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Uncertainties and Barriers to CCS Acceptance & Implementation

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ABSTRACT

Implementing carbon capture and storage (CCS) technologies is essential to mitigate the damaging effects of climate change due to the earth's temperature increase. However, despite the potential benefits of CCS, its acceptance has been slow. This paper identifies and examines the barriers to CCS acceptance, which include technical, economic, regulatory, and social factors. Economic barriers include the lack of financial incentives while regulatory barriers include the absence of a comprehensive legal framework. Lastly, social barriers include the lack of public awareness and understanding of CCS and the negative perception of technology. Technical barriers include a deficiency of desired infrastructure in all stages of CCS including capture, transportation, and storage.

1. Introduction

Global warming means the average temperature increase on the surface of the earth, which is mainly attributed to human actions e.g. the combustion of fossil fuels [1]. The Paris Agreement (PA) is an internationally voluntary compliance treaty to limit the increase in the global average temperature to less than 2°C above pre-industrial levels, with a further goal of pursuing efforts to maintain the temperature rise below 1.5°C. Recently, the emphasis has been on keeping global warming below 1.5°C by the end of this century, as highlighted by world leaders [2]. Carbon, capture, and storage (CCS) technology has the potential to prolong the operational lifespan of power plants, cement producing plants, and oil refineries that would have been decommissioned because of their high emission levels. It has the potential to lower carbon dioxide emissions by around 80-90% for a typical contemporary conventional power plant [3].

Globally, the current capacity of CCS facilities to capture CO2 is approximately 45 million metric tons. However, to effectively combat climate change, this capacity must be increased to capture over 220 million metric tons of CO2 annually. The total CO2 emissions worldwide are over 34 billion metric tons, highlighting the urgent need for significant improvements in CCS technology and infrastructure [4]. The successful implementation of CCS technologies depends on several important factors, including economic feasibility and public acceptance, as well as technological progress and environmental impact [5]. It can be concluded that CCS is a system of a complex nature that includes not only the technical aspects of capture, transport, and storage but also it is an organizational system that involves a group of people together with workers, managers, and all other stakeholders [6]. The complex system can be divided into four subsystems including:

1. Human and organizational subsystem
2. Capture
3. Transportation
4. Storage

Each of the subsystems has its barriers and obstacles preventing technology acceptance and extensive utilization. In general, the paper is divided into two types of barriers, human and organizational challenges, and technical challenges.

2. Human and Structural Barriers

Studying the social barriers of CCS is as important as studying the technical barriers of CCS technology. **Error! Reference source not found.** shows the triangle of social acceptance. Socio-political acceptance pertains to the broad acceptance of policies and technologies by key social actors such as policymakers and the general public. On the other hand, market acceptance is more specific and considers the diffusion of innovations among consumers and the decisions by investors who operate in national and/or multinational markets. Lastly, "public acceptance is the acceptance of particular projects at the local level by all stakeholders, which includes residents and local authorities in the area of growth" [7].

Based on a survey, the main challenges attributed to social acceptance revolve around human and organizational behaviors. These obstacles can be summarized as follows [8]:

(1) the cost and recovery of expenses,
(2) the absence of a financial incentive,
(3) the presence of risks of long-term liability, and
(4) the lack of an all-encompassing regulatory framework

The current high cost and uncertainties are two significant obstacles to the implementation of CCS [9]. The key challenge to the extensive utilization of CCS technology is "the expense related to its deployment" [10]. Lowering the cost of CO2 capture is crucial in reducing the overall cost of CCS, as it accounts for around 70% of the total cost. The operating expenses of CCS are considerably higher than its capital costs due to the commercial prices of fuel and electricity. If the energy generated by the facility could be utilized, the operating expenses would significantly decrease [11].

CCS liability is typically categorized as either operational or post-injection. Operational liability pertains to health, safety, and environmental risks associated with the capture, transportation, and injection of CO2. Conversely, post-injection liability covers health, safety, environmental, and climate risks caused by CO2 that travel from the intended storage site to another subsurface unit or back to the atmosphere [12].

