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Review

Accelerate the offshore CCUS to carbon-neutral China

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ABSTRACT

Offshore carbon capture, utilization, and storage (CCUS) is to capture CO₂ from emission sources and then inject the captured CO₂ into sub-seabed geological reservoirs, thus it will be permanently isolated from the atmosphere. CCUS was therefore proposed as a technological decarbonization strategy to prevent millions of tonnes of anthropogenic CO₂ from entering and remaining in the atmosphere. In this review, the necessity and suitability of offshore CCUS in China are explored, involving examining the potential for sedimentary basins offshore China to act as carbon sinks for industrialized coastal regions and investigating the opportunities of developing a commercial full value chain. In China, the CO₂ emissions from the 14 coastal provincial administrative regions are estimated to be over 4.2 Gt, occupying ~41% of the country's carbon emissions, whereas the storage capacity of the sedimentary basins offshore China is estimated to be 573–779 GtCO₂. This could total 140–190 years of emissions from China's coastal regions, which also avoids complex legal regulation and public opposition. However, economic costs pose substantial challenges to deploying offshore CCUS on a commercial scale, which requires significant technological innovations, national contributions, and business investments, particularly in the eastern and southeastern regions.

1. Introduction

To achieve China's goal of carbon neutrality by 2060, greenhouse gas emissions from atmospheric sources of carbon need to be mitigated and preferably permanently sequestered. This has encouraged the development of methodologies to mitigate CO₂ emissions, including electrification, fuel switching, renewable energy, bio-energy, and carbon capture, utilization, and storage (CCUS). China has made substantial progress in electrification and renewable energy deployment, while the carbon-intensive generation reflects a paradox in China's energy revolution, suggesting the necessity of an extra substantial carbon emission reduction strategy. The large-scale deployment of the CCUS can avoid the failure of assets in existing fossil energy industries and reduce the resistance of incumbents [1]. With an estimated storage capacity between 1873 and 3067 GtCO₂, China has enormous potential for CCUS deployment.

Of the 34 provincial administrative regions in China, 12 are along the mainland coast and 2 are islands, which occupy less than 14% of the nation's territorial area, but contribute approximately 41% of the country's CO₂ emissions [2,3]. In these regions, most large stationary sources, e.g., power plants, refineries, and cement plants, are along the coast. The water area close to the coast comprises China's ten offshore

sedimentary basins, which cover ~1.7 million square kilometers. These basins were proposed to allow for point elimination of greenhouse gases through a complete technically workable and safe full-chain offshore CCUS (Fig. 1). This value chain can be developed by engaging contractors and suppliers, whereas the potential risks must be fully characterized and mitigated.

The CCUS in China has been tested both onshore and offshore [2,4–8]. Onshore geologic reservoirs in China are mostly in the northern and western regions, which are distant from the industrialized and populated coastal regions and may raise extra costs and safety issues. Compared to onshore storage sites, access to offshore sites will not pose issues such as CO₂ contamination of drinking water, and potential damage to agricultural and industrial operations [13]. In addition, to provide energy for the CCUS offshore infrastructure, low-carbon opportunities from wind, solar, waves, and tides could be introduced [14].

Globally, the distribution and thickness of sediment accumulations over continental margins have been mapped for prospective offshore storage resource regions [15]. And it is inferred that the cumulative storage of over 100 GtCO₂ by 2050 is the most efficient achieved with 5–7 regions pursuing an offshore well development model on a Norwegian scale [15]. These regions include the North Sea, Tomakomai Port Japan's offshore area, Brazil's Santos Basin, the South China Sea,

Abbreviations: CAPEX, capital expenditures; CBS, cost breakdown structure; CCUS, carbon capture, utilization, and storage; CEPCI, the Chemical Engineering Plant Cost Index; CNY, Chinese Yuan; CO₂, carbon dioxide; DOGF, depleted oil and gas fields; EOR, enhanced oil recovery; FEED, front-end engineering and design; GDP, Gross Domestic Product; NPC, net present costs; OPEX, operating expenses; SA, saline aquifers; SCC, social cost of carbon.

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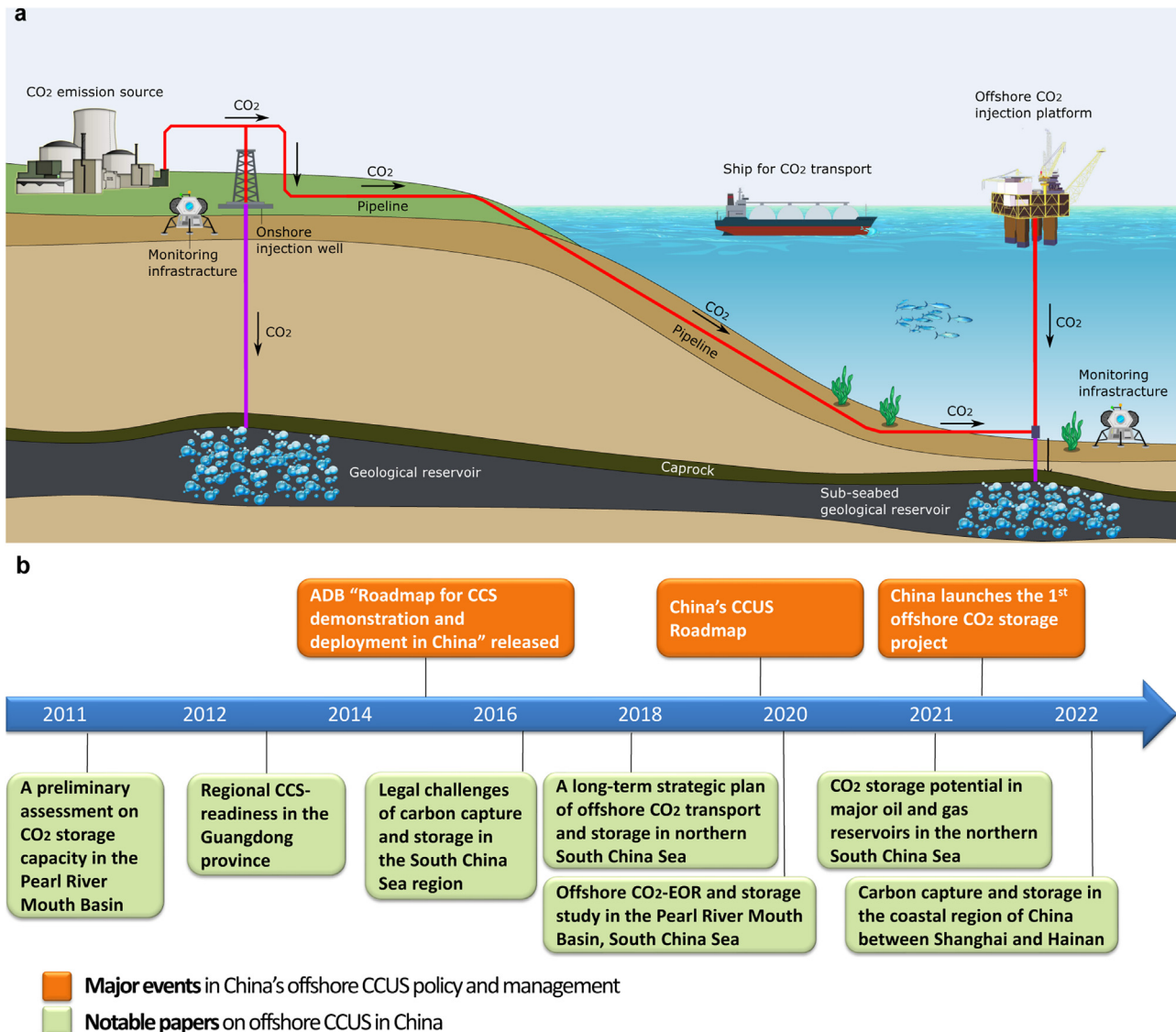


