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Discussion Paper

Enabling Blue Hydrogen for a Low-Carbon Future

Certifying Emissions and CO_2 Storage

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Introduction

As part of a diverse energy portfolio, hydrogen can support global efforts toward transitioning to a more sustainable energy system. This would align with climate goals, such as those outlined in the Paris Agreement. For hydrogen to fulfill this potential, its production method needs a paradigm shift. The prevalent method used today relies on unabated natural gas and other fossil fuels, leading to significant greenhouse gas emissions. Thus, clean production processes need to be adopted that either eliminate, capture or significantly reduce GHG emissions to meet specific sustainability benchmarks.

The push for clean hydrogen is gaining significant momentum, as evidenced by the growing pipeline of announced projects. According to Bloomberg New Energy Finance, countries responsible for 69% of global emissions committed to net-zero targets by the end of 2022, and many of these nations view hydrogen as a key enabler and regulatory frameworks are starting to materialize. The U.S. has prominently introduced hydrogen production tax credits under the Inflation Reduction Act, while the European Commission has inaugurated the Hydrogen Bank under the Net-Zero Industry Act. These initiatives aim to provide incentives and mechanisms that bridge the cost gap between clean hydrogen and hydrogen produced by unabated methods.

A critical component of building a sustainable hydrogen economy is the implementation of standards and certifications. While standards act as predefined criteria or benchmarks, certification is the process that confirms whether those standards have been met. To ensure an effective pathway to GHG reduction, it is essential for certification to cover not just the production of hydrogen but the whole supply chain, including storage and transportation up to the point of use. This ensures that throughout its life cycle, the hydrogen maintains its clean credentials.

Given the current relatively modest scale of the global clean hydrogen industry, there is limited experience in hydrogen certification. Consequently, it is anticipated that existing schemes will undergo evolution and refinement over time.

Most existing and proposed hydrogen certification schemes, both voluntary and mandatory, focus on renewable hydrogen produced through electrolysis using renewable electricity, i.e., green hydrogen. In contrast, only a few include pathways based on hydrocarbon production with carbon capture and storage, known as blue hydrogen (Box 1). This situation is unsatisfactory given the significant role blue hydrogen could play in accelerating the commercialization of clean hydrogen globally.

This paper aims to address this disparity by reviewing the essential requirements of blue hydrogen certification, particularly focusing on elements related to the performance of geological CO_2 storage. The goal is to propose a comprehensive framework for blue hydrogen certification.

The paper begins by exploring the potential role of blue hydrogen in supporting efforts to decarbonize the global economy. This includes discussing the costs and emissions associated with this hydrogen production pathway and comparing it to other options. The paper goes on to review the current state of certification frameworks for hydrogen with a focus on addressing issues related to the certification of geological storage.

Box 1. The Color of Hydrogen.

Although hydrogen is a clean-burning fuel, its production can have a significant GHG footprint. Since hydrogen can be produced through multiple pathways, colors are used to categorize these production methods.

Approximately 99% of hydrogen is currently produced from fossil fuels without carbon capture, leading to high GHG emissions. **Gray hydrogen**, derived from natural gas through steam methane reformation without CO_2 capture and storage, is the most prevalent type.

Efforts are underway to transition to clean hydrogen production methods. One approach involves implementing CCS technologies in fossil fuel-based hydrogen production, resulting in what is known as **blue hydrogen**. When a substantial portion of CO_2 generated during natural gas reforming is captured and stored, the resulting hydrogen can serve as a low-carbon energy carrier.

Alternatively, clean hydrogen can be produced through electrolysis. The environmental impact of this method depends on the source of the electricity used. Optimal sustainability is achieved when electricity is generated from renewable sources, such as wind and solar, leading to what is known as **green hydrogen**.

The Role of Blue Hydrogen Within a Global Clean Hydrogen Portfolio

According to scenarios by the International Energy Agency, the International Renewable Energy Agency, and the Hydrogen Council, clean hydrogen is expected to make up a substantial portion of final energy consumption. This could range from 10% to 22% by 2050, a remarkable increase from its almost negligible presence today (Hydrogen Council 2021; IEA 2021; IRENA 2022).

Currently, hydrogen is predominantly produced from natural gas (62%), as illustrated in Figure 1. This production is a significant source of CO_2 emissions, accounting for 2% of global annual emissions. Various factors contribute to these emissions, including methane flaring and venting during the natural gas extraction process and the steam methane reformers utilized in gas-to-hydrogen production. The associated emission intensity ranges between 10 and 14 kilograms of CO_2-equivalent per kilogram of hydrogen produced. Coal is the second largest feedstock source for making hydrogen, contributing to approximately 21% of the global annual hydrogen supply. It possesses an emission intensity almost double that of hydrogen produced from natural gas.

The production of hydrogen through water electrolysis, commonly referred to as green hydrogen, currently constitutes a meager 0.1% of the global supply, making its contribution negligible.

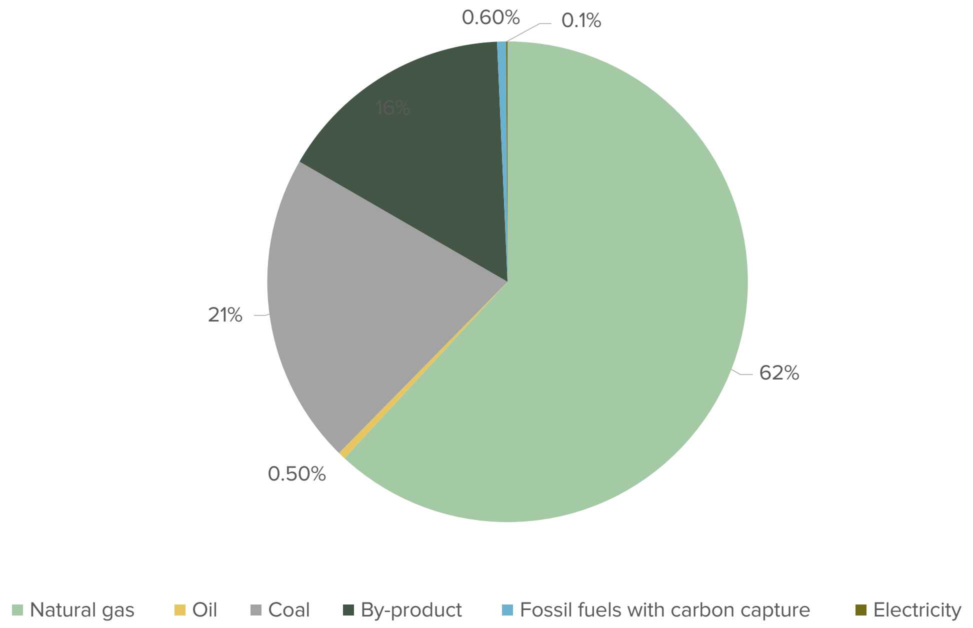
The climate impact of hydrogen production can be markedly diminished by capturing substantial amounts of CO_2 during the gas-reforming step and storing it in deep geological formations. Hydrogen produced in this manner is termed blue hydrogen and currently constitutes 0.6% of the global supply.

Blue hydrogen possesses numerous attractive features. It is a technology that is scalable and technologically mature, not requiring significant innovation for deployment. This allows blue hydrogen production to facilitate rapid and substantial reductions in emissions. Due to the scarcity of green hydrogen in the short to medium term, blue hydrogen can act as a transitional technology, aiding in developing hydrogen infrastructure and fostering the move toward widespread hydrogen utilization in various applications.

Interestingly, blue hydrogen can also bolster the growth of renewable energy. Its availability can avoid the inefficient redirection of renewable electricity from the power sector to hydrogen production, thereby conserving essential resources, such as land and raw materials.

Blue hydrogen presents an opportunity for both developed countries and the Middle East and North Africa regions to make substantial contributions toward achieving climate change stabilization targets. Considering these countries' access to low-cost natural gas reserves and CO_2 storage capabilities, blue hydrogen emerges as a feasible option to capitalize on these resources.

