipeline transport and subsurface CO_2 operations from the oil and gas (O&G) industry and the relatively mature landscape (regulatory policy, tax policy and operating standards) from over 40 years of EOR activity. These elements came together in the 2000s when the Department of Energy (DOE) ramped up efforts to address CO_2 emissions from the domestic use of coal in response to climate-action concerns. This was a significant theme for CCUS funding, leading to major efforts in the areas of lower-cost capture technologies and the geological sequestration of CO_2. In addition, strategic investments by DOE in the form of financing support have been and continue to be instrumental in launching 'first-mover' projects in both the RR and GG space [34–36]. The success of the Port Arthur and Petra Nova projects and the implementation of the 45Q tax credit have sparked a new wave of projects using captured CO_2 for EOR [17, 37, 38]. Although RR continues to be the primary pathway for CCUS projects in the USA, changes in the landscape are creating an opening for GG and LCG to play a larger role going forward. Over the past decade, cheap natural gas from shale production has shifted the energy mix away from coal. This has led the DOE to diversify its R&D funding into power from natural gas, NETs, and utilization and conversion options [39]. Increased private-sector investment in these areas signals a growing comfort level with these types of projects—a necessary step towards expanded GG activities in the USA. Grid evolution is also accelerating and recent developments related to technical factors (e.g. reserve capacity margin challenges in Electric Reliability Council of Texas, ERCOT, during summers) or policy (e.g. California's net-zero emissions target) may be the necessary impetus for attempts to integrate power plants equipped with flexible capture [40, 41].

Canada and Australia—two countries endowed with significant fossil-energy reserves—have also had success with the RR-development model. In Alberta, the Quest CCS project sequesters about 1 million tons per year of CO_2 captured from industrial H_2 production in support of bitumen upgrading, while the Boundary Dam project captures a similar amount from a coal-fired power plant for use in EOR [18, 42]. The Alberta Carbon Trunkline (ACTL), which has recently become operational, will expand existing CCUS capacity by about 1.5 million tons per year of CO_2, while also demonstrating the efficacy of a multiparty business model involving CO_2 captured from different sources (initially fertilizer production and refinery operations) [43]. The scale of these operations is rivaled by the Gorgon project in Western Australia, which will sequester up to 4 million tons per year of CO_2 captured from gas processing as part of an liquefied natural gas (LNG) project [44]. Canada and Australia also share a strong posture towards environmental responsibility and technology investment that has created fertile conditions for CCUS development according to the other archetypes. Although the politics remain complex at the time of this writing, Canada is actively evolving its carbon-tax policy and the re-establishment of a CO_2 levy on fossil fuels could be an important driver for GG projects [45]. Both countries maintain a significant technical capacity in CCS and are global leaders in knowledge sharing through the efforts of the International CCS Knowledge Centre, and the CO2CRC and the GCCSI; the Shand CCS feasibility study is the first attempt to design a full-scale flexible CO_2-capture system in support of LCG [32, 46, 47]. Australia is moving forward with a national H_2 strategy that includes zero-carbon H_2 production, through a brown-coal-based H_2-energy supply chain (HESC) and CCS through the related CarbonNet projects in Victoria, and a less advanced black-coal-based project with CCS in the Surat Basin in Queensland [17, 24]. Challenges in integrating increasing levels of VRE into its electricity grid also provide an opening for CCUS under the LCG model; the AGL Loy Yang plant is one of a limited number of facilities globally that have investigated the possibility of flexible CO_2 capture [48].

Europe has exhibited significant political and social leadership in global climate-change-mitigation efforts, but interest in CCUS varies across the continent. The situations in Norway, the Netherlands and the UK provide some perspective into the differences across the region. Norway is notable in its consistent, sustained interest in CCS over several decades [49]. Norway's Sleipner CCS project has been operative for >20 years; in addition to its role in managing CO_2 for natural-gas production, it has been an invaluable source of data for injection into offshore reservoirs and a vital test bed for the development of site characterization and monitoring capabilities [49–51]. Moreover, the establishment of Gassnova in 2005 as a state-run enterprise to support CCS research, development and deployment and its role towards establishing an industrial hub provides a real-world example for a hybrid RR–GG approach that is increasingly pivoting towards a GG model [52]. In contrast, the Netherlands have adopted the GG approach directly and is actively pursuing the development of an industrial hub in Rotterdam [53]. Such a hub has the potential to receive CO_2 from other countries on the continent, providing valuable experience on how to improve cross-border coordination. The UK is a third case. It has had a long-standing interest in CCUS, as evidenced by its strong record of academic contributions and three waves of significant investment in demonstration projects, and recently signalled intentions to support a fourth wave in its 2020 budget announcement [54–56]. Between 2005 and 2015, the UK pursued several large full-chain projects for coal power plants (Longannet and White Rose), influenced in part by similar efforts in the USA [57, 58]. These projects were cancelled primarily due to cost challenges. Recognizing the differences between the energy systems of the USA and the UK requires adapted approaches; the UK is now ramping up investment in GG-type efforts including industrial capture (Acorn and Teesside) and bioenergy CCS (BECCS, Drax), and continues to be a thought leader in the use of flexible capture as an enabler for LCG [21, 25, 59, 60].

China is at an important point in the development of its CCUS capability [61]. Research investment and demonstration activity has been steadily increasing over the past decade. While much of this work has been influenced by the experiences of the USA and other countries (particularly for EOR and storage projects), there is a growing awareness of the need to consider the specific conditions within the country [62, 63]. For example, noting the rise in submissions from Asia, an editorial in the *International Journal of Greenhouse Gas Control* in 2014 encouraged researchers to not duplicate previous work, but to explore new ground, including issues related to the local deployment of CCUS [64]. Specific challenges include the dominant share of coal in the energy and industrial system, financial barriers related to the relatively young age of its coal-power-plant fleet (over half of its nearly 1000 GW in capacity is <15 years old), a steep learning curve for CO_2 transport and storage, the aggressive growth of wind and solar generation with attendant challenges in grid integration and curtailment, and a dynamic policy landscape featuring electricity-market reform and the launch of a national carbon-trading market in 2020 [65–69]. Solutions to these challenges build on concepts and approaches pioneered in the West, but unique features in China's energy and regulatory landscape will necessitate adaptation or new thinking for the most effective approaches. All three archetypes are relevant to China's efforts to scale CCUS and can provide guidance in this regard. As the world's largest emitter of CO_2, China's ability to deliver in both the near and the longer term will greatly impact efforts to meet global climate-action goals.

Finally, we note interest and activity in other parts of Asia, specifically Japan and South Korea. Both countries have active technology development and demonstration ecosystems. Japan, in particular, is noteworthy, given that it is home to a number of industrial companies that are world leaders in CO_2-capture technology (e.g. Mitsubishi's KM-CDR) [70, 71].

2 Role of regional differences in infrastructure, policy and markets

2.1 Energy and industrial infrastructure landscape

The existing landscape for energy and industrial infrastructure is important for the simple reason that it sets the starting point from which CCUS networks develop. Fig. 3 shows the distribution of regional CO_2 emissions by source. Globally, the power sector accounts for >40% of total CO_2 emissions, with industrial and transportation contributions at about 20% and 15%, respectively. Other contributions include commercial processes, residential activities and agriculture. Even at this coarse level of detail, differences emerge in the relative proportions of the sectors across regions (e.g. different states in the USA, provinces in China or nations in Europe). Within the power sector, there are variations that impact the nature and costs of CO_2 capture. For example, the fuel type impacts the concentration

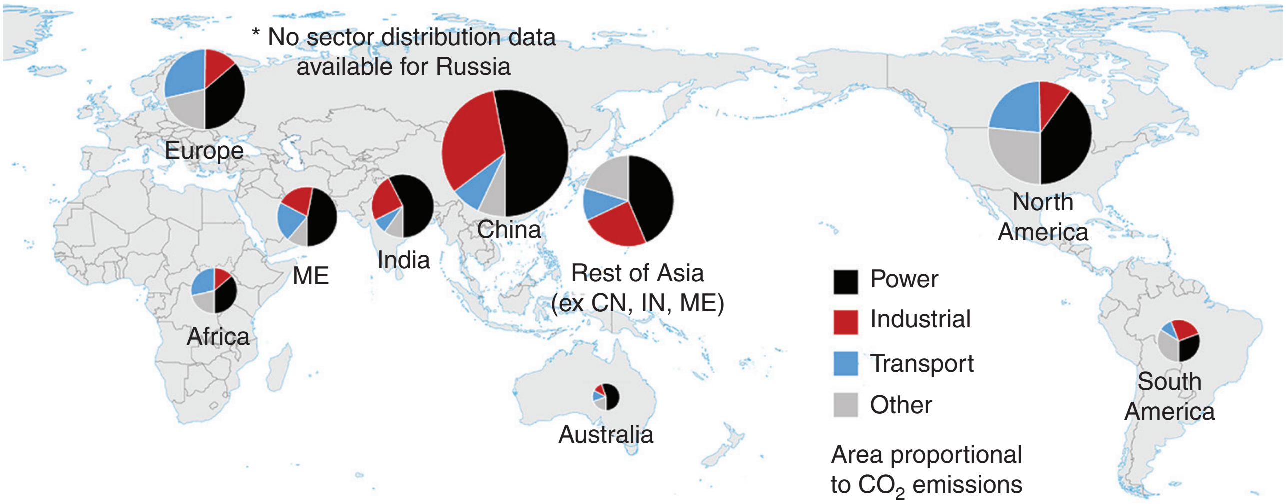

Fig. 3: Global distribution of CO_2 emissions by region and sector. The area of each circle is proportional to the total regional CO_2 emissions from 2017, with the breakdown shown from 2010, the last year for which comprehensive global sector data are available [72, 73].

of CO_2 in the flue-gas stream, with the concentration ranging from ~4% to ~12% for natural-gas and coal plants, respectively. The relative share of coal- and natural-gas-fired power is strongly correlated with the local fuel price; coal dominates China's power sector, while natural gas is ascendant in the USA. A secondary source of variability impacting CO_2 capture is the design of power plants. CO_2 capture from combined heat and power (CHP) facilities differs from power-only facilities and capture from plants cooled by water differs from dry-cooled plants.

Industrial sources are the other broad class of CO_2 emissions, alongside power, that can be amenable to CCUS in the near term. These sources vary widely in composition, temperature and pressure, flow rates, requirements for pretreatment or CO_2-product conditioning and requirements for flexibility. Among the more favourable options are applications that produce high-purity CO_2 (e.g. natural-gas processing, biorefining of ethanol, ammonia production, hydrogen production) and those with low capture costs (cement, iron and steel production) [74–78]. The largest driver of industrial CO_2 emissions (across multiple applications) is process heat from combustion in boilers and furnaces. CO_2 capture from industrial boilers has a number of technical similarities to post-combustion capture from power plants. In this regard, the paths to CCUS in the power and industrial spaces may utilize similar technology, regardless of whichever a region chooses to emphasize first.