Fig. 1. Offshore CCUS and notable publications. (a) Key elements and processes in offshore CCUS. Offshore CCUS is to capture CO₂ from industrial emission sources, transport it via either pipeline or ship, and inject it into sub-seabed geological reservoirs, contributing to the isolation of CO₂ from the atmosphere. (b) Timeline indicating the evolution of notable papers [2,4–9] concerning China's offshore CCUS as on 31 Oct. 2022, and major moments [10–12] in China's key events in offshore CCUS policy and management.

the Gulf of Mexico, and the Gippsland Basin of Australia. These areas have been prospective targeted large-scale geologic storage sites for full-chain offshore CCUS (Table 1), among which two have been completed ("K12-B" in the Netherlands and "Tomakomai" in Japan) and four are active ("Sleipner" and "Snöhvit" in Norway, "Lula" in Brazil and "Enping" in China). These projects, particularly the "Sleipner" and "K12-B", have several decades of safe CO₂ injection. Among these projects, the "Lula" project in Brazil uses offshore carbon dioxide-enhanced oil recovery (CO₂-EOR) in the ultra-deepwater field, which produces approximately 800,000 barrels per day [16,17]. The "Tomakomai" project in Japan captured CO₂ from the refinery's hydrogen production facility and reduced CO₂ emissions from onshore industries. There are also several planned advanced offshore CCUS projects based on the development of industrial hubs, aiming to benefit from economies of scale and reduce integration risk through shared CO₂ transport and storage infrastructure. These include the Port of Rotterdam (Porthos) project in the Netherlands, the Acorn & Net Zero Teesside projects in the UK, and the CarbonNet project in Australia. To explore the involvement of renewable energies in the chain, several of these off-

shore CCUS hubs involve the production of low-carbon hydrogen [18].

In 2021, China launched its first offshore CCUS project in the northern South China Sea's Pearl River Mouth Basin (PRMB). Under this project, the injection of 1.46 MtCO₂ into sub-seabed saline formations was planned by 2026, which would achieve near-zero emissions from offshore oil production [12,19]. This has provided a prior workable test of the long-term performance and security of offshore CO₂ storage for maturing China's offshore CCUS as an attractive and efficient long-term strategy [15,20], particularly for those industrialized coastal regions to achieve their "ahead of time" Carbon Neutrality commitments.

In this review, to evaluate the necessity and feasibility of developing offshore CCUS in China, Section 2 presents the distribution of national carbon emissions and Section 3 assesses the potential capacity of offshore basins to mitigate CO₂ emissions in China. While the large-scale deployment of offshore CCUS in China faces cost challenges and technology gaps, these are discussed in Sections 4 and 5, respectively. To progress China's net-zero emissions, opportunities for developing offshore CCUS are explored in Section 6. And Section 7 summarizes the

Table 1
Commercial offshore CCUS projects completed, in operation, and planned in 2022.

Country	Project	Operation date	Termination date	Source of CO ₂	Capture capacity (Mt/year)	Primary storage type
Norway	Sleipner	1996	/	Natural gas processing	1.0	Dedicated
Netherlands	K12-B	2004	2017	Natural gas processing	0.02	Dedicated
Norway	Snöhvit	2008	/	Natural gas processing	0.7	Dedicated
Brazil	Lula	2011	/	Natural gas processing	0.7	EOR
Japan	Tomakomai	2016	2019	Hydrogen production	0.1	Dedicated
China	Enping	2021	/	Natural gas processing	0.3	Dedicated
Norway	Northern Lights	planned	/	Onshore industries	0.8	Dedicated
Norway	Longship	planned	/	Onshore industries	1.5	Dedicated
Netherlands	Porthos	planned	/	Onshore industries	2.5	Dedicated
Australia	CarbonNet	planned	/	Onshore industries	5	Dedicated
UK	Acorn & Teesside	planned	/	Onshore industries	10	Dedicated
US	Houston Ship Channel	planned	/	Onshore industries	50-100	Dedicated

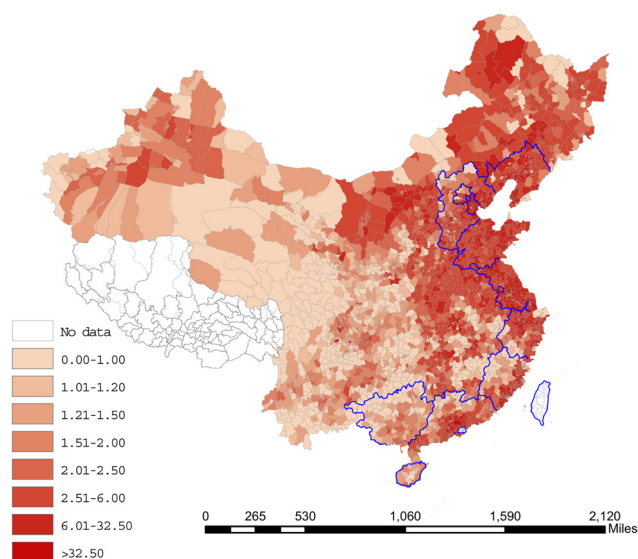


Fig. 2. China mainland's county-level CO₂ emissions from energy combustion in 2017 (unit: million tons) (modified from Chen et al. [25] (GS(2019)1822)). ~41% of China's annual CO₂ emissions are from the eastern and southeastern regions. Borderlines of the 14 coastal provincial administrative regions are highlighted in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

path of accelerating offshore CCUS to achieving China's target of Carbon Neutrality by 2060.

2. Distribution of carbon emissions

In China, carbon emissions vary geographically depending on the level of industrial development. Most communities and industries are in the east and southeast coastal regions, which are also the most populous. These coastal regions contribute 64% of the national Gross Domestic Product (GDP), account for 43% of the country's energy use, possess 39% of the country's population, and have been dominantly driving China's economy in the last 40 years [21,22]. While contributing to the economy, these areas also account for ~41% of the country's annual CO₂ emissions, i.e., ~4.2 Gt [2], scattering notable CO₂ emission hotspots (Fig. 2). This is because fossil fuels are widely used to provide energy supplements [2]. Apart from mobile emissions sources such as aircraft, shipping, and automobiles, many world-class stationary CO₂ emission sources are in these regions [22], including power plants, cement and refineries, and steel and iron foundries [8,23,24].

In 2020, China emitted 10.67 GtCO₂, burning coal, oil, and gas for 70%, 15%, and 6%, respectively [26]. To reduce the consumption of

coal, China has justified ongoing efforts to support the use of renewable energy and natural gas, while over 50% of the electricity mix is still from coal-fired power plants, this represents potential emissions of 85 GtCO₂ if they continue to operate at current load factors for the remaining of their lives [27]. A more worrying thing is that some of the world-class CO₂ emission sources in China are from relatively newly built power plants, the average of which is less than 15 years and could still operate in 2060 [28]. This poses a particular challenge in meeting the national goal of carbon neutrality. More severely, in recent years, because of climate change, renewable capacity has indicated an unstable electric power supply, which makes it unlikely to be a stable alternative to replace the coal-fired power plants in the following 40 years. As a result, retrofitting the power plant is an indispensable means of achieving the Carbon Neutrality target, and geological storage has the greatest potential. In the IEA Sustainable Development Scenario relative to the Stated Policies Scenario, the CCUS accounts for nearly 15% of the cumulative reductions in carbon emissions from 2020 to 2070 [29]. To realize this, China, particularly the eastern and southeastern regions with the heavy industry of large CO₂ emissions and with limited access to onshore storage, has to adopt high-efficiency retrofits on its coal-fired plants and develop offshore CCUS.

3. Geological storage in offshore sedimentary basins

For the best candidate, the geological storage sites for the retrofits of the CCUS in power plants are of critical importance, considering the distance, cost, technology, and public perception (Table 2) [27]. China's coastal water zone extends over ~4.73 million square kilometers and comprises ten offshore sedimentary basins (Fig. 3). This provides excellent opportunities for the permanent sequestration of CO₂ at sea near coastal regions [2] and makes the transport of CO₂ at sea less costly and has fewer safety concerns.