Figure 1. Share of hydrogen production by source.

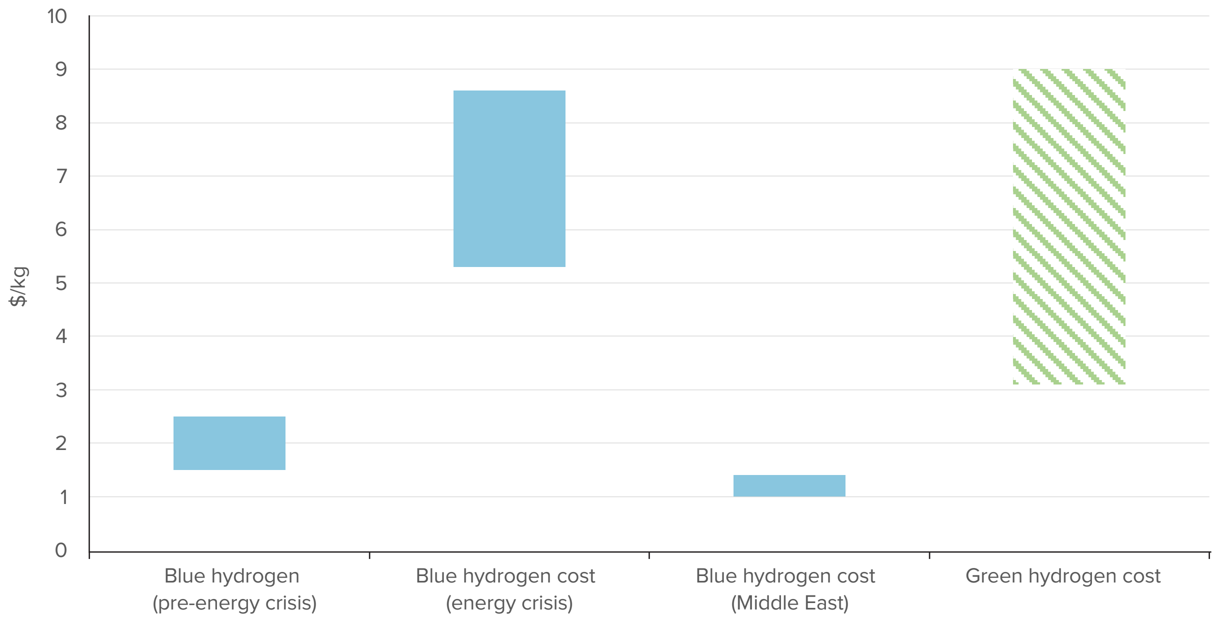


Source: IEA. 2023a. Global Hydrogen Review 2023. Paris: IEA Publications. https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf.

Assessing the Cost of Blue Hydrogen

In 2021, before the price increase in the wake of the Russia–Ukraine conflict, blue hydrogen offered the cheapest method of producing clean hydrogen with costs averaging between $1.5 and $2.5 per kilogram, as shown in Figure 2 (IEA 2023b). From that period to now, green hydrogen averaged between $3.1 and $9.0 per kilogram. During the energy crisis in 2022, natural gas prices in Europe and Asia reached record highs, and blue hydrogen prices increased from $5.3 to $8.6 per kilogram with natural gas accounting for three-quarters of the overall cost (IEA 2023b). Prices of natural gas have since receded but remain volatile, and the economic viability of blue hydrogen is contingent on the price of natural gas. .

Figure 2. Estimated price ranges of blue and green hydrogen.



Source: Authors' adaptation from IEA (2023b)

Natural gas prices in MENA countries are among the lowest in the world and range between $1.5 per million British thermal units and $4 per million British thermal units, translating to estimated blue hydrogen costs of between $1 and $1.4 per kilogram. This makes the region one of the most important for the deployment of significant large-scale blue hydrogen production within the decade (Table 1). Other regions, such as North America, also have low-priced gas and favorable policies that could support rapid deployment of blue hydrogen.

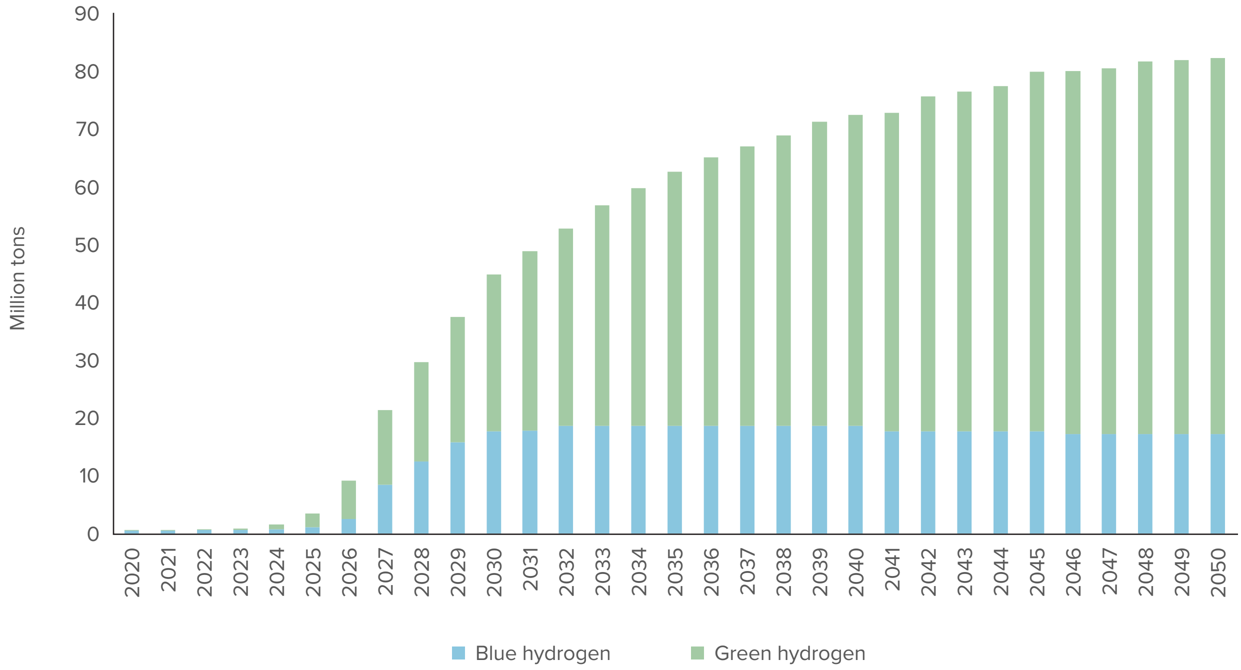
Table 1. Announced blue hydrogen derivatives projects in MENA.

Plant name	Type	Ammonia or Methanol Capacity (MTPA)	Stakeholders	Location	Announced Startup Date
Ta'ziz ammonia plant	Blue ammonia	1.0	Fertiglobe, Mitsui and GS Energy	Al-Ruwais, UAE	2025
Ta'ziz methanol plant	Blue methanol	1.8	ADNOC and Proman	Al-Ruwais, UAE	2025
Ammonia-7 project	Blue ammonia	1.2	QatarEnergy and QAFCO	Mesaieed Industrial City, Qatar	2026
Sipchem blue ammonia project	Blue ammonia	1.2	Sipchem	Jubail, Saudi Arabia	-

Source: Authors.

