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EDITED BY
Qi Xu,
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REVIEWED BY
Jiangtao Qian,
Dalian Maritime University, China
Linghao Meng,
Shanghai Academy of Social Sciences, China

*CORRESPONDENCE
Meng Zhang
meng.zhang@har.lu.se

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Barriers or boosters? the role of governance pathways in deploying offshore carbon capture and storage: comparative implications from the EU and China

Jinpeng Wang[1] and Meng Zhang[2,3]*

[1]School of Law, Ocean University of China, Qingdao, China, [2]Department of Business Law, School of Economics and Management, Lund University, Lund, Sweden, [3]Centre for Climate Change Law and Governance, University of Copenhagen, Copenhagen, Denmark

Offshore carbon capture and storage (CCS) deployment has been hailed as a game changer in the ever-changing climate game in the era of Paris Agreement. In the European Union (EU), rigorous regulation within a legal framework governs cross-border offshore CCS projects, while China adopts a flexible policy-oriented approach. This article employs a multi-method research approach, combining legal doctrinal analysis, comparative studies, and discourse analysis, to examine the role of governance tools in offshore CCS deployment in the EU and China, highlighting their differing models and the implications for effective governance. The discrepancies in governance models for offshore CCS deployment between the EU and China arise from variations in legal traditions, disparities in the legal status of marine areas hosting offshore CCS projects, and differences in involved industries. The paradox between normative governance and offshore CCS deployment finds resonance and explanation in the "Collingridge Dilemma". Experiences from both the EU and China underscore the significance of a tailored-made and well-balanced governance portfolio of legal and policy tools in regulating and facilitating offshore CCS deployment. Policy and law should act hands in hands as twin engines in a sound governance framework propelling the momentum of offshore CCS deployment forward.

KEYWORDS

offshore carbon capture and storage, European union (EU), China, governance framework, policy-driven, Collingridge Dilemma

1 Introduction

According to estimates by the International Energy Agency (IEA), global energy-related carbon dioxide emissions grew by 0.9% in 2022, increasing by 321 million tons to a new high of 36.8 billion tons (IEA, 2020). It is predicted that with technological advances and commercial application, the emission reduction potential of carbon capture and storage (CCS) could reach 33% of total global carbon emissions by 2050, much higher than the carbon reduction effect of other methods (Stangeland, 2007). This projection surpasses the efficacy of other carbon reduction methods, establishing CCS as a promising technology endorsed by nations worldwide. Its application facilitates large-scale low-carbon utilization of fossil energy, contributing to global energy security (Han et al., 2009). In order to grasp the potential advantages of future CCS technology, developed countries, including the United States, the EU Australia, Canada, and Japan, have invested substantial resources in research and development and demonstration activities (Cai et al., 2021). These countries have concurrently implemented regulations and policies to propel the growth of CCS (Zhong et al., 2012). Compared to in-land geologic CO2 storage, offshore CCS has received relatively little

attention due to challenges in the development, operation, and costs (Schrag, 2009). However, offshore CCS may also be socially beneficial since it could avoid heavily populated areas (Kim et al, 2016). In accordance with the International Intergovernmental Panel on Climate Change (IPCC), offshore CCS is defined as a process consisting of the separation of CO_2 from industrial and energy-related sources, the transport via pipelines or ships to a storage location in sub-seabed geological formations and long-term isolation from the atmosphere (IPCC, 2005). As a response to feckless global actions to address climate change, the offshore deployment of CCS – a bridging technology for climate mitigation – has been hailed as a game changer in the ever-changing climate game in many jurisdictions who have ambitious climate goals to implement the Paris Agreement.

However, multi-dimensional governance challenges triggered by offshore CCS deployment are neither straightforward nor uncontroversial. Technically, offshore CCS deployment requires the modification and improvement of existing techniques albeit in a novel combination and scale. Environmentally, it promises to avoid carbon emissions into the atmosphere through the permanent storage and isolation of the resultant CO_2 in subsurface geological formations, while this promise does not come for free but with a series of undesirable environmental risks and impacts. Economically, like most forms of innovative technological options for climate mitigation and energy transition, offshore CCS deployment is more costly than conventional means. Societally, it triggers controversies both in local communities concerned over a potentially risky process, and amongst those with ethical opposites against extending the usage of fossil fuels (Ghaleigh, 2016). Legally, it couples regulatory requirements with each of these concerns at a variety of levels and in a range of forms (Zhang, 2021). As the two crucial powers in global climate governance, both the European Union (EU) and China have renewed their ambitions to accelerate climate actions to keep the 1.5 °C Paris Agreement goals within reach. Under the 2019 European Green Deal, the EU strives to be the first climate neutral continent in the world, pledging to reduce emissions by at least 55% by 2030 (EC, 2019). Comparably, China, through President Xi Jinping's announcement at the general debate of the 75th Session of the United Nations General Assembly on September 22, 2020, has pledged to scale up its Nationally Determined Contributions (NDCs) by adopting more vigorous policies and measures, striving to peak CO_2 emissions by 2030 and achieving carbon neutrality by 2060, which has been further developed as China's flagship national climate action strategy–'3060 Dual Carbon' strategy (National Development and Reform Commission of PRC, 2021). More notably, both the EU and China have included offshore CCS deployment as a crucial pillar in their ambitious climate action landscape. However, divergent governance pathways and models have been adopted by the EU and China to regulate and facilitate the offshore CCS deployment – the former is in favor of a law-based governance model, while the latter prioritizes a policy-driven governance pathway. Standing at the turning point of the global momentum of offshore CCS deployment, a sound governance framework is as much needed as it is still a long way off globally and in many jurisdictions.

Governance issues surrounding technologies that mitigate climate change are profound, which are best illustrated in the challenging question of how to regulate and facilitate the offshore CCS technology (Zhang, 2021). In this article, offshore CCS governance refers to the supervision and management of carbon capture, storage, and potential utilization in coastal and marine areas by governments or competent authorities through legal and policy instruments. The objective is to promote the application of CCS technology to achieve carbon reduction targets while preventing significant adverse environmental impacts. This article aims to demonstrate the world a sound governance pathway to regulate and facilitate offshore CCS deployment based on comparative implications and lessons learned from the EU and China's experience. Through comparing the different offshore CCS governance models in the EU and China, the article contributes to unveil the ground stones of the two divergent governance models. Particularly by invoking the theoretical framework of "Collingridge Dilemma" that vividly sketched the governance paradox in technology deployment, this article further sheds new light on the role of law-policy interactions in deploying offshore CCS projects. In order to effectuate the research aim, an integrated portfolio of research methodology is employed in this article, embracing three specific and synergetic strands. Firstly, the legal doctrinal method is applied in the doctrinal analytical dimension of this research to investigate the role of different governance tools such as binding legal instruments and policy documents in deploying offshore CCS in the EU and China. Secondly, throughout this article stands a crucial method of comparative studies. This method is invoked to identify the commonalities and discrepancies between the law-based governance mode in the EU and the policy-driven governance regime in China and to explore their implications for the offshore CCS deployment. The "tertium comparations" of this research lies in the fact that both the EU and China have prioritized

offshore CCS deployment in their climate actions but adopted two different representative models to govern the deployment pathway. Last but not least, the discourse analysis is employed as an innovative method in this legal research. Discourses and narratives of governance paradox built in the theory of "Collingridge Dilemma" offer an interdisplinary analytical lens beyond the conventional legal dogmatic perspective to rethink the role of law and policy in governing CCS and to reshape a sound governance model for offshore CCS deployment.