Regions with extensive O&G activities are natural candidates for the RR archetype; natural-gas separation and EOR are both widely practised in several countries and a number of them have taken steps in this direction. The role of RR in the USA, Canada and Australia has already been introduced and individual projects will be examined later. China also has a diversified blend of RR-style demonstration projects in power and industry. South Africa, with a similar dependence on coal for both power and an indigenous coal-to-chemicals industry albeit on a smaller absolute scale, could follow a similar trajectory to China [79]. Co-location of high-concentration industrial sources and favourable geological sequestration sites reduce the costs, and consequently the financial risk, for GG development. In addition, RR and GG projects can also coexist and their development is intertwined in some parts of North America, China and Australia. All three regions have undertaken a number of industrial demonstration projects related to capture from high-purity industrial sources over the past decade [80, 81]. In contrast to Europe's heavier emphasis on industrial CCUS, the USA and Canada are pursuing a more balanced portfolio with both power and industrial demonstrations and projects; the majority of these projects involve RR [36, 42, 43]. Brazil, with an active O&G industry, significant investment in bioenergy (viz. ethanol biorefineries) and most of its storage capacity offshore, could also follow either or both of the RR and GG models [82].

Growing shares of VRE in the USA, Europe, Australia and China make these regions natural candidates for LCG-type activities. Each of these regions already faces challenges related to energy mix, grid stability and curtailment of renewable-energy generation. In addition, these regions are also taking early steps towards the use of CO_2-capture technology to decarbonize transport applications through electrification or zero-carbon fuels via the GG or LCG pathways.

Selected features and trends in the power sectors of the three leading CO_2-emitting regions are briefly discussed below. Despite distinct features in their energy and infrastructure landscapes, the core archetypes remain readily recognizable in local efforts to move CCUS forward.

- In the USA, the successful development of shale-gas resources during the 2010s has dramatically increased the supply of natural gas, while simultaneously reducing costs by ~40% from 2010 to 2017. Growth in natural-gas generation, along with increases in solar and wind generation, have eroded the share of coal generation to

~30% and reduced its average capacity factor to <70% [83]. The primary CCUS opportunities in the USA power sector now appear to be retrofitting existing coal or natural-gas power plants or the construction of new natural-gas plants with CO_2 capture or hybrids of coal and gas, as in the case of the Petra Nova retrofit [35].

- Europe's energy infrastructure varies widely across the continent. Renewable share has also increased between 2010 and 2017, but deployment has been uneven across the continent [84–86]. Seven countries in Europe (viz. France, 2022; Italy, 2025; the UK, 2025; Finland, 2030; the Netherlands, 2030; Portugal, 2030; Germany, 2038) have announced coal phase-out plans. Coal still generates a sizeable share of power in Eastern Europe, including the extensive use of higher-CO_2-intensity lignite coal. Efforts on CCUS in Western Europe are primarily focused on industrial sources (the UK, Norway, the Netherlands), with the UK also interested in (flexible) capture from natural-gas power plants [87, 88].
- Coal power dominates China's power sector, accounting for 69% of installed capacity and 74% of total electricity production in 2018 [65, 66]. At the same time, China is making progress towards its goals for renewable power generation of 15% by 2020 and 20% by 2030, and wrestling with high levels of wind-energy curtailment in most of its northern provinces [67, 89–91]. Sustained investment and recent progress in developing domestic shale-gas reserves bear watching over the upcoming decade [92]. The largest CCUS opportunities in China are related to coal. The lowest-cost capture option is the coal-to-chemicals industry, with >100 $MtCO_2$/yr potentially available at 150–200 RMB/tCO_2 ($20–25/$tCO_2$) [93]. The power sector represents the largest opportunity. Overcapacity in the coal fleet, and its relatively young average age, suggests that capture retrofits will be important, but greenfield coal installations may be an option for coal-dominated provinces such as Shaanxi, Hebei and Inner Mongolia [67, 94]. Constraints due to renewables integration, must-run CHP capacity required for winter heating in the north and limitations from the electricity market will impact local strategies for flexibility.

2.2 Government policy and markets

Governments play an important role in defining the overall energy and policy landscape, determining pricing for CO_2 emissions and incentive structures for their reductions, and in ensuring compliance. Government structure and regional choices can directly or indirectly favour or hinder CCUS development under different archetypes.

First, governments define the overall energy and policy landscape. This ranges from general guidance on energy mix, to performance and emissions standards for specific sectors or industries, to support for research, development and demonstration (RD&D) and innovation. Regulatory structures and political will for CCUS differ among nations and this manifests in how CO_2 emissions are regulated and priced, and the existence or absence of incentives for CCUS [95]. The tiered nature of government also means that considerable nuance can exist across provinces, states or other jurisdictions within a nation [96]. International agreements and treaties also matter and can promote broad co-ordination (e.g. the Paris Agreement) or create constraints on the practical implementation of CCUS (e.g. the London Protocol until 2019) [97]. Finally, political will and priorities can change over time in response to economic cycles (e.g. the effect of 2009 global recession on emissions-trading systems (ETS) markets), significant events (e.g. the effect of Fukushima on Japanese energy policy, 2020 coronavirus pandemic) or changes in leadership (e.g. the outcomes of elections or other transitions in power) [98–101]. This last point is especially important, as policy stability will facilitate in setting both a deliberate strategy to shift RR projects towards deeper decarbonization and consistency in regulations and incentives valuable for de-risking GG and LCG projects.

In the energy space, wide-ranging support for renewable energy means that CCUS deployment in most parts of the world will need to be aware of and compatible with this trend. One area in which differences have already started to emerge is in electricity markets. North American and Western European markets operate on an economic dispatch basis, where electricity generators bid into markets and the lowest-cost providers win. Policy support for specific cases can occur as feed-in-tariffs or tax credits. In contrast, incentives in China's regulated economy can take on different forms, including differentiated tariffs for different modes of generation [102]. Efforts to model markets and develop LCG solutions must be cognizant of both the current situation and market-reform efforts [103]. Together, these drive local costs and carry consequences for interaction between CCUS and the other components of a low-carbon energy system [104, 105].

As part of their policy-setting imperative, government support for CCUS can include: providing funding for RD&D; financing support for projects; convening stakeholders to drive compliance and catalyse partnerships; and backstopping the long-term liability associated with storage projects [13, 80]. The presence of support is important, but so is its nature [106, 107]. The specific types of support offered will create incentives and disincentives, and thoughtfully targeted support for near and long-term objectives of the different archetypes in a region can accelerate progress while also avoiding wasted resources. For example, Norway's decision to create Gassnova has helped to advance the country's evolution from a purely RR model towards one that is more aptly characterized as GG [52]. Canada's support of the Quest and Boundary Dam projects as well as the ACTL also support its evolution from a purely RR model to a diversified hybrid RR–GG model [43]. Over the past decade, China has also increased its investment and demonstration activity, and in 2019 issued a roadmap for CCUS development through 2050 [20, 108–112]. The archetype framework can aid knowledge diffusion by identifying the most transferrable technical and policy lessons from a region.

A second important role played by governments is determining pricing schemes for CO_2 emissions and incentive structures for their reduction. All three archetypes are impacted by this factor, with the GG especially sensitive to the details. Direct mechanisms that place a price on CO_2 include taxation systems, ETS and tax credits [113, 114]. Table 1 lists some of the tax and ETS markets that are operating around the world [115]. More general mechanisms also exist in the form of portfolio standards in power generation or taxes on fuels (e.g. coal tax in India); these also affect the competitiveness of fossil fuels against lower-carbon alternatives for fuel or feedstock, or prioritize certain classes of technologies. Pricing mechanisms can be limited to particular sectors. Electricity-market interventions such as contracts for difference (CfD), which are applicable to CCS in the UK, or tariff-based incentives used to promote the rapid and widespread deployment of air-quality-pollution controls at coal-fired power plants across China might also be harnessed to provide support for CCUS [63]. Finally, transfer structures can play within any of these mechanisms to enable CO_2 reductions in one locale to be credited for reductions in another (e.g. CDM from Kyoto Protocol). The specific design of these systems, including the regulatory authority, participation requirements, the process for setting tax levels or allocation of allowances, and trading rules all matter [116]. Such regional differences can make it difficult to transfer learning across jurisdictions and can also favour one form of technology over another [117]. For example, China's national ETS is expected to double the amount of global CO_2 emissions subject to trading markets; however, its use of a rate-based-allowances structure, rather than mass-based allocations used in the EU system, will make linkage of these markets challenging [118, 119]. Finally, international trading (e.g. shipping of CO_2 across international boundaries for storage, transport of low-carbon H_2 produced using CCS from Australia to Japan) has the potential to become an important mechanism for carbon management [120, 121]. In theory, nations could leverage differences in the cost of CO_2 capture and storage, combined with variations in ETS pricing, leading to greater reductions of CO_2 through CCUS in lower-cost regions accompanied by payments from high-cost areas to low-cost areas. In practice, many issues remain to be resolved.

- The policy situation in the USA is dynamic. Despite an announced intention to withdraw from the Paris Agreement, the USA has several mechanisms in place to support carbon management. This includes the federal 45Q and 48A tax credits, offered for CO_2 stored underground via EOR or sequestration and for investment in coal-power improvements, respectively [7, 37, 122]. There are also net-zero-emissions commitments by California, and New York and regional market

Table 1: Pricing and scale of existing carbon taxes and ETS markets as of August 2017 [115]

Carbon taxes					**Emission-trading systems**				
Jurisdiction	Launch year	Tax* (USD/tCO_2)	Share of emissions (%)	Emissions covered (Mt$CO_{2,eq}$)	Jurisdiction	Launch year	Price (USD/tCO_2)	Share of emissions (%)	Emissions covered (Mt$CO_{2,eq}$/)
Finland	1990	69–73	36	21	EU	2005	6	45	1963
Poland	1990	<1	4	16	Alberta	2007	24	45	118
Norway	1991	4–56	60	32	New Zealand	2008	13	51	40
Sweden	1991	140	42	22	Switzerland	2008	7	35	17
Denmark	1992	27	45	23	RGGI (USA)	2009	4	20	86
Slovenia	1996	20	24	4	Saitama	2011	14	35	7
Estonia	2000	2	3	1	California	2013	15	20	365
Latvia	2004	5	15	2	Tokyo	2010	14	18	10
British Columbia	2008	24	70	42	Quebec	2013	15	85	66
Liechtenstein	2008	87	26	0	Beijing (CN)	2013	8	40	5
Switzerland	2008	87	35	17	Guangdong (CN)	2013	2	60	388
Ireland	2010	24	33	20	Shanghai (CN)	2013	5	57	170
Iceland	2010	12	55	3	Shenzhen (CN)	2013	6	40	30
Japan	2012	3	70	913	Tianjin (CN)	2013	1	55	100
UK	2013	24	25	122	Chongqing (CN)	2013	<1	40	126
France	2014	26	40	186	Hubei (CN)	2013	2	35	324
Mexico	2014	1–3	46	332	South Korea	2014	18	68	470
Portugal	2015	8	26	18					
Average		**USD 13.04**	**46.69%**		Average		**USD 7.79**	**48.01%**	
Range		<1 to 140 USD	3 to 70%	**Total 1774**	Range		<1 to 24 USD	18 to 85%	**Total 4286**

Notable features of the regions with the largest CO_2 emissions are briefly discussed below. Important differences exist at the subregional level and studies of variability across selected states and provinces are highlighted.

mechanisms in these states and New England covering almost 450 $MtCO_{2,eq}$ [41, 123, 124].

