Costs, Risks, and Realities: Reassessing CCS and Afforestation as Climate Solutions

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Abstract. With the development of technology, people are gradually adapting to utilizing more and more machines. However, this type of matter causes the release of carbon dioxide, which leads to the greenhouse effect. Therefore, the global temperature continues to increase. As a result, people have developed several methods to reduce CO2 concentration, including carbon capture and storage and afforestation. However, these methods have some drawbacks, and people tend to be overly optimistic about them, although they can reduce carbon dioxide emissions to a certain extent. Thus, this article highlights some problems by examining official data and conducting experiments. In brief, both methods have adverse effects, such as increasing the cost, and they appear to reduce carbon dioxide emissions but actually increase them behind the scenes.

Keywords: carbon dioxide, afforestation, carbon capture and storage.

1. Introduction

To solve the problem of releasing carbon dioxide into the atmosphere, scientists have explored various ways, and two of the most attractive ones are CCS and afforestation. We can see that both are promoted effectively through policies and large-scale projects. CCS refers to people collecting CO2 and transporting it to suitable places to store it permanently. Afforestation means that people plant more trees to lower the concentration of CO2 by utilizing the feature of trees--absorbing carbon dioxide. These two ways can reduce CO2, but the problems still exist. Further, people overly trust these ways instead of finding problems in the production system and society's demands. Thus, this article takes a critical review perspective. In fact, it aims to let people know more about CCS and afforestation and help people select an accurate address and time to maximize this technology's use.

2. Literature review

2.1 Carbon Capture and Storage (CCS)

Carbon capture and storage (CCS) is a comprehensive process that captures carbon dioxide from industrial or power generation sources, compresses and transports it, and stores it permanently in geological formations to prevent atmospheric release. While CCS is often promoted as an effective and feasible solution for mitigating atmospheric CO_2 accumulation, its practicality remains limited by high costs and significant energy penalties.

The financial burden of CCS primarily stems from its capture stage, which accounts for the majority of total expenses. Depending on the technology and industry, capture costs typically range between $20 and $110 per ton of CO_2, with coal and gas-fired power plants, refineries, and cement industries showing the highest variability. Transport and storage further add to the expense, with pipeline transport costs increasing considerably for offshore routes, and geological storage costs fluctuating by location and formation type. Onshore depleted reservoirs are the most economical, while offshore saline formations remain the most costly.

When these components are combined, the overall cost of CO_2 avoidance can range from roughly $25 to $150 per ton across different sectors. Such high costs substantially increase the levelized cost of electricity (LCOE), with CCS-equipped power plants being notably less economical than those without capture. The cost increase reflects both higher capital expenditures and elevated operational and maintenance costs.

Beyond its financial challenges, CCS introduces substantial energy penalties that reduce plant efficiency. Coal-fired units experience an efficiency loss of 15–28%, while natural gas and integrated gasification combined cycle plants face penalties of 15–16% and up to 20%, respectively. These energy demands translate to greater fuel consumption and lower overall system effectiveness, negating part of the intended environmental benefit.

The capital and operational costs of CCS facilities are significantly higher than those of conventional plants, with coal-based systems requiring between $3,500 and $6,800 per kilowatt of installed capacity. First-of-a-kind (FOAK) projects, which dominate the CCS landscape, remain prohibitively expensive, and even as technologies mature (NOAK stage), projected cost reductions are modest—around 3–9%. Despite ongoing learning effects, the overall conclusion remains that CCS units are consistently more expensive and less efficient than non-CCS counterparts.

Although CCS plays a potentially vital role in achieving carbon neutrality, its high cost, energy intensity, and limited scalability hinder its widespread adoption. Continued research and technological advancement may reduce expenses over time, but as it stands, CCS remains an expensive interim measure rather than a definitive solution to global CO_2 mitigation.

2.2 Slow Progress of CCS Deployment

Despite widespread recognition of its importance, the global adoption of carbon capture and storage (CCS) technologies has been notably slow and regionally concentrated. According to the Global CCS Institute, only 39 large-scale CCS projects worldwide are currently at the development, construction, or operational stage, and just 17 are fully operational—primarily located in the United States, Canada, Norway, Brazil, Saudi Arabia, and the United Arab Emirates. Within the power generation sector, only two demonstration projects—Boundary Dam in Canada and Petra Nova in the U.S.—are active, with most other projects confined to industrial or natural gas processing facilities. While the number of operational projects has grown modestly over the past decade, the overall global project count has declined, revealing a pattern of technical feasibility without corresponding large-scale implementation.