Out of the total 38 MTPA of announced clean hydrogen projects that are scheduled to emerge online by 2030, 13 are classified as blue hydrogen projects, while the remaining 25 are green hydrogen (Hydrogen Council 2023). Looking ahead to 2050, as Figure 3 shows, green hydrogen is expected to play a larger role in the long term due to a predicted drastic decline in production costs compared to those of blue hydrogen. At the same time, the assertion that green hydrogen costs will continue to decline is being challenged because of increasing capital costs due to supply chain bottlenecks in renewable energy, shortages in electrolyzer manufacturing capacity, and regulations defining what counts as green hydrogen (Polly 2023). Nevertheless, blue hydrogen will play a more dominant role in the near term, and both production pathways will have a role to play in the future given the scale of clean hydrogen production required to meet climate stabilization targets.

Figure 3. Announced clean hydrogen projects expected by 2050 as of Q3 2023.



Source: Authors.

Comparing Emission Intensities

In addition to cost, blue hydrogen must compete on emissions performance. The principal sources of GHG emissions in the production of blue hydrogen stem from the steam methane reformer. Emissions within the natural gas supply chain, which encompasses the extraction, storage, and transportation of natural gas, can significantly raise the emission intensity of the hydrogen produced. Capturing these emissions and submitting CO_2 to long-term storage in appropriately selected deep geological storage sites could present a viable strategy for mitigating these emissions (Box 2).

Box 2. Geological CO_2 Storage.

Geological storage of CO_2 entails the injection of CO_2 into deep geological rock formations. In these formations, CO_2 accumulates in the pore spaces between rock grains and displaces existing fluids, such as water, gas, or oil. Suitable storage sites should be overlaid by an impermeable rock layer, known as the cap rock, which acts as a barrier to prevent the upward migration of CO_2. Upon injection, CO_2 rises, filling the pore spaces beneath the cap rock. Over time, a fraction of the CO_2 will dissolve in resident brines and may eventually undergo mineralization. These processes occur on varying timescales and collectively contribute to the long-term trapping of CO_2. Injecting CO_2 into coal seams and basalt formations offers alternative methods for geological storage. However, these options have limited storage capacity and are not widely available.

Figure 4a. Natural gas and carbon flows in blue hydrogen production.

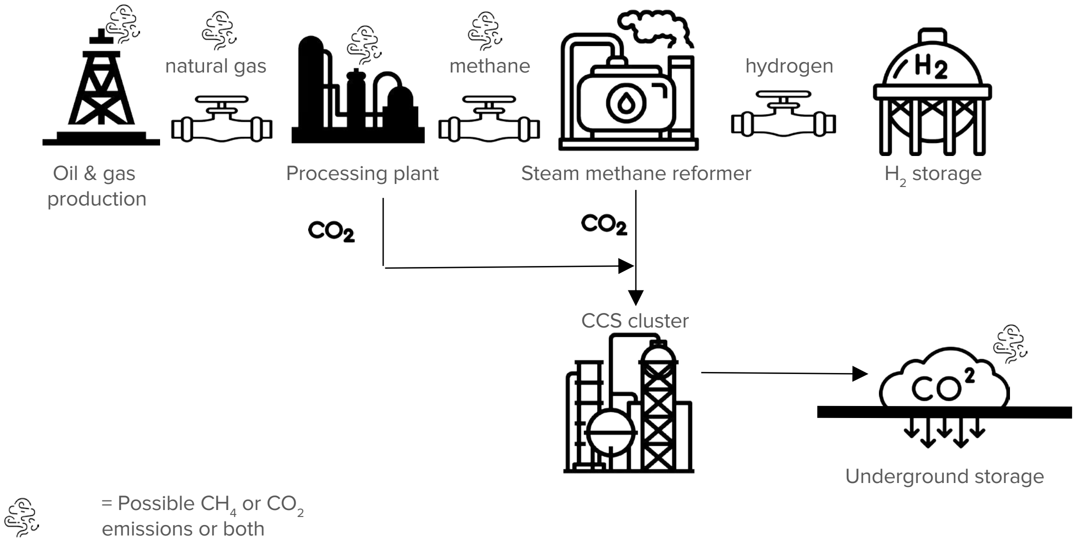
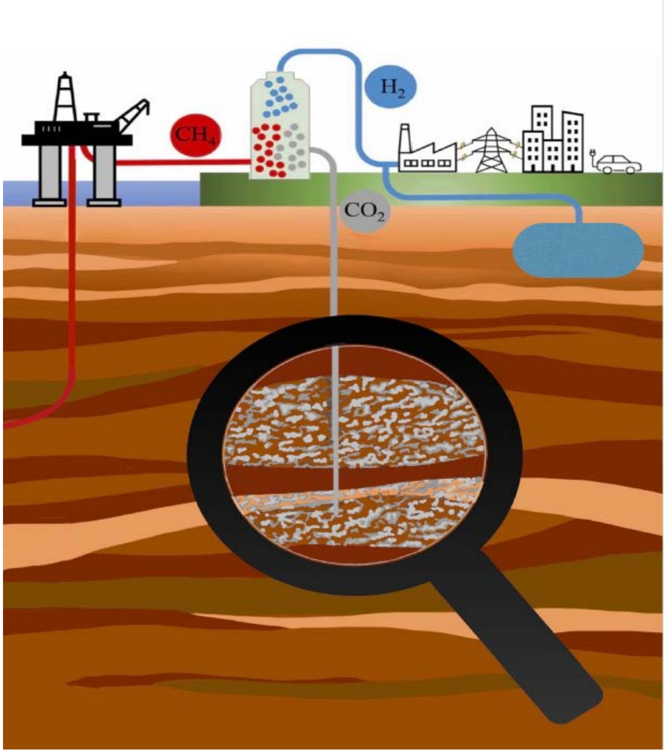


Figure 4b. Geologic CO_2 storage.

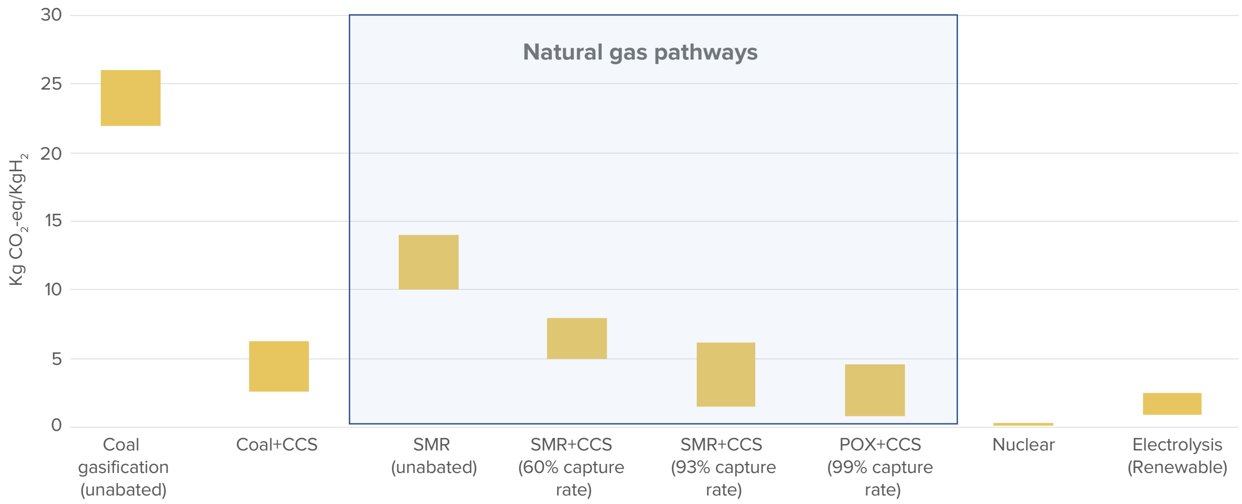


Source: Adapted from Massarweh et al. (2023).

The carbon intensities of natural gas pathways differ depending on the capture rates of the CCS technologies and the methane emissions from the upstream and midstream parts of the natural gas supply chain.