2 The EU's pioneering role in deploying offshore CCS and developing a matching legal framework

2.1 The EU's deployment of CCS in a nutshell

Europe's future depends on a healthy planet, to which climate change has become an existential and imperative threat. As warned by the newest IPCC AR6 Synthesis Report, forecasts for the catastrophe of climate change are being marvelously revised up — markedly for human beings, materially for the nature, and massively for the whole world in a majorly planetary scale (IPCC, 2023). Since the 2005 IPCC Special Report on CCS, which marked a milestone raising the profile of CCS and securing its recognition as a promising bridging technology for carbon emissions mitigation (IPCC, 2023), CCS has been hailed as a game changer in EU's climate actions (IPCC, 2005).

Yet, the adventure towards CCS deployment in the EU was not without its trials and tribulations. Much of the first European CCS momentum was not maintained when the UNFCCC COP 15 in Copenhagen[1] failed to fulfil expectations for more ambitious climate goals and actions. During the slowdown of CCS deployment in the EU, the collapse of the Dutch CCS project ROAD[2] in 2016 casted the darkest shadow on the prospects for CCS deployed in European power sectors, marking the last proposal standing for large-scale coal/gas power CCS project in the EU at that time (Gerard, 2017). Notably, several formidable challenges emerged during this dark phase, impeding the growth of the momentum to deploy CCS in the EU. Environmentally, CCS promises to avoid carbon emissions into the atmosphere through the storage of the resultant CO_2 in subsurface geological formations, while this promise does not come for free but with a series of undesirable environmental risks and impacts. Economically, like most forms of innovative technological options for climate mitigation and energy transition, CCS is more capital intensive than conventional means. Societally, it, on the one hand, falls victim to the public backlash rooted in the classical 'nimbyism' - Not In My Backyard Syndrome, while on the other hand triggering ethical opposition nourished by misconceptions that CCS threatens the development of renewables, extends the reliance on fossil fuels, and therefore delays the low-carbon energy transition. Strategically, CCS was not yet afforded 'policy parity' – an equitable level of policy recognition and facilitation – alongside renewables and the energy efficiency.

However along the whole world strode forward into the new Paris Agreement Era, particularly thanks to the 2018 IPCC Report on Global Warming of 1.5 °C that resounds with climate urgency (IPCC, 2018), the 2019 Resolution to the 2009 London Protocol amendment (IMO, 2019b) that legalizes the offshore cross-border CCS deployment (IMO, 2019a), and the increasingly improved EU Emissions Trading System (ETS) that strengthens the carbon price signal, came a pivotal turning point for a renewed momentum of CCS deployment in the EU (EC, 2021).

2.2 The rejuvenated momentum of offshore CCS deployment in the EU

The rejuvenated European momentum of CCS deployment is characterized as transboundary offshore deployment focused, energy-intensive industries oriented, and flagship industrial ports centered, which is demonstrated by some cross-border offshore CCS projects in the North Sea region. First, this renewed CCS deployment momentum in the EU shifted its focus away from emissions of fossil fuel electricity generation, especially the coal-fired power plants, towards carbon emissions reduction in energy-intensive industries, marking a pivotal change in strategy. On the one hand, following the energy transition of phasing out coal-fired power plants from the energy structure, the CO_2 emissions from fuel combustion have been declining dramatically in Europe, which inadvertently weakened the European impetus for CCS deployment in the energy sector that had initially been the focal point for CCS initiatives. On the other hand, energy-intensive industries (EIIs) that also encompass process emissions along the entire value chain, responsible for 15% of the EU's emissions, have become the hardest thorn in the EU's green transition towards climate neutrality (EC, 2024). The challenge is rooted in how to lower emissions while keeping industry competitive and positioning it to exploit the huge potential global market for low-emission technologies and services. CCS, which can be applied on industrial installations, provides an indispensable technical option to dealing with the EIIs' emissions that cannot be tackled only through electrification, ensuring that these industries can contribute to Europe's 2050 climate-neutrality ambitions. Secondly, cross-border offshore deployment is necessary to enable CCS an effective, feasible and acceptable measure to combat climate change, attracting the spotlight of the renewed European momentum to deploy CCS. Technically and legally, long-term CO_2 storage in suitable and safe geological formations is required by sustainable and successful CCS deployment. Due to the

1 The 15th session of the Conference of the Parties (COP 15) to the United Nations Framework Convention on Climate Change (UNFCCC), commonly known as the COP15 to the UNFCCC, was held in Copenhagen, Denmark, between 7 and 18 December 2009. A framework for climate change mitigation beyond 2012 was to be agreed there.

2 Rotterdam Opslag en Afvang Demonstratieproject (Rotterdam Capture and Storage Demonstration Project).

fact that land-based geological storage resources are very limited and are closely restricted by human activities, which are often considered as inappropriate sites for large-scale of carbon storage or subject to the NIMBY Syndrome, cross-border CCS deployment for sub-seabed storage is extremely vital, more promising and less controversial for those countries do not have suitable sub-seabed geological formations for carbon storage (CATO-2, 2011; Langlet, 2014). Thirdly, large industrial ports with a "clustering effect" of CCS infrastructures and installations are playing a central role in the cross-border offshore CCS deployment. Large-scale cross-border offshore CCS projects often involve and rely on a series of complex CCS infrastructures and facilities such as sources, sinks and pipelines, which are very expensive and of interdependency business risks. Accordingly, a CCS business model based on integrated hubs and clusters where economies of scale can reduce unit costs and on a diversified source of emissions that can reduce the risk of asset stranding is favored by governmental strategies, capital choices, and industrial actors. In this regard, large industrial ports with diversification in types of industrial sources of CO_2 emissions and plenty of space for the development of industrial installations are the ideal "nexus" to provide regional CCS infrastructures and facilities for large-scale capture, transport and storage.

Accordingly, the cross-border offshore CCS deployment in the EU can be portrayed as that captured CO_2 from the country of origin will be transported to the oceans from the port via ships or pipelines, and artificially piped or injected into large geological formations under the seabed in the country of storage. This model of offshore CCS activities that are not limited by the boundary of any single country require robust regional cooperation based on solid EU policy incentive and clear legal frameworks, which has been demonstrated by some cross-border offshore CCS projects in the North Sea region such as the "Antwerp@C" (Port of Antwerp Bruges, 2024) and "Kairos@C" projects at the Port of Antwerp-Bruges, and the "SDR Carbon Connect Delta" Program in the Schelde-Delta Region (SDR) around the North Sea Port (Smart Delta Resources, 2024). The EU is intended to replicate such projects across the EU in order to de-risk investments in CCS and to ensure its deployment at scale. As a remarkable milestone in deploying offshore CCS, the EU, through the operation of the Greensand Project between Belgium and Denmark, demonstrates the world's first ever full value chain project for cross-border offshore CCS deployment. The Greensand Pilot Project shows to the world for the first time the feasibility of CO_2 storage from being captured in Belgium, to being transported cross-border and finally safely and permanently stored in a depleted oil field under the Danish North Sea (Greensand, 2024). More promisingly, building on the success of the Greensand Pilot, a larger scale of full value chain project – Greensand Future – is scheduled to be operated with initiate offshore storage into the INEOS-operated Nini field in the Danish North Sea at the end of 2025/early 2026 (Greensand, 2025). It further aims to safely capture and permanently store 400.000 tons of CO_2 each year as a start allowing for the gradual expansion of storage capacity as CO_2 volumes increase with a potential to store 8.000.000 tons of CO_2 per annum, which marks the EU's first operational offshore CO_2 storage facility in addressing climate change (Greensand, 2025).

