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Benchmarking National Carbon Management Strategies: A Six-Dimensional Comparative Analysis Related to Carbon Capture, Utilization and Storage

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The accelerating climate crisis induces effective national carbon management. This paper compares the carbon management and CCU/S strategies of the United States, Canada, Sweden, France, and Austria using a six-dimensional framework – political-legal, economic, organizational, technological, ecological, and social aspects. Present study maps each strategy's design choices, deployment pathways, and governance mechanisms, finding common emphasis on hard-to-abate sectors and multi-stakeholder oversight but wide variation in regulatory maturity, incentive structures, and community engagement. Results show that technological readiness must be paired with clear legal frameworks, aligned financing, and inclusive stakeholder processes to enable the deployment of CCUS. These insights guide policymakers toward best practices and identify key areas for future implementation research.

Keywords: carbon dioxide management, strategy comparison, carbon capture, utilization and storage

1. Introduction

In the global race to achieve climate neutrality, carbon dioxide (CO_2) is no longer viewed solely as a by-product of industrial activity, but increasingly as a managed resource – captured, transported, utilized, or stored within emerging low-carbon value chains (Hölscher et al. 2012, Kamkeng et al. 2021, Ullas Krishnan–Jakka 2022, Nimmas et al. 2024). Carbon capture, utilization and storage (CCU/S) technologies have therefore become critical components of national and supranational decarbonization strategies, particularly for hard-to-abate sectors such as cement, steel, chemicals, and waste-to-energy (European Commission [no date][a]).

The transition towards a net-zero carbon economy has fundamentally reshaped the political, economic, and industrial landscape across the globe. As climate targets become more ambitious, national carbon management strategies (CMS) have emerged as key pillars of climate policy. CCU/S technologies – once considered peripheral or experimental – are now widely acknowledged as essential for decarbonizing hard-to-abate sectors and for compensating for historical and residual emissions that cannot be eliminated through renewable energy or energy efficiency measures alone. In this context, a new era of industrial competition is emerging – one structured not only by emission reduction targets, but by the capacity of nations to lead in carbon management infrastructure, innovation, and policy design (Dou et al. 2023).

The European Union (EU) has positioned itself as a front-runner in this global contest with showing commitment of several climate policies. Through the

2021 European Climate Law, the EU enshrined its commitment to at least a 55% net reduction in greenhouse gas emissions by 2030, relative to 1990 levels, and to achieving net-zero by 2050 (Európai Parlament 2021). This legislative foundation is complemented by a series of interlinked policy instruments: the Fit for 55 package in 2021 (European Council 2021), the revised EU Emissions Trading System (ETS) in 2023 (European Commission 2023a), and the Net-Zero Industry Act (2024) (European Commission [no date][b]), which aims to scale up manufacturing of clean technologies, including CCU/S, and mandates the creation of at least 50 Mt of CO_2 storage capacity by 2030 (European Commission [no date][b]).

Most notably, in February 2024, the European Commission published its Industrial Carbon Management Strategy (ICMS) – the first of its kind globally – which establishes a long-term roadmap for deploying CCU/S across Europe. It calls for a single, internal EU market