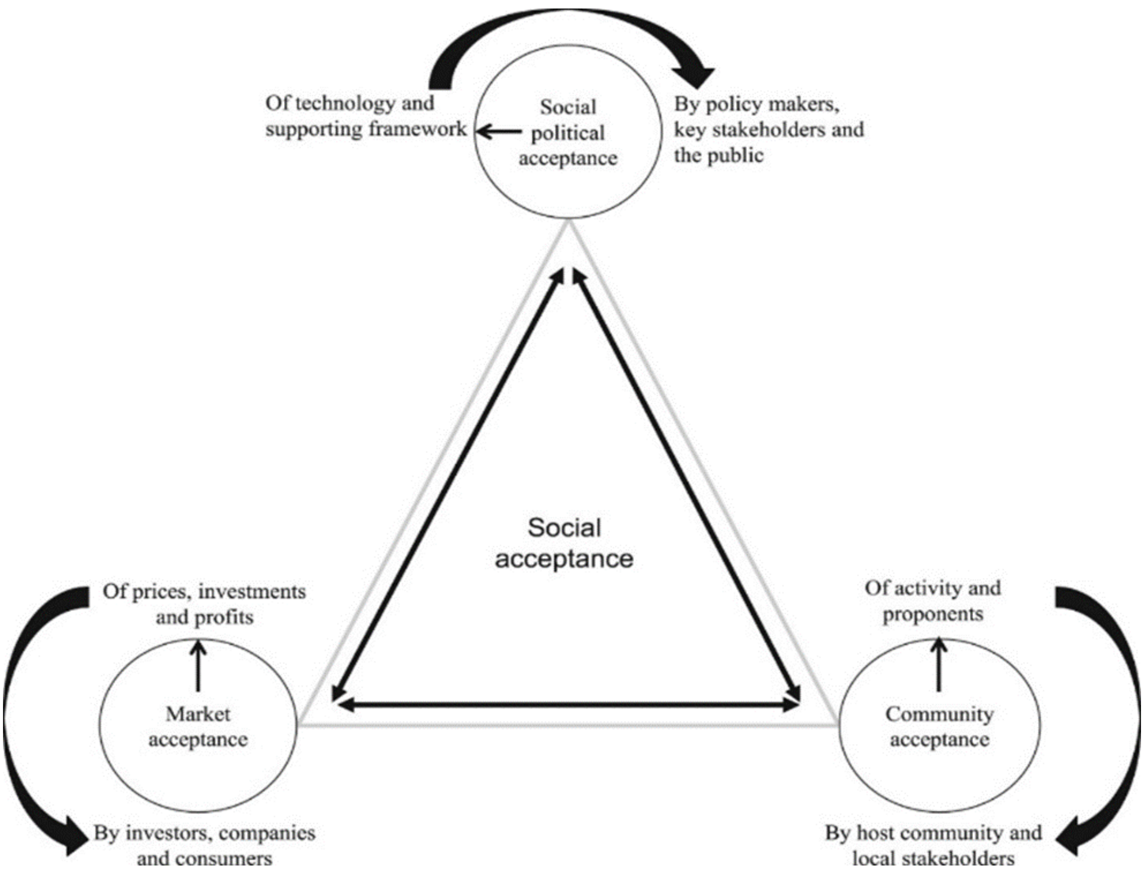

Figure 1. The triangle of social acceptance [7]

"The liability throughout the lifecycle of CCS can pose a significant challenge which eventually can be a barrier to the CCS investment and utilization of the technology" [13]. The storage of significant amounts of CO2 will result in considerable financial obligations. Therefore, entities operating within this sector must have the ability and willingness to take on such responsibilities [14]. Projects usually demand substantial capital investment and infrastructure, leading to a prolonged investment period. As a result, investors who intend to support CCS projects must be prepared to make a long-term investment commitment [15]. Lack of financial inspiration and lack of financial support from the government reduce the investment in technology [16]. Relying solely on public funding as the primary source of investment for CCS is not sufficient to sustain the required level of investment in CCS. CCS facilities require significant capital investments, which leads to high material costs for projects, ultimately reducing their economic viability

[17]. Barriers to investment in CCS are listed as follows [18]:

- Lack of financial motivation for investing in carbon dioxide capture and storage.
- Cross-chain risk is a possible difficulty. This risk can be addressed by the government where the establishment of shared transport and storage infrastructure by either investing in the infrastructure directly or creating a regulatory framework that enables cost-effective network development.
- The absence of a clearly defined legal and regulatory framework that plans the liabilities of carbon dioxide storage operators may pose a long-term liability risk that discourages private sector investment.
- Lack of adequate financial support through grants, concessional loans, accelerated depreciation, or other means to attract private investment in carbon capture and storage projects.
- Failure to identify and evaluate further policy measures that can mitigate specific financial risks.
- Lack of research data and information to measure the influence of various risk categories on the cost of debt discourages private sector investments.

The regulations for enforcement aim to ensure the safety and security of the process, proper storage, and monitoring and verification before and after injection [19] [20]. In Canada, the regulations were designed to promote the development of CCS by eliminating barriers to long-term CO2 storage and security [21]. Insufficient environmental regulations on CO2 emissions have been a significant obstacle to the implementation of carbon capture in power plants [22]. The policy complications such as lack of appropriate supervision and lack of regulations such as dividing the liability between public and non-governmental organizations and insufficient environmental regulations on CO2 all create an unsafe environment for the CCS technology practice and can be barriers to its implementation [16] [22]. Other barriers such as inadequate government support can be an obstacle to the wide use of CCS. Despite some countries, such as China, the USA, and Australia, being able to overcome the obstacles associated with CCS projects, their implementation is currently experiencing a slowdown due to inadequate government support [23]. "Trust in decision-makers and perceptions of procedural and distributive justice are crucial factors that can influence the success of deploying specific projects" [24]. Public trust is higher in non-governmental organizations compared to governmental industrial organizations [25]. The absence of incentives, political will, and public support are among the factors that may lead to public opposition, consequently contributing to discouraging CCS technology usage [26]. Companies in the CCS industry are expected to exhibit a commitment to mitigating potential incidents and hazards through the conduction of environmental and health-related risk assessments. This expectation is placed not only by the public, customers, and governments but also by in-plant personnel [27]. Noting that numerous projects are being pursued jointly by the industry and government, it becomes challenging to determine who should be responsible for leading the communication plan. Some people believe that it is the government's responsibility to reach out to the public and lead education initiatives. It is acknowledged that a collaborative strategy would yield the best results by creating unified messages from different stakeholder groups, thereby reducing the likelihood of any misunderstandings [28]. Limited and insufficient knowledge of technology as a whole also creates a problem and thus decreases the funding of the technology [16].