Currently, steam methane reforming without CCS is the prevalent pathway for hydrogen production. This process releases between 10 and 14 kilograms CO_2-equivalent per kilogram of hydrogen, with the exact emissions contingent upon upstream and midstream methane releases and other GHG emissions, as shown in Figure 5. Reducing methane intensities in gas production and increasing capture and storage rates can significantly decrease the life-cycle emissions of natural gas-based hydrogen. In certain scenarios, these improvements may yield emission rates that are comparable to those of hydrogen produced via electrolysis powered by renewable electricity, i.e., green hydrogen.

Figure 5. Carbon intensity of various hydrogen production pathways, including upstream and midstream emissions (well-to-plant gate).

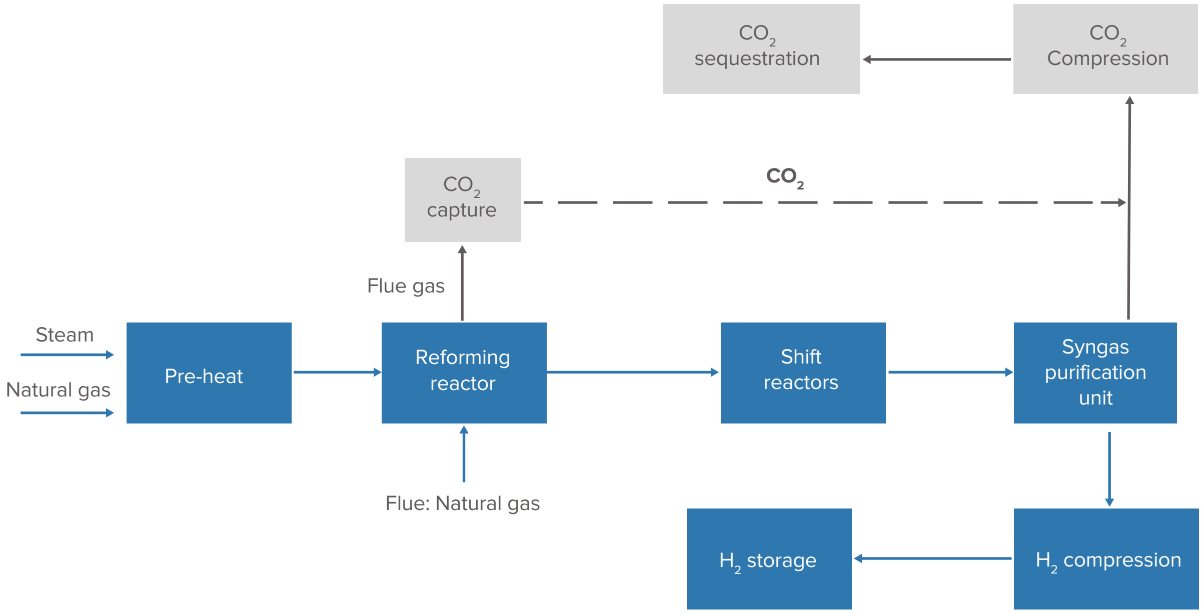


Source: Authors based on data from IEA (2023b).

Note: SMR = steam methane reforming; POX = partial oxidation; CCS = carbon capture and storage.

Existing steam methane reforming facilities with CCS—such as Shell's Quest project in Alberta, Canada, and Air Products' facility in Port Arthur, Texas—achieve CO_2 capture efficiencies of 50%–60%, predominantly from the synthetic gas purification process (Bauer et al. 2022). Capture rates exceeding 90% are feasible with CCS by also addressing CO_2 emissions from the flue gases produced in the reformer furnace's combustion process, as illustrated in Figure 6. Furthermore, advanced technologies, such as partial oxidation reforming and autothermal reforming—which uses a combination of steam methane and partial oxidation reforming—have the potential to surpass capture rates of 95%. While no operational plant has yet achieved these elevated capture levels, there are two projects presently under construction in North America that plan to capture 90%–95% of carbon emissions.[1]

Figure 6. Simplified process of SMR plus CCS to attain high capture rates.



Source: Oni et al. 2022. "Comparative Assessment of Blue Hydrogen from Steam Methane Reforming, Autothermal Reforming, and Natural Gas Decomposition Technologies for Natural Gas-Producing Regions." *Energy Conversion and Management 254* (February): 115245. https://doi.org/10.1016/j.enconman.2022.115245.

Hydrogen Certification Landscape

The primary objective of hydrogen certification is to provide evidence that the method used to produce hydrogen meets a set of predefined environmental criteria and standards. In addition, there are other significant aspects of hydrogen certification that are relevant in the present context.

Incentive Alignment

Certification plays a crucial role in securing policy support for clean hydrogen production. Policy-driven incentives are instrumental in positioning clean hydrogen as a competitive, low-carbon energy carrier by alleviating the higher production costs associated with clean hydrogen production.

Supply Chain Integrity

Certification schemes can be designed to encompass the entire life cycle of hydrogen production, extending beyond the production stage to account for emissions related to the delivery of hydrogen to its point of use. The objective is to safeguard the low-carbon attributes of hydrogen throughout its life cycle from production to end use.

A paradigm for such comprehensive certification can be gleaned from the green electricity market. Systems such as Guarantees of Origin in Europe and International Renewable Energy Certificates facilitate the traceability of each megawatt-hour of green electricity produced. Such mechanisms allow end users to authenticate and validate their consumption of green electricity based on registered information within a dedicated database, avoiding the risk of double counting and establishing a robust framework for verifiable green energy consumption (Noorbhasha 2022).

Market Growth Support

Certification can act as a catalyst for the global shift toward clean energy by facilitating the international trade of certified clean hydrogen. This can stimulate global investment in clean hydrogen production, furthering the expansion of this sustainable energy sector. Given the nascency of the clean hydrogen market and uncertainty relating to future demand, it is difficult to quantify the role of international trade in scaling up hydrogen use. Nonetheless, this role is expected to be substantial. To meet the 1.5-degree Celsius climate target, global trade of hydrogen is projected to constitute as much as one-fifth of total consumption by 2050 (Truby, Philip, and Lorentz 2023).

Hydrogen certification schemes and the standards they implement differ between countries due to a variety of factors, such as regulatory approaches, energy policies, technological advancement, and specific climate and environmental goals. These differences can pertain to disparate GHG footprint thresholds, the system boundary of accounting for emissions (e.g., well-to-plant gate or well-to-wheel[2]), and the methodology by which emissions sources are calculated and tracked along the supply chain (chain of custody). In some certification systems, the sustainability criteria implemented extend beyond accounting for GHG emissions to include social impacts, such as land and water use, labor rights, and the rights of indigenous people.

Table 2 provides an overview of certification systems currently in development and operation. The table highlights disparities in GHG thresholds, labeling practices, emissions boundaries, production pathways, and tracking systems across various chain-of-custody models. Included within the table are both mandatory schemes, which align with the established legislative framework of a specific jurisdiction (Sailer et al. 2022), and voluntary schemes in which organizations or individuals can choose to participate on an optional basis.

Table 2. Sustainability criteria of selected hydrogen certification systems.