3.1. Distribution and capacity assessment for storage reservoirs

The evaluation of the suitability and capacity of geological CO₂ storage in China has been intensively conducted over the past decade [30,31]. Twenty three main onshore and ten main offshore sedimentary basins account for 1300–2288 GtCO₂ and 573–779 GtCO₂ storage capacity, respectively, which could total 200–300 years of emissions from China [10,32]. For these basins, onshore formations are dominantly in north and west China, while offshore formations are available along most of the coastal regions, providing potential offshore CCUS locations [11] (Fig. 3a).

For the carbon source-sink pairing, the heavily industrialized eastern and southeastern coastal regions would have less access to the abundant onshore storage basins as they are normally over 750 km from the potential large-scale onshore CO₂ reservoirs, which potentially raises the transportation cost and the safety risk. Many large emission

Table 2
Pros and Cons of the offshore CCUS compared to the onshore CCUS for various factors.

Offshore vs. Onshore	Pros	Cons
Geographical	1. For East and Southeast China, access to onshore CO ₂ storage would normally be greater than 750 km, while the offshore sites can be within 200 km.	n/a
Social	1. Offshore CO ₂ storage is unlikely to damage the groundwater, agricultural and industrial operations, which could be an issue for onshore storage. 2. Offshore storage may face less opposition as it takes away CCUS infrastructure and the associated perceived risks from populations. 3. Offshore sites provide jurisdictional simplicity. 4. The unlikely leakage offshore is less damaging than onshore, as CO ₂ can disperse into the seawater column.	n/a
Economic	1. For East and Southeast China, the shorter distance from offshore storage sites may need to pay less for CO ₂ transport. 2. Offshore CO ₂ transport and storage do not have to pay high land prices. 3. Managing the offshore geological pressure of storage reservoirs avoids the production of brine onshore, the cost of which can be high.	1. Operational complexity and costs can increase with offshore conditions.
Technical	1. Managing formation pressure from large-scale CO ₂ injection into offshore geological formations is relatively simpler than onshore. 2. Offshore sites can provide electrical generation opportunities through low-carbon technologies, such as wind, waves, and tides.	1. Limited space and weight on offshore platforms. 2. Extra effort to adjust to sub-sea conditions.

sources, such as power plants, in the coastal regions, have no suitable onshore geologic basins within 1500 km, which makes the onshore access to them less cost-effective as it would need to develop long-distance CO₂ pipeline infrastructure to the distant northern and western onshore reservoirs [18]. In contrast, large-scale offshore sub-sea basins may be available within 50 to 300 km in most of the coastal regions and the average CO₂ transport distance may be within 200 km. This offers lower overall costs and makes offshore storage a more natural and primary option for disposing of CO₂ for the eastern and southeastern coastal regions where high CO₂ emissions are located [6] (see Section 4.1).

Most offshore storage capacity is in saline formations, with the CO₂ storage capacity estimation of the PRMB to 70–300 Gt, the Yinggehai Basin to 56–160 Gt, the Beibu Gulf Basin to 24–57 Gt, and the Qiongdongnan (Southwest Hainan) Basin to ~41 Gt, etc. (Fig. 3b) [4,32,33]. Amongst these basins, PRMB is the most studied (in terms of publication numbers related to offshore CCUS) and has been the focus of research on the targeted carbon storage site for the Guangdong-Hong Kong-Macao Greater Bay Area. Taiwan, the largest island in China, where the onshore storage capacity is estimated to be 2.8 Gt while the offshore West Taiwan Basin (3.6–13.7 Gt) and the Southwest Taiwan Basin (~68 Gt) can provide 72–82 Gt capacity for CO₂ geological storage [32,35,36]. In these basins, oil and gas fields account for ~2.5% of the total 4 GtCO₂ storage capacity [7]. The reservoir geology of these fields has now been well understood and there is existing offshore infrastructure (pipeline and platforms), which is considered a priority for near-term offshore CO₂ storage project opportunities [37].

3.2. Social reflection

While offshore storage reservoirs provide sufficient volume to dispose of CO₂ from eastern and southeastern China, there are fewer safety concerns with the offshore CCUS. In some regions, such as the North, onshore CCUS could be economically and technically workable, while concerns have been related to health, safety, and environmental issues relative to pipeline construction and CO₂ storage sites [38,39]. These concerns are mainly coming from the potential leakage of CO₂ from the pipelines and/or the geologic reservoirs in their vicinity, threatening the human community, local property, agriculture, and livestock [40–42]. According to a statistical investigation in China concerning the development of onshore CCUS, over 90% of respondents do not object to it, but few of them were willing to allow a CCUS project within 100 km of where they are living [43].

In the social sciences [41,44,45], some planned onshore CCUS projects have been criticized and led to strong protests among local communities [42]. This raises a critical warning about the large-scale deployment of onshore geological CO₂ storage in populated northern

China, such as Shandong, Hebei, and Liaoning provinces. In contrast, offshore CO₂ storage moves infrastructure away from coastal populations, which reduces these challenges and is therefore preferred. In addition, it offers jurisdictional simplicity for regional governments to manage the utilization of area of jurisdiction for CO₂ storage as offshore transport would be less visible and would unlikely impact the local population and could be easier to perform the carbon source-sink pairing for the highest economic benefit. Further, the seawater column off the coast (minimum 50 km in the South and the East China Sea) acts as a natural barrier, which not only minimizes the unlikely environmental risk to the coastal communities but also reduces underwater hazards to the marine environment and ecosystem by dispersing the unlikely CO₂ leakage.

4. Cost evaluations and reduction potentials

High costs are currently the major impediment to the deployment of the offshore CCUS and opportunities to reduce costs need to be explored to minimize them. To evaluate the cost reduction potentials for future offshore CCUS projects, the specific net present costs (NPC), Chinese Yuan (CNY or ¥) ton⁻¹ of CO₂ stored have to be firstly estimated. Estimates are based on updated data from industrial engineering studies and operational cost calculations for the offshore CCUS [46–55]. The cost estimates from the capture, transport, and storage are often provided in a cost breakdown structure (CBS) for detailed analyses (Table 3) [53], i.e., the capture for a specific plant type, the transport to the nearest suitable geological storage site, and the storage at that site determined by the type of the geological resources in offshore depleted oil and gas fields (DOGF) or saline aquifers (SA). With specific contributions to the technology and supply chain development of each component of the offshore CCUS, a full demonstration value chain will lower costs.

4.1. Cost evaluations

When estimating the large-scale full value chain of the offshore CCUS, costs are expected to decrease due to scale effects [49]. Fig. 4 shows cost reductions from the increased transport and field storage capacity, as well as the average cost per ton for possible large-scale onshore and offshore CCUS implementations for China's eastern and southeastern regions. Note that the inputs to explore the cost estimate are evaluated from literature values multiplying currency exchange rates and the Chemical Engineering Plant Cost Index (CEPCI) [56] for the cost year of study [51]. For transport and storage, the cost per ton decreases significantly when the value chain capacity is fully used from 2.5 to 20 million tons per annum (Mtpa) for transport and from 40 to 200 Mtpa for storage [47,48]. This is due to increased capacity utilization in transportation and storage facilities. This includes short-distance