The Intergovernmental Panel on Climate Change (IPCC) reports that the current rate of CCS deployment remains far below the levels required to achieve the 1.5°C or 2°C temperature targets. Meeting these climate goals will demand stronger policy mechanisms, public engagement, and technological breakthroughs. Even under optimistic projections, the International Energy Agency (IEA) estimates that if all announced CCS projects were realized, global capture capacity would reach only about 435 million tons per year by 2030—less than half of the 1 gigaton per year required under the Net Zero Emissions (NZE) scenario. In reality, as of 2024, total operational CCS capacity stands at just 51 million tons annually, potentially doubling to a little over 100 million tons if all projects under construction come online. This figure represents merely one-tenth of the 2030 target, highlighting the significant gap between ambition and achievement.

The IEA's *Net Zero Roadmap 2023* underscores that the history of CCS has been "largely one of underperformance." Despite an influx of announced projects in recent years, few have reached the final investment decision (FID) stage due to financial risks, unclear policy frameworks, and insufficient infrastructure. The report stresses the need for strong government incentives, coordinated investment strategies, and clear carbon pricing mechanisms to accelerate deployment. Without these supports, CCS will continue to face slow progress, limiting its potential contribution to global decarbonization targets.

In summary, although CCS remains a technically viable pathway for large-scale carbon mitigation, its deployment is hindered by high costs, uneven policy support, and infrastructure bottlenecks. Achieving meaningful global impact will require not only technological innovation but also decisive political and economic coordination across regions.

2.3 Geological Storage Risks in CCS

The selection of geological sites for CO_2 storage presents both opportunities and potential risks. Deep saline aquifers—porous rock formations saturated with saline water and sealed by impermeable caprocks such as shale or salt—are currently the most common choice due to their wide distribution and high storage capacity. However, despite their potential, saline aquifers pose several critical challenges related to uncertainty, pressure management, and long-term safety.

While the theoretical storage capacity of saline aquifers is vast, estimated by the OGCI CO_2 Storage Resource Catalogue (2024) to exceed 14,000 gigatons globally, these figures remain highly uncertain. Many reserve estimates are based on preliminary data, lacking detailed site-specific characterization. The Global CCS Institute's Storage Resource Management System (SRMS) was introduced to standardize classifications and reduce such uncertainties. Nevertheless, in practice, large discrepancies persist between declared and permitted storage capacity, particularly in countries such as the United States, where many proposed sites have yet to receive official approval. This underscores the gap between theoretical potential and actual operational readiness.

Continuous CO_2 injection into saline formations can significantly increase subsurface pressure, reducing effective stress and potentially triggering fractures or small seismic events. This pressure buildup also heightens the risk of caprock failure and CO_2 leakage. Studies, including the U.S. DOE/NETL Brine Extraction Storage Tests (BEST) project, emphasize active pressure management through controlled brine extraction as a necessary safety measure. Analytical modeling by Cihan (2013) further demonstrates that injection-induced pressure can propagate regionally, necessitating careful monitoring and engineering control to prevent fault slippage and leakage through adjacent formations.

Ensuring the long-term security of stored CO_2 depends on rigorous site selection, continuous monitoring, and strict regulatory oversight. Although multiple trapping mechanisms—structural, residual, dissolution, and mineral—help ensure stable storage, their reliability depends on geological integrity, injection control, and sustained post-operation supervision. Leakage risks are generally categorized into two types: natural geological pathways (faults, fractures, or weak caprock zones) and anthropogenic ones (improperly sealed or abandoned wells). These are low-probability but high-impact events that require continuous vigilance.

Regulatory frameworks, such as those established by the IPCC's *Special Report on CO_2 Capture and Storage* and the U.S. EPA's Class VI program, stress the need for full lifecycle monitoring, including 4D seismic imaging, in-well pressure tracking, and groundwater quality surveillance. The U.S. National Academies' 2019 report on *Negative Emissions Technologies and Reliable Sequestration* further highlights the importance of assigning long-term responsibility for storage sites and investing in advanced monitoring technologies.