- Europe was the first to establish an ETS, which now covers almost 2000 $MtCO_{2,eq}$. The ETS has had mixed results, due partly to an overabundance of allowances leading to prices too low to drive CCUS in the region [114, 125]. Underground onshore CO_2 storage is restricted in Germany and the Netherlands, but is being considered elsewhere on the continent, such as Spain and Italy. Favourable offshore-storage conditions also exist in the North Sea and this is being actively investigated [50, 126]. In the UK, the CfD mechanism used to support low-carbon electricity generation is also available to prospective CCS power plants, providing generators with a guaranteed power price for a finite period [127]. Thus far, negotiations with CCS projects have been unable to settle on a mutually acceptable 'strike price', although, at the time of writing, a new business model retaining the CfD for capture, but separating transport and storage, is being consulted upon in the UK [128]. There is strong social support for climate action in Western Europe; an Innovation Fund was established to provide financial support for climate-action projects, and several countries have declared net-zero emissions targets by or before 2050 [129, 130].
- China recently consolidated its environmental regulatory and climate-policy responsibilities into a Ministry of Ecology and Environment, which will administer national efforts and provide guidance for province-level activities [91, 131]. The country has operated seven regional ETS market pilots since 2013 and is preparing to launch a national ETS in 2020. For a more detailed discussion of the history of CO_2 policy and lessons learned from China's regional ETS systems, the interested reader is referred to three published reviews [61, 114, 132]. The national ETS system will initially cover ~7000 enterprises in the power sector, with an initial rate-based compliance target of 550 g CO_2/kWh. The market definition is interesting on a number of levels: it corresponds roughly to the emissions intensity of unmitigated natural-gas power plants, fleet average compliance using CCS would only require an ~50% effective capture rate for coal plants and the rate-based-allowances structure may make it difficult to establish linkages across sectors or with other markets using mass-balanced allocations [118, 119]. These issues should receive attention in the 2020s as the situation in China continues to evolve.

State-owned enterprises (SOEs) are another notable feature of the situation in China [131]. The power, transmission and O&G sectors in China are dominated by a limited number of SOEs. These entities have the potential to act meaningfully at scale in response to policy guidance; a recent example is the nationwide installation of air-pollution scrubbers at all power plants >300 MW in under a decade [133]. However, coordination across industrial silos (e.g. power, transmission and O&G) will be needed and this may prove challenging. Finally, the impacts of potential electricity-market reform should not be underestimated; successful liberalization of the power sector has the potential to reduce the carbon price needed to achieve a given level of non-fossil generation by half relative to the current regulated dispatch and pricing system [69].

3 Technical imperatives across the archetypes

Although the underlying scientific principles and core engineering-design concepts are universal, the manner in which component technologies are assembled into systems at the level of individual power plants, CCUS networks and the broader energy system can vary in different parts of the world and according to archetype. This section examines three aspects of how regional similarities and differences affect how the technical imperatives of the archetypes are met in different parts of the world.

3.1 Technology and costs

Costs impact the relative competitiveness of CCUS-based solutions within the broader energy system and drive commercial decisions on the design, construction, operation and evolution of networks, impact technology selection at the level of individual projects and provide metrics and targets for technology development. Here, we review cost variations and their drivers, discuss the importance of distributions when thinking about costs and comment on how CCUS economics might differ across archetypes. The discussion emphasizes CO_2 capture due to the larger body of regional cost estimation; the general observations can be extended to transport and storage.

In the literature, costs are commonly expressed in terms of cost per unit of product or cost per unit of CO_2 [134–138]. These two metrics are interrelated. In the power sector, the cost of CO_2 is expressed in terms of the *(added) cost of electricity* (COE), *captured cost* and *avoided cost*. Metrics for industrial CO_2 capture include *captured* and *avoided costs*, defined in a manner analogous to the definitions for the power sector. Offtake costs are expressed in costs per unit of CO_2 transported or stored. Revenue from utilization is typically the market rate for CO_2 as an input to the specific application. Many analyses focus on the operational cost of CCUS—namely the cost of capture, transport and storage—and experience across the world suggests that, in viable projects, capture costs represent the largest share. Whilst this is true from the perspective of a simple techno-economic analysis, in reality, the financing costs associated with cross-chain risk and long-term liability for stored CO_2 are what really drive project costs [139]. For this reason, an overemphasis on the development of new technologies for capturing CO_2 in the expectation that this alone will result in the material reduction of the cost of CCS is likely misguided.

3.1.1 *Cost variations across countries*

Estimates of the cost of CO_2 capture have been reported under a wide range of applications in different regions. Notable work includes reviews by the Global CCS Institute, the World Bank and the International Energy Agency, alongside a large body of primary literature [140–145]. When considering local embodiments and costs of CO_2 capture, it is important to distinguish between features in design and operation driven by site-specific factors from features driven by regional considerations. Simply put, regional factors *systematically influence* the majority of sites in an area. It is not always possible to fully separate the contributions of regional influences from purely site-specific factors, but they can be identified by looking for trends across multiple sites.

Cost differences due to technical considerations should be distinguished from differences that arise from non-technical factors. Many cost metrics for CO_2 are defined relative to a baseline reference; the choice of reference plant and the underlying assumptions can also contribute to cost differences. For capture from the power sector, greenfield cost calculations assume the reference is a plant with the same net output [146]. Retrofit cases assume a plant with the same gross output, with parasitic energy consumption by the capture island reducing the net output. This can artificially inflate cost estimates for retrofit plants, since cost is divided over less total power. Another example involves comparing regional cost estimates in different currencies calculated for different years. For example, in the USA, a major cost escalation was observed in 2003–07 due to materials costs and increased global competition. Cost estimates published in different years may use different currency bases. Correcting for currency and time requires careful attention [147]. The year-to-year relationship between currencies can change due to business cycles, differing inflation rates and geopolitics. This means that simply indexing for inflation in a base currency and then converting using a final-year currency-conversion rate could give a different result than converting currency in the base year and then indexing for inflation in a second region. Care should be taken to ensure the proper attribution of the root causes for differences in cost when making comparisons across regions.

Table 2 presents the cost multipliers used to adjust contributions related to capital (equipment), materials and labour in several regions. There are a number of notable features in the data. First, developed countries or regions tend to have higher costs, with the differential most pronounced in the cost of labour. Second, capital and materials are less expensive in China, although the advantage is lower in 2018 relative to 2010. Applying this to post-combustion CO_2-capture systems at coal-fired power plants, both the Global CCS Institute and the IEAGHG found the lowest costs for CCS (in US$/MWh) associated with China. Conversely, the most expensive locations for coal-fired generation with CCS (in US$/MWh) were Europe. In Canada, higher labour and equipment costs are partially offset by the lower cost of coal (primarily in the western part of the country). Lower costs in Mexico and China are driven by low labour costs and China also benefits from less expensive equipment. Higher costs in Germany and Poland are due to higher labour costs in Germany but higher coal and equipment prices in Poland. In Germany, rising coal and labour costs resulted in COE inflation of 20–36%. Overall, countries with lower labour costs (such as China, Mexico, Indonesia and Poland) and low energy costs (such as Saudi Arabia) have the lowest potential cost for implementing CCS. The role of regional differences in operating conditions and fuel costs should also be recognized; Singh et al. found that, despite the lower overall levelized cost of electricity (LCOE) values, the share of the total LCOE associated with fuel costs at coal-fired power plants retrofitted with CO_2 capture in China could be up to twice that at comparable plants in the USA due to the higher costs of coal and lower operating hours in China [148]. Additional analysis was performed with other modes

Table 2: Cost multiplier for different contributors to CO_2-capture costs in different countries (adapted from ref. 136)

Cost multiplier	GCCSI, 2011 (ref. year = 2010)			IEAGHG (ref. year = 2018)		
Region/country	Equipment	Materials	Labour	Equipment and materials	Labour (productivity)	Labour (costs)
US—Gulf coast	1	1	1	1	1	1
US—Midwest	–	–	–	0.95	1.19	1.04
Canada	1.08	1.01	2.16	1.10	1.40	1.30
Euro region	1.19	1.16	1.33	1.01	1.25	1.36
Eastern Europe	1.01	0.81	0.79	1.60	0.55	0.96
China	0.81	0.81	0.05	0.87	2.86	0.21
India	1.27	1.11	0.26	0.94	3.03	0.35
Japan	1.21	1.41	1.84	0.90	1.22	0.92
Southeast Asia	–	–	–	0.93	2.22	0.32
Australia	1.21	1.21	1.58	1.01	1.54	1.87
Middle East	1.27	1.21	0.35	0.94	2.30	0.32
South America	1.16	1.16	0.97	2.00	0.38	1.08
South Africa	1.27	1.11	1.04	1.05	2.80	0.95

of power generation, namely natural gas. Avoided costs were estimated for both types of power generation, as well as for industrial processes for iron and steel, cement, natural gas, fertilizer and biomass to ethanol.

The literature contains numerous studies that cite cost estimates from earlier studies. One pitfall is that sometimes the assumptions carried over from previous studies are inaccurate for the new region. Despite increasing recognition of the importance of using local costing and market-operation assumptions for both individual technologies and for network-design objective functions, some studies still use inappropriate costing assumptions for a given region. Work is already underway to establish appropriate standards and the community should continue to be vigilant about this issue going forward [134–138, 149]. This is a particular concern for cost estimates outside of the USA or Europe, or for papers that use heuristic estimates based on Western costing assumptions. This leads to uncertainty and inaccuracies in costing numbers.

3.1.2 *The importance of distributions*

Cost variations within sectors and across nations have the potential to significantly impact CCUS-deployment trajectories. Fig. 4 illustrates the relative costs of capture from coal and natural-gas power and industrial capture (of different types) in different locations. At a technical level, the concentration of the CO_2 to be separated is an important driver of the capture cost. On average, the capture costs from coal-plant flue gas are lower than for natural-gas plants, and separation from highly concentrated CO_2 industrial gas streams is lower still. Other factors also contribute to the costs and this creates a range of costs (with a distribution around the averages), represented by the stems in Fig. 4.