2.3 The matching legal framework to regulate and facilitate the offshore CCS deployment in the EU

The EU's deployment of cross-border offshore CCS projects is regulated and facilitated within a law-based framework. The EU has long embraced the pioneering role of a global trendsetter in building up and developing CCS legal framework. In a nutshell, the EU's CCS legal and regulatory architecture demonstrates a comprehensive, multi-layered approach to balancing environmental protection with economic incentivization for offshore CCS deployment. Central to this framework is the pioneering EU CCS Directive (EU, 2009), establishing stringent regulatory conditions for site selection, environmental impact assessments, and robust liability management throughout the CCS lifecycle. This Directive is effectively integrated with broader environmental regulatory instruments, such as the EU Environmental Impact Assessment Directive, the Industrial Emissions Directive, and the Directive on Environmental Liability, thereby ensuring a consistent environmental safeguarding framework across CCS operations. Economically, the EU Emissions Trading System (ETS) and the EU Innovation Fund (NER 300) provide crucial financial stimuli, reducing economic uncertainties and fostering the development and scaling of offshore CCS technologies. The recent adoption of the EU Net Zero Industry Act Regulation (EU, 2024) significantly advances this integrated framework, setting ambitious, legally binding targets for annual CO_2 storage capacities, streamlining permitting processes, and further facilitating investment conditions. Collectively, this multifaceted and evolving regulatory architecture embodies a law-based dynamic governance strategy, uniquely designed to promote CCS deployment at scale while simultaneously safeguarding environmental integrity and achieving the EU's overarching climate neutrality objectives. (See Table 1)

As illustrated in Table 1, the EU adopts a law-based approach and pathway to navigate the deployment of offshore CCS through a specific CCS legal framework with the CCS Directive playing a central role to regulate the environment safety of offshore CCS deployment. In 2009, at the vanguard of establishing regulatory frameworks for CCS deployment, the EU adopted the CCS Directive, sealing the world first CCS specific legislation (EU, 2009). The EU CCS Directive aims to ensure the human and environmental safety of CCS deployment, particularly regulating the storage process of CCS deployment. It lays down extensive requirements for the selecting sites for CO_2 storage, providing that a site can only be selected if a prior analysis shows that, under the proposed conditions of use, there is no significant risk of leakage or damage to human health or the environment (EU, 2009). In general, no offshore geological storage of CO_2 will be possible without a storage permit. In addition, before receiving any construction and operation permits, offshore CCS projects need to conduct an EIA addressing all environmental concerns – a detailed assessment of the site selection and develop a monitoring plan addressing all possible leakage risks (EU, 2009).

TABLE 1 EU's CCS legal architecture in a nutshell (elaborated by the author: Meng Zhang).

Legal/Regulatory Instrument	Scope and Objectives	Key Provisions Relevant to Offshore CCS
EU CCS Directive (2009/31/EC)	Regulatory framework for CCS to ensure environmental safety	- Site selection based on no significant leakage risks - Mandatory Environmental Impact Assessment (EIA) - Monitoring, closure, and post-closure obligations - Liability transfer criteria from operators to Member States
EU Emissions Trading System (ETS)	Economic incentive to reduce emissions by setting a carbon price	- Creates financial incentives for CCS investment - Provides indirect financial support through carbon pricing
EU Environmental Impact Assessment Directive	Evaluation of environmental effects for projects requiring permits	- Requires comprehensive environmental assessments for CCS projects
Industrial Emissions Directive	Regulates emissions from industrial installations	- Applicable to CCS-related industrial activities - Ensures integration of CCS within emission control measures
Directive on Environmental Liability	Liability framework for environmental damage prevention/remediation	- Clarifies environmental liability related to CCS storage sites - Ensures long-term environmental accountability
EU Innovation Fund (NER 300)	Financial support for innovative low-carbon demonstration projects	- Provides funding for commercial-scale offshore CCS projects - Mitigates financial risks associated with CCS deployment
EU Net Zero Industry Act (NZIA, Regulation 2024/1735)	Accelerates net-zero technologies to meet climate neutrality goals	- Binding annual CO_2 storage target (50 million tonnes by 2030) - Facilitates investment through regulatory simplification and enhanced market conditions

More importantly, the Directive also covers closure and post-closure obligations, and sets out criteria for the transfer of responsibility from the operator to the Member State, which demonstrates to the world an innovative model to arrange and regulate the liability for unlimited long-term storage risks that has been long considered as a crucial hurdle for the commercialization of offshore CCS deployment (EU, 2009). The EU CCS Directive, while pioneering in nature, imposed a web of regulatory requirements on the early-stage development of CCS projects, leaving the balance between regulation and facilitation elusive.

More importantly, the resurgence of CCS deployment found powerful allies in the form of the European Green Deal unveiled in 2020, and the subsequent Fit for 55 packages adopted in 2021 that aim to translate the ambitions of the Green Deal into law. In order to deliver on the commitments under the Paris Agreement, the EU, through its European Green Deal, strives to be the first climate neutral continent in the world, pledging to reduce emissions by at least 55% by 2030 (EC, 2019). Aiming at achieving this ambitious climate goal, the European Green Deal reset the EU on the path of a comprehensive green transition into a fair and prosperous society with a modern, resource-efficient and competitive economy through a holistic and cross-sectoral approach (EC, 2019), which to some extent shapes the Deal to a "constitution" of EU climate neutral transition. These comprehensive policy and legislative initiatives breathed fresh life into the prospect offshore cross-border CCS deployment across Europe, highlighted the imperative of CCS in the broader context of EU climate neutrality transition. Against this background, the EU Net Zero Industry Act (NZIA), formally known as Regulation (EU) 2024/1735, was proposed by the European Commission on 16 March 2023, adopted by the EU legislatures on 13 June 2024, and eventually entered into force on 29 June 2024 (EU, 2024). The EU NZIA turns the policy commitment to the legal confirmation that facilitates the offshore CCS deployment in Europe (EC, 2023). From a broader EU law perspective, this Act is part of the Green Deal Industrial Plan's pillar for a predictable and simplified regulatory environment, which focuses on promoting investments in the production capacity of products that are key in meeting the EU's climate neutrality goals (EC, 2023). Specifically, the EU NZIA aims to enhance European manufacturing capacity for net-zero technologies and their key components, addressing barriers to scaling up production in Europe, increasing the competitiveness of the net-zero technology sector, attract investments, and improve market access for clean tech in the EU (EU, 2024). This supports the clean energy transition and improves the EU's energy resilience, in which offshore CCS deployment makes up the backbone of an affordable, reliable, and sustainable clean energy system in the EU (EC, 2023). By accelerating the development and production of net-zero technologies, the EU NZIA encompasses products, components and equipment necessary for deploying offshore CCS. Particularly, as a crucial component of the NZIA accelerating offshore CCS deployment across the EU, the Act sets a goal for net-zero manufacturing capacity to meet at least 40% of the EU's annual deployment needs by 2030, providing predictability, certainty and long-term signals to manufacturers and investors in offshore CCS deployment (EU, 2024). More importantly, by 2030, the EU NZIA aims to create a Union market for CO_2 storage services, setting a Union-level goal and mandates an annual CO_2 storage capacity of at least 50 million tonnes (EU, 2024). This binding requirement under the EU NZIA will remove a major barrier to developing CO_2 capture and offshore storage as an economically viable climate solution, in particular for hard-to-abate energy-intensive sectors. In general, the new EU Act has the potential of acting as a game changer to increase investment and improve permitting procedures for deploying offshore CCS projects (EC, 2023).

2.4 Analytical implications of the EU governance approach on offshore CCS

From the early CCS Directive, the world's first CCS-specific legislation, to the recent NZIA under the Green Deal Industrial Plan, the EU's regulatory approach illustrates a nuanced example of balancing rigorous environmental governance with pragmatic industrial policy. The two-decades journey along the EU's offshore CCS pathway further provides valuable insights into the governance paradoxes of the "best timing" in regulating technological development in addressing climate change and energy transitions. Early, stringent regulatory frameworks introduced without adequate facilitative measures demonstrated how excessive regulation could inadvertently inhibit technology deployment. Conversely, recent legislative adjustments under the EU NZIA reflect an evolving understanding that regulatory certainty must be paired with active incentives to successfully scale offshore CCS.