Title	Label	Emissions threshold ($kgCO_2$-eq/ kgH_2)	System boundary	Production pathways	Chain-of-custody model[3]
Voluntary schemes					
Australia Smart Energy Council Zero Carbon Certification Scheme	Renewable H_2	No Threshold	Production plant only	Renewable electricity	Mass balance
China Hydrogen Alliance	Renewable H_2	4.9	Production plant only	Renewable electricity and biogas	Not specified
	Clean H_2	4.9	Production plant only	Grid electricity and fossil fuels plus CCS	Not specified
	Low-carbon H_2	14.5	Production plant only	Fossil fuels plus CCS	Not specified
EU CertifHy	Green H_2	4.4	Well-to-plant gate	Renewable electricity	Book and claim
	Low-carbon H_2	4.4	Well-to-plant gate	Nuclear electricity and fossil fuels plus CCS	Book and claim
Germany TÜV SÜD CMS 70	Green H_2 (non-transport sector)	2.7	Well-to-plant gate	Renewable electricity and biogas	Book and claim
	Green H_2 (transport sector)	2.8	Well-to-wheel	Renewable electricity and biogas	Mass balance
Japan Aichi Prefecture Low-carbon Hydrogen Certification	Low-carbon H_2	No threshold	Plant gate-to-wheel (excludes upstream emissions)	Renewable electricity and biogas	Book and claim
International Green Hydrogen Organization	Green H_2	1.0	Well-to-plant gate	Renewable electricity	Not specified

Mandatory schemes					
UK Low Carbon Hydrogen Standard	-	2.4	Well-to-plant gate	Renewable electricity, nuclear, biogas and natural gas plus CCS	Not specified
EU RED II	-	3.4	Well-to-wheel	Renewable electricity and low-carbon electricity (<65g CO_2-eq/kWh)	Mass balance
Low-Carbon Fuel Standard (California only)	-	Different thresholds based on the source of production ranging from 1.3 to 14.1 $kgCO_2$-eq/kgH2	Well-to-wheel	Natural gas, biomethane, grid electricity and renewable electricity	Book and claim
US Clean Hydrogen Production Tax Credit	-	4.0	Well-to-plant gate	All	Not specified
Canada Clean Hydrogen Investment Tax credit	-	4.0	Well-to-plant gate	Renewable electricity and natural gas plus CCS	Not specified

Source: Authors' adaptation from IRENA and RMI (2023) and IEA (2023b).

Disparities in clean hydrogen standards and certifications could pose substantial challenges, potentially obstructing trade and suppressing investment flows. Such disparities may result in a market for hydrogen that is both inefficient and underdeveloped, thereby diminishing the essential role that low-carbon hydrogen could fulfill in a globally decarbonized economy.

This issue is of relevance for countries in the MENA region that aspire to become exporters of clean hydrogen. Production facilities must be intricately designed and optimized to satisfy a diverse array of requirements, catering to both local and international markets. Such complexities inevitably elevate the barriers to investment, making realizing a global clean hydrogen market a more formidable objective.

An examination of Table 2 reveals a notable paucity of certification systems, be they voluntary or regulatory, that address blue hydrogen pathways. A certification framework for blue hydrogen should include criteria for the geological storage site, particularly its capability for indefinite CO_2 containment. These critical subsurface considerations are omitted from prevailing hydrogen certification protocols.

The European Commission has made a pivotal advancement by finalizing the specification of green hydrogen under the RED II framework (European Commission 2023). However, regulations pertaining to blue hydrogen production pathways remain underdeveloped and have received mixed reactions among EU member states. Despite this, the European Commission has announced that a proposed methodology for evaluating GHG emissions savings for low-carbon fuels, which include blue hydrogen, is slated for publication by the end of 2024 (European Commission 2023).

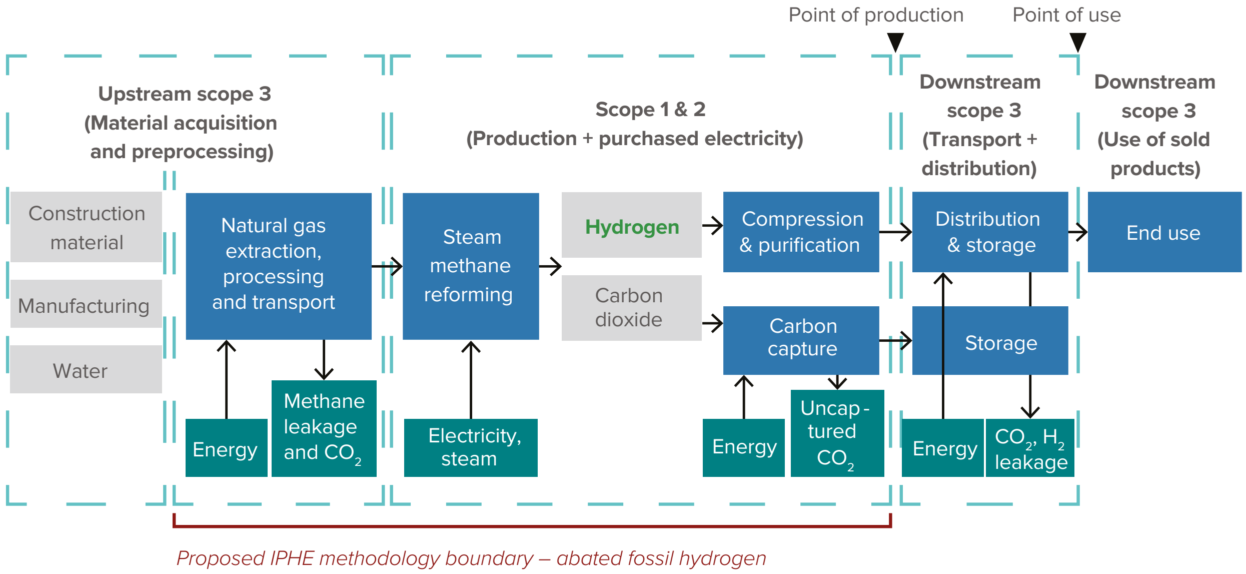
In the U.S., incentives under the Inflation Reduction Act, which was signed into law in August 2022, include generous hydrogen production tax credits based on emission intensities under tax code section 45V. The legislation also upgraded the existing tax credits for stored CO_2 under the 45Q tax credit for facilities implementing CCS. While more guidance from the U.S. Department of the Treasury is expected on the implementation of the 45V hydrogen tax credit, the guidance on receiving the 45Q tax credit is far more established. The 45Q tax credit allows developers, including blue hydrogen producers, to receive $85 per ton for the permanent storage of CO_2 or $60 per ton for storage via utilization, e.g., enhanced oil recovery. A facility is deemed qualified for the CCS credits if it meets a minimum emission threshold,[4] and construction of the facility must begin prior to January 1, 2033 (Trendafilova 2023). Facilities must also demonstrate secure geologic storage and are subject to the U.S. Environmental Protection Agency's Subpart RR – Geologic Sequestration of Carbon Dioxide regulation (EPA 2021).

Elsewhere, regulations for blue hydrogen are yet to be finalized. This includes countries, such as Japan and South Korea, that rely significantly on blue hydrogen for achieving their climate targets.

The International Partnership for Hydrogen and Fuel Cells in the Economy, an intergovernmental organization, has embarked on the development of a universally applicable methodology for quantifying GHG emissions from various hydrogen production pathways, including blue hydrogen, as shown in Figure 7 (Gül and van Hulst 2023). However, the IPHE's current proposed emission system boundaries for blue hydrogen do not extend beyond CO_2 capture.

To date, the clearest guidance pertaining to the subsurface dimensions of blue hydrogen production appears to be given in the proposed UK Low Carbon Hydrogen Standard. The standard mandates that "there must be evidence supplied by the CO_2 network operator that the CO_2 injected into the network by the hydrogen producer will be permanently sequestered" (BEIS 2023, 24). The following sections elaborate on the criteria necessary for certifying the enduring sequestration of CO_2 in geological storage.

Figure 7. Supply chain and system boundary of blue hydrogen as presented by the IPHE.



Source: IRENA and RMI. 2023. Creating a Global Hydrogen Market: Certification to Enable Trade. Abu Dhabi: IRENA. https://www.irena.org/Publications/2023/Jan/Creating-a-global-hydrogen-market-Certification-to-enable-trade.

Certification of Geological Storage

Certification of geological storage entails two fundamental aspects: first, confirming the injection of a specified quantity of CO_2 into a geologically suitable formation for CO_2 storage, and second, ensuring measures are in place to ensure the long-term permanence of the storage, specifically the isolation of the stored CO_2 from the atmosphere over extended periods. Achieving the status of permanent geological storage requires meeting various technical, managerial, and institutional criteria. These requirements have been outlined by the Intergovernmental Panel on Climate Change in a special report on CCS (IPCC 2005)..