Cost distributions can be estimated in at least two ways. One method involves assigning a distribution to each cost contribution and propagating the results using a probabilistic analysis method to establish uncertainty ranges [150]. This approach is helpful in identifying key drivers or when inadequate data are available. The second method is to directly compute the distribution from a known fleet of assets. Distributions computed from this approach can be more informative when used in network design but require significantly more information about the design and operation of individual assets. Fig. 5 compares the estimated cost distributions for retrofit CO_2 capture at coal power plants across the USA and China. The shapes of these distributions reflect differences in the local infrastructure base and there is a wide range of costs, with the LCOE as the lowest-cost power plant, equipped with CO_2 capture of 74% and 36% less than the mean LCOE in the USA and China, respectively. The width of the distribution in China is narrower, ostensibly due partly to standardized designs being deployed more consistently across a younger fleet.

Marginal abatement cost (MAC) curves developed to visualize the CO_2-capture costs versus the size of the opportunity can also help in this endeavour. MAC curves have been published for the power sector in the USA and China, and industrial sectors in the USA, Europe and China [7, 153–156]. Combining these MAC curves across sectors to produce an integrated curve should be a relatively simple exercise and could inform efforts to develop staged deployment plans. Looking at capture technologies and costs from this perspective could also help the research community to allocate its resources and attention to the areas where progress is most needed on the path to deep

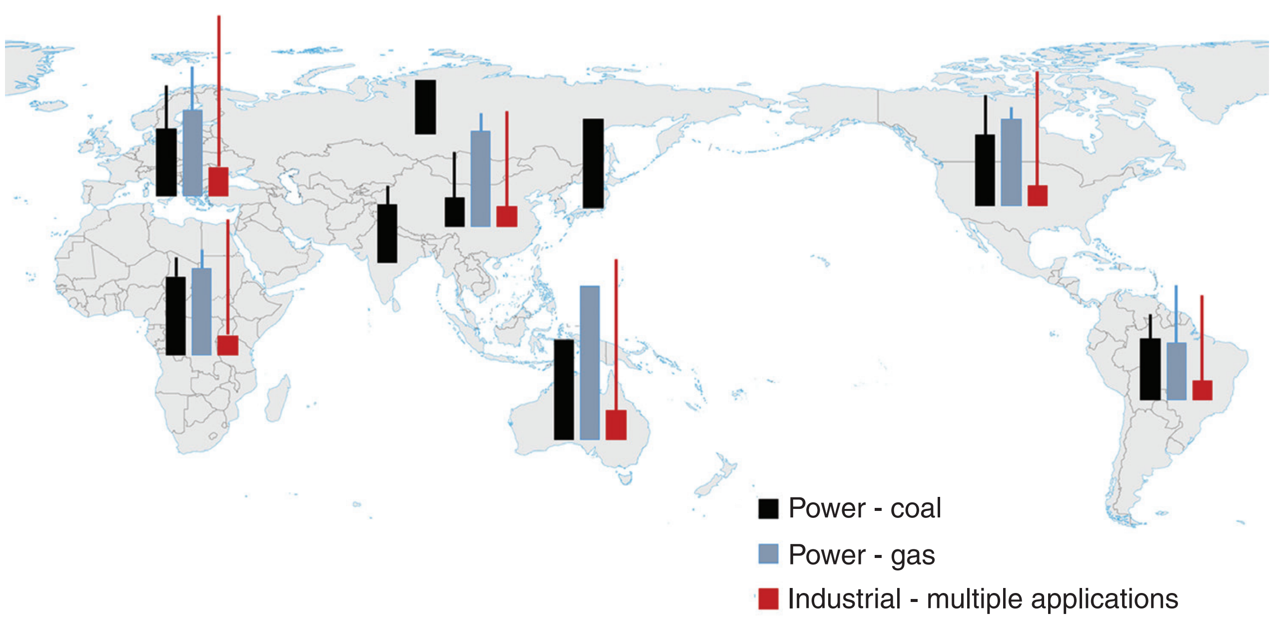

Fig. 4: Estimated cost ranges for CO_2 capture in different parts of the world. The height of each bar represents the lowest estimated cost scaled consistently in 2016USD/tCO_2; the stems reflect the range of costs from different references. The black bar represents the cost of capture from coal-fired power plants, the blue bar corresponds to capture from natural-gas power plants and the red represents capture from industrial applications.

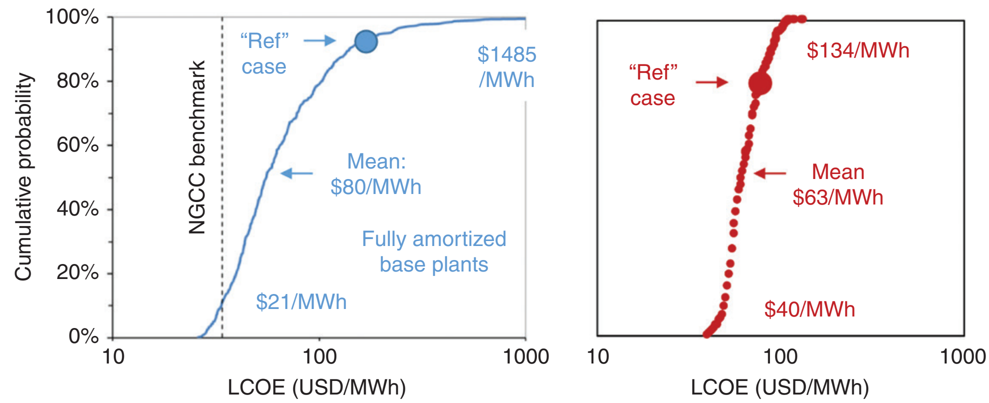

Fig. 5: Cost curves across the power-plant fleet in the USA (left) and China (right). LCOE for coal plants retrofitted with post-combustion capture. The US-fleet data cover 497 full amortized units with a cumulative capacity of 180 GW computed by Zhai [151]. The China-fleet data cover 500 units with a cumulative capacity of 310 GW computed from IEA data [152]. The reference-case LCOE for the US and China cases are $133/MWh and $94/MWh [148].

decarbonization. Simply put, the urgency of the challenge means that the lowest-cost opportunities are likely to use commercial or near-commercial technologies; efforts to develop second-generation technologies should balance general improvements in generic CO_2-separation processes and focused efforts on the more expensive applications within different regions.

A final note concerns variability and uncertainty in cost estimates and distributions. Variability arises from real differences in actual assets. Uncertainty arises from variability in certain components of the cost. The most precise cost data are held by operators of actual projects, some of which are retained as proprietary information. Engineering estimates are expected to be accurate to within a level of uncertainty (e.g. low –15 to –30%, high +20 to +50% for Association for the Advancement of Cost Engineering Class 4 feasibility estimates) and it is important to avoid over-interpreting the significance of these values. One way to manage this is to look at cost ranges and distributions in costs. Sites within a region have a range, which arises from site-to-site variability. An extreme example of this is the cost of the storage component of the Gorgon LNG Project, which is variously estimated at A$2–3 billion (US$1.5–2 billion). This cost is largely a reflection not of the cost of CCS, but of the cost of undertaking a complex operation on an isolated island, requiring exceptional measures to protect a unique environment and which is subject to extreme tropical weather events. Gorgon should not be used as an indication of the cost of CCS. The ranges for regions should be compared in the context of this paper. It is also necessary to deconvolute the effects of site-to-site variability within a region from more systematic differences due to region-to-region variability.

3.1.3 *CCUS economics and archetypes*

We conclude by commenting on two areas in which CCUS economics might differ across archetypes and require attention.

At the level of individual technology components, costs have been extensively studied and confidence levels for capture, transport and storage technologies used in the RR and GG archetypes are not expected to vary significantly [146, 147]. In contrast, the component technologies may be required to operate flexibly under the LCG archetype and cost models will need to account for the additional incurred costs from flexible operation. Studies of flexible capture to date have focused primarily on operability and the use of dispatch electricity prices to enable plants to achieve profitability [29–32, 157]. Work has also begun on understanding the economics of a network operated in a dynamic manner [25, 158, 159].

The second issue relates to business models, specifically offsetting revenue and financing risks. Offsetting revenue improves the value proposition for any project and all three archetypes have potential avenues for generating it. However, the sources differ and confidence levels vary across different methods for estimating their value. In RR-type projects, revenue is derived primarily from the sale of recovered hydrocarbons. Models exist to forecast productivity and prices, and the extensive historical experience and expertise of the O&G industry can be applied to develop RR business models with a relatively high degree of confidence [160, 161]. Under the GG development model, potential revenue is primarily derived from regulatory incentives (e.g. 45Q tax credits in the USA), avoided penalties (e.g. carbon taxes in Europe) and, for CCU-type projects, the sale of conversion products. Offsetting revenue for GG will translate across borders, but the specifics of market pricing and regulatory incentives/penalties will be location-dependent. For example, a premium for low-carbon products (e.g. concrete, polymers) might be offered in some regions but not in others. In LCG, revenue might be generated by a combination of low-carbon power and capacity payments or some other transfer payment mechanisms [162]. Work is needed to further define the actual frameworks for assessing value, instruments for grid services and mechanisms for making payments.

We also note that risk can differ across archetypes, which can impact the ability of projects to secure financing.

A historical record of success and established business models means that RR-type projects can be evaluated on their individual merits. GG-type projects can carry a higher degree of risk due to nascent business models associated with CO_2 storage and utilization. These are expected to decrease as experience is gained and this learning curve is expected to benefit projects across regions. The relative risks in different regions can be increased by policy uncertainty or reduced by the availability of green bonds or other forms of climate finance [163, 164]. LCG-type projects are the most complex and difficult to evaluate from a financing-risk perspective because the evolution of electricity markets and grids presents a moving target for projects. Aggressive transitions towards low-carbon grids can be facilitated by government support, but the nature of this support will need to be adapted to the specific situations in each country. In liberalized electricity markets, the financial risk might be mitigated in part through mechanisms such as capacity payments and eligibility for support offered to other types of 'firm' low-carbon power [165, 166]. In more regulated markets (e.g. China), direct interventions such as market rules related to dispatch priority, electricity pricing, carbon pricing and directed capital allocation may also be possible [63, 167].

3.2 CCUS networks

The distinguishing features of archetypes emerge most clearly at the level of CCUS networks. This section briefly reviews network design and cross-chain effects, surveys regional differences in networks and considers how networks might be expected to evolve during their lifetimes.