While deep saline aquifers offer immense potential for CO_2 storage, their uncertain characterization, pressure-related risks, and long-term monitoring demands present formidable challenges. Effective deployment requires stringent geological assessment, robust engineering management, and clear regulatory accountability to ensure both environmental safety and public confidence in CCS technology.

2.4 Policy and Market Challenges

The development of carbon capture and storage (CCS) technologies is tightly intertwined with the structure of global carbon pricing systems, primarily through carbon taxes and cap-and-trade (emissions trading systems, ETS). A carbon tax imposes a fixed price per ton of greenhouse gas emitted, prompting industries to reduce emissions by making pollution financially costly. In contrast, a cap-and-trade system sets a total emissions limit and allocates or auctions emission permits that can be traded, allowing the market to determine the carbon price based on supply and demand. Since CCS does not generate tangible products, its only measurable outcome is the reduction of emitted CO_2, which carbon pricing mechanisms translate into financial value ($\$/tCO_2$), theoretically turning CCS from a cost-heavy burden into a potential investment.

However, CCS projects remain economically unattractive due to high operational costs and insufficient carbon prices or subsidies to ensure financial viability. Even though the World Bank emphasizes that carbon pricing helps “internalize external costs” and “mobilize clean technology investments,” global coverage remains limited. As of 2024–2025, only 24–28% of global emissions are directly priced, generating roughly $100 billion in public revenue but at price levels too low to support large-scale CCS deployment. Furthermore, the absence of predictable long-term carbon pricing deters private investment, especially in capital-intensive industries that require stable policy frameworks for decision-making.

According to the United Nations Framework Convention on Climate Change (UNFCCC), carbon pricing coverage and intensity remain inadequate. Only around 40 countries and 25 subnational regions currently operate carbon pricing mechanisms, collectively covering about 15% of global emissions (roughly 8 $GtCO_2e$). The policy landscape is fragmented, featuring 46 mechanisms either in operation or planning—split evenly between ETS and carbon taxes, with some adopting hybrid models that allow large offset use. This inconsistency across regions makes it difficult for corporations to base long-term CCS investments on these unstable and heterogeneous policy systems.

Globally, the effective carbon tax in most economies remains below $10 per ton of CO_2 equivalent, far below the cost threshold required for CCS viability. Given that the full-chain cost of carbon capture, transport, and storage typically ranges from tens to hundreds of dollars per ton, low carbon prices fail to create meaningful incentives for CCS adoption. As a result, most projects rely heavily on government subsidies, tax credits, or “contracts for difference” to offset operational losses. Even when accounting for both ETS and carbon taxes, global coverage remains limited, and the average carbon price insufficient to stimulate large-scale CCS investment.

In essence, the slow advancement of CCS is not just a technical issue but also a reflection of weak market and policy environments. Without stronger and more predictable carbon pricing mechanisms, comprehensive international coordination, and long-term financial incentives, CCS will remain economically unviable. The success of global decarbonization efforts thus depends on establishing clear, consistent, and sufficiently high carbon prices that make CCS a financially sustainable pathway rather than a policy-dependent experiment.