According to this, the IPCC states that an appropriately chosen and well-managed storage site is expected to retain more than 99% of the stored CO_2 for at least a thousand years. From a practical standpoint, such storage can be considered permanent. However, the assessment of permanence is contingent upon fulfilling several conditions, which primarily revolve around aspects such as storage site selection and characterization, risk assessment, appropriate monitoring, and long-term stewardship.

In the following sections, we delve into these critical factors and discuss their significance in ensuring the effective and lasting geological storage of CO_2.

Site Characterization

Geological storage sites for CO_2 are not uniformly distributed across the globe, exhibiting significant variation in quality and capacity from one location to another. Certain sites will have an exceptional ability to store substantial amounts of CO_2 securely and efficiently, while others will be suboptimal choices for storage. The first step in gaining confidence that a potential storage site is suitable for long-term CO_2 storage is its detailed geological characterization. This entails developing an exhaustive geological model of the subsurface storage complex, encompassing the spatial distribution of critical petrophysical properties, such as porosity and permeability. This model forms the basis for numerical simulations, enabling accurate predictions of the site's performance, including the fate of injected CO_2, the displacement and pressurization of in-situ fluids accompanying CO_2 spread, and optimization of the number, type, and location of CO_2 injection wells to accommodate expected CO_2 quantities during the site's operational period.

To achieve this thorough characterization, a range of geophysical tools is available for exploring both shallow and deep underground structures. Among these tools, seismic methods stand out, as they provide an image of underground structures and, to some extent, the heterogeneities within the storage formation. By using seismic structural exploration, suitable locations for exploratory drilling can be determined, allowing the retrieval of rock core samples. These samples play a vital role in understanding the rock formation's conditions, chemical composition, porosity, and permeability, which are crucial parameters for predicting CO_2 movement in the subsurface.

Additionally, various exploration methods are available to focus on the shallow subsurface, soil, and groundwater aspects. However, there is no standardized methodology for site characterization, and financial constraints may influence the extent of data collection during the process.

Risk Assessment

To ensure the safe and permanent geological storage of CO_2, it is crucial to understand, assess, and possibly mitigate the associated risks. These risks can be broadly categorized as local and global (Wilson, Johnson, and Keith 2003). Local risks encompass potential threats to health, safety, and the environment, while global risks are primarily related to uncertainties concerning the effectiveness of CO_2 containment.

Although a robust knowledge base should underpin a risk assessment, it is crucial to acknowledge that essential information pertaining to assessing the long-term permanence of storage may be inherently uncertain or not fully known. A significant source of uncertainty arises from the geological model itself, which inherently represents reality in a limited manner. Seismic exploration, borehole measurements, and core examinations provide valuable information for developing the geological model of subsurface structures. However, this data is inevitably incomplete and may not be fully representative of the entire storage formation. One of the reasons for this is that extrapolating geophysical measurements from exploration wells over large distances is only reliable up to a certain range in geostatistical terms.

Modeling the flow and physicochemical behavior of the injected CO_2 in the subsurface also introduces considerable uncertainty. Simulating the movement of CO_2 over extended periods requires assumptions and simplifications of complicated subsurface interaction processes to make computations feasible, potentially compromising accuracy. Moreover, simulations rely on input parameters that may not be precisely known.

A structured and systematic risk assessment involves three main activities. First, all potential hazards are identified and cataloged. Next, the probability of each hazard's occurrence is determined. Finally, the consequences and severity of potential incidents are thoroughly analyzed.

Various tools are available to support the systemization of storage risks, but no universally accepted standardized method exists. Different approaches have been proposed. One approach is to use graphical representations of risk pathways from causes to consequences, such as the bow-tie method, widely used in the chemical and oil industry. Another approach is the use of generic data codifying hundreds of potential risk events, such as the features, events, and processes approach, adapted from radioactive waste management practices. For a detailed overview, refer to the paper by Pawar et al. (2015).

A risk assessment framework that appears to be particularly well suited for the certification objective has been put forward by Oldenburg et al. (2009). The approach is structured such that the potential impacts of hazards on different assets to be protected, referred to as compartments, are analyzed separately. The following compartments are considered by Oldenburg et al. (2009):

- Atmosphere
- Human health and safety
- Near-surface environment
- Underground sources of drinking water
- Hydrocarbon and mineral resources

An attractive feature of this risk assessment framework is that its structure facilitates the differentiation of global risks from local risks. As will be seen in the next section, this separation becomes relevant in the context of accounting for CO_2 emissions in national CO_2 inventories. It is the risk of upward leakage on the atmosphere compartment that needs to be reflected in national CO_2 inventories.

Monitoring

Two distinct monitoring strategies are typically utilized for a storage project, each with its own set of objectives.

- Conformance monitoring: This type of monitoring is focused on tracking pore pressure development and the behavior of CO_2 within the storage unit. Its primary objectives are to ensure the efficient utilization of available storage capacity and to provide essential data for CO_2 inventory reporting. By closely monitoring the filling process of the storage complex, operators can assess whether the CO_2 injection is proceeding as planned and if the storage unit is performing as expected.

- Containment monitoring: Containment monitoring aims to verify the proper containment of CO_2 within the storage formation and to ensure that there are no adverse environmental effects outside the storage complex. It plays a critical role in promptly identifying any deviations from expected behavior, enabling timely implementation of control measures to prevent potential risks or leaks.

Key considerations for a robust monitoring program include:

- Site-specific approaches: Each geological storage site is unique, with its own characteristics and challenges. Therefore, the monitoring program must be tailored to suit the local circumstances. Flexibility is essential, as the monitoring regime may need to be adjusted if the situation changes over time.
- Risk-based monitoring: An effective monitoring regime should be informed by the results of a prior risk assessment exercise. By identifying and prioritizing potential hazards based on their likelihood of occurrence and severity of consequences, monitoring efforts can be focused on areas of higher risk. This risk-based approach to monitoring allows for the efficient allocation of resources and enhanced attention to critical aspects of the project.
- Compliance with regulatory requirements: Adherence to regulatory requirements is essential to safeguard local assets and ensure the compliance of the project with relevant environmental and safety standards. An all-encompassing monitoring program must conform to these regulations and actively reinforce them.

By combining conformance and containment monitoring strategies while adhering to site-specific, risk-based, and regulatory considerations, operators can obtain the information required for the safe management of the storage project.

Long-Term Stewardship

The sequestration of injected CO_2 in the subsurface must endure far beyond the operational lifespan of corporations. Only public institutions can provide credible commitments spanning these extended periods. This implies that the long-term stewardship of underground storage sites should transition to the public domain.

There are different operational phases in the lifetime of a storage project. A typical injection project operates for a period of 10–40 years before CO_2 injection ceases and the site is closed. After site closure, the storage operator retains liability, which includes responsibility for continued monitoring of the site to verify its integrity and performance. Liability for the stored CO_2 can transfer to the public domain at the end of the post-closure period only when monitoring shows that the CO_2 plume in the subsurface behaves as projected by numerical simulations and that there is no foreseeable risk of future leakage. Expenses for the long-term care of the storage site, including eventual remedial actions, should be funded during site operations by the storage operators.