Consequently, the EU experience further demonstrates the critical importance of timing and proportionality in regulatory intervention, highlighting that successful governance frameworks must dynamically adjust to evolving technological maturity and market conditions. Such a governance model not only addresses regulatory predictability and environmental safety but also aligns economic incentives with strategic climate objectives, offering important lessons for jurisdictions developing offshore CCS governance strategies worldwide. The EU's pioneering governance pathway exemplifies a sophisticated, adaptive, and integrated legal framework, evolving from stringent regulation towards balanced incentivization and facilitation, reflecting key lessons learned about the critical interplay between policy timing, regulatory intensity, and technological development stages. However, it is also worth noting that, unlike China, the EU is not a sovereign state with centralized governance model, it is therefore still unclear how and to what extent Member States will effectively implement this ambitious Act in real-world scenarios with different states' diverse socio-economic circumstances.

In summary, the twenty years' history of CCS development in Europe tells a dynamic storyline of the interaction between CCS momentum and legal milestones – sustainable CCS momentum cannot exist without a suitable legal framework; a climate neutral future cannot be delivered without successful CCS deployment. This section of the article therefore navigates the intricate interplay between the EU's newfound momentum for CCS deployment and the evolving EU CCS legal framework, particularly within the ambit of the European Green Deal. By comparing the experiences and outcomes of different governance models for offshore CCS deployment in the EU and China, this article in following sections further unearths invaluable lessons and sweeps roadmap that will guide the trajectory of successful offshore CCS deployment under a suitable governance framework with legal certainty, regulatory predictability and policy parity.

3 The deployment of offshore CCS and the development of a supporting policy architecture in China

3.1 Background and practice of offshore CCS deployment in China

China, cognizant of its role as a responsible major nation, has proposed a voluntary commitment to reduce emissions. China acceded to the Paris Agreement in 2016, committing itself to "keeping the increase in global average temperature within 2°C and working towards keeping the temperature increase within 1.5° C". In 2020, President Xi Jinping, in his speech at the general debate of the seventy-fifth session of the General Assembly of the United Nations, for the first time proposed the goals of "carbon peaking" and "carbon neutrality", framing the innovative "dual-carbon" objective. Internationally recognized pathways for carbon reduction encompass carbon less, carbon use, and carbon-free strategies. Among them, CCS technology falls under the "carbon use" category (Xie et al., 2012). For technical and other reasons, it is expected that by 2060, China will still have hundreds of millions of tons of greenhouse gases that will be difficult to reduce. At the same time, the proportion of fossil energy consumption in China will remain at around 70 per cent (GEIDCO, 2021). CCS technology is considered to realize near-zero emissions from fossil energy use, promote deep emissions reductions in hard-to-abate industries such as steel and cement, and be a means of touting net-zero carbon emissions (Zhang et al., 2011).

Despite global testing of CCS since the 1990s, its adoption in China was delayed for an extended period. In December 2005, the Chinese Ministry of Science and Technology (MOST) signed a memorandum of understanding (MOU) on CCS, marking the official start of the research program. Notwithstanding, national support for CCS technology, manifested through policy documents and science and technology programs, has catalyzed the research and development efforts of several large enterprises. China has begun to carry out CCS demonstration projects and program practices. Since the 11th Five-Year Plan period, the National Natural Science Foundation of China (NSFC), the 973 Program, the 863 Program, the National Key Research and Development Program and other science and technology programs have continued to support the research and development of offshore CCS technology (Yuan et al., 2022). Through the enhancement of basic research, key technology research, and project integration and demonstration, the development of offshore CCS and other technical aspects has been rapid, and a series of results have been achieved.

China's offshore CUS practice began relatively late but has developed rapidly. China's sea areas are rich in CO_2 storage resources, primarily located in regions such as the Pearl River Mouth Basin, the East China Sea shelf, the Bohai Bay. The fixed emission sources in China's coastal areas are well-matched with

potential storage sites, creating a favorable 'source-sink' alignment (Peng et al., 2013). This matching advantage has provided a strong foundation for large-scale offshore CCS implementation. In June 2023, China launched its first offshore industrial-scale CCS demonstration project at the Enping Oilfield. Led by China National Offshore Oil Corporation (CNOOC), the project employs a separation-injection-storage technical approach, with a designed annual storage capacity of 300,000 tons (Zhang et al., 2024). The carbon dioxide associated with the Enping 15–1 crude oil drilling platform, located roughly 200 kilometers southwest of Shenzhen (CCTV News, 2023), is captured, separated, and pressurized into a supercritical state. It is then injected into a 'dome'-shaped geological formation located about 3 kilometers from the platform and 800 meters beneath the seabed, ensuring long-term stable storage (Xinhua, 2023). The successful implementation of this project represents a significant milestone for China in the deployment of offshore CCS technology. The China CCS Annual Report (2023) points out that in recent years, China has made significant progress in various aspects of CCS technology (Zhang et al, 2023). China has developed the foundational capabilities for large-scale carbon dioxide capture, pipeline transport, utilization, and storage system design, with the potential for achieving large-scale applications in the near future. The lack of robust policy support may hinder the further development of core technologies in practice. Recognizing this challenge, the current state of offshore CCS policy in China holds significant research value and presents promising avenues for future development. By scrutinizing the historical trajectory and current landscape, valuable insights can be gained to guide policy improvements and foster sustained growth in the critical domain of CCS technology.

3.2 Overall policy architecture in governing offshore CCS in China

In recent years, China has significantly escalated its support for CCS deployment and demonstration projects, expanding its focus from singular technology research or pilot testing to encompassing industrial-scale full-process demonstrations. With the introduction of the "dual-carbon" goal, technology development and demonstration have also been incorporated into national-level science and technology planning (Zhao et al., 2023). With the establishment of China's policy framework for carbon peaking and carbon neutrality, known as the "1+N" policy system, a corresponding policy system for CCS is also taking shape. By the end of 2022, China had issued more than 70 policy documents related to CCS, covering aspects such as planning, standards, roadmaps, and technology catalogs (Zhang et al., 2023). There is an obviously increasing mention of offshore CCS in Chinese national and local-level policies related to carbon peak and carbon neutrality. The existing policies in China cover various aspects of CCS, including master plans and programs, technical research and development, investment and financing, and specific applications in related industries (See Table 2). These policies reflect both the top-level design of national policies and the specific policy guidance of various ministries such as the NDRC, the Ministry of Ecology and Environment, and the Ministry of Industry and Information Technology, as well as positive initiatives by local governments. These policies have contributed to the rapid development of offshore CCS in China.

3.2.1 Master plans and programs

The Opinions on Implementing the New Development Concept and Doing a Good Job in Carbon Peaking and Carbon Neutrality (Central Committee of the Communist Party of China, 2021a), the Action Plan for Carbon Peaking by 2030 (State Council of PRC, 2021) have actively deployed measures for CCS technology research and development, standards, and financing. The State Council has issued impactful directives, including the 2021 Guiding Opinions on Accelerating the Establishment of a Sound Economic System with Green, Low-Carbon, and Circular Development. These initiatives encourage pilot demonstrations, such as the integration of offshore CCS, technological innovation, and the construction of whole-process scale demonstration projects.