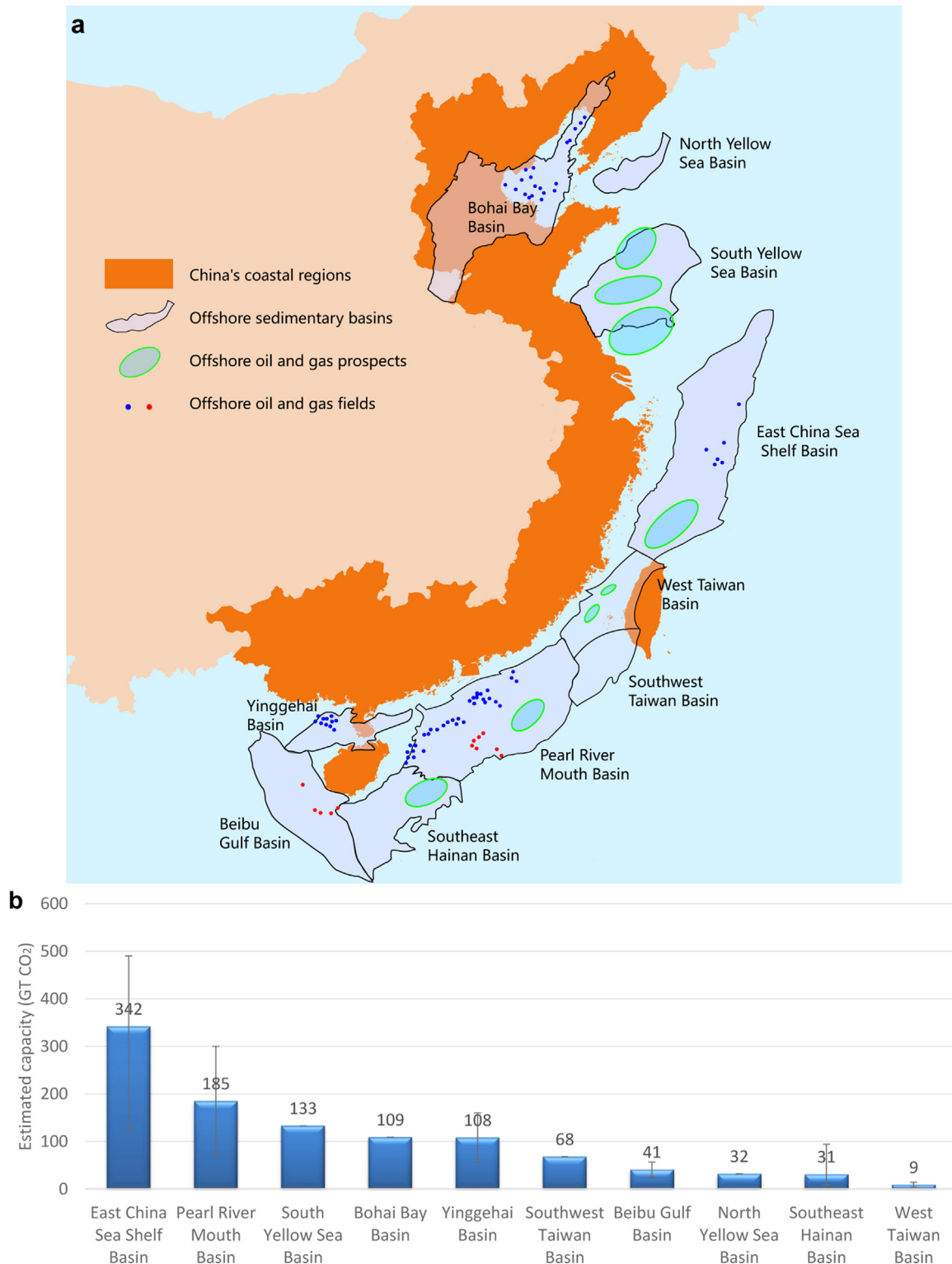


Fig. 3. Distribution of the ten main offshore sedimentary basins in China and its adjacent sea area (modified from Hao et al. [30]). (a) A Map (GS(2019)1822) of offshore China's sedimentary basins for CO₂ geological storage. (b) Estimated CO₂ storage capacity of the ten offshore basins in China [4,9,32–36]. Some error bars are not shown because of a lack of reliable data sources.

offshore pipeline transport (i.e., 180 km to offshore storage sites) instead of transport by ships and long-distance onshore pipeline transport (i.e., 750 km or 1500 km to the major north or northwest onshore storage sites) with both cost reductions and savings. When the accumulated storage capacity increased from 40 to 200 MtCO₂ annually, the cost levels could be reduced by about 3/4, indicating that field capacity has a

high effect on costs for storage sites. The estimation also reveals that pipeline transport is normally cheaper than shipments; onshore storage is normally cheaper than offshore; qualification of storage in DOGF is normally cheaper than the qualification of storage in SA, and cost savings can be achieved if legacy wells and infrastructure can be re-used. It is also worth noting that even though a “general” cost could be estimated

Table 3

Cost breakdown structure of the full offshore CCUS value chain. These estimates could estimate potential cost reduction curves based on future economies of scale, value chain optimization, and technology development [53].

Capture		Transport		Storage	
Integration	Connection to Chimneys	CAPEX		Docks	Quay & items offloading to interim storage
CO₂ capture	Pre-treatment of flue gases CO ₂ Absorbion	OPEX		Temporary storage	Interim storage Pump & temp. control Landfall for pipeline
Treatment for transport	Solvent regeneration Compression, liquifaction, conditioning	Docks	Onshore transport to interim storage, Transport to ships/pipes	Injection	CO ₂ injection well(s) Control system
Temporary storage	Transport to temporary storage Temporary storage	Pipes	Offshore CO ₂ pipes Subsea items Umbilical	Monitoring	Monitoring equipment for CO ₂ storage location Control system
Ancillary systems	Ancillary systems Additional costs Owners costs	Ships	Compressed tankers Fuels	Ancillary systems	Ancillary systems Additional costs Owners costs

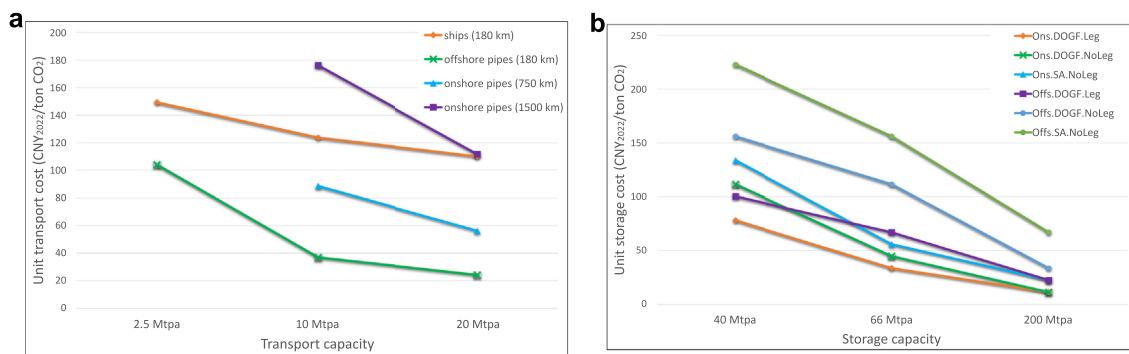


Fig. 4. Levelized costs in constant CNY₂₀₂₂ ton⁻¹ CO₂. (a) Transport costs [47] per type and distance case; 180 km is a case of distance from the southeast coast to an offshore storage site, whereas 750 km and 1500 km are cases of onshore transport distance to the far north. (b) Storage costs per field capacity case to 40 Mtpa, 66 Mtpa, and 200 Mtpa scenarios [48]; Ons: onshore, Offs: offshore, DOGF: depleted oil/gas field, SA: saline aquifer, Leg: legacy infrastructure, No Leg: no legacy infrastructure.

Table 4

Overview of data for integrated offshore CCUS cases with a 40-year horizon [46–49]. Costs for power plants and CO₂ capture calculated for medium fuel costs; costs for pipeline transportation calculated for medium volume capacity 10 Mtpa; costs for storage reservoirs calculated for medium field capacity 66 Mtpa each field. All values are in constant CNY₂₀₂₂.