3.2.1 *Network design and cross-chain effects*

Optimization of the CCUS network design requires more than just optimizing the individual components related to capture, transport and storage. Interactions between components can create global optima that might not be recognized in attempting to minimize the costs of each of the components. Technology and design choices in one part of a CCUS supply chain can impose significant constraints on other parts (e.g. more stringent impurity specifications on CO_2 make capture more difficult and offtake easier with the exact optima dependent on the local situation, CO_2 can be transported at purity levels of 99.9%, 95% and 90%). The impact of regional effects on cross-chain trade-offs needs to be understood and taken into account in efforts to establish commercial CCUS networks. An example of this is the effect of CO_2 purity on the overall costs of a network. Setting pipeline specifications at the lowest levels needed for practical feasibility can lead to significant savings due to less stringent purification and conditioning at the capture sites. For a network in the UK, Kolster et al. found that reducing the CO_2-pipeline purity from 99% to 96% could produce a 17% saving in the total cost of the project [168]. Another example relates to the implications of increased renewable energy on the grid. The non-steady flows associated with flexible CO_2 capture from power plants could pose challenges for saline aquifer injection, which may prefer steady-state operation. This tension might be resolved through appropriate scheduling of CO_2 sources or through the installation of tank storage capacity at appropriate points in the network. Either option, or both, could be viable, depending on the specific network configuration. Finally, CO_2 utilization differs from geological storage in the contributed value to the overall system and in the constraints associated with CO_2 quality and transport; efforts to understand how to properly model these differences are still in the early stages [169].

Cross-chain effects amplify the impact of uncertainty and risk in project financing decisions. CCUS networks are large capital projects and investment decisions take into account both the estimated cost *and* the variance; risk anywhere in the chain can make it difficult to finance the investment, despite the attractiveness of specific components. One example is the quality of the reservoir characterization at different storage sites. Poor data quality creates high uncertainty around the capacity and injectivity, and whether a plume will stay within the lease boundaries. Fine-scale heterogeneity is known to significantly impact the migration of CO_2 and pressure within a reservoir but, at the present time, 3D reservoir models are limited in the extent to which they can handle plume and pressure behaviour, which results in an added uncertainty to a project. A site that fails to accommodate CO_2 at its design capacity and rate or where the CO_2 plume extends beyond the approved lease boundaries can have negative operational and economic consequences across an entire network. Consequently, a site with higher confidence around its performance is favoured over a site with potentially larger capacity but greater uncertainty from an investment perspective [170, 171]. In this sense, regions with better subsurface characterization, such as regions where there has been extensive O&G exploration, are equipped to deploy CCUS networks faster than regions that must first engage in detailed geological surveys. Beyond the technical concerns around storage, uncertainty around regulatory policy and long-term liability can also make financing difficult. Finally, financing decisions can differ in liberalized versus regulated markets and efforts should be made to appreciate these differences. In market situations with multiple players rather than a single vertically integrated entity, there is also financial risk inherent in the relationship between capture operator and storage operator. Potential non-delivery of CO_2 is an uninsurable risk for operators of storage sites; and capture plant operators see the potential unavailability of storage in the same way. The willingness of governments to provide a liability backstop to stored CO_2 is currently particularly important for the GG archetype. The possibility of leakage during operation or after closure poses a risk, since the operator must bear the costs; different carbon policies would value this in different ways and policy clarity is essential to defining the risk in a way that it might be insurable. Currently, backstops exist in North America, Europe and Australia, but the post-closure interval before this can be exercised, during which extensive monitoring is usually required of the operator, ranges from 15 to 50 years [172–174].

3.2.2 *Survey of hubs and network design across regions*

The design of networks is not a new problem—analogues include roads, utility lines (e.g. water and sewage) and O&G infrastructure. Efforts to design CCUS networks have benefitted, in particular, from historical experience with natural-gas pipeline networks [175]. Network design was initially formulated as a linear programming problem, with information about the geographic distribution and performance of sources and sinks encoded as boundary conditions, and an objective function based on economics to arbitrate between different topologies [176–178]. Over time, stochastic-modelling approaches have become popular due to their ability to capture the effects of uncertainty in flow variability over time and storage capacity [179–181]. In both cases, a key step in problem formulation is establishing the appropriate objective functions to assess the value of competing configurations. Currently, objective functions for CCUS networks can be adapted to the RR and GG archetypes by including appropriate terms for the regulatory penalty for CO_2 emissions, the costs of capture, transport and storage, and the value for CO_2 sold, as illustrated in Fig. 6. The contributions of different factors related to the system design, operation and costs can be independently calculated for each source and storage node, as well as the contributions for different routing configurations for transportation. 'Policy' factors related to the cost of CO_2 emissions and incentives offered by local governments are shown as a separate contribution. The degree of granularity and details for these terms are one of the differentiating features among various studies. It is also now well recognized that the cost function can be non-linear and non-convex.

Real-world experience in the construction and operation of full-chain CCS projects includes point-to-point topologies and simple hubs. Table 3 lists existing projects by CO_2 source, overall capacity, offtake arrangements and start-up date. Interest in CCUS at large power plants remains high in China and there currently appears to be growing enthusiasm around industrial capture opportunities in North America, Europe and Australia. Of the 30 projects in the list, 19 are solely RR-type projects, 6 are solely GG, 4 are a combination of RR and GG (the Sleipner and Snohvit projects included significant studies of sequestration, the Quest and Port Arthur projects focus on H_2 production) and 1 is RR with early-stage LCG (SaskPower's Boundary Dam plant and Shand feasibility study). The data are drawn from the Global CCS Institute projects database and include a separate section for projects currently under construction or in advanced development [182]. The cumulative global capacity of these projects is ~40 $MtCO_2$/yr, with the majority of the captured CO_2 used primarily in EOR operations. Most of these projects use dedicated CO_2-transportation systems between point sources and sinks.

Network design specifically for CCUS has been under study for some years in Europe, North America and Australia. Early studies focused on matching sources with sinks and the effects of the transportation mode (e.g. pipeline, rail, ship) and routing on costs [183–190]. Over time, modelling efforts grew more sophisticated to accommodate increased complexity in the network architecture, including trunk lines and hubs with multiple sources and sinks, and have laid the groundwork for GG development [191–197]. A key challenge in optimizing pipeline networks is maintaining adequate flows and the question of how to schedule flows from sources with time-varying profiles has received considerable attention [198]. Progress has been made in understanding and encoding technical constraints associated with coming CO_2 captured from different types of sources, with an emphasis on compatibility related to impurities and minor components [168, 199, 200]. Screening tools and heuristics have been developed to reduce the computational effort required to arrive at meaningful solutions in regions with more extensive existing energy and industrial infrastructure, such as the USA and Europe [201–203].

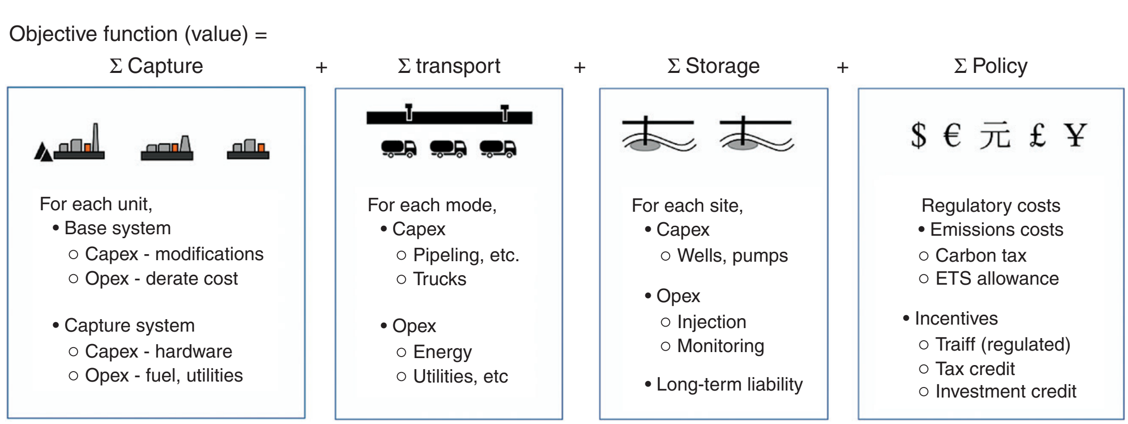

Fig. 6: Conceptual definition of objective functions used in network optimization

Table 3: List of existing full-chain CCS projects and details about their network configurations [182]

Project/location	Country	Operator	Start year	Nature of the CO_2 source	CO_2 volume (Mtpa)	Offtake avenue	Archetype	Additional ref(s)
Terrell	USA		1972	NG processing	0.4–0.5	EOR	RR	
Enid	USA	Koch Nitrogen	1982	Fertilizer	0.7	EOR	RR	
Shute Creek	USA		1986	NG production	7	EOR	RR	
Sleipner	NOR		1996	NG processing	1.0	Saline aquifer	RR (+GG)	[50]
Weyburn-Midale	USA/CAN	Great Plains Synfuels	2000	SNG	3.0	EOR	RR	[204]
In Salah	ALG	BP, Sontrach, Statoil	2004	NG processing	1.0–1.2	Depleted gas reservoir	RR	[205]
Snohvit	NOR		2008	NG processing	0.7	Saline aquifer	RR (+GG)	
Century	CAN	Century	2010	NG processing	8.4	EOR	RR	
Hellisheioi	ICE	Carbfix	2012	Geothermal		Basalt mineralization	GG	[206]
Port Arthur	USA	Air Products	2013	SMR	1.0	EOR	RR+GG	
Coffeyville	USA	Coffeyville Nat Resources	2013	Fertilizer	1.0	EOR	RR	
Lost Cabin	USA		2013	NG processing	0.9	EOR	RR	
Santos Basin	BRA	Petrobras	2013	NG processing	1.0–2.5	EOR	RR	
Boundary Dam	CAN	SaskPower	2014	Coal power	1.0	EOR + Saline aquifer	RR (+LCG)	[42, 207, 208]
Quest	CAN	Shell	2015	H_2 production	1.0	EOR + Saline aquifer	RR+GG	[18, 209, 210]
Uthmaniyah	Saudi Arabia		2015	NG processing	0.8	EOR	RR	
Mussafah	UAE	Emirates Steel Industries	2016	Iron/steel	0.8	EOR	RR	
Decatur	USA		2017	Ethanol	1.0	Saline aquifer	GG	[36, 211]
Petra Nova	USA	NRG	2017	Coal power	1.4	EOR	RR	[35, 212]
Jilin	CHN	CNPC	2018	NG processing	0.6	EOR	RR	[61, 213]
Under construction/ advanced development								
Beijing Shuangang LanzaTech	CHN	Lanzatech	2018	Utilization	0.09	Utilization	GG	[61]
Alberta Carbon Trunkline	CAN	ACTL/Agrium	2019	Fertilizer	0.3–0.6	EOR	RR	[43]
Gorgon	AUS	Chevron	2019	NG processing	4.0	Saline aquifer	RR	[44]
Jinjie	CHN	China Energy	2019	Coal power	0.15	Saline aquifer	GG	[61]
Ordos	CHN	Yanchang Petroleum	2020–21	Coal-to-chemicals	0.41	EOR	RR	[110]
Rotterdam	NL	Port of Rotterdam	2021	Multiple industrial	2.0–5.0	Saline aquifer	GG	[53]
Lake Charles	USA	Lake Charles Methanol	2022	Methanol	4.2	EOR	RR	
Northern Lights	NOR	Gassnova	2023–24	Multiple industrial	0.8	Saline aquifer	GG	[52]
Shengli	CHN	Sinopec	2020s	Coal power	1.0	EOR	RR	[61]
Gippsland basin	AUS	CarbonNet	2020s	Industrial	1.0–5.0	Saline aquifer	GG	[24]