3.2.2 Technical research and development

The "National Standardization Development Outline" (Central Committee of the Communist Party of China, 2021b), the "Science and Technology Supporting Carbon Peak Carbon Neutral Implementation Programme" (Ministry of Science and Technology of PRC, 2022), the "Implementation Plan for Accelerating the Establishment of a Unified and Standardized Carbon Emission Accounting System" (National Development and Reform Commission of PRC, 2022a) and Work Program for Improving the Carbon Emission Statistics and Accounting System (National Development and Reform Commission of PRC, 2024) proposed improvements and advancements in the CCS technology standard system and related research.

3.2.3 Investment and financing

Key financial institutions and regulatory bodies, such as the People's Bank of China (PBOC) and the National Development and Reform Commission have played pivotal roles. The Green Bond Endorsed Projects Catalogue (2020 Edition) issued by PBOC incorporates CCS, demonstrating a commitment to environmental sustainability. Furthermore, the PBOC has synchronized the establishment of a carbon emission reduction support tool to issue carbon emission reduction loans to enterprises within the key areas of carbon emission reduction, providing financial support at 60% of the loan principal. Documents such as the "Climate Investment and Financing Pilot Program" (Ministry of Ecology and Environment of the Peoples Republic of China, 2021 and the "Green Bond Support Project Catalog (2021)" (People's Bank of China, 2021) include provisions for CCS-related technologies in investment and financing policies.

TABLE 2 China's CCS policy architecture in a nutshell (elaborated by the author: Jinpeng Wang).

Dimensions	Name of Documents (Year)	Aspects of CCS
Master plans and programs	Opinions on Implementing the New Development Concept and Doing a Good Job in Carbon Peaking and Carbon Neutrality (2021)	Promote the research and development, demonstration and industrial application of large-scale CCS technologies. Increase support for projects on CCS.
	Action Plan for Carbon Peaking by 2030 (2021)	Explore pilot demonstrations of hydrogen metallurgy and carbon dioxide capture and utilization integration, and promote the development of low-cost carbon dioxide capture and storage.
Technical research and development	National Standardization Development Outline (2021)	Study and formulate standards for ecological carbon sinks, CCS.
	Science and Technology Supporting Carbon Peak Carbon Neutral Implementation Programme (2022)	Accelerate the key technology research on carbon negative emissions. Strengthen carbon dioxide geological utilization, efficient conversion of carbon dioxide into fuel chemicals, direct air carbon dioxide capture, biochar soil improvement and other carbon negative emission technology innovation.
	Implementation Plan for Accelerating the Establishment of a Unified and Standardized Carbon Emission Accounting System(2022)	Promote research on accounting for carbon capture, storage and utilization to further strengthen the methodological basis.
	Work Program for Improving the Carbon Emission Statistics and Accounting System(2024)	Strengthen research on carbon capture, utilization and storage accounting methodology, and clarify the scope and methods of accounting.
Investment and financing	Climate Investment and Financing Pilot Program(2021)	Carrying out pilot demonstrations of carbon capture, utilization and storage.
	Green Bond Support Project Catalog (2021)	Carbon Dioxide Capture, Utilization and Storage construction and operation included in the catalog
Applications in related industries	Guidelines for Energy Conservation and Carbon Reduction Upgrades in Key Areas of High-Energy-Consumption Industries (2022)	Relying on the carbon dioxide utilization and storage conditions around the project, carry out pilot projects of high-concentration carbon dioxide capture, utilization and storage.
	Opinions on Improving the Institutional Mechanisms and Policy Measures for Green and Low-Carbon Energy Transition(2022)	Improve the support policy for research and development and pilot demonstration projects on CCS technology in the field of thermal power. Strengthen the promotion and demonstration of CCS technologies.
	Implementation Plan for Carbon Peaking in the Industrial Sector(2022)	Make breakthroughs in promoting a number of key core technologies such as CCS.
	Notice on the issuance of the Implementation Plan for Synergistic Efficiency in Pollution Reduction and Carbon Reduction(2022)	Strengthen the pilot application of technologies such as carbon capture and utilization.

3.2.4 Applications in related industries

The application of CCS technology in various industries is receiving increased attention, expanding gradually from power generation and oil and gas industries to more challenging sectors, such as industries with difficult-to-reduce emissions. This has garnered broader policy attention and practical applications. The National Development and Reform Commission and the National Energy Administration (NEA) have issued the "Opinions on Improving the Institutional Mechanisms and Policy Measures for Green and Low-Carbon Energy Transition" in2022. These opinions underscore the need to enhance policies supporting the research, development, and pilot demonstration of CCS technologies in thermal power generation, enhancing the overall breadth and depth of CCS technologies. Other Documents such as the "Guidelines for Energy Conservation and Carbon Reduction Upgrades in Key Areas of High-Energy-Consumption Industries (2022)" (National Development and Reform Commission of PRC, 2022b), the "Implementation Plan for Carbon Peaking in the Industrial Sector" (Ministry of Industry and Information Technology of PRC, 2022) and the "Notice on the issuance of the Implementation Plan for Synergistic Efficiency in Pollution Reduction and Carbon Reduction" (Ministry of Ecology and Environment of the Peoples Republic of China, 2022) have set

CCS technology application targets for industries like steel and cement that face challenges in emission reduction.

Furthermore, local governments are strengthening their support for the development of CCS technology, with provincial-level policies on carbon peaking and carbon neutrality emphasizing the deployment of CCS technology. By the end of 2024, more than ten provinces, municipalities, and autonomous regions in China had issued opinions or work plans related to carbon peaking and carbon neutrality, incorporating CCS technology research and promotion based on their specific regional contexts. The carbon peaking implementation plans of provinces such as Jiangsu, Shandong, Shanxi, and Shaanxi highlight the key role of CCS in achieving the dual carbon goals. Additionally, Beijing, Guangdong, Guizhou, and Anhui have introduced policies identifying CCS as a strategic emerging industry. Provinces such as Hubei and Shanxi have further emphasized the use of CCS to drive the transformation and upgrading of traditional industries (Carbon Capture, Utilization and Storage Association, 2025).

3.3 Features of China's policy architecture for offshore CCS deployment

The top-level design of China's offshore CCS policy has achieved a commendable level of sophistication. It operates under a policy-driven mode, wherein the formulation and execution of policies align with the country's developmental objectives, societal needs, and realistic conditions in a systematic and step-by-step manner. The necessity of a policy-oriented driving mode becomes apparent in light of China's heavy reliance on state-invested demonstration projects for offshore CCS application. Given the substantial upfront investment, extended return cycles, and modest product competitiveness associated with offshore CCS development, policy guidance and support become pivotal. Policy layout concurrently presents significant challenges to the widespread implementation of offshore CCS projects in China.

Under the layout of environmental laws such as the Environmental Protection Law, Measures for Administrative Punishment of Environmental Protection, Environmental Impact Assessment Law and Water Pollution Prevention and Control Law, China has a relatively perfect regulatory system in the top-level design of energy conservation, emission reduction, clean and renewable energy and other fields. While the top-level design for energy conservation, emission reduction, and clean energy is comprehensive, specific rules and programs for implementing, assessing, and monitoring offshore CCS technology are lacking. It is difficult for enterprises and other private entities to draw up their own offshore CCS policy measures with reference to the existing rules. The policy system is the core factor affecting the synergistic development of the industry, and the CCS program spans across multiple industrial chains, including oil, coal, electricity and chemicals, and needs to be scaled up across the whole industry chain. The absence of coordinated guiding rules, incentives, and subsidies across multiple industrial chains—oil, coal, electricity, and chemicals—may lead to inefficiency and disorder. Additionally, the scientific uncertainty surrounding CCS technology, particularly the unpredictable safety risks associated with CO_2 storage, demands a cautious approach. CO_2 in the stratum will have physical and chemical reactions with the surrounding rock, groundwater, and magma hydrothermal fluids and other mediums, thus destabilizing the stratum (Zhao et al., 2023). Recognizing these uncertainties, a measured and cautious attitude is advisable when formulating specific plans for offshore CCS implementation.