	CO ₂ Capture		CO ₂ Transportation						CO ₂ Storage			Integrated		
	Capacity	Cost	Volume	Transport		Cost		Accum.	Type	Legacy	Cost	Cost		
				km	type	CAPEX	OPEXpa					¥/t	¥/t	40y T¥
	MWh	¥/t	Mtpa					40y Mt	Medium	Wells	¥/t	¥/t		
Coal-fired power plant	700	300	10	750	onshore	M¥9970	M¥50	89	400	DOGF	Yes	33	423	169
	700	300	10	750	onshore	M¥9970	M¥50	89	400	DOGF	No	45	434	174
	700	300	10	750	onshore	M¥9970	M¥50	89	400	SA	No	56	445	178
	700	300	10	1500	onshore	M¥19807	M¥100	176	400	DOGF	Yes	33	510	204
	700	300	10	1500	onshore	M¥19807	M¥100	176	400	DOGF	No	45	521	209
	700	300	10	1500	onshore	M¥19807	M¥100	176	400	SA	No	56	533	213
	700	300	10	180	offshore	M¥3765	M¥53	37	400	DOGF	Yes	67	404	162
	700	300	10	180	offshore	M¥3765	M¥53	37	400	DOGF	No	111	449	181
	700	300	10	180	offshore	M¥3765	M¥53	37	400	SA	No	156	494	197

based on industry data, the cost, in reality, could be highly site-specific and a project cost estimation would need to take a range of practical implementation factors into account to reduce uncertainties.

A cost estimate for a value chain based on ZEP reports is presented in Table 4 [46–49]. The estimate is based on captured CO₂ from a coal-fired power plant with a 700 MWh electric capacity, which is expected to capture approximately 10 MtCO₂ annually via post-combustion capture. The CO₂ will be transported by pipes to an onshore storage site in the far northern or northwestern regions (750 km and 1500 km as examples) or an offshore site in the coast’s vicinity (180 km as a case [12]) with a medium field capacity of 66 Mtpa. The option of the offshore CCUS value chain with DOGF storage for China’s east and southeast

industrialized regions shows the lowest cost level (i.e., the NPC for a 40-year horizon is CNY₂₀₂₂ 404 ton⁻¹ CO₂). This is mainly because of the short distance transport from the capture site to the offshore storage reservoir and the avoidance of implementing new facilities. Notably, the simplified application does not account for the significant economies of scale that come with planned pipelines or shipment networks organized to facilitate efficient transport from clusters of emissions point source locations to clusters of geological sinks [57].

The capture cost shown in Table 4 is an average of several realistic estimates for coal-fired power plants [46,55]. It accounts for more than half the cost of the value chain [49,53]. Capture is the least mature part of the value chain and therefore has the greatest potential for re-

Table 5
Opportunities to reduce direct and/or indirect costs for each component of the offshore CCUS.

Components	Cost reduction opportunities
Capture	<ol style="list-style-type: none"> 1. From practice-based learning & economy of scale. Move from small pilots to large demonstration volumes, which will indicate capture costs and lessons learned from newer capture facilities. 2. From generic learning rates. Implementing technology in the engineering processes of capture plants could reduce the overall cost. 3. From the improvement of post-combustion technologies. Post-combustion capture represents the current state-of-the-art technology to capture CO₂ from flue gas. 4. From next-generation capture technologies. Cost savings are expected by continuing to research and develop promising breakthrough concepts.
Transport	<ol style="list-style-type: none"> 1. From an understanding of the constraints for each transport case. The necessary CO₂ specifications vary from chain to chain and some excessive designs may be reduced. 2. From technology development and deployment. Optimal cost design for a pipeline network and, to a lesser extent, shipping.
Storage	<ol style="list-style-type: none"> 1. From reciprocal arrangements for alternative CO₂ storage. Offshore CCUS projects could consider themselves as an option for storing their CO₂ emissions. 2. From the reuse of existing infrastructure and established clusters. Offshore assets could be re-used if they were connected to a CO₂ transportation system before decommissioning. 3. From technology development and deployment. This includes site characterization, injector drilling, operations, maintenance, and monitoring. 4. From offshore CO₂-EOR in a short term. CO₂-EOR would make the offshore CCUS a cost-effective technology.
Value chain	<ol style="list-style-type: none"> 1. From the first complete process of offshore CCUS. This includes industry capture, ship and pipeline transportation, and DOFG or SA-based storage. 2. From the establishment of predictable regulatory regimes. This can transfer risk categories and remove barriers for the private sector to invest in the offshore CCUS.

ducing future costs. Pipeline costs are roughly proportional to distance and consist primarily (normally greater than 2/3) of capital expenditures (CAPEX) over 40 years. Because of high technical and commercial risk, the construction of a “point-to-point” offshore pipeline for a single demonstration project may be less attractive than ship transport, which is less CAPEX-intensive (normally less than 1/2 of total annual costs).

4.2. Cost reduction potentials

One of the major barriers for offshore CCUS has been to establish a viable business model which can cover the costs for the handling of CO₂ through carbon capture, transport, and permanent storage. The other major barrier is that there are high initial costs for demonstration projects and substantial risks of the high investments for first-movers, which are needed for a full value chain of permanent storage [53]. Future scale-up and cost reductions depend first on the increased capacity utilization of the established infrastructure. The next step would be to develop further clusters with the expansion of volumes with large-scale capture and additional large-scale storage sites with direct pipeline injection. Large-scale offshore CCUS networks and implementation with several clusters are necessary to establish a commercially competitive offshore CCUS industry [53]. It is also important to investigate the logistics in more detail since it can be less expensive to use an easily accessible storage site closer to a CO₂ source, even if it is an offshore site than to transport CO₂ over long distances to an onshore established storage site. Details on the potential for cost reduction of an offshore CCUS value chain are presented in Table 5.

4.2.1. Cost reduction in capture

The application of the offshore CCUS on a regional scale would likely incorporate a variety of technologies that optimize plant-specific retrofitting costs. Post-combustion capture as a technology category for combustion processes is mature and is considered to have a high level of technological preparedness for the offshore CCUS. Despite this, there is still a lot to learn from applying these technologies to different emission sources, on a larger scale, and optimizing energy use. At present, the greatest potential for cost reduction is the application of the technology to many industrial sources. This will promote research into future large-scale solutions and optimize existing technologies. Future large-scale emerging technologies that could contribute significantly to reducing capture costs are oxy-combustion and the redesign of cement and steel processes. Less advanced capture technologies can also help reduce costs in the long run.

4.2.2. Cost reduction in transport

For choosing an appropriate mode of transportation for CO₂, economics and regulatory frameworks are key considerations. For large volumes and moderate distances, pipelines are the most economical to transport. There may be volumes from remote areas that would depend on vessel transportation to a nearby hub with additional pipeline transportation. The selected transport solution with ships could be selected to make the offshore CCUS chain flexible, and because of the relatively low volume of CO₂ over long distances and short time-frame. In China, particularly in the eastern and southeastern regions, strong transport capacity could situate the CO₂ transport networks in advance [58], and retrofitting the existing offshore infrastructure could enable cost reduction [59].

4.2.3. Cost reduction in storage

In China, SA has been used for CO₂ storage in the “Enping” offshore CCUS project. The injection and storage of approximately 0.3 MtCO₂ annually at individual sites are technically viable, and innovative research has therefore gone beyond the viability of the technology. This project requires government support and currently cannot be described as commercial. To reduce CAPEX, CO₂-EOR has been practiced onshore in China for several years to enhance oil recovery from depleted or near-depleted reservoirs. There is a wealth of existing experience and knowledge, which has enabled CO₂-EOR to reach the highest level of technological maturity and operate commercially with bankable assets. Storage in DOFG is normally less expensive than storage in SA, particularly when EOR applies to make the offshore CCUS an economically viable technology today. However, its economic viability is subject to the cost per ton of CO₂ delivered and the evolution of the oil price [60–62]. A 2016 review estimated that Brent’s price of £66–76 per barrel would be required for CO₂-EOR projects to be viable [63].