Table 4 summarizes the results from network-design studies from around the world. These studies consider configurations of larger scale and scope than currently exist as operating projects. GG-type projects represent a majority of the total, reflecting a greater interest in CO_2 storage among prospective studies relative to commercial projects (cf. Table 3). Mixed networks with large power-plant contributions and smaller industrial contributions will be operated differently than networks that have a more equitable distribution of sources. In the former case, the largest sources will dominate; in a more level field, mechanisms will be needed to coordinate flow. Networks with highly intermittent operations may favour discrete transport options such as ship or rail, rather than pipelines. Economic growth rates can impact network design through the rate at which sources are added or removed from the network (e.g. faster in Asia, slower in North America and Europe). Regions with large existing asset bases may have opportunities for retrofitting with CO_2-capture systems, the repurposing of abandoned pipelines or rights-of-way and integration with oilfield operations or the use of depleted oil fields. Another notable difference relates to CO_2 sinks; limited onshore-storage options due to geological constraints or social acceptance in some areas could shift networks towards offshore storage or, in some cases, set an upper limit on the extent of CCUS deployment in particular locations. Much is still unknown about how actual CCUS ecosystems perform, the most effective business models and the unintended consequences associated with different operating rules.

The importance of using proper costing assumptions must be reiterated. Over a third of the studies (11 of 27) inappropriately adapted costing models developed in one region of the world to describe costs in another. Abundant public data and standardized costing methodologies exist in the USA and Europe, and these are appropriately used in most studies performed in these regions. Interestingly, there are some studies where US pipeline-costing assumptions were used for studies performed for European cases. In other parts of the world, researchers used US or European costing assumptions [231]. Some studies that used this approach noted that this was a deliberate decision, given the dearth of appropriate guidelines for the country in question; other papers were less clear on whether this nuance was appreciated. Progress has been made on this front, with local costing assumptions developed for China, Canada and Australia; however, the adoption of these is still inconsistent across research groups [232]. A third approach was to convert US or European costs to local currency using exchange rates, but not to otherwise alter the underlying cost structure. For studies seeking to screen between different pipeline configurations, the loss of accuracy associated with this issue is not insurmountable. However, as these studies incorporate more of the supply chain, including capture costs at different sources and injection costs at different sinks, getting the economic assumptions right takes on increasing importance. Even in studies that use appropriate costing assumptions, many still simplify the costs at individual nodes by assuming homogeneous cost structures in their calculations. These issues are expected to resolve as models become more granular and increasing rigor is applied in the modelling of potential commercial networks.

The work summarized in Tables 3 and 4 indicates that all topologies are possible and that optima depend on local conditions. There do not appear to be general principles that constrain RR-type networks. In contrast, the need to aggregate flows from smaller industrial sources to meet the flow-rate requirements for saline-aquifers storage may require a degree of branching in certain GG networks like industrial hubs. Independently of archetype, important constraints that drive the selection of topology include the local terrain, the geographic distribution of sources and sinks, and local regulatory requirements. Regions with relatively small or geographically isolated infrastructures may have less flexibility and face higher (average) costs in their CCUS supply chains. A major practical issue that influences topology is the level of commitment to deployment. Absent strong political and economic drivers (GG model) to support the financing of large pipeline networks, adoption to date is dominated by point-to-point projects (small-scale RR models). Several studies have commented that building a network piecemeal could lead to a different final configuration that might be less 'optimal' than one that is built on a more aggressive schedule. The issue of deployability, and network evolution more generally, is addressed in the next section.

3.2.3 Network evolution

Networks can be *forced* to evolve in response to changes in their local situation (e.g. the addition or loss of individual source or sink nodes, the introduction or cancellation of regulations) or *designed* to evolve according to longer-term strategic purposes.

Forced evolution is not uncommon for large infrastructure projects. Robustness can be designed into networks by incorporating the ability to add, reroute or establish multiple configurations in the original design. This can be a useful hedge against changes in source or sink productivity, both increasing the operational resilience of the network and providing flexibility over its lifetime [175]. Work on 'right-sizing' pipelines in networks, path dependency, the risks of lock-in or stranded CO_2 and the costs of 'getting CCS wrong' has uncovered a number of interesting issues for future attention [218, 233, 234]. For example, while networks could be designed to accommodate the planned addition and closure of CO_2 sources with a range of compositions, unplanned changes in the flow profiles (e.g. due to flexible capture at power plants) stress the network. Similarly, planned closure of CO_2 sites once they reach full capacity could be incorporated into the initial design, but surprises due to uncertainty in the actual capacity could

Table 4: List of selected CCUS network-modelling studies

Region	Features	Nodes	CO_2 volume (Mtpa)	Costing basis[a]	Study year	Archetype	Ref(s)
North America							
Alberta (Canada)	Industrial	22 sources + 20 sinks	36	Canadian (2011)	2018	GG	[170]
California (USA)		37 sources + 14 sinks (EOR)		US (2008, 2012)	2009	GG	[194]
Texas (USA)		8 sources + 3 sinks	16	US (2007)	2012	GG	[175]
USA	Power and industrial			US (2007)	2014	GG	[214]
Appalachian (USA)	Industrial 3 scpc power	6 sources + 7 sinks	3.9	US (2011)	2018	GG	[198]
Europe							
Europe	336 power plants, regional perspective		1375	IPCC (2005), Rubin (2015) 1.38USD:EUR	2017	GG	[215]
Europe	Industrial	1335 sources (38 clusters) + 66 sinks	772	EU (2010)	2012	GG	[216]
Utsira (North Sea)	Hub to offshore	8 sources + 1 sink (offshore)	150	European (2010)	2011	GG	[217]
NL	Electricity + cogen (24) + 15 industrial	43 sources (7 clusters) + 173 sinks (8 clusters)	15	European (2003)	2010	GG	[203]
Amsterdam-Ijmuiden (NL)	2 NGCC + 1 CHP-CCGT + 6 industrial//6 reservoirs	9 sources + 6 sinks	8.3	European (2014)	2015	GG	[218]
NL	Industrial capture + storage in offshore saline + O&G	35 sources + 47 sinks	86	US (2014)	2017	GG	[219]
Rotterdam (NL)	Industrial	4 sources	29	European (2009)	2017	GG	[53]
Scotland	Industry	13 sources	5.7	US NETL (2016)	2016	RR–GG	[220]
Asia							
Hebei (China)	42 power + 9 iron/steel + 18 cement + 16 ammonia + 3 oil refineries	88 sources	232	Unspecified (likely Chinese)	2010	GG	[187]
Ordos basin (China)	Coal power and industry	80 sources + 3 sinks	350	US (2007)	2014	RR	[221]
Jing-Jin-Ji (China)	218 PP (24 >300MW ~2/3 capacity)	16–23	108	IPCC capture costs; China pipeline costs (2009)	2017	RR	[222]
Northeast China	Power, cement, iron/steel	94 sources (top 17 = 50%) + 3 sinks	281 (130)	EU (2011)	2018	RR	[223]
North China	Coal power	108 sources + 6 sinks		US (2006)	2018	GG	[224]
India	National perspective	521 sources	1438	Indian (2014)	2017	GG	[225]
East coast (South Korea)	Mix of gas and coal	23	102	US—Rubin/Rao (2007)	2017	GG	[177]
Yeosu industrial (South Korea)	Industrial boilers + turbines	5	2.4	Unspecified	2018	GG	[226]
National (South Korea)	Industrial + offshore	15 sources + 2 sinks	267	South Korean (2015)	2018	GG	[227]
Australia							
Queensland (Australia)	Power—4 coal or 5 NG + 1 refinery	10 sources + 3 sinks	27	US w/0.85USD:1AUD	2012	GG	[185]
South America							
Brazil	Cement factories	10 sources + 3 sinks	9.7	US (2007)	2017	GG	[228]
Central/south Brazil	Ethanol distilleries (seasonal) + fossil + refineries	236 distilleries + 5 oil refineries + 1 NG PP	83	US and European (2008–13)	2018	RR	[82]
Brazil	Ethanol distilleries with hubs, pipelines and trucks	236 distilleries (8 hubs)	16	US (2011)[a] recognized issue	2018	RR	[229]
Africa							
Morocco (+ Iberia)	Power + industry	285 sources + 163 sinks	209	European (2008–14)	2015	GG	[230]

[a]Red font denotes studies that use a *costing basis* from a region different from the study region.

create serious disruption and require significant additional investment to address. Differing growth rates across economies might impact flows in networks. Higher degrees of uncertainty are expected in faster-growing economies, but there may also be opportunities for synergistic effects where infrastructure buildout can leverage broader investment. In addition, broader initiatives around climate finance could be applied to CCUS [163, 164]. Non-linear interaction effects could also emerge and these issues will need to be explored as they are uncovered. Finally, policy factors can also force networks to evolve. Efforts to quantify the effects of policy uncertainty are in the early stages. Significant differences in the policy outlooks and processes for investment decision-making in the USA, Europe, China, India, Australia and other parts of the world mean that both intentional and unintended different headwinds and tailwinds could emerge as these nations manage changes in their energy and industrial ecosystems over the next few decades. For example, nations that have made net-zero commitments by 2050 or earlier may only have one cycle of infrastructure turnover and this will require a CCS network design compatible with this objective.

Planned evolution can facilitate CCUS deployment in the short term and also maximize its contribution to global decarbonization in the long run. An example of near-term planned evolution is staged deployment. Constraints around financing, social acceptance and cross-chain effects may require networks that are less optimal than theoretically possible; incorporating the possibility of strategic evolution into the original design offers a way to address this constraint. Given their large capital requirements, the sequential buildout of a network development starting with lowest-cost sources and sinks as the strongest candidates and more expensive nodes added later could reduce the initial required outlay and improve the financial-risk profile of a project. Staged development could also reduce the risks associated with market or regulatory immaturity.

The transformation of RR-type networks into GG-type networks is an example of long-term planned evolution. Such a transition could take advantage of the strengths of the RR model in rapidly deploying CCUS capability in the near term, while also addressing the longer-term need to move away from O&G in support of decarbonization. Such a transition would not be without significant technical, commercial and regulatory challenges. Technically, the idea of repurposing an established capture-and-transport infrastructure is appealing, but work needs to be done to understand possible changes in the operating procedures and specifications, necessary upgrades to systems to accommodate storage and the actual transition procedure. Systematic study of this issue is recommended to identify and address unrecognized risks. From a commercial perspective, a transition in the operation of the network could change the operating model and risk profile of a project. A network designed to make the transition could incur extra up-front costs. For example, pipeline routes optimized for future expansion to aquifer storage are likely to be longer than direct source–sink routing. Government incentives may be needed to offset the financial risks in support of longer-term societal objectives.