4 Rationales underlying the discrepant offshore CCS governance models in the EU and China

The remarkable discrepancies in governance models for offshore CCS deployment between the EU and China are rooted in multifaceted rationales in the legal dimension and beyond. These include variations in offshore CCS development stages, differences in the legal status of the sea areas where offshore CCS projects are situated, and variances in the industries involved in these projects between the EU and China.

First, the EU and China are at different stages of offshore CCS development. The EU regulates and facilitates cross-border offshore CCS projects within a comprehensive law-based framework. With a history of pioneering initiatives, the EU has established itself as a global trendsetter in developing and enhancing the legal framework for offshore CCS. China's offshore CCS practice is still in the exploratory stage. China places significant importance on national-level policies for driving the development and practical exploration of science and technology in emerging fields. In addressing issues within the emerging field of offshore CCS, the Chinese government tends to employ policies to regulate and promote advancements. Moreover, it adopts a gradual approach, characterized by exploration and learning by doing.

Second, legal status of the sea areas where offshore CCS projects are located is different in China and the EU. Majority of EU offshore CCS projects extend beyond the jurisdiction of an individual State. This necessitates cooperation between EU member states for offshore CCS projects, and the transboundary impacts generated also require coordinated regulatory measures among these States. This implies the need for clear legal provisions to define the mechanisms of international cooperation and their respective rights and obligations. For example, Northern Lights, a joint venture project by Equinor, opens new tab, TotalEnergies, opens new tab and Shell, plans to start injecting up to 1.5 million tonnes per annum (mtpa) of CO_2 into saline aquifer near the Troll gas field in 2024. There are plans to increase storage capacity to over 5 mtpa

from 2026, pending demand. The project, which calls itself the world's first open-source CO_2 transport and storage infrastructure, plans to import CO_2 from the Netherlands and Denmark in addition to local sources (Reuters, 2023). China is promoting offshore CCS projects within areas under its jurisdiction. China autonomously decides on the construction and operation of these projects. This also means that China does not necessarily require clear legal arrangements to achieve cooperation with other countries on offshore CCS projects.

Third, industries involved in offshore CCS projects in China and the EU differ significantly. The EU has experienced a decline in hard coal consumption and production since 1990, and numerous coal projects have been decommissioned. EU offshore CCS projects primarily target energy-intensive industrial production around ports. These industries are mainly operated by large multinational corporations. The operation of these companies requires legal certainty to control legal risks and provide predictability. China's CCS projects primarily target the traditional power generation industry, especially the coal industry. For the Chinese coal industry, CCS is currently the viable way to rationalize and clean its utilization, particularly considering that coal consumption accounted for 57% of total energy consumption in China in 2020. As China aims to achieve carbon neutrality by 2060, CCS technology is indispensable in the process of achieving zero carbon emissions from coal (Chen and Lu, 2022). According to the calculations from the Development Research Center of the State Council, by 2030, China's peak energy demand is estimated to reach 5.9 billion tons of standard coal. In terms of the development pattern of new energy, the rapid replacement of coal power is challenging due to cost issues associated with new energy sources like wind and solar, as well as the impact of the fluctuating nature of these power sources on the stability of the power grid. The difficulty in achieving a rapid transition from coal power is exacerbated by the early stages of development in the energy support services market, spot trading market system, and energy storage market (Song, 2023).In this situation, China can only gradually restrict the use of coal and steadily reduce the proportion of traditional fossil energy sources, such as coal, in the overall energy structure. Based on this, China needs to maintain a certain level of flexibility in offshore CCS projects related to the coal industry, balancing energy security and achieving carbon neutrality goals. From this perspective, policies are more suitable than laws. In addition, Chinese state-owned enterprises dominate the energy industry in China. For example, in 2022, large state-owned enterprises such as State Grid and China National Petroleum Corporation (CNPC) played a significant role in the energy sector. In the coal industry, major state-owned enterprises like National Energy and China Coal Group accounted for 52% of China's total coal production in 2022 (Liu, 2022). Chinese state-owned enterprises are market entities, but they differ from market entities driven solely by capital. Guiding state-owned enterprises through policies is also more efficient.

5 How far is current offshore CCS governance regime from a well-integrated law and policy portfolio? – lessons learned from the EU and China models

5.1 The Collingridge Dilemma: navigating the challenges of "timing" in regulating net-zero technologies

Efforts to move a certain technology from research and development and piloting phases through to the early deployment phase – that is, through the so-called "valley of death" (IEA, 2016) – involve balanced support and regulation, which has proven more challenging for legal intervention. Particularly, the complex role of law in regulating the deployment of offshore CCS is presented in two dimensions: the "when dimension" – when is the best timing for legal intervention, and the "how dimension" – through what legal principles, approaches and frameworks to regulate the deployment of offshore CCS, which to some extent rests with the perception of the types of different risks.

This paradox between legal intervention and offshore CCS deployment is echoed and explained by a classical social science-originating theory referred to as the "Collingridge Dilemma" concerning the governance of new technologies. Accordingly, "*Attempting to control a technology is difficult, and not rarely impossible, because during its early stages, when it can be controlled, not enough can be known about its harmful social consequences to warrant controlling its development. By the time these consequences are apparent, control has become costly and slow*" (Collingridge, 1980). If translating this sociological dilemma into legal languages based on the work of Reins (Reins, 2018), it reflects within the regulation of offshore CCS deployment, the "time" variable also becomes decisive in determining the time for regulatory intervention (Bennett, 2011) as well as brings a challenging question to the legal arena: the right timing for legal intervention within the development of offshore CCS deployment. As is sketched by the Collingridge Dilemma, legal intervention to premature a stage is difficult due to possibly insufficient, conflicting or confusing data about the nature and impact of the offshore CCS deployment(Laurie, 2012) at the early stage as well as the legal agenda and implications behind (Moses, 2007). The detrimental impact on a society and the environment is not clear, or rather subject to uncertainty at the early stage of offshore CCS deployment. An efficient regulatory regime thus may not be possible to establish at such a point (Reins, 2018). If, however, the legal interventional actions come too late in the development process of offshore CCS deployment, it will have become entrenched in the society, and different interest groups (eg. Industry and NGOs) holding divergent viewpoints will probably make it increasingly difficult, slow and

expensive for regulatory authorities to introduce any change into the existing regime (Laurie et al, 2012). This Collingridge Dilemma vividly mirrors the complex dynamic between legal intervention and new technology development and provides a robust theoretical pillar to rethink the role of law within the full value chain of offshore CCS deployment (Zhang, 2021).

5.2 EU's offshore CCS regulatory framework: early intervention through binding legal instruments

The EU CCS legislation and regulatory framework remarkably illustrate this early intervention scenario under the Collingridge Dilemma. Through the deployment of offshore CCS in the EU stands a coherent, consistent, and comprehensive CCS legal framework including the EU CCS Directive (EU, 2009) and the newly adopted EU Net Zero Industry Act (EU, 2024) as the two essential pillars. As the world's first free-standing and specific CCS legislation, the EU CCS Directive (Directive 2009/31/EC) was adopted in 2005 at the early stage of the European momentum to deploy offshore CCS, providing a clear regulatory framework for the safe offshore transport and storage of CO_2.