4.2.4. Cost reduction for the value chain

To offset the high cost, the most effective measure could be “smart planning”, including smart source-sink pairing and regional network design, as well as the smart use of existing infrastructure when the offshore hydrocarbon fields are depleted. The platforms in these fields are distributed in groups and clusters, facilitating CO₂ transport and source-sink pairing with the quantified CO₂ storage capacity in the sub-seabed reservoirs. An offshore CCUS value chain can be designed with different configurations, with different parts of the value chain at high or low costs. High-cost capture volumes require more operational experience and learning on a broader scale before more of these volumes are

Table 6

Technological challenges and innovation gaps associated with the capture, transport, storage, and utilization of CO₂ offshore [17,19,83–85]. S: require strong effort; A: require additional effort; O: on track.

Offshore CCUS	Technology challenges	Innovation gaps
CO ₂ capture	1. High-capacity materials: materials (e.g., sorbents, solvents, membranes, etc.) with minimal energy requirements for regeneration, low toxicity, and long lifetime. (offshore & onshore)	S
	2. Cost reduction: configurations and engineering solutions that minimize costs, particularly in large-scale post-combustion capture. (offshore & onshore)	O
	3. Flexible and retrofit: offshore engineering solutions that allow the capture of CO ₂ by bolting on the side steps required for large-footprint permanent structures.	A
	4. Sub-sea separation: technologies that run sub-sea to unlock cheaper offshore CO ₂ separation closer to the storage point.	A
	5. Direct air/seawater capture: technologies to decouple CO ₂ capture from point sources, allowing flexibility in the approach of a full carbon reduction facility.	A
CO ₂ transport	1. Corrosion: characterization and coatings and material solutions to prevent corrosion because of contaminants present in anthropic CO ₂ . (offshore & onshore)	O
	2. Crack propagation: predictive maintenance solutions to prevent crack propagation and maintain pipeline integrity. (offshore & onshore)	O
	3. Pressure control: low-cost control valves to maintain consistent pressure, especially in long sub-sea pipelines. (offshore & onshore)	O
	4. Retrofit aging gas pipelines: clear understanding of costs and methods for retrofitting existing gas pipelines. (offshore & onshore)	O
CO ₂ storage	1. Modeling: more robust modeling of CO ₂ migration and interactions in various rock structures to predict the risk of leakage. (offshore & onshore)	O
	2. Site selection and injection strategy: compare disparate datasets of key metrics to optimize site selection and injection strategy. (offshore & onshore)	O
	3. Geological behavior of CO₂: improved characterization of in situ CO ₂ behavior at different injection sites. (offshore & onshore)	A
	4. Site monitoring: standardized, low-cost, long-term post-sealing CO ₂ monitoring. (offshore & onshore)	O
CO ₂ utilization	1. Compact CO₂ treatment equipment: low-cost, compact treatment equipment to allow offshore CO ₂ handling for EOR.	A
	2. Sub-sea CO₂ separation and injection: technologies that work sub-sea and can unlock the cheaper offshore CO ₂ separation closer to the point of injection.	A
	3. High-efficiency CO₂ conversion: low-cost CO ₂ utilization pathways to value-added products, e.g., blue hydrogen.	S

provided cost-effectively for storage. Improved technologies can help reduce heat or electricity consumption from a first pilot project. The goal of pilot projects would need to limit CAPEX while still getting industrial and relevant learning, reduce cost for following projects and enable further industrial opportunities related to offshore CCUS. Government investment support may have to optimize investment costs rather than the current net cost. It is expected that contingencies and allowances will be higher for the first-in-kind and subsequent initial projects than for future projects that have well-identified risks and measures to manage them.

5. Technology gaps in the offshore CCUS

Uncertainty about the costs of implementing the offshore CCUS is an efficiency penalty and should be reduced by the technological improvements and risk premium reductions faced by pioneers. To effectively achieve cost reduction and large-scale deployment, multiple ocean-based technologies need to be grouped and key bottlenecks at each stage of the offshore CCUS chain need to be identified (Table 6).

5.1. Offshore CO₂ capture technology

In China, many CO₂ capture or separation technologies (e.g., amine-based chemical solvents, selectively permeable membranes, solid sorbent agents, and cryogenic separation [64,65]) have been in commercial use for decades [66]. While only a small-scale pilot CO₂ capture project is located offshore China, i.e., the Enping 15-1 [12], which makes the commercial prospect of offshore CO₂ separation challenging. However, two CO₂ separation methods could be considered: natural gas treatment and post-combustion CO₂ capture. Well-head gas with higher impurities must be treated and post-combustion CO₂ capture technology is the most established. However, space constraints on platforms make the deployment of logistics and economical technology offshore. Centralized offshore capture concepts have therefore been proposed [67], in which

emissions from multiple nearby platforms are collected and treated on a fixed or floating central platform. This would bypass space constraints and provide economies of scale for carbon capture. A further feasibility study should be carried out on this concept. For the foreseeable future, mitigating platform emissions through hydrogen fuel switching or electrification is a more likely strategy to reduce carbon emissions in China.

The economics of offshore CO₂ capture is affected by the concentration of CO₂ in the gas/oil stream, the pre-treatment process filtering out impurities [68,69], and the inherent limitations of the capture materials [70]. Emerging capture technologies, such as polymeric membranes [71], solid absorbent processes, and looping technologies, mitigate some of these challenges in specific industrial applications [72]. Additional innovations combine new CO₂ capture materials with engineering to form flexible and hybrid solutions. In the long term, technologies such as direct air/seawater capture (DAC/DSC) could also be deployed offshore as a complement to offshore bolt-on capture solutions, compensating for residual CO₂ that is uneconomical to capture directly from plant emissions [17].

5.2. Offshore CO₂ transport technology

In China, there is over 165,000 km of gas & oil pipelines in operation; a significant portion of these are offshore to connect gas & oil platforms and to transport gas & oil from offshore fields (e.g., Bohai and Chunxiao) to onshore industrial hubs (e.g., Circum-Bohai Sea Economic Zone and Yangtze River Delta Economic Zone). There are ongoing studies on the potential of repurposing existing gas pipelines for CO₂ transport to build out an offshore CCUS value chain to transport CO₂ [73,74], rather than having to build new pipelines, to save on capital costs and progressing offshore CCUS projects. However, there are still technological challenges related to retrofits, long-term integrity, and monitoring, which could be resolved through the expertise of the oil and gas industry.

Table 7

Key suggestions for accelerating full-chain offshore CCUS development in China concerning components in Fig. 5. The differentiation between certain components may not be definitive.

Components	Key suggestions on accelerating full-chain offshore CCUS in China
Feasibility study	1. Offshore sites can provide electrical generation opportunities through low-carbon technologies, such as wind, waves, and tides.
Concept selection	1. Use the social cost of carbon (SCC) to evaluate China's offshore CCUS assets. 2. Low-carbon portfolio standard with tradable certificates. 3. Minimum standards, such as a requirement for offshore CCUS for new facilities beyond 2030.
Definition (FEED)	1. Use existing or new frameworks to facilitate the identification of offshore CCUS opportunities nationally or sub-nationally.
Source-sink data	1. Confidently assess the storage site for ongoing carbon sequestration. 2. Estimate and publish a confirmed sub-seabed carbon storage inventory. 3. Provide full offshore storage capacity at the source of carbon emissions.
Identify knowledge gaps	1. Develop a national sub-sea carbon storage map to estimate the wealth of the offshore CCUS. 2. Understand fluid migration in sub-seabed storage formations and potential pathways. 3. Estimate the time taken for the offshore CCUS to achieve net-zero emissions. 4. Assess options and consider the reuse of existing offshore facilities.
Demonstration projects	1. Fully leverage CO ₂ -EOR to balance the investment and financial returns. 2. Develop tools for cost-effective capture, transport, storage, and utilization of CO ₂ offshore. 3. Develop new tools for monitoring CO ₂ fluids in the sub-seabed and seawater column. 4. Develop demonstration projects to highlight successes and failures at the regional deployment level, and to create data sets, information, and outreach for future offshore CCUS projects. 5. Identify cost-effective pairs of carbon source-sink for the deployment of offshore CCUS pilot projects.
Cross-disciplinary engagement	1. Develop public, interactive maps of China's carbon emissions and offshore storage data. 2. Combine measures to improve the suitability of offshore storage and capture capacity to enable carbon source-sink connections.
Policy, legal & regulatory	1. Fully integrate the offshore CCUS within carbon source-sink policies and mechanisms. 2. Improve standard protocols for accounting for the benefits of decarbonization to improve the feasibility and uptake of carbon credit projects. 3. Establish a carbon tax credit to lower the cost of the offshore CCUS.
Carbon markets	4. Reduce insurance premiums for the offshore CCUS related to the carbon isolation of the atmosphere. 1. Establish blended financing for the CCUS to deliver societal benefits and financial returns. 2. Introduce the carbon trading system.