3.3 Integration of CCUS with the broader decarbonization efforts

3.3.1 CCUS and low-carbon grids

The world is in the midst of energy-system transformations driven by advances in digitization and the increasing penetration of wind and solar power generation. Renewable energy enjoys strong social acceptance in many nations and governments have adopted favourable policies to support its continued growth [235–237]. To this end, the large-scale deployment of renewable-energy systems is widely considered a significant climate-change-mitigation strategy, although the question of whether the world can reach a 100% renewables solution is still being debated [238–240]. While this may be possible, it is not necessarily the most affordable or speediest option [241].

The relationship between CCUS and renewables has been explored from a number of angles. Policy debates on decarbonization often frame the discussion in terms of selecting a 'winner' among different modes of power generation (i.e. renewables vs CCUS vs nuclear) rather than looking at the most cost-effective, reliable and resilient energy mix for reducing the carbon intensity of energy production. This is also reflected in climate finance, where capital flows have strongly favoured renewable-energy investments over the past decade [166]. However, there is growing recognition of the need for complementary activity, in the form of demand response and dispatchable low-carbon power (including CCUS). Here, we advocate an inclusive approach that involves thoughtful selection of the appropriate technology mix for each regional situation [242, 243].

Successful deployment of CCUS into energy systems that have large shares of VRE generation presents both challenges and opportunities [165, 244]. System-level modelling has shown that fossil power with CCUS plants imparts a degree of flexibility and affordability that can facilitate energy-system transformations at both the global level and in specific regions such as the UK and parts of China [181, 245, 246]. The intermittent nature of wind and solar power increases the need for flexibility on dispatchable generators, including fossil power plants equipped with CO_2 capture [25, 27]. At a technical level, the component capabilities of CCUS were developed under the assumption of steady operation and the need to dynamically operate capture, transport and injection systems introduces new engineering nuances that will need to be addressed. Commercially, the need to balance increasing levels of renewable generation against grid-level considerations such as reliability and affordability has been a major driving force for electricity-market reform. The specific nature, degree and stage of reform vary by location, but there is a widespread move towards markets and energy systems that can effectively value and incorporate large shares of intermittent renewable power [247–256]. Together, these technical and commercial considerations will shape how CCUS will be developed for the power sector.

There is also an opportunity for new concepts that couple CCUS with wind and solar generation to create more affordable system-level solutions. Some initial work to understand appropriate strategies for the dispatch of electricity from CCS-equipped power generation into existing or hypothetical liberalized dispatch markets has already been performed for cases in the USA, the UK, Australia and China [158, 159, 257–260]. There have also been some studies looking at the prospects of integrating renewables with CCS—for example, the use of renewable energy to offset the parasitic energy loads associated with CO_2 capture or the use of renewable wind energy that would otherwise be curtailed for CO_2 conversion [261]. One interesting direction is CO_2 bulk energy storage (CO_2-BES). An example is the use of CO_2 to augment the pressure in geothermal resources; CO_2 captured from large point sources could be pressurized and injected into geothermal resources using renewable energy to time-shift energy to match electrical demand [262].

Other approaches include electrical or electrochemical CO_2 conversion to decouple chemical production from fossil resources, reducing annual greenhouse gas emissions by ≤3.5 Gt $CO_{2,eq}$ in 2030 [263]. Fully exploiting this potential would require >18.1 PWh of low-carbon electricity, corresponding to 55% of the projected global electricity production in 2030, and this may not be the most effective use of available resources. It is more likely that CCU concepts will be deployed selectively in cases where the local value of the products exceeds alternatives available through direct power-to-X approaches, rather than as a single one-size-fits-all solution used uniformly across the world.

3.3.2 CCUS as negative-emissions technology

The possibility of negative emissions is valuable for longer-term efforts towards deep decarbonization, but pathways for deployment require further attention [156]. A leading option is BECCS [264–267]. In a broad sense, BECCS refers to industrial and power applications where biomass is used as a feedstock and CO_2 emissions are captured and stored, resulting in net negative CO_2 emissions over the life cycle of the process. Given the lower energy densities of biomass, this approach generally falls under the GG archetype. Implementation of BECCS in different countries can vary the terms of integration into the energy system and the specific local emphasis carries technical implications as well. For example, equipping biofuels production (viz. ethanol distilleries) with CCS presents different challenges than adapting power-plant boilers for co-firing or full substitution with biomass. As a result, BECCS in a Brazilian context could diverge significantly from BECCS in the UK. Estimates of the BECCS potential based on the logistics of obtaining sufficient biomass to operate systems at scale, the life-cycle CO_2-reduction potential and techno-economic feasibility have been performed for the UK, the USA, Brazil, China, Australia, South Korea, Japan and Indonesia [268–279]. Currently, research groups in Europe and the USA are the strongest proponents of BECCS and have collaborated with local researchers to perform scoping studies for other parts of the world.

Direct air capture (DAC) is a second negative-emissions approach [280, 281]. The drivers and challenges for DAC are aligned with the GG archetype. Here, we note that this approach has garnered significant interest in Western nations and has progressed to the point of pilot demonstrations. The technology is still under development and, while there are likely to be differences in the cost structures related to materials, engineering, energy use and CO_2 storage, the underlying technical challenges of capturing CO_2 from the atmosphere are not expected to vary significantly in different countries. The more significant challenges will be commercial and more experience is needed to understand how to set up the most effective business models in different regulatory and commercial situations. In this regard, early efforts such as the announced partnership between Carbon Engineering and Occidental Petroleum to use CO_2 captured from DAC for EOR are an example of how GG development can also include secondary elements related to the RR approach [282]. This area also warrants continued attention as the technology and policy landscapes mature.

3.3.3 CCUS and the decarbonization of transportation

CO_2 emissions from transportation based on petroleum-derived fuels contributed ~20% of the global total in 2010. Led by countries in Western Europe, several regions are looking at mandating phaseouts of internal combustion engine (ICE) vehicles by 2050 or earlier [283, 284]. The three leading replacement options—battery-electric vehicles, hydrogen fuel cells and biofuels—are all amenable to CCUS (via the GG and LCG models) [285]. The specific pathways taken by each region will determine the extent to which the commercial development of CCUS can aid in decarbonizing their transportation systems [286].

There is extensive literature on the impacts of battery-electric-vehicle adoption on total electricity demand and load profiles [287–289]. With regard to CCUS, the availability of dispatchable low-carbon power could assist in meeting the incremental energy demand and provide an additional degree of freedom in managing load. A transition to hydrogen fuel cells can leverage existing hydrogen production, which is currently dominated by steam reforming and CG. These sources are amenable to CCUS, with costs for pre-combustion capture modes generally lower relative to post-combustion capture from power-plant flue gases [290]. Decarbonized hydrogen can also be produced by water electrolysis using electricity from carbon-free sources, but currently these processes are more expensive than hydrogen produced from SMR or CG with CCS [291–294]. CO_2 capture can also be implemented in biofuels production [295]. Large-scale capture from ethanol fermentation has been demonstrated at the 1-Mtpa scale at the Decatur project in Illinois and studies of the potential for capture from biorefineries in the USA and Brazil suggest the opportunity could be significant, provided that challenges with offtake can be overcome [296]. A key question is how these approaches can be scaled to the production levels needed for future transportation scenarios. On the policy side, programmes such as the California Low Carbon Fuel Standard offer incentives of ≤$180/t$CO_2$ for low-carbon fuel consumed in California, provided the production methods are in compliance with protocols establishing their life-cycle-emissions benefits [297]. Scenarios differ by region and some regions could develop hybrid approaches in which multiple options are adopted at scale. The roles of power generation with CCUS in balancing a grid under high-penetration electric-vehicle scenarios or the proper split between hydrogen production from fossil fuels with CCUS and electrolysis from carbon-free electricity under different transition scenarios is still an open question.

4 Where do we go from here?

This concluding section looks to the future. The discussion is divided into three parts. First, we make some observations regarding CCUS deployment that apply across all archetypes. Next, we look at near-term priorities for each archetype and how they can manifest as specific actions in different regions; technical and policy examples are provided from the situations in the USA and China for illustrative purposes. Finally, we elaborate on the suggestions shown at the bottom of Fig. 1 for maximizing the chances that current trajectories will converge towards global deep decarbonization over the long term.

We begin with five general comments:

- Technology-development efforts need to take a holistic perspective.

  Members of the research community working on fundamental components in CO_2 separation, storage or conversion need to be aware of the system-level drivers that may present unrecognized opportunities (e.g. relaxed specifications such as CO_2 purity or pressure for capture). Progress on this front will require systems engineers and government funding agencies to articulate more clearly, and revisit underlying constraints and assumptions in a manner more accessible to the technology-development community.

- Cost is not just a number.

  In the analysis of costs, we stress the need to use appropriate assumptions that reflect the local situation and to report distributions (or at least uncertainties or ranges). Despite increasing recognition of the importance of using suitable costing and market-operation assumptions in techno-economic assessments, studies that use inappropriate costing assumptions are still being published. The community should continue to be vigilant about this issue going forward. One related issue is the need to harmonize costing methodologies and assumptions across archetypes (e.g. capture from power vs capture from industrial sources vs grid-service functions).

  There is also still a tendency in the technical literature to report costs as a single number. While this is useful for comparisons of well-defined cases, it can have the unfortunate effect of oversimplifying choices under real-world scenarios. The effects of cost *distributions* will become more important as the industry scales up. This will become evident as the number of projects in the pipeline builds and system-level analysis studies (e.g. technology selection, hub design) should begin to take this into account now.

- A diversity of business models will persist.

  While there may be similarities within an archetype, the community should resist the idea of a 'one-size-fits-all' business model for CCUS development. Business models should be tuned to local incentives and constraints, and allowances made for these differences when attempting to translate 'best practices' across regions. Of particular interest will be approaches that can mobilize private capital (including green bonds and finance providers) and creatively balance climate action and social considerations such as employment and economic competitiveness. Models for supporting start-ups for CO_2-utilization projects and venture capital funding are developing as part of the innovation ecosystem in the West and it is worthwhile to consider how these might be extended to other parts of the world [298]. Approaches that monetize indirect benefits from CCUS could be especially compelling given the larger pool of capital available to LCG activities.

  We also note that considerable experience and expertise developed by the private sector remain behind proprietary firewalls. It would be helpful to consider what additional mechanisms might be put in place to accelerate the sharing of CCUS knowledge from the private sector, while also safeguarding any proprietary interests.