Table 1. Number of workers in a carbon capture plant [29]

			Project Jobs	**Operation Jobs**
Carbon capture retrofit	Industry	Steel mill	1,680 – 3,030	170 - 310
		Refinery	440 - 760	40 - 70
		Cement plant	430 – 690	60 – 110
		Hydrogen plant	175 – 300	20 - 30
		Ethanol plant	30 - 50	5- 10
	Power	Coal power plant	1,800 – 3,350	160 – 300
		Natural gas combined-cycle power plant	1,140 – 2, 090	100 – 180
CO2 transport infrastructure		Trunk line (20" diameter pipeline, 200 miles long)	1,250 – 2,190	8 – 20
		Feeder line (12" diameter pipeline, 50 miles long)	250 - 370	2 - 5

According to Table 1, in the short term, there could be a larger pool of available workers because the project jobs need a larger number of skilled workers and as soon as the facilities start to operate, the number of workers decreases during the operating phase [29]. In the long run, a potential obstacle could arise due to the lack of skilled labor [10].

Integrating CCS systems presents challenges both technically and organizationally, and there is currently no clear plan on how this integration will be accomplished. Moreover, it is unclear how mature and scalable the current CCS technologies are, and the pace at which they can be further developed is uncertain [30].

3. Technical Barriers

“Carbon capture plants are large process plants with impacts relating to appearance, emissions, noise, traffic, safety and environmental hazards and other potential impacts” [14]. All these terms can be a barrier to the development of CCS plants. From a technical perspective, the behavior or quality of one component in a system can affect other components. For instance, the quality of the capture stage can determine the level of impurities in the system. This, in turn, can lead to consequences like “corrosion during transport and injection, as well as the geochemistry of the storage in the long run” [31]. The introduction of CCS in different industries may have an impact on the competitive environment. This is because the cost of implementing CCS is higher, which could affect the competition between sectors that adopt CCS and those in regions that do not face similar restrictions [32]. When it comes to CO_2 utilization, there are two primary aims in increasing urea yield. Firstly, the fluctuating prices and demand for urea and NH_3 make it difficult to conduct long-term assessments. Secondly, there is the potential issue of high capital costs associated with implementing CO_2 capture infrastructure [33]. Utilizing CO_2 in the process of concrete curing has a main barrier which is the financial constraints when it comes to adopting new technologies due to operating in a fiercely competitive market where capital is limited [33].

Oil and gas reservoirs that have been depleted are located all over the world. Nevertheless, it is uncertain that people will readily accept the notion of storing CO_2 in reservoirs that are situated near residential areas or beneath them. As a result, CO_2 must be transported to distant fields, away from the source, which adds to the cost of CCS projects [34]. Infrastructure limitations, including the absence of storage facilities nearby and inadequate connectivity to transportation and storage infrastructure, can pose significant obstacles to the implementation of CCS [32]. The ownership and operation of the various components in a carbon capture chain by different companies can be an obstacle to the project if any of these elements become unavailable during its lifespan [35]. Reliance on the availability of some equipment in the CCS chain could result in extra costs and potentially discourage investment in the project.

Currently, the global storage capacity for CO_2 is substantial however determining the portion of the capacity that can be utilized needs considering a range of factors such as geography, injection, as well as the necessary institutional and business capacities [37]. Broadly speaking, areas where storage supply estimates are well-established, indicate that Carbon Capture and Storage (CCS) is not likely to face limitations due to the availability of local storage resources. On the other hand, in areas beyond the developed regions, the availability of storage resources is uncertain. However, considering the global distribution of sedimentary basins, very few sites may experience local storage resource limitations [10].

For retrofit projects, in case the power plant site lacks sufficient space to accommodate the CO_2 capture facility, the plant may not be feasible for CCS retrofit from a technical standpoint [37]. Due to the extra energy required for the capture process, there will be an increase in emissions during transportation in the CCS life cycle as a result of the fuel penalty [38]. For example, a significant rise in direct emissions of Ammonia (NH_3) is predicted compared to the non-CCS scenario. Ammonia is a poisonous and toxic gas [38].