International Regulatory Initiatives

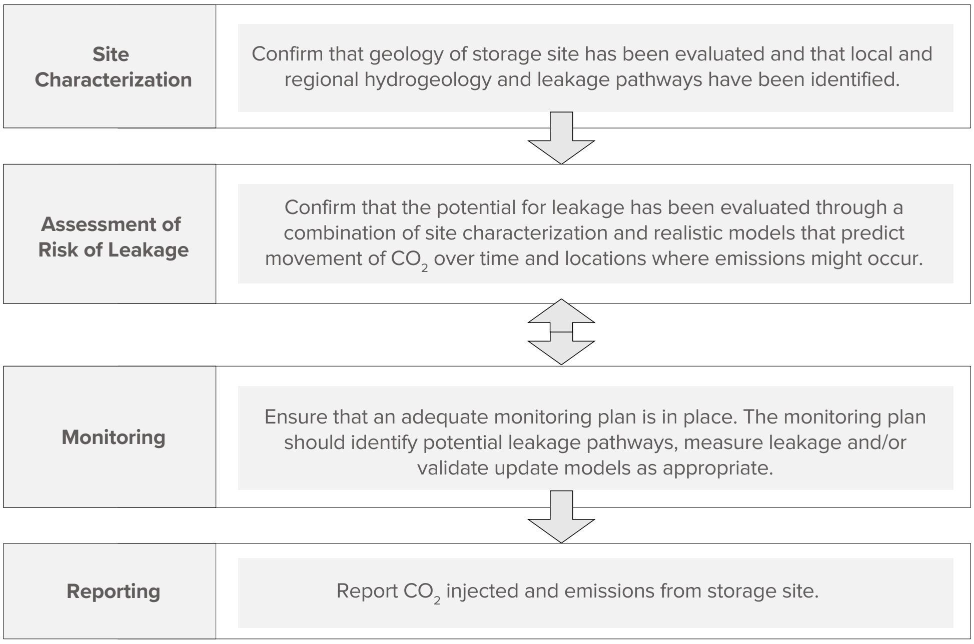
An effective international certification scheme for geological storage must tackle the aforementioned concerns. To achieve this, the scheme can draw upon globally recognized resources that are directly pertinent to this endeavor. These resources include:

- GHG Accounting: The IPCC 2006 Guidelines for National Greenhouse Gas Inventories

The IPCC is mandated by the United Nations Framework Convention on Climate Change to prepare methodologies for the compilation of national GHG inventories. The “IPCC 2006 Guidelines for National Greenhouse Gas Inventories” is the most up-to-date guidance available for the purpose of compiling emissions inventories (IPCC 2006). Despite being rather technical, the guidelines are essential tools for the development of climate change policies and for monitoring the impact of related technologies.

The 2006 guidelines comprehensively address emissions from the CO_2 capture and transport stages and any losses from CO_2 stored in the subsurface. In line with its function as an emissions accounting framework, the IPCC guidelines consider only emissions pathways that lead to CO_2 leaking to the ground surface or the seabed from geological storage sites. The procedure for the accounting of emissions from CO_2 storage is summarized in Figure 8 and is based on the principles for site characterization, risk assessment and monitoring discussed above.

Figure 8. Estimating, verifying, and reporting emissions from CO_2 storage sites.



Site Characterization

Confirm that geology of storage site has been evaluated and that local and regional hydrogeology and leakage pathways have been identified.

Assessment of Risk of Leakage

Confirm that the potential for leakage has been evaluated through a combination of site characterization and realistic models that predict movement of CO_2 over time and locations where emissions might occur.

Monitoring

Ensure that an adequate monitoring plan is in place. The monitoring plan should identify potential leakage pathways, measure leakage and/or validate update models as appropriate.

Reporting

Report CO_2 injected and emissions from storage site.

Source: Adapted from IPCC (2006).

The procedure for estimating CO_2 emissions from storage projects detailed in the IPCC guidelines is fully supported by the IPCC special report, “Carbon Dioxide Capture and Storage.” The procedure has been used as the basis for the establishment of other CCS reporting methodologies internationally, as well as regionally in the EU, Japan, Australia, and elsewhere. The 2006 IPCC guidelines provide the common global basis for the reporting of emissions from CO_2 storage sites.

- An Offset Mechanism for CCS: The Clean Development Mechanism

The Clean Development Mechanism is an integral part of the climate change policy architecture established under the Kyoto Protocol of the UNFCCC. Even though the Kyoto Protocol has been superseded by the Paris Agreement, the CDM continues to operate in a transitional capacity. It is widely anticipated that future mechanisms within the UNFCCC framework that incorporate geological storage will build upon the foundational principles established by the CDM rules for CCS.

The CDM functions as an offset mechanism, allowing emission reduction projects in developing countries to earn credits, which can be utilized by industrialized nations to partially fulfill their emission reduction targets as set by the Kyoto Protocol. In 2011, CCS was included in the CDM as an eligible project activity with detailed requirements and guidelines specified in a modalities and procedures document (UNFCCC 2011).

According to the modalities and procedures document, countries hosting CCS projects must have an effective regulatory framework in place to support the deployment of such initiatives. This explicit requirement for national regulations, as a complement to international UNFCCC governance, is unique and not a condition observed in other CDM activities. Complying with the CDM rules for geological storage necessitates national regulatory coverage to manage local environmental health and safety risks and to ensure the long-term stewardship of the storage site even after the crediting period has concluded (Box 3). Striking the right balance between respecting the sovereignty of host countries and ensuring the generation of high-quality and fungible emission reduction credits is a fundamental aspect of the governance of the CDM or any other international crediting scheme for geological storage.

Box 3. CDM Participation Requirements for Countries Hosting CCS Projects.

To be eligible for earning CDM credits, CCS projects must be located in countries with established national laws and regulations governing CCS (referred to as participation requirements). These laws and regulations should be designed to address the following key aspects:

- Permitting procedures: The laws should include permitting procedures that align with specific technical guidance in the modalities and procedures document. These procedures must ensure appropriate selection, characterization, and development of geological storage sites for CCS projects.

- Rights and access to subsurface pore space: Clear provisions should be defined in the regulations to confer rights to store CO_2 in subsurface pore space and grant access to project proponents.

- Redress mechanisms: The laws must establish timely and effective redress mechanisms for affected entities, individuals, and communities in the event of significant damages caused by the CCS project activity. This includes environmental damage, harm to ecosystems, other material damages or personal injuries, even in the post-closure phase.

- Remedial measures for leakage and environmental restoration: The regulations should mandate timely and effective remedial measures to halt or control any unintended physical leakage or seepage of CO_2. Additionally, they should outline procedures for restoring the integrity of defective geological storage sites and recovering long-term environmental quality significantly affected by CCS project activities.

- Liability arrangements: The laws need to establish mechanisms for addressing liability arrangements specifically related to CO_2 geological storage sites.

Ensuring compliance with these obligations might necessitate the modification of existing laws, such as those applicable to mining, oil and gas extraction, as well as environmental permitting. It may also require the creation of new laws tailored to accommodate the unique requirements of CCS projects. Many developed countries have already established national laws and regulations that meet these criteria, setting examples for others to follow in promoting safe and sustainable CCS initiatives.

- Best Engineering Practices: ISO Standard for CCS

Developed by the International Organization for Standardization, ISO standards are voluntary standards that follow a consensus-driven approach involving the input of professionals and experts from various sectors, including industry, NGOs, academia, and governments worldwide. One such standard is ISO 27914:2017, which aims to provide recommendations for the safe and effective storage of CO_2 in the subsurface, drawing from extensive operational experiences in the oil, gas and mining industries (ISO 2017). This standard offers detailed guidelines covering all phases of a geological storage project, except for the post-closure period, and is applicable for storage in aquifers.

While ISO 27914:2017 offers recommendations rather than mandatory requirements, it holds significant relevance for the development and management of geological storage projects for two key reasons. First, the involvement of a broad range of international stakeholders in its development adds a high degree of legitimacy and credibility. Second, its existence sets common expectations for environmental performance among companies involved in the storage business.

It is essential to note that the technical specifications in the standard should not be seen as a replacement for a robust regulatory framework governing geological storage. One critical aspect of such a framework is the establishment of liability rules.

Together, the IPCC guidelines, the CDM modalities and procedures, and the ISO standard for CCS form the foundation for a multilateral certification scheme ensuring the permanence of geological storage of CO_2. They collectively cover the following essential aspects of these projects:

- The IPCC guidelines establish an overarching accounting framework for geological CO_2 storage and outline the requirements for projects to avoid reporting injected CO_2 in national GHG inventories.