However, the EU CCS Directive has been criticized as falling to provide sufficient and suitable facilitation to deploy offshore CCS projects that are capital intensive and largely demand policy parity at the early stage of project development and deployment (Reins, 2018). Although there are various unique legal issues arising from the project lifecycle of offshore CCS deployment which need to be well addressed by suitable legal frameworks, over-imposed regulatory burdens have long been raised as a potential 'showstopper' for the widespread commercial deployment of offshore CCS projects at the early stage (Macrory and Havercroft, 2011). Particularly, some negative effects of the EU CCS Directive have also been criticized by industrial actors as over-regulating at the early stage of the development of offshore CCS. In the situation that CCS deployment is still at the early stage of its development in Europe, unexpected and unpredictable regulatory hurdles and legal barriers were generated from the stringent EU CCS Directive due to more focus on regulating the environmental safety of deploying offshore CCS without taking into account how to facilitate the full value chain deployment of offshore CCS projects. All the peculiarity and complexity of the regulatory requirements and burdens under the stringent EU CCS Directive were considered by industrial actors as beyond their capacity to manage and operate capital intensive large-scale offshore CCS projects, which hampered the willingness of industrial and energy enterprises to invest in and deploy offshore CCS projects in Europe (Global CCS institute, 2020). Recently, this specific EU CCS legal framework has been further evolving and developing under the European Green Deal to balance the facilitation and regulation functions through the introduction of the EU Net Zero Industry Act Regulation (EU, 2024). However, greater efforts from the policy and law makers must be directed towards adopting a both commercially and environmentally friendly legal framework for offshore CCS projects and dispelling barriers to the wide scale commercial deployment of offshore CCS caused by overburdened and unbefitting conventional environmental regulatory regimes.

5.3 China's offshore CCS policy-driven model: late intervention through learning-by-doing policy tools

The other scenario to escape the dilemma is presented in China's experiences, where the early stage of offshore CCS deployment is governed by policy-driven incentive mechanisms and non-binding instruments. With the intention to "make CCS deployment fly" to show the world the country's ambition on addressing climate change, Chinese authorities have pursued a laissez-faire, learning-by-doing approach to regulate offshore CCS deployment, which is based on the adoption of existing environmental legal framework instead of establishing a tailored binding CCS legislation at its early stage (Zhang, 2021). There is an obviously increasing inclusion of offshore CCS deployment in China's national and local-level policies related to carbon peak and carbon neutrality. These policies have contributed to the rapid development of offshore CCS in China (Lin and Tan, 2021). Additional policy developments related to offshore CCS may also emerge in the future. For instance, in 2021, the Chinese national carbon emission trading market was officially launched, becoming the world's largest carbon market. "Blue carbon" trading is a crucial measure for China to achieve its carbon peak and carbon neutrality goals. The first "blue carbon" trade in China was successfully completed in Ningbo in 2023 (Li et al., 2023), and the industry standard "Accounting Methods for Ocean Carbon Sinks" has been implemented (Ministry of Natural Resources of the PRC, 2022). Ocean carbon sinks in China have entered the stage of market-oriented trading. If China incorporates ocean carbon sinks increased by geological sequestration projects into the carbon trading system, it not only contributes to achieving emission reduction targets but also has the potential to create new economic growth points, promote the protection and restoration of marine ecosystems, and bring about economic and social benefits.

However, the development and deployment of offshore CCS in China is mainly policy-driven and is in lack of solid regulations and clear standards. This deficiency in the legal system poses challenges in regulating the construction and operation of offshore CCS projects, which may entail safety and environmental risks. The lack of legal regulations has resulted in uncertainty, impeding the future development of offshore CCS projects in China. This situation could lead to issues such as developers withholding information and even disregarding public opinions. To prevent the occurrence of practices akin to "unregulated development," it is essential for national, provincial, and local administrative authorities to establish corresponding laws and regulations (Jiang et al., 2020). These legal frameworks would serve as the foundational conditions and fundamental basis for the large-scale implementation of offshore CCS projects. China needs establishing specific regulations, including environmental impact assessment systems, administrative licensing systems, and supervision and

inspection systems. Additionally, it emphasizes the gradual improvement of technical and industrial standards for CCS in China. For the selection and implementation of ocean geological carbon sequestration, it is necessary to comply with China's marine functional zoning and other plans for the utilization and protection of the ocean. China needs to specify in regulations the zoning and planning requirements that ocean carbon sequestration must follow. Additionally, it is important to clarify how the potential affected public around the marine areas can participate in relevant decision-making processes.

5.4 Achieving a smart mix of integrating law and policy: towards a harmonious offshore CCS governance model

It is, by so far, either too early to conclude whether China's policy-driven model with the intention to facilitate offshore CCS deployment would be the antidote to cure the Collingridge Dilemma or to affirm whether the law-based EU governance model would balance the facilitation and regulation in order to eventually save the new momentum of offshore CCS deployment from being trapped in the Collingridge Dilemma (Zhang, 2021). However, both the experience and lessons from the EU and China's models might shed new light on navigating the role of governance framework in regulating and facilitating the new momentum of offshore CCS deployment worldwide. Although developing CCS-specific legislations is often considered as time-consuming and resource-intensive for many governments, a specific, free-standing and tailored made CCS legal framework has been proved to play a crucial role in providing legal certainties and minimize regulatory risks for the deployment of full value chain offshore CCS projects (Global CCS institute, 2020; Macrory and Havercroft, 2011). Both the EU and China's experience and lessons have emphasized the importance of both certainty and pragmatism within legal and regulatory regimes governing offshore CCS deployment. Delays in addressing crucial legal issues, even in jurisdictions where CCS projects have been developed, will result in considerable uncertainty and significant barriers to further offshore CCS deployment (Global CCS institute, 2020; Macrory and Havercroft, 2011). With national climate commitments under the Paris Agreement to keep the 1.5-degree climate target within reach, especially net-zero policy ambitions calling for offshore CCS deployment, a specific, free-standing and tailored made CCS legal framework must be completed to ensure the legal and regulatory certainties for the commercialization of offshore CCS deployment. Particularly where jurisdictions have signaled policy commitment to accelerate offshore CCS deployment but are yet to consider their legal and regulatory response, there is growing urgency to begin with efforts on establishing CCS legal framework in order to meet the needs of both regulatory certainty and project deployment.

As demonstrated from experience and lessons in the EU and China, it is sobering to emphasize that tailored-designed policy portfolio also serves as a crucial pillar in a sound governance regime to facilitate the deployment of offshore CCS, which needs to be integrated with specific CCS legal framework. Policy and law are born as twin sisters, serving as the two-wing engines to boost the momentum of offshore CCS deployment.

Theoretically, the policy comprises substantial measures by a government or legislature in order to tackle a problem or provide a service (Woerdman et al., 2021).[3] Although a policy is not tantamount to a certain legal act, they are related to each other: the content of a law reflects the policy the legislature pursues on the regulatory field and can thus be seen as its materialization in binding social rules (Woerdman et al., 2021). In the context of climate mitigation, climate change implies costs for all the countries which are tangible "social costs", also referred to as external costs or negative externalities (Coase, 1960). However, there is a "free-rider" problem to deal with the costs of climate change. The reason for this is that the reduction of carbon emissions has a public good character: everyone prefers to enjoy the benefits of the emission reductions without having to contribute to the costs of bringing them about (Woerdman et al., 2021). The consequence is a so called "tragedy of the commons" (Hardin, 1968). Thus, by implementing climate policies via command-and-control approach or economic incentive measures, emitters are forced to take account of those social costs. Besides, for some centralized regimes, such as China, the policy even plays a more important role in the environmental governance as well as many other state affairs.