“This can be a possible barrier since according to energy system transition models that aim to restrict global warming to below 2°C, the consumption of fossil fuel reserves by 2050 is estimated to be 26% if CCS technology is not employed. However, if CCS is employed, the estimated consumption of fossil fuel reserves by 2050 is 37%” [10].

One obstacle to the implementation of CCS is the weak manufacturing ability of certain countries, which obstructs their ability to develop profitable carbon capture technologies. Governments must consider their interest in promoting the growth of domestic CCS technologies against the option of importing potentially better technologies from foreign countries [39]. Moreover, the affordability of decarbonization alternatives can be a barrier to the implementation of carbon capture in certain situations [14].

4. Uncertainties of CCS

There are uncertainties in the deployment of CCS, which include technical, economic, political, and financial issues, as well as acceptance by the communities, without the government's support to make CCS a part of the climate mitigation mix. There is a need to provide evidence and analysis to inform and assure the government and investors, regarding financing climate change mitigation measures. The first step is to identify the known uncertainties and seek solutions to reduce, mitigate, and manage their impact. The effects of some of these uncertainties, together with suggested methods for assessing and their mitigation are summarized in **Error! Reference source not found.**.

Table 2. Uncertainties and recommended actions

	Key uncertainties	References
1	**Diversity of methods** The wide range of methods available in technology poses a challenge for investors and policymakers, as it introduces uncertainty. While choosing a method early on can expedite development, it also carries the risk of committing to less effective technologies.	[40]
2	**Secure storage** The long-term CO2 geological storage safety is uncertain, and there is a lack of confidence in methods for accurately assessing and managing the associated risks.	[41]
3	**Scaling up and timeline for implementation** There is a lack of clarity regarding the feasibility and pace at which CCS technologies can be effectively scaled up, and improved to reach maturity level.	[42]
4	**Integration of CCS systems** It is uncertain how CCS systems would be integrated to act as one system. Integration of elements of CCS is a technical challenge, as well as organization and governance issues.	[43]
5	**Feasibility in terms of economic and financial aspects** The implementation of CCS carries significant uncertainty regarding its future financial implications and risks, with policy factors strongly influencing the level of economic uncertainty.	[9]
6	**Policy, politics, and regulation** The implementation of CCS is significantly impacted by political and regulatory uncertainties, as well as the selection and structure of policies	[44]
7	**Public acceptance** Community acceptance is crucial to CCS development but acceptance is uncertain. Social interactions shape attitudes towards CCS acceptance	[25]
8	**Public knowledge** CCS deployment is directly affected by public knowledge of the technology. The level of uncertainty in technology increases as People's understanding of it decreases.	[44] [45]
9	**Technology Uncertainties** CCS technologies, which can be complex and costly, often involve technologies that have not yet been proven at a commercial scale. The uncertainties decrease with the wider use of technology.	[14]
10	**Other decarbonisation Options** Some possible alternatives for decarbonization include reducing demand, substituting products, electrifying processes, improving efficiency, and switching fuels. It is uncertain how much other decarbonisation methods will develop and how it will affect CCS.	[14]

5. Technology Readiness Level

"Technology Readiness Levels (TRL) are a measurement system utilized to evaluate the level of maturity of a specific technology" [46]. TRLs are commonly used as a standard measure to indicate the readiness level of new technologies or the modification of existing ones for integration into a product [47]. A TRL rating is assigned to each technology project after it is evaluated against the parameters for each technology level, taking into consideration the project's progress. TRL range from 1 to 9, with TRL 1 being the lowest and TRL 9 being the most mature technology as shown in **Error! Reference source not found.** [48] [49].

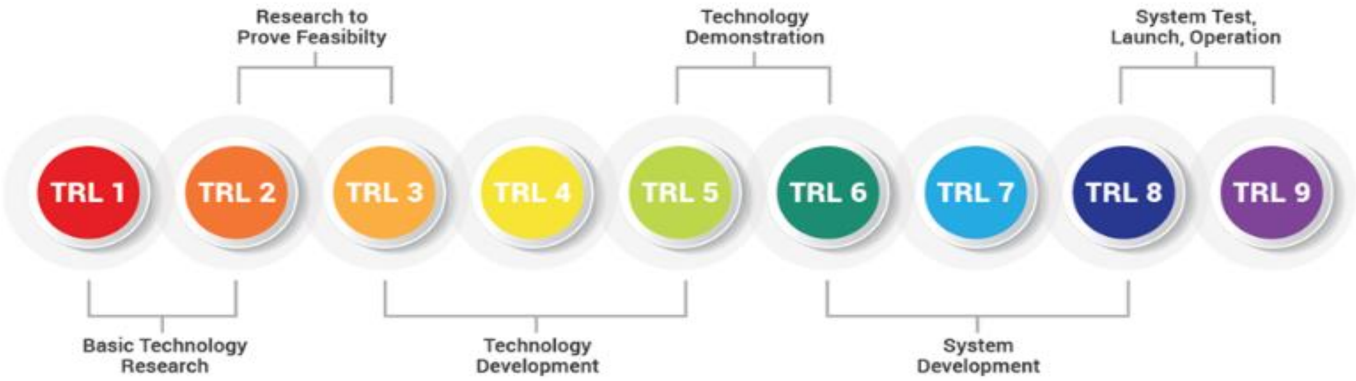

Figure 2. Technology Readiness Level (TRL) [49]

"To ensure that technology developed in science and technology programs, or adopted from industry or any other sources, is considered mature enough for the previous product, then it must be assumed in a new environment at TRL 6 and preferably in an operational environment at TRL 7" [19][47][50][51][52].