- Hubs will need to evolve.

  Energy systems around the world are in a period of (relatively) rapid change and CCUS hubs will need to evolve in response to these changes. The assumption that infrastructure will be used in a static situation for several decades is increasingly suspect. Instead, networks will need to adapt to changes in CO_2 flows and routing related to economic growth, as well as shifts in the policy and regulatory landscape during their service lifetime. One interesting aspect of the evolution will be the interaction between utilization and storage activities. This may present an opportunity for cooperation, where storage may contribute to the scale-up of utilization and vice versa. The specific trajectories will depend on the archetype and local conditions, and tools are needed to understand these dynamics more fully. Of particular interest will be the evolution in nations (and jurisdictions) with net-zero targets by mid-century or earlier. These regions will have roughly one cycle of infrastructure turnover to meet these climate goals.

- The archetypes are not mutually exclusive (of each other nor of other decarbonization options).

 The communities associated with each archetype should not have an adversarial posture towards each other. In particular, the tension between advocates of the RR and GG approaches needs to be defused. Supporters of the GG path must acknowledge the role of RR-type projects in demonstrating and maturing CCUS technologies. At the same time, the RR community must articulate and take clear steps to move along a path towards lower carbon intensity. Efforts should be made to further establish the realistic value of CCUS as a complementary capability as part of the LCG pathway.

In the near term, each archetype has a few primary issues that should command the majority of the attention of its respective community:

- Resource recovery—scale up infrastructure and gain operational experience balancing recovery and storage.

 Maturation of CCUS as an industry can only be achieved by executing a pipeline of increasingly large-scale and complex projects in a clear regulatory landscape. Efforts to move from source–sink projects at the ≤1-million-tons-per-year scale to networked topologies (such as the ACTL) at larger scales will be especially educational. This process can be accelerated, in part, by leveraging prior experience elsewhere, but the unique features for each regional ecosystem will be determined by the interplay between technology and the local economic and regulatory landscape. In this regard, there is no substitute for experience in reducing project costs and building public acceptance. As more and more regions gain experience, there is the possibility that technical expertise in the different aspects of CCS can diffuse to places with less O&G activity. We note that scaling-up involves more than just construction of infrastructure. A learning curve is expected in terms of operations—from handling of CO_2 along the entire chain to interactions with regulatory authorities. In addition, hub-level projects will provide the opportunity to validate the wide range of modelling tools that have been developed for network design and provide data to extend their capabilities to support network operation. Standardization of designs, design practices and maturation of manufacturing supply chains are also an expected outcome.

 A second priority for RR operations is to develop technical expertise in the trade-offs between asset productivity and CO_2 storage. Although research is underway to understand how these operations might be modified to increase CO_2 retention without compromising productivity, there is an opportunity to go further and establish the technical basis to transition from RR towards CO_2 storage. There is also a need to definitively determine the extent to which CO_2-EOR be carbon-negative and the monitoring regime required for verification.

- Green growth—launch industrial hubs and de-risk large-scale investment in CCUS.

 The successful launch of industrial hubs in the UK, the Netherlands, the USA, China and Australia will provide valuable experience in many aspects of hub operations (e.g. scheduling, pricing and liability) as a step towards de-risking CCUS projects under the GG archetype. Business models will need to consider local incentives and constraints, the management of liability, the role of services as part of an extended ecosystem and the proper design of financial derivatives and other mechanisms to improve market operation.

 The question of how utilization (the ‘U’) and storage (the ‘S’) in CCUS might work together should also be considered more deeply. In other words, what opportunities exist for utilization to contribute to the scale-up of storage and vice versa (e.g. to what extent can utilization and storage work together to help manage flow variability in CCUS networks)?

- Low-carbon grids—pilot the use of CCS for grid stability and validate business models around indirect value.

 A case has been made through modelling studies that low-carbon dispatchable power provided by CCS-equipped power plants (or the use of hydrogen in the energy system derived from fossil-fuel gasification with CCS) can reduce the total capital investment needed for low-carbon grids. The key gap that must be addressed in the near term is real-world verification of these potential benefits. This ambitious, but necessary, undertaking will require detailed engineering studies, careful analysis to determine the actual benefits and a commitment by a project team to demonstrate flexible capture under relevant operating scenarios. This must be accompanied by techno-economic verification of the competitiveness of CCUS against energy storage and other forms of grid stabilization over a range of time scales using actual operating data.

- Interactions between archetypes within a region.

 In the USA, all three archetypes can play a role in energy-system transformation. National policy is an important driver, but infrastructure and policy variations across states will amplify or hinder the adoption of different archetypes. An example of this is the 45Q federal tax credit. This incentive offers support for EOR and sequestration projects, theoretically applicable to both the RR and GG options. At the time of this writing, there are multiple projects in the 45Q pipeline focused on EOR in the south or central parts of the country, as well policy discussion in Congress on how the policy might be adjusted to support long-term sequestration in support of the GG archetype. The USA also has a promising ecosystem in the area of CO_2 utilization and conversion indicative of activity following the GG model. The ecosystem includes both established corporations and start-up companies, is geographically distributed around the entire country and is supported by funding from federal and state governments, private-sector sources and venture capital. Finally, the USA is a global leader in renewables-integration research. It is our hypothesis that Texas—with its growing share from wind generation, an independent system operator with a history of interest in integration renewables and natural-gas-based generation, and suitable geology for CCUS and local industrial experience in EOR—is a promising candidate for LCG-integration trials.

In China, the landscape is conceptually similar—all three archetypes are relevant, but with variations of suitability across the country. A key question in China, as in the rest of the world, is where CCUS hubs will develop first and what sources and sinks will be involved in their operation. The geological and historical perspective strongly favours the northern parts of the country due to the location of oil fields in which EOR demonstration projects have been performed and the availability of saline aquifers suitable for storage. From the perspective of capture cost, the 'low-hanging fruit' is coal-to-chemical plants; however, the national carbon market will initially focus on the power sector. Ultimately, the resolution of this question is not about whether the RR or the GG archetype will dominate, but how the competing motivations can be recognized and used to rationally advance CCUS within the country. In addition, north-eastern provinces are fertile ground for LCG development. The energy systems in these provinces operate a majority share of coal-fired CHP plants that are must-run in the winter due to district heating requirements, host active oil fields where EOR is being used, struggle with curtailed electricity at the TWh scale due to the significant deployment of wind-generation capacity and are actively engaged in electricity-market-reform experiments in an effort to improve the overall performance of their systems.

We note that the archetype model suggests some interesting models for cross-regional learning. Rather than providing an exhaustive discussion of relatively straightforward examples, we simply point to the intriguing possibility that, despite very different political and market landscapes, potential LCG activities in Texas and north-eastern China might benefit from information-sharing related to the technical aspects of wind integration onto the grid, alongside fossil generation with the potential for CO_2 capture and EOR.

We conclude by briefly commenting on how each archetype can offer complementary pieces for global efforts to achieve deep decarbonization in the second half of this century:

- Resource recovery—evolve an infrastructure base towards a lower net carbon footprint.

  As the CCUS industry grows and reaches a critical mass, it will be crucial to develop and articulate a roadmap for evolving existing infrastructure from pure RR purposes towards a lower net carbon footprint through the permanent storage of CO_2. Once established, the infrastructure is then potentially subsequently available for GG and LCG. The timing of this roadmap can vary regionally to accommodate the local situation, but identification of the core technical elements and applicable policy incentives early on will allow research into areas that are currently underappreciated and exploratory actions to align incentives or regulations. Steps in this direction in the USA are outlined in the National Petroleum Council's CCUS roadmap and include technical work looking at oil recovery versus CO_2 retention in EOR projects as well as recommendations on adjusting the differential values in the 45Q tax credit offered to aquifer storage relative to EOR to motivate action in existing projects [7].

- Green growth—harmonize policy and standards across regions and scale NETs.

  Progress in different parts of the world in implementing a GG model can provide motivation to harmonize policy and technical standards. To this end, early pilots with industrial hubs will provide valuable experience in the issues related to cross-jurisdictional cooperation. While different business models can persist, increased integration across regions could provide the cooperation and flexibility necessary to reach deep-decarbonization targets in the second half of the century. Among the possibilities is the formation of cross-border carbon markets that could allow countries with poor CO_2-storage capacity to utilize reservoirs in other countries. Success within the GG archetype in de-risking CCUS projects can ultimately create a favourable environment for the scale-up of NETs. NETs can also benefit from the repurposing of existing CCUS infrastructure from the RR model.

- Low-carbon grids—expand electrification-based decarbonization across industry and transportation.

  Despite being the least technically mature at the moment, this archetype has the potential to become the path by which CCUS could have its greatest impact in reducing carbon emissions, not least because all models are based on the assumption that the demand for electricity will increase in a low-carbon world. The broader benefits of CCUS as an enabler for electrification-based decarbonization is a relatively unexplored space. For example, the use of renewable electricity to power CO_2 capture may seem counter-intuitive, but may offer some advantages when used to arbitrage between heat and power for CHP or industrial applications in regions seeking to integrate significant amounts of renewable energy. More broadly, the possibility of using renewable electricity (that would otherwise be curtailed) to power CCU applications such as the production of low-carbon hydrogen or chemicals from fossil fuels offers a path towards the decarbonization of 'difficult' industrial applications and the transportation sector. Not every scheme will be technically feasible, economically attractive or with net-zero or negative carbon but, in time, it is possible that the indirect value provided by CCUS through electrification-based decarbonization may grow to exceed the direct CO_2 reductions from capture operations.

CCUS is an essential option for addressing climate action as part of a larger energy-system transformation. The path towards commercial deployment is expected to vary across regions and the three-archetypes framework presented in this paper offers a way to appreciate how and why different trajectories might develop, what technical issues and policy needs should receive the most attention in the near term and what deliberate steps can be taken to ensure they converge in support of deep decarbonization. The lines between different archetypes will naturally begin to blur as CCUS finds its place as part of an integrated effort to reduce global emissions and the development of clusters that bring together two or more of the archetypes over the long term would not be surprising.

5 Postscript

This paper covers developments through to the end of 2019. During the manuscript-review process in the first quarter of 2020, a novel coronavirus pandemic (COVID-19) has created severe social, economic and political disruption. While the ultimate consequences are far from clear at the time of this writing, the situation already presents opportunities and challenges for CCUS deployment in the near to intermediate term. For example, the economic contraction and disruption from shutdowns could create headwinds for projects reliant on EOR revenues or tax equity provisions for financing (e.g. 45Q tax credits) akin to issues encountered by renewable energy in the aftermath of the 2008–09 global financial crisis [299]. Conversely, the possibility of economic stimulus could provide momentum to CCUS, depending on policy priorities. The framework presented in this paper can assist in identifying challenges and corresponding solutions, as well as provide guidance on setting strategic priorities for investment and recovery.

Conflict of Interest

None declared.

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