In terms of offshore CCS deployment, while there could be a host of reasons for this global slow-down during the past decade, in many instances the absence of clear and creditable government policy incentives on offshore CCS deployment has resulted in legislation becoming deprioritised, abandoned or simply overlooked (Global CCS institute, 2018). In another words, policy enacted through legislation is critical to CCS uptake because it provides the tool by which governments can achieve their various objectives. Accordingly, the integration of the role of the policy into the offshore CCS legal framework should be the essential legal issue that a sound offshore CCS governance regime shall contemplate. In general, policy tools incentivise offshore CCS deployment through the way of "stick and carrot": command-and-control approach and economic incentive mechanisms. Targeted government financial-related programmes are particularly important policy tools in enabling CCS projects to become operational. Despite different pathways to govern offshore CCS deployment, both in the EU and China, various tailored CCS incentive mechanisms have been considered or deployed in many aspects, which includes the introduction of the carbon value, capital support in form of subsidies, public private partnerships (PPP) (IEA, 2016) and strict emission standards that encouraging industrial and energy sectors to deploy offshore CCS projects. For instance, policies in China such as the "Climate Investment and Financing Pilot Program" (General Office of the Ministry of Ecology and Environment, 2021) and the "Green Bond Support Project Catalog (2021)"(Development and

3 The term "policy" derives from the ancient Greek word "ta politika" ("the political things"), which refers to issues concerning the *polis* (city or city-state). It describes the aggregate of tasks necessary for the formation and maintenance of a state and its society. Whereas the terms "polity" and "politics" cover the formalistic and procedural aspects, "policy" means the content-related dimension of political activity.

Reform Commission of the People's Bank of China, 2021) include provisions to incentivize investment and financing support for offshore CCS deployment. Additionally, policy documents such as the "Guidelines for Energy Conservation and Carbon Reduction Upgrades in Key Areas of High-Energy-Consumption Industries (2022)" (National Development and Reform Commission, 2021), the "Implementation Plan for Carbon Peaking in the Industrial Sector"(Ministry of Industry and Information Technology Development and Reform Commission, 2022) and the "Implementation Plan for Coordinated Pollution Reduction and Carbon Reduction Efficiency Enhancement" (Ministry of Ecology and Environment of the Peoples Republic of China, 2021) have set offshore CCS technology application targets for industries like steel and cement that face challenges in emission reduction. Within the EU, a funding programme pooling together about EUR 2 billion for innovative low-carbon energy demonstration projects called NER 300 under the EU Innovation Fund was conceived as a catalyst for the demonstration of environmentally safe offshore CCS projects on a commercial scale (EU, 2019). More remarkably in in turning the policy commitment to the legal confirmation that facilitates the offshore CCS deployment, the proposed EU NZIA sets up the world's first binding target for CO_2 storage capacity, removing a major barrier to developing CO_2 capture and offshore storage as an economically viable climate solution, in particular for hard-to-abate energy-intensive sectors.

Based on the lessons learned from the EU and China's stories in governing and deploying offshore CCS projects, it is crucial to explicitly delineate the essential components and illustrate their interdependencies within a harmonized governance framework for offshore CCS deployment. Specifically, the following four critical pillars must be identified and systematically structured in offshore CCS governance frameworks: (1) a tailored legal framework providing regulatory clarity, liability allocation, and procedural transparency; (2) integrated policy incentives including economic instruments, financial support schemes, and targeted command-and-control measures to stimulate industrial uptake; (3) robust institutional coordination mechanisms facilitating inter-agency collaboration, capacity building, and stakeholder engagement; and (4) adaptive governance tools allowing iterative adjustments based on technological advancements and socio-economic feedback. These elements are interdependent, with the legal framework providing foundational certainty upon which policy measures can effectively incentivize deployment, while institutional coordination ensures coherent policy-law alignment, and adaptive governance mechanisms enable dynamic responses to evolving challenges in offshore CCS deployment. Clearly articulating and integrating these components into a cohesive governance framework significantly enhances its actionable value and operational effectiveness in regulating and facilitating offshore CCS deployment.

However, another point of significance is that while promising policy and legal progress is on the way in some certain jurisdictions like the EU and China, the global momentum is still unlikely to mature fast enough with a sufficiently robust policy-law portfolio to support commercial investment in offshore CCS deployment at the scale and pace needed in the near term to achieve ambitious climate target. Flexible policy tools and binding legal instruments are the two main engines to drive the acceleration of offshore CCS deployment. How to achieve a sound governance regime in the pursuit of making law and policy – those two key governing actors – harmoniously perform together is a challenging question for the world and particularly for jurisdictions that have ambition but have not yet successfully deployed any offshore CCS pilots under their national climate actions.

6 Conclusion

The offshore deployment of CCS has been increasingly prioritized by many jurisdictions in order to keep their climate goals under the Paris Agreement within reach, particularly to accelerate climate actions in their hard-to-abate sectors. The EU, known for its leading role in deploying cross-border offshore CCS projects, meticulously regulates and facilitates these endeavors within a robust law-based framework. Pioneering a global role, the EU has been instrumental in establishing and evolving the legal framework for CCS. In contrast, China follows a policy-oriented approach, aligning policy formulation and execution with developmental objectives, societal needs, and realistic conditions in a flexible and learning-by-doing manner. The governance models of offshore CCS between the EU and China differ due to variations in legal traditions, differences in the legal status of sea areas hosting these projects, and disparities in the involved industries. Drawing from experiences in the EU and China that vividly mirror the "Collingridge Dilemma" in governing offshore CCS deployment, it is crucial to highlight the importance of a tailored-made and well-balanced governance portfolio of legal and policy tools in regulating and facilitating offshore CCS deployment. Both facilitative policy Architectures and regulative legal frameworks must be seamlessly integrated with each other in a sound, systematic and synergetic governance fabric, emphasizing the intertwined nature of policy and law as twin engines propelling the momentum of offshore CCS deployment globally.

Particularly, in order to explicitly delineate the essential components and illustrate their interdependencies within a harmonized governance framework for offshore CCS deployment, the following four critical pillars must be identified and systematically structured: (1) a tailored marine legal framework providing regulatory clarity, liability allocation, and procedural transparency; (2) integrated policy incentives including economic instruments, financial support schemes, and targeted command-and-control measures to stimulate industrial uptake; (3) robust institutional coordination mechanisms facilitating inter-agency collaboration, capacity building, and stakeholder engagement; and (4) adaptive governance tools allowing iterative adjustments based on technological advancements and socio-economic feedback. These elements are interdependent, with the legal framework providing foundational certainty upon which policy measures can effectively incentivize deployment, while institutional coordination ensures coherent policy-law alignment, and adaptive governance mechanisms enable dynamic responses to evolving challenges in offshore CCS deployment. Clearly articulating and integrating these

components into a cohesive governance framework significantly enhances its actionable value and operational effectiveness.

Moreover, it is also worth highlighting that future research on offshore CCS governance should further explore how legal frameworks can adapt to different stages of technology maturity, especially under the lens of the Collingridge Dilemma. This includes assessing the legal design of regulatory sandbox mechanisms and phased permitting models that allow regulatory flexibility while preserving marine environmental safeguards. Additionally, more granular analysis is needed on the legal mechanisms that facilitate integration of economic incentive instruments within binding regulatory structures – such as the legal treatment of carbon contracts for difference, state aid compatibility, and long-term liability transfer models. Further doctrinal inquiry should also interrogate the role of constitutional environmental rights and procedural justice principles (e.g., public participation, access to information, and redress mechanisms) in shaping legitimate and durable offshore CCS governance. Finally, comparative legal studies could critically examine how different jurisdictional approaches – particularly between centralized and multi-level governance systems – address fragmentation, legal uncertainty, and regulatory overlap in governing cross-border offshore CCS value chains. Looking ahead, the future of offshore CCS governance hinges not only on navigating the complexities of law and policy in climate regimes, but on the courage to design suitable marine environmental protection regimes and institutions today for emerging offshore climate technologies that will define the climate legacy of tomorrow.

Author contributions

JW: Formal analysis, Investigation, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. MZ: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing.

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