Similarly, the technology readiness assessment can be done for CCS technology. **Error! Reference source not found.** shows that congestion is commonly encountered in the development stages of technologies at TRL 3, TRL 6, and TRL 7. "Progressing a technology beyond TRL 3 usually requires additional funding, while improving it beyond TRL 5 and TRL 7 necessitates significant investment and/or commercial interests" [53]. When it comes to CO2 capture technologies, amine solvents and physical solvents have a TRL of 9 and are widely used where encapsulated solvents and ionic liquids have the lowest TRL of 2 to 3 among the liquid solvents [54][55]. TRL 9 means that the technology is mature enough and is in commercial operation.

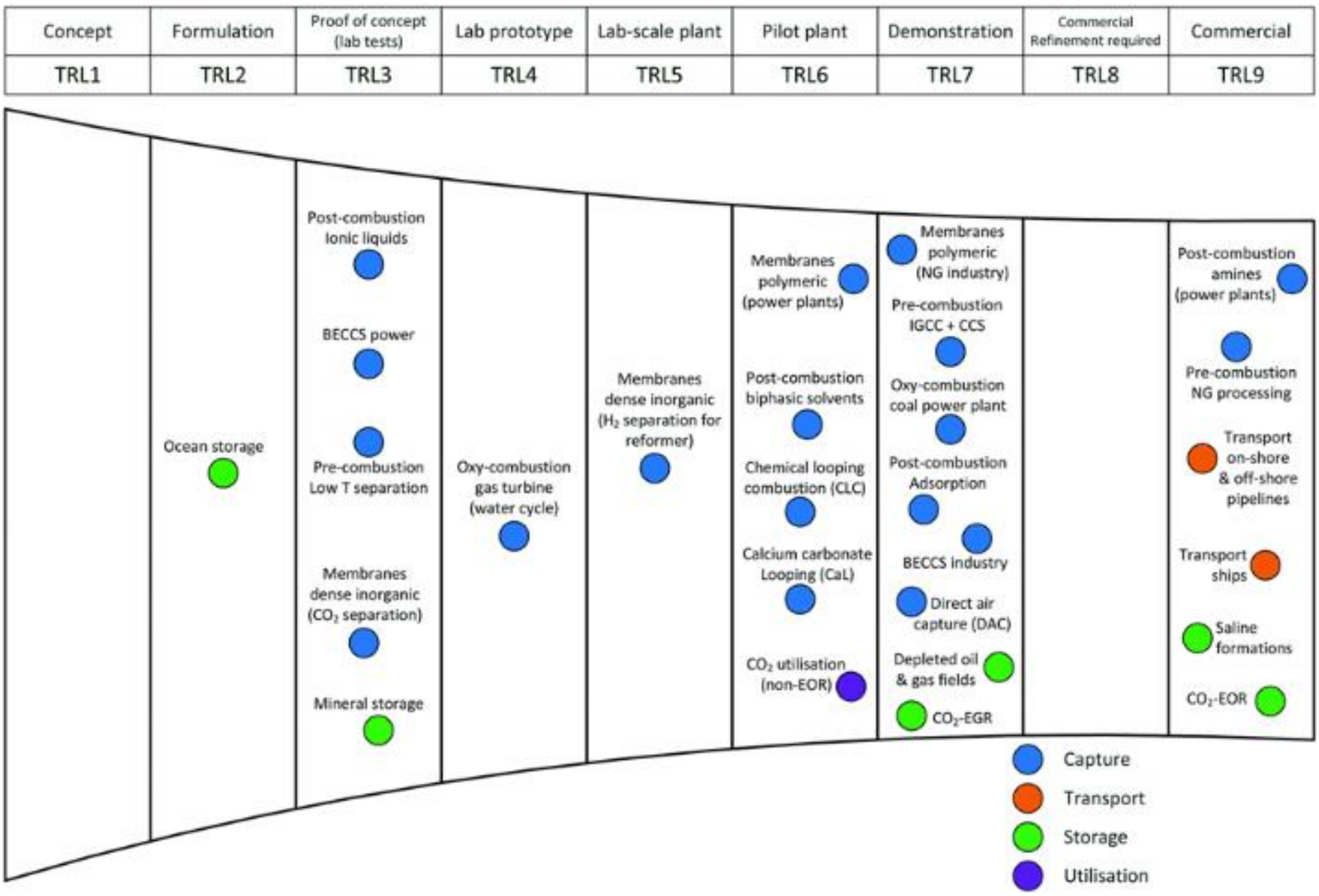

Figure 3. CCS in terms of TRL [53]

An issue with the TRL framework is that it cannot convey the level of effort or difficulty needed to reach the next TRL rank in a development cycle. This deficiency suggests the need for modifying the TRL framework to include the assessment of difficulty to better understand timing and resource allocation [56].