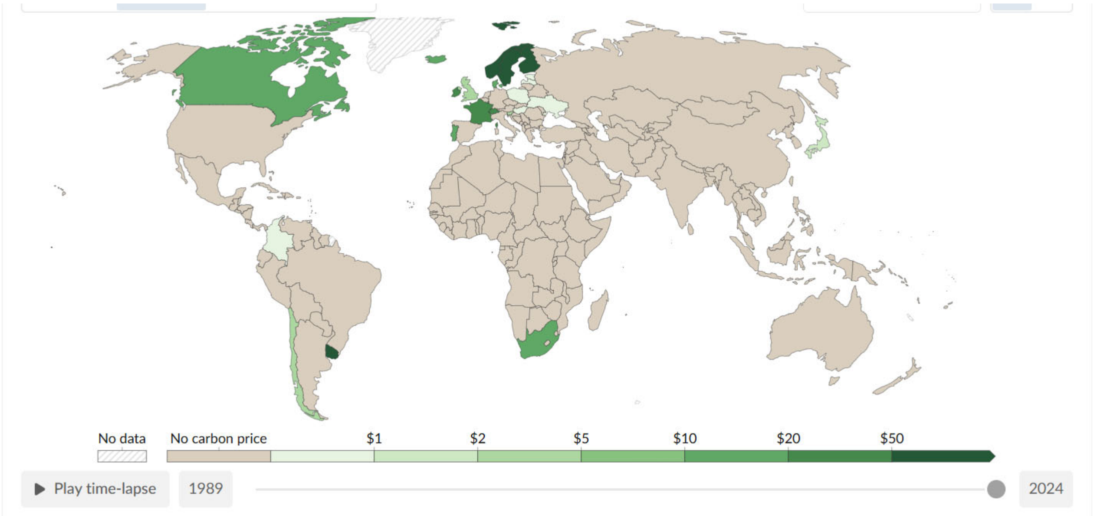

Figure 1. Carbon tax distribution over the globe.

3. Afforestation and Its Limitations

Afforestation, the practice of planting trees in areas previously devoid of forest cover, has been widely promoted as a natural solution to mitigate climate change by absorbing atmospheric CO_2 and storing it in biomass and soil. While theoretically effective in reducing greenhouse gases, large-scale afforestation projects carry several ecological and climatic drawbacks that complicate their role in long-term carbon management.

3.1 Water Resource Impacts

Afforestation significantly affects regional water cycles. By increasing evapotranspiration, tree plantations often reduce surface runoff and groundwater availability. Studies across multiple small watershed experiments show that a 10% increase in canopy cover can decrease annual runoff by 17–25 mm for broadleaf and coniferous forests, and by up to 330 mm in fully forested catchments. This demonstrates a clear trade-off between carbon sequestration and water availability, particularly in arid and semi-arid regions where water scarcity is already critical.

3.2 Increased Fire Risks

Artificial forests—especially monoculture plantations—also heighten the risk of catastrophic wildfires. Statistical data from 17 temperate countries indicate that plantation forests have roughly twice the probability of large-scale fires compared to natural forests. In regions like Chile and Portugal, pine and eucalyptus plantations, which dominate reforested landscapes, have been linked to higher fire frequency and intensity due to their dense structure and high flammability. The 2017 Pedrógão fire in Portugal, where 70% of the burned area was composed of eucalyptus and pine plantations, illustrates the dangers of poorly managed afforestation dominated by combustible species.

3.3 Carbon Effectiveness and Climate Feedbacks

The net carbon benefit of afforestation is often overestimated. Planting trees can lower surface albedo, meaning that more solar radiation is absorbed rather than reflected, which can locally increase temperatures and counteract cooling effects from CO_2 sequestration. Furthermore, the process of establishing plantations—using heavy machinery such as bulldozers and rollers—releases additional CO_2. Life Cycle Assessments (LCAs) estimate establishment emissions of 2–10 tCO_2e per hectare, creating an initial "carbon debt" that may take decades to offset. Programs like the Woodland Carbon Code in the UK account for these establishment emissions, recognizing that early-stage afforestation projects may temporarily increase, rather than decrease, atmospheric carbon levels.

While afforestation contributes to CO_2 reduction and ecosystem restoration, its effectiveness as a climate mitigation strategy is constrained by hydrological impacts, fire risks, and indirect emissions. Large-scale monoculture plantations, in particular, can exacerbate ecological imbalances if not carefully designed and managed. Effective afforestation must therefore prioritize ecological diversity, regional hydrology, and life-cycle carbon accounting to ensure that it genuinely supports climate goals rather than introducing new environmental challenges.

3.4 Ecological Risks of Monoculture Afforestation

Although artificial forests—often dominated by fast-growing monoculture species such as Chinese pine or red pine—can effectively absorb carbon dioxide, their ecological drawbacks frequently outweigh their short-term climate benefits. Monoculture plantations, by reducing species diversity and ecosystem resilience, may inadvertently create new environmental vulnerabilities.

Extensive research shows that monoculture afforestation significantly reduces biodiversity compared to natural or mixed forests. A meta-analysis of 138 studies across 28 tropical countries found that plantation forests consistently support lower species richness and exhibit drastic shifts in community composition compared to primary forests. This pattern holds across various taxa and geographic regions, reinforcing that "primary forests are irreplaceable for maintaining tropical biodiversity." The decline in biodiversity not only destabilizes forest ecosystems but also introduces uncertainty into their carbon sequestration potential, as ecosystem resilience plays a crucial role in long-term CO_2 storage stability.