The cost of retrofitting will ultimately depend on the current state of existing pipelines. Differences between natural gas pipelines and CO₂ pipelines are minimal and center on the level of controls required to maintain safety and asset integrity over time, especially with anthropogenic CO₂ [75]. CO₂ pipelines often need more meters, pumps, and controls to maintain their condition. Anthropogenic CO₂ in addition is more likely to contain corrosive contaminants [75], which would need to be controlled with corrosion-resistant pipeline materials or through additional purification measures at loading, to protect asset integrity over time.

Unlike fixed offshore pipeline infrastructure requiring enormous capital outlay, shipping CO₂ in tankers could serve as a near- to mid-term solution to help demonstrate multiple CO₂ storage sites on the annual scale of <1 MtCO₂ [17]. Full-scale CO₂ tankers are like commercial, semi-refrigerated liquefied natural gas (LNG) tankers, but any larger vessels would require significant refit. Despite industry hesitancy about the viability of flexible containers and the lack of regulatory frameworks, marine transportation does not present major technical barriers. In contrast, it provides a viable option for long-distance and low-volume CO₂ transport [76].

5.3. Offshore CO₂ storage technology

Several offshore storage sites have been nominated as high-priority storage clusters because of their known physical geological attributes, e.g., Bohai Basin and part of PRMB [7–9,32]. Oil and gas operators in China (e.g., CNOOC) have been collecting subsurface data for decades [77,78], providing a solid foundation for characterizing potential storage in offshore DOGF or SA [19]. To date, there is an abundance of geospatial data available to characterize basins offshore China, while various technologies and knowledge gaps exist. These gaps include issues related to data availability, interoperability of different data sets, and the ability to model CO₂ behavior over time, which presents technical challenges (Table 6).

Standard methods are first needed to model CO₂ migration and interactions [79] in various rock structures and potential cracking and chemical reactions through the multiple stages of storage (e.g., pre-

injection, operation, and post-sealing) [80]. This is important for existing wells, which may be at a higher risk of leakage. In addition, it is difficult to compare disparate data sets of key metrics during site selection and to optimize injection strategies for different storage sites. This requires further research and development on the behavior of hydrocarbons before extraction. Moreover, CO₂ behaves differently in its various phases, which can affect the trapping mechanisms after injection. This phenomenon needs to be carefully studied across the unique rock formations present offshore China, particularly in highly depleted gas/oil fields, e.g., some could exist in the Yinggehai Basin [81] over the next several decades. Finally, the industry lacks a standard set of tools and guidelines to establish safe and cost-effective long-term monitoring of storage sites [80] and thus some cross-project learning and interdisciplinary research would be required [82].

5.4. Offshore CO₂ utilization technology

Most offshore CO₂ use pathways require significant development before they can be fully deployed. Besides the CO₂ storage innovation gaps for CO₂-EOR, industries in China are also grappling with the deployment of offshore infrastructure and sub-sea technologies. Space and weight limitations on existing offshore platforms limit the viability of large-footprint CO₂ equipment, such as compressors and recycling units. A large centralized CO₂ processing unit could overcome several challenges in single-platform injection, including lower flow quantity, variable flow rate, and physical constraints. This concept needs further exploration to verify its economic and logistic feasibility. While all the components for gas/oil processing are already commercially available, adapting these to sub-sea conditions could be challenging and it would be critical to bringing down the cost.

6. Practical aspects of deployment

Technological innovations are key to minimizing the implementation costs of the offshore CCUS and accelerating the demonstration of the full-chain offshore CCUS [15]. While the underlying deployment of offshore CCUS technology in China is at a pilot scale, uncertainty

in cost and performance largely reflects the lack of integrated applications and workable business models of large-scale commercial operations [17,27]. Grants supporting the construction of commercial-scale offshore CCUS projects promote one-of-a-kind construction that allows for learning, feasibility testing, and risk reduction for future commercial implementations [86]. Coordinated financial and political support will be necessary to create the right conditions for the start-up of the offshore CCUS industry.

6.1. Relevance to nationally determined contribution (NDC)

Achieving the scale of offshore CCUS deployment to deliver maximum decarbonization benefits requires strong governance and support from governments, recipient industries, corporations, and communities. In China, regulation of the offshore disposal of CO₂ and ocean jurisdiction remains unclear, including the development of procedures and standards for undertaking a full-chain offshore CCUS, as well as a concrete legal framework to guide offshore CCUS public participation and consultation [87]. To avoid interaction without rules, associated regulations and laws at the national, provincial, and local levels are expected to be planned on a specific and legitimate mandatory basis before the large deployment of offshore projects [43]. To facilitate the cost-cutting of the offshore CCUS, environmental policy initiatives should be supported by the Chinese government to encourage world-class construction. This is important to guarantee regulated income for service providers on full-chain offshore CCUS components [86,88].

To make offshore CCUS projects commercially viable, a tax on CO₂ emissions from the offshore oil and gas industry could be introduced by the Government of China. This provides strong revenue and viable incentive, which will draw down the cost of offshore CCUS as that has been introduced by Norway and the United States (45Q tax credit) [89,90]. While uncertainty exists in all CO₂ pricing systems, the 45Q tax credits allot >US\$35 ton⁻¹ for CO₂ utilization and >US\$50 ton⁻¹ for permanent sequestration of CO₂ in geologic reservoirs [88]. It helps companies deliver offshore CCUS solutions to develop supply chains in a coordinated way [87]. If China's carbon tax were introduced, it should avoid most of CCUS costs for the infrastructural establishment of the supply chain, and let the cost of carbon increase sufficiently to be an important driver for the profitable offshore CCUS business.

The initial development of specialized offshore CCUS projects is an expensive process. For large-scale CO₂ storage below the seabed, detailed geological mapping and site characterization of abandoned drilling and reservoirs are required. This requires substantial investment, which is a disincentive for independent organizations to invest in offshore storage infrastructure and related technologies, particularly when combined with the uncertainty of future revenues. China has large state-owned enterprises, where direct investment can support the first offshore CCUS projects. This could boost deployment, guarantee sufficient investment returns, and help develop the carbon market through procurement policies [18,90]. In China, an offshore CCUS project is already implemented in the northern South China Sea, which is currently generating valuable information about the cost and operation experience for offshore CCUS and therefore offers opportunities to develop market-based mechanisms that take advantage of existing frameworks for carbon offsets. Future projects can be developed in partnership with those wanting to purchase offsets, whether in the public or private sector, with the chance to make additional contributions from other financial streams [91,92].