6. Overcoming Barriers

Several countries have had programmes to build large-scale CCS installations during the last two decades. By the second quarter of 2023, 37 operational facilities (equivalent to around 50.6 $MtCO_2/y$) will be operating worldwide [57]. The expenses associated with setting up a pilot plant are typically significantly greater than those of a full-scale installation. This is primarily attributed to several factors, including economies of scale, standardized manufacturing processes, minimized contingencies, more affordable financing options, and the utilization of shared CO_2 transport and storage infrastructure. [58][59].

CCS is fundamentally dependent on government intervention in some form of incentive to store CO_2 [26]. "In the absence of adequate climate-based incentives, the majority of contemplated projects have used captured CO_2 for enhanced oil recovery (EOR), and many are based on the relatively straightforward removal of CO_2 from natural gas" [60]. A market-oriented approach, such as implementing an emission cap and credit trading system, can be beneficial. It allows companies that can perform abatement at the lowest cost to take on most of the responsibility while other firms purchase emission credits. This strategy encourages continuous improvement in technology efficiency, unlike command-and-control policies that incentivize minimizing compliance costs with performance or technology standards [22].

The cost of the CCS pilot plant exceeds the available incentives, and this financial gap is worsened by various risks specific to the technology. These risks make the private sector reluctant to invest due to the uncertainty surrounding the investment [18]. These are primarily related to the need for a substantial new infrastructure for CO_2 transport and storage. The process of identifying appropriate geological formations for CO_2 storage is both time-consuming and expensive. Additionally, the potential cost of CO_2 leakage is uncertain and can be considered an uncertain risk under certain regulatory bases [61]. Developers would not be inclined to provide infrastructure for the transport and storage of CO_2 without assurances of a reliable and guaranteed source of CO_2, even though it would be more efficient to have infrastructure that can accommodate multiple CO_2 streams [62]. Therefore, to cover the costs and risks associated with the deployment of CCS infrastructure, it may be necessary for the government to play a larger role by providing financial support, such as regulating a fixed revenue for CO_2 storage and funding the assessment of storage sites. Social acceptance is directly influenced by people's trust in CCS shareholders. "People will accept technology more if they have the opportunity to give their opinion. The lack of significant attention given by CCS experts to early and meaningful engagement implies that there is an opportunity to enhance the transfer of knowledge from the research literature on public engagement to those responsible for implementing it" [63].

The close connection between the success of CCS and international commitments to decarbonization highlights the importance of coordinated efforts. "The challenges encountered by the growing CCS industry also indicate potential additional advantages that can be derived from global collaboration" [64].

The Carbon Sequestration Leadership Forum (CSLF), International Energy Agency (IEA), and Global Carbon Capture and Storage Institute (GCCSI) are well-known international organizations that have been actively advocating for increased political commitment towards the deployment of CCS technology. "Their efforts have been primarily directed towards advocating for the advancement of substantial demonstration CCS initiatives, fostering the development of CCS capabilities in non-OECD (Organisation for Economic Cooperation and Development) nations, and enhancing public and political understanding of the technology" [64]. "International organizations have long helped create awareness and tackle the challenges of climate change. They serve three necessary tasks in driving climate mitigation efforts, including" [65]:

1. Spreading research-based knowledge and offering recommendations.
2. Monitoring the progress of nations in achieving climate targets and analyzing data provided by national governments.
3. Enabling collaboration between governmental and non-governmental entities. Merging international funds towards one large project may be an important route toward CCS pilot plants.

The law requires the Department of Energy (DOE) to allocate funds for carbon capture demonstration projects at different levels of technological advancement and to continue funding projects related to carbon storage. "To speed up the implementation of commercial-scale CCS, various regional initiatives have been introduced. These initiatives require knowledge sharing as a prerequisite for receiving public funding support. The idea behind this is to accelerate innovation through experiential learning and make the deployment of CCS more efficient and effective" [66].

An implicit value on emissions has been placed by regulation, which has also contributed to facilitating the implementation of CCS. The possibility of a forthcoming carbon tax has also been a factor in the decision to implement CCS. "This underscores the significance of future policies, in addition to current ones, in influencing an investor's support for a CCS initiative" [67]. CCS deployment currently returning to the political agenda in many countries, leading to an increase in research funding. However, international activity to date has arguably focused largely on the role of research in finding ways to improve the economics of CCS, but there is a much more fundamental need for political action to encourage private investment in large demonstration projects.

7. System Thinking

In this section, we lay the foundation of an SD model to gain insight into CCS technology diffusion.