Monoculture plantations also heighten the risk of pest outbreaks and disease spread. When vast areas are planted with a single tree species, the ecosystem becomes highly susceptible to speciesspecific pests that can rapidly expand and devastate large tracts of forest. This phenomenon, known as the loss of "associational resistance," has been observed worldwide. Wingfield (2015) noted that global trade and forest expansion facilitate the rapid movement of invasive pathogens, with monoculture plantations—often composed of pines, eucalyptus, or acacia—acting as ideal hosts. The Food and Agriculture Organization (FAO) emphasizes that pest prevention should be a mandatory consideration in afforestation planning, including species selection, seed sourcing, and site management.

Further studies (Gougherty, 2019; 2022) provide quantitative evidence that greater tree species diversity reduces infection probability and mitigates pest establishment. These findings support the principle of "reducing risk through diversity," suggesting that ecologically balanced afforestation strategies—featuring mixed species, native trees, and structured planting—can enhance ecosystem resilience and lower maintenance costs.

4. Discussion

Both carbon capture and storage (CCS) and afforestation are theoretically effective strategies for reducing atmospheric CO_2 concentrations, yet their practical outcomes are often shaped by complex regional, economic, and ecological factors. People tend to trust these methods due to a few successful examples that have been widely publicized. For instance, Norway's Sleipner project in the North Sea has become a benchmark for effective CCS. Since 1996, it has safely stored over 13 million tons of CO_2 in saline aquifers, monitored continuously through seismic and gravity surveys with no detected leakage. This case demonstrates that, under strict regulation and continuous observation, long-term CO_2 storage can be both technically feasible and environmentally safe.

However, such success is not universal. The failed Kemper County IGCC project in the United States revealed the fragility of large-scale CCS investments. Initially hailed as a flagship of clean coal technology, it faced massive cost overruns and technical difficulties, ultimately abandoning its CCS component in 2017. This failure underscores the financial and engineering risks inherent in deploying CCS without adequate policy support, cost control, and technological readiness.

Similarly, afforestation offers both success stories and cautionary lessons. Niger's Farmer-Managed Natural Regeneration (FMNR) program stands out as a sustainable model, using natural root regeneration rather than costly replanting. Over two decades, it restored nearly two million hectares and 200 million trees, improving soil health and agricultural productivity. In contrast, monoculture plantations in Chile and Portugal—dominated by pine and eucalyptus—have shown how poorly planned afforestation can backfire. These plantations, highly flammable during dry seasons, contributed to catastrophic wildfires in 2017, releasing vast amounts of CO_2 and erasing years of carbon gains.

These examples illustrate that both CCS and afforestation require context-specific implementation. Geological conditions, ecosystem characteristics, and socio-political environments must all be carefully evaluated before large-scale deployment. Simplistic replication of "successful cases" across diverse regions can lead to failures or unintended consequences. For instance, before launching afforestation projects, planners must consider local albedo effects, biodiversity, and fire risk rather than focusing solely on CO_2 absorption metrics.

5. Conclusion

While CCS and afforestation remain crucial components of global climate mitigation strategies, both are constrained by economic, environmental, and technical limitations. CCS faces challenges related to high costs, policy uncertainty, and geological risks, while afforestation struggles with ecological trade-offs such as reduced biodiversity, water depletion, and fire vulnerability. The path forward lies not only in advancing these technologies but also in developing integrated, regionally adaptive frameworks that balance environmental effectiveness with economic feasibility. Climate solutions must evolve from isolated technical interventions into system-level transformations, supported by long-term monitoring, consistent policy incentives, and a deep understanding of local ecological contexts.

References

[1] IPCC. (2005). *Special report on carbon dioxide capture and storage* (SRCCS). Cambridge University Press. https://www.ipcc.ch/report/srccs/U.S.