6.2. Economic activities

The offshore CCUS, as a solution to reduce carbon emissions, is considered a commercial activity and maybe a future industry component, while coal-fired power and steel assets present a particular challenge. In east and southeast China, to retire existing power and industrial plants

early or repurpose them to operate at lower rates of capacity utilization or with alternative fuels, offshore CCUS is the only alternative. Retrofitting CO₂ capture equipment can enable the continued operation of existing plants and supply chains, but with significantly reduced emissions. It would also help to preserve employment and economic prosperity in the emissions-intensive industrialized coastal regions of the east and southeast while avoiding the economic and social disruptions caused by early retirements. Therefore, to support coal mine and power plant owners and the communities that will be affected, a compensation package would have to stimulate the economy. This could involve novel approaches, such as blended financing whereby a commercial project provides societal benefits plus financial returns to investors, and/or pairing with co-benefits such as reduction of insurance premiums related to carbon isolation, which can help enhance uptake and progression to verification in the coming years (see Table 7).

To date, state-owned enterprises in China have been major players in the execution of CCUS projects, while they often face incentive opportunities and frameworks to access financing that differ from their private sector counterparts [27]. For private property in the orbit of free initiative, they can conduct activities in an environment of free competition [93]. Such competition in the offshore CCUS can be a priority for accessing the best CO₂ storage locations or a preferred shared offshore CO₂ storage site, such as for CO₂-EOR. This might guide to develop of industrial hubs with shared CO₂ transport and storage infrastructure, which would open up new investment opportunities and improve the economics of offshore CCUS by reducing unit costs through economies of scale as well as reducing commercial risk and financing costs by separating the capture, transport and storage components of the value chain. To provide guidance and optimize the investment environment of consistent offshore CCUS development, an acceptable risk allocation of commercial debt is expected to be demonstrated, and a standardized financial template should be introduced [27]. Large-scale offshore CCUS projects are complex and expensive, where debt might be available, particularly for early offshore projects where grant funding can help to close a significant financial gap [27].

6.3. Cross-disciplinary engagement

Another major challenge to the development of the offshore CCUS is the problem of coordination. The CO₂ emission sources are scattered in the main industrial clusters of the eastern and southeastern regions (Fig. 2), while the offshore geological investigation and exploration are operated by various enterprises, such as large state-owned petroleum companies. In addition, offshore CCUS research and development is carried out by universities and research institutions, and financial support and debt are provided by public sector banks. Therefore, good cooperation and coordination mechanisms among governments, businesses, research organizations, and financial sectors are important to accelerate the development of the offshore CCUS in China.

For the design of offshore CCUS projects, a wide range of procedures and risks must be reviewed and assessed. This involves collaboration in studying the feasibility of storage reservoirs, carbon source-sink database, identifying knowledge gaps, front-end engineering and design (FEED), leakage monitoring, as well as external quality assurance, etc., as mapped in Fig. 5 and summarised in Table 7. In addition, specific non-technical uncertainties related to supply across the chain, regulatory framework, liabilities, financial factors, social acceptability, etc., should be considered. These critical considerations will require a clear regulatory framework. Therefore, continuous research on full-chain offshore CCUS technologies and the development of pilot demonstration offshore CCUS projects should be carefully conducted, which will accelerate incremental steps toward maturing offshore projects and minimizing uncertainties and comprehensive risks [14]. Our current challenge today is to overcome the scientific, technological, financial, social, governance, and policy barriers that currently prevent the widespread deployment of offshore CCUS projects. Particular attention should be given to new

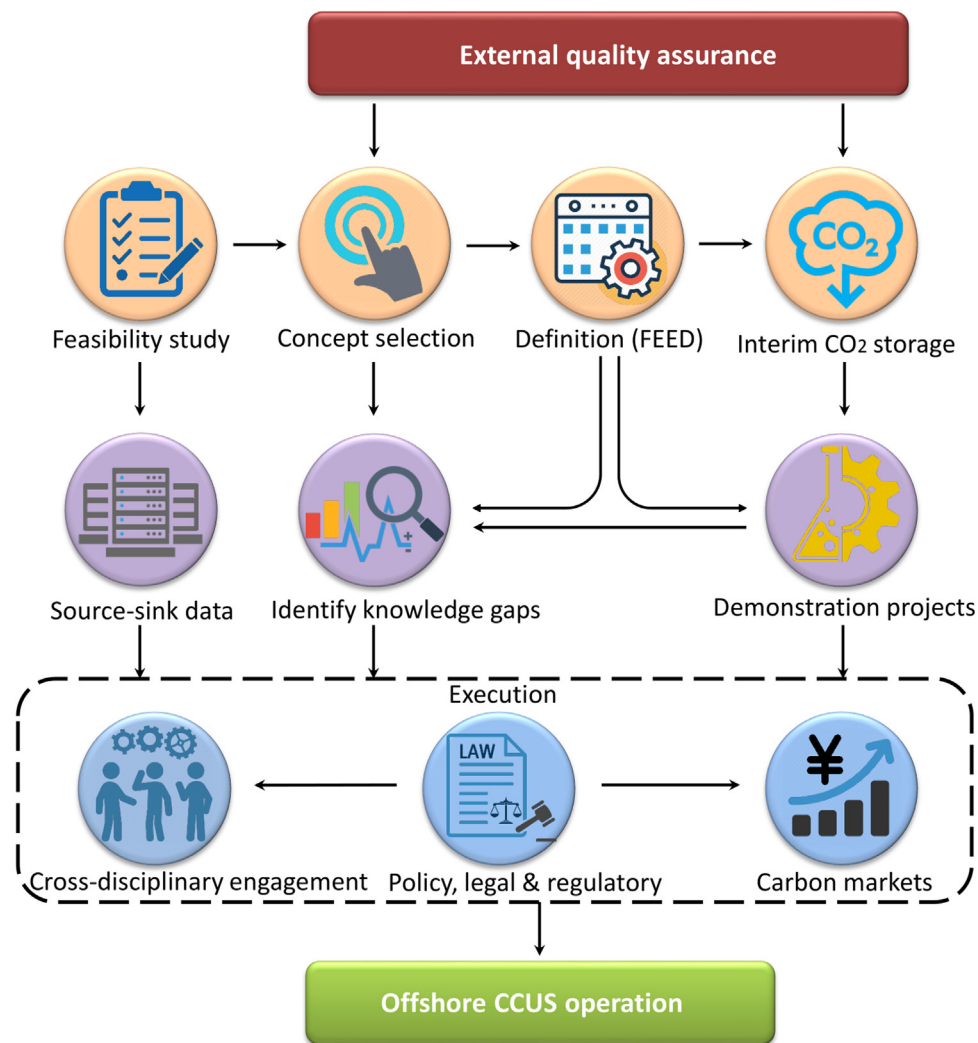


Fig. 5. Roadmap of a full-chain offshore CCUS project development model. The timing of the external quality assurance is required by large public projects, from the start of the feasibility study to the start of an offshore CCUS project [94]. There are various linkages and feedback between these development stages. Table 7 provides the main suggestions for those components.

offshore CCUS projects, in which the associated technical and financial risks are relatively high, a joint cross-disciplinary development should be considered coinciding risk reduction with offshore CCUS success for long-term commercial adoption and commitment to carbon credits [86].

7. Summary and path to 2060

Offshore CCUS as a decarbonization strategy in China is exciting, workable, and indispensable, with the potential to significantly mitigate carbon emissions to the atmosphere, particularly in the coastal regions where onshore geological CO₂ storage is distant or suffering from public opposition. To maintain the uptake and progression of offshore CCUS toward large-scale deployment, suitable incentives and requisite political backing to create a commercial environment and favorable regulations must be included in the national plan. The deployment of large-scale offshore CCUS is complex and must take a range of factors into account, including emission source accounting, geographical spreading of storage sources, technology implementations, project designs, risk assessments, economic effects, financing, social factors, and administrative policies. These complexities are not insurmountable, but they require careful planning and further research, including consideration of how national and subnational policies can better reward long-term sustainable deployment of offshore CCUS to achieve China's national target of Carbon Neutrality by 2060.

Declaration of competing interest

The author declares that there is no conflicts of interest in this work.

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