Technology diffusion encompasses a range of processes, starting from research and development (R&D) to the successful commercialization of products, which involves promotional and marketing efforts. The diffusion of technology holds significant potential to influence and transform society [68]. The socio-technical systems (STS) approach investigates the connections between social/community aspects and technical processes. STS approach encompasses several levels of interaction, between mechanical (hardware), informational (software), psychological (people), and social (public). By adopting such a comprehensive approach, the goal is to comprehend the interdependent relationships among a range of social and plants. "These elements engage with social motivations and work together to achieve a set of social goals that would otherwise be impossible" [69].

System thinking is an inclusive approach characterized by considering various perspectives and involving multiple stakeholders to adopt teamwork and collaboration in addressing intricate issues. According to Senge "Systems Thinking is a discipline for seeing the entire system with all its connectivity and their strength and feedback" [70].

That is there is a direct relationship between systems thinking and the notion of a system. A system consists of a set of interrelated components (variables). These components together with their inter-relationship define the system behaviour. The principles of systems thinking are listed below [71]:

1) every system is made of subsystems and sub-subsystems

2) The behaviour of a system is governed by the strength of the relationship between its components and feedback

3) There are balancing and reinforcing loops. Balancing loops pushes the system toward stability while reinforcing loops push the system toward extremes, zero or infinity. The role of feedback is to assure the stability and balance of a system,

4) Due to interactions between components they may be emerging behaviour

System-level modelling requires the combination of individual process models to create a comprehensive simulation of the entire CCS system. This approach takes into account the interactions between various components and their influence on the overall performance of the system. Many forms of system dynamic approach exist, that can be characterized using the following concepts [72]:

1. State and force: This concept involves understanding the current state of the system and the forces that influence its behaviour.
2. Feedback loops: Feedback is present when the interaction between elements A and B impacts the manner or strength of B's effect on A.
3. Nonlinearity: Non-linearity is a common characteristic of causal relationships that are not proportional.
4. Deadlines: A situation that initially follows a certain pattern can transform when a factor with a specific deadline is considered by the variable that is affected by it.
5. Structural change: In theory, a structure can experience changes in causalities that can occur at any time. These fluctuations serve as a reflection of the system's history.
6. A system boundary. In regression models, two types of variables can be observed [73]:
   - "Endogenous variables: These are variables that are influenced or determined by other variables present in the model.
   - Exogenous variables: These are variables that are not influenced or explained by other variables within the model. They are external variables."

The system boundary can help to identify internal or external variables.

Systemic modelling is frequently used in the field of industrial safety to detect potential hazards caused by delays or subtle changes that may be challenging to identify through manual or automated means. Modelling plays a crucial role in connecting technical elements with social or human aspects of organizations [72]. Modelling the human behaviour and non-technical part of CCS is important.

❖ It plays a crucial role in offering valuable insights and data that can aid in policy development and decision-making regarding CO2 capture and storage. It enables the assessment of the potential effects of various policy measures, such as carbon pricing or subsidies, on the implementation and efficacy of CCS technologies.

Modelling CCS systems helps in evaluating the environmental impact of the entire process. It enables the evaluation of other environmental aspects, including air pollutants, water usage, and waste generation. This data is crucial for assessing the sustainability and environmental advantages of CCS projects. The technical part of the technology diffusion includes:

- ❖ Modelling the capture process is important for the assessment of different capture technologies. It is important to find the most cost-effective means of CO_2 capture. It assists in determining the effectiveness of CO_2 capture, the energy demands involved, and the potential environmental consequences.
- ❖ Modelling the transport of CO_2 is crucial for determining the most economical methods of transportation. This can be achieved through simulations of pipeline networks, taking into account factors such as pressure drop, flow rate, and distance to ensure efficiency and cost-effectiveness [74].
- ❖ Understanding the behaviour of CO_2 in storage sites is essential to guarantee the stability and safety of the stored CO_2 in the long term. This involves analyzing factors like reservoir characteristics, mechanisms that trap the CO_2, and pathways that could potentially lead to leakage [74].

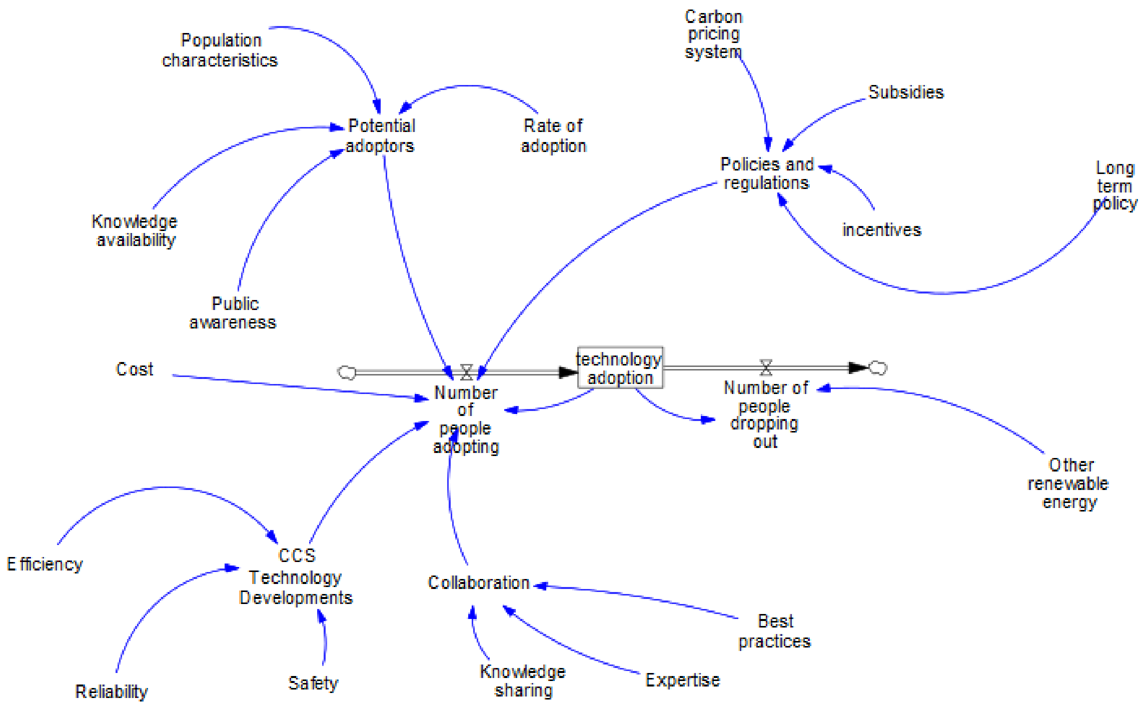

Figure 4. SD model for the analysis of Carbon Capture technology diffusion

To build a system dynamics model for the analysis of carbon capture technology diffusion, you would need to consider several key components.

Several crucial variables are important for the diffusion of carbon capture and storage (CCS) technology:

1. Policies and Regulations: Supportive government policies and regulations are vital in facilitating the widespread adoption of CCS technology. This includes incentives, subsidies, and a carbon pricing system [22][26].
2. Cost and Economics: The cost of implementing CCS technology is a significant factor in its diffusion. "Technological advancements and economies of scale have the potential to reduce the cost of CCS, thereby increasing its request to industries and investors" [16].
3. Technological Developments: It is crucial to continually invest in research and development to enhance CCS technology and facilitate its widespread adoption. Advancements in capture, storage, and monitoring techniques can enhance efficiency, reliability, and safety, making CCS more possible and attractive [42][75].
4. Public Acceptance: Public approval of CCS technology plays a vital role in its diffusion. Raising awareness about the advantages and safety of CCS is important to gather public support and effectively address any concerns or misunderstandings [25].
5. Infrastructure Development: The availability of a well-developed infrastructure for CO_2 transportation and storage is critical for the diffusion of CCS technology. With increased

usage and advancements in technology and further improvements and innovations, the cost of the technology is likely to drop, and therefore it can be more widely adopted. "Constructing pipelines, storage sites, and related infrastructure can facilitate the successful deployment of CCS projects" [76].

6. Collaboration: Collaboration between countries, various CCS projects, and research institutions is fundamental for the diffusion of CCS technology. Sharing knowledge, expertise, and best practices can facilitate the global implementation of CCS at an accelerated pace [77].
7. Long-term stable policy: Attracting investments heavily relies on the presence of stable and enduring policies and regulations. CCS liability is typically categorized as either operational or post-injection. A long-term, stable policy that covers post-injection liability is necessary to provide comprehensive. Figure 4 shows a system dynamic model for the analysis of carbon capture technology diffusion.

8. Conclusions

Judging from the literature surveyed, one can conclude that there are several barriers to the acceptance and implementation of CCS technology. Some of the obstacles that implead the acceptance and implementation of CCS technology are the following: the high costs and financing uncertainties, insufficient public awareness and trust, legal and regulatory barriers, as well as technical and operational challenges. Additionally, the lack of a clear policy framework and political support might stop the deployment of CCS projects in many countries. Overcoming the aforementioned barriers requires addressing the economic, social, and environmental aspects of CCS and engaging stakeholders in a transparent and participatory process. Furthermore, policymakers need to provide a supportive regulatory and financial environment to encourage the deployment of CCS technology. Finally, public awareness is required to raise awareness about the benefits and risks of CCS and to build trust in technology.

List of Symbols

CCS	Carbon Capture and Storage
CO2	Carbon Dioxide
COP	United Nations Climate Change Conferences
CSLF	Carbon Sequestration Leadership Forum
DoE	Department of Energy
EOR	Enhanced Oil Recovery
GCCSI	Global Carbon Capture and Storage Institute
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
NH3	Ammonia
OECD	Organisation for Economic Cooperation and Development
PA	Paris Agreement
R&D	Research and Development
STS	Socio-Technical System
TRL	Technology Readiness Level

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