[2] Environmental Protection Agency. (2013). *Underground Injection Control Program: Class VI well area of review evaluation and corrective action guidance* (EPA 816-R-13-005). https://www.epa.gov/uic/final-class-vi-guidance-documents

[3] U.S. Department of Energy, National Energy Technology Laboratory (NETL). (2024). *Brine Extraction Storage Tests (BEST)*. https://netl.doe.gov/carbon-management/carbon-storage/BEST

[4] Zoback, M. D., & Gorelick, S. M. (2012). Earthquake triggering and large-scale geologic storage of carbon dioxide. *Proceedings of the National Academy of Sciences, 109*(26), 10164–10168. https://doi.org/10.1073/pnas.1202473109

[5] Vilarrasa, V., & Carrera, J. (2015). Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which CO_2 could leak. *Proceedings of the National Academy of Sciences, 112*(19), 5938–5943. https://doi.org/10.1073/pnas.1413284112

[6] Miocic, J. M., Gilfillan, S. M. V., Frank, N., Schroeder-Ritzrau, A., Burnside, N. M., & Haszeldine, R. S. (2019). 420,000-year assessment of fault leakage rates shows geological carbon storage is secure. *Scientific Reports, 9*, 769. https://doi.org/10.1038/s41598-018-36974-0

[7] Global CCS Institute. (2024). *Global status of CCS 2024*. https://www.globalccsinstitute.com/resources/global-status-of-ccs-2024/

[8] International Energy Agency. (2023). *Net zero roadmap: A global pathway to keep the 1.5 °C goal in reach (2023 update)*. International Energy Agency. https://www.iea.org/reports/net-zero-roadmap-2023

[9] International Energy Agency. (2025). *CCUS—Tracking clean energy progress* (updated page). International Energy Agency. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage

[10] Gibson, L., Lee, T. M., Koh, L. P., Brook, B. W., Gardner, T. A., Barlow, J., … Sodhi, N. S. (2011). Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature, 478*(7369), 378–381. https://doi.org/10.1038/nature10425

[11] Barlow, J., Gardner, T. A., Araujo, I. S., Ávila-Pires, T. C., Bonaldo, A. B., Costa, J. E., … Peres, C. A. (2007). Quantifying the biodiversity value of tropical primary, secondary, and plantation forests. *Proceedings of the National Academy of Sciences, 104*(47), 18555–18560. https://doi.org/10.1073/pnas.0703333104

[12] Sahin, V., & Hall, M. J. (1996). The effects of afforestation and deforestation on water yields. *Journal of Hydrology, 178*(1–4), 293–309. https://doi.org/10.1016/0022-1694(95)02829-9

[13] Trabucco, A., Zomer, R. J., Bossio, D. A., van Straaten, O., & Verchot, L. V. (2008). Climate change mitigation through afforestation/reforestation: A global analysis of hydrologic impacts with four case studies. *Agriculture, Ecosystems & Environment, 126*(1–2), 81–97. https://doi.org/10.1016/j.agee.2008.01.015

[14] Betts, R. A. (2000). Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature, 408*(6809), 187–190. https://doi.org/10.1038/35041545

[15] Peng, S., Piao, S., Zeng, Z., Ciais, P., Zhou, L., Li, L. Z. X., … Myneni, R. B. (2014). Afforestation in China cools local land surface temperature. *Proceedings of the National Academy of Sciences, 111*(8), 2915–2919. https://doi.org/10.1073/pnas.1315126111

[16] Jactel, H., & Brockerhoff, E. G. (2007). Tree diversity reduces herbivory by forest insects: A meta-analysis. *Oecologia, 152*(4), 1–14. https://doi.org/10.1007/s00442-007-0689-0

[17] Castagneyrol, B., Giffard, B., Péré, C., & Jactel, H. (2014). Plant apparency, an overlooked driver of associational resistance to insect herbivory. *Journal of Ecology, 102*(3), 616–624. https://doi.org/10.1111/1365-2745.12286

[18] Wingfield, M. J., Brockerhoff, E. G., Wingfield, B. D., & Slippers, B. (2015). Planted forest health: The need for a global strategy. *Science, 349*(6250), 832–836. https://doi.org/10.1126/science.aac6674

[19] Food and Agriculture Organization of the United Nations. (2001). *Global forest resources assessment: Protecting plantations from pests and diseases* (tech. guidance). https://www.fao.org/forestry

[20] World Bank. (2024). *State and trends of carbon pricing 2024*. World Bank. https://carbonpricingdashboard.worldbank.org/

[21] Dolphin, G., & Merkle, O. (2024). *Carbon taxes across the world* (dataset & brief). Our World in Data. https://ourworldindata.org/

[22] World Bank. (n.d.). *What is carbon pricing?* (explainer). https://www.worldbank.org/en/programs/pricing-carbon