- The modalities and procedures of the CDM define minimum requirements for a regulatory scheme for geological storage, including arrangements for the long-term stewardship of stored CO_2.

- ISO standard 27914:2017 proposes best technical practices in designing, operating and closing storage projects that operators should follow in the absence of specific host country regulations on these matters.

The challenges of reaching multilateral agreements on rules, such as those within the UNFCCC, make it particularly significant that a certification mechanism for storage can rely largely on pre-existing resources and established international rules.

Operationalization

To ensure that blue hydrogen is recognized as a sustainable energy carrier, it is imperative to delineate its CO_2 emissions accounting within a detailed and, preferably, international framework. From a certification standpoint, it is beneficial and logical to differentiate between surface and subsurface emissions. The former are inevitable during the hydrogen production process, which is dictated by technology choices and operational procedures. In contrast, subsurface emissions, involving the leakage of CO_2 from the geological structure containing it back into the atmosphere, are influenced by factors independent of the production process. Key factors include the geostructural, geophysical, and geochemical features of the geological storage formation. Notably, geological formations, when meeting specific requirements, possess the capability to retain CO_2 indefinitely, offering permanent storage without surface emissions.

To address this scenario, the certification process for blue hydrogen should be divided into two components, each requiring a distinct certificate. Certifying blue hydrogen production would necessitate a certificate for the carbon footprint of the production process and an additional certificate attesting to the permanence of storage.

The principles and procedures established for certifying the permanence of storage hold validity beyond the narrow application to blue hydrogen. They are equally relevant to other technologies that yield climate benefits through the permanent geological storage of CO_2 of particular importance in this context are technologies that leverage geological storage to generate negative emissions, such as bioenergy with CCS and direct air capture with carbon storage. The certification process for storage should be designed to accommodate these applications (Box 4).

It is evident that governments will have to play a crucial role in any storage certification scheme. First, most of the global subsurface pore space suitable for storage, except for that of a few countries, is under public ownership. Thus, CO_2 storage projects need to involve the use of a state-owned natural resource, namely subsurface pore space. Second, carbon accounting for the stored CO_2 is carried out on the national scale and will affect the GHG inventory of the host country, which, in turn, could have implications for its emission reduction targets. Third, only governments can provide the regulatory framework governing CO_2 storage, such as liability arrangements for the operational and post-abandonment phases of a storage project.

These points strongly advocate the establishment of a storage certification architecture by governmental organizations. It is challenging to envision non-state actors constructively taking over state functions as governors of a geological certification mechanism. Moreover, many governments have strategic interests in geological storage to achieve net-zero targets, limiting their willingness to grant non-state actors a key role in the certification process.

To prevent a fragmented landscape of national certification schemes with varying requirements, it is crucial to establish storage certification as an intergovernmental activity. Anchoring the certification of geological storage on internationally agreed upon requirements and criteria, supported by an intergovernmental governance structure, enhances trust in this mitigation technology and facilitates its widespread adoption. A unified certification mechanism under intergovernmental oversight, applicable to all technologies utilizing geological sinks, will reinforce the fundamental role that geological storage needs to play in achieving global net-zero emissions targets.

Beyond its primary role in advancing the utilization of geological sinks, the international certification framework under consideration has a pivotal role in driving the growth of the global blue hydrogen market. Its influence on this expansion is twofold:

- Fostering trust in blue hydrogen's low carbon credentials: By instilling confidence in the low-carbon attributes of blue hydrogen, the certification framework for geological storage underpins demand in international markets for blue hydrogen.
- Streamlining the global blue hydrogen supply chain: Additionally, it can act as a catalyst in shaping an interconnected global supply chain for blue hydrogen. By addressing and eliminating inconsistencies that may exist between national storage certification frameworks, the international certification framework can facilitate the development of an efficient global supply network for blue hydrogen.

Box 4. Carbon Storage Units.

There are various practical ways to add storage certification to the climate policy toolkit. A recent approach involves unitizing storage certification through the process of creating verified records for each ton of CO_2 stored in a certified storage site. Carbon storage units created in this way would support not only the blue hydrogen certification process but also the claims of permanent storage, including bioenergy with CCS and direct air capture with carbon storage. The concept of carbon storage units was introduced in the climate policy discussion a few years ago by Zakkour and Heidug (2019) and Zakkour et al. (2021). They proposed novel instruments that could provide incentives for fossil fuel providers to use geological storage. Their use within the context of blue hydrogen certification testifies to the versatility of the concept.

Issuance or transfer of carbon storage units could follow established precedents. A quantity of carbon storage units that corresponds to the amount of the CO_2 meeting storage certification requirements could be issued electronically by the storage company into a holding registry together with key information on the stored CO_2. This information could include the source of the stored CO_2, such as fossil, biogenic, or air, the method of its capture, and information on the geography and time of the involved operations, including the location of the storage site and the type of geological storage, e.g., aquifers. The storage units booked in the registry could then be claimed, i.e., retired, by hydrogen producers as low-carbon characteristics for their produced hydrogen. Such a book-and-claim model is currently being piloted for sustainable aviation fuels (see https://aveliasolutions.com). Blockchain technology could provide an option for enabling transparent and secure tracking and transfer of the storage units.

Conclusion

Blue hydrogen production is expected to play an important role in the clean hydrogen portfolio, complementing the role of green hydrogen. There are still significant uncertainties surrounding the potential of both technologies, including their scalability and feasibility. Although both technologies can produce hydrogen with similarly low GHG intensities, blue hydrogen holds a cost advantage over green hydrogen. This advantage relies on the management of upstream methane emissions and the successful deployment of geological storage, which poses a policy and regulatory challenge rather than a technological one.

This paper sheds light on appropriate actions in this area, proposing that certifying the low-carbon credentials of blue hydrogen requires two independent certificates: a product certificate and a certificate for the anticipated long-term containment of CO_2 in a geological storage site. To ensure credibility and to avoid the complexities of a multitude of different national schemes, the storage certificate should be issued by an intergovernmental institution dedicated to storage certification. Since recourse to state resources and functions is essential for secure long-term storage, the certification process is best led by states rather than private actors.

From a practical standpoint, establishing an intergovernmental storage certification architecture would be a relatively straightforward task. Existing internationally agreed upon guidance already provides detailed requirements. This negates the need for time-consuming negotiations on the topic. To advance storage certification, interested countries can form a coalition either within the framework of the Paris Agreement or independently. This coalition would connect blue hydrogen supplier and consumer countries, offering benefits for all members. The implementation of an intergovernmental certification system for geological storage has the potential to provide critical support for two essential objectives: the widespread adoption of geological storage on a large scale and the cultivation of international markets for low-carbon hydrogen.

Endnotes

[1] Air Products is building both plants: the Canada Net-zero Hydrogen Energy Complex and the Louisiana Clean Energy Complex.

[2] A well-to-plant gate boundary includes emissions up to the point of hydrogen production. Well-to-wheel extends the emissions boundary to the point of use.

[3] Chain of custody refers to how hydrogen is traced throughout the value chain. In the book-and-claim tracking model, the physical delivery of the hydrogen and the certificate issuance can be traded apart. In the mass-balance tracking model, the hydrogen and the certificate are linked along the chain of custody.

[4] The minimum emission threshold for electricity-generating facilities is 18,750 tons of CO_2 per taxable year to be eligible for the 45Q tax credit. Other industrial facilities, which include blue hydrogen facilities, must have a minimum threshold of 12,500 tons of CO_2.

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Notes

Notes

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About the Project

Hydrogen is emerging as an important energy vector that can accelerate the transition toward net-zero emissions. Given its diverse applications and its potential to abate carbon emissions, it is ideally suited to enable the circular carbon economy. This project investigates the different pathways toward a hydrogen economy and the role of resource-rich countries in offering low-cost, clean hydrogen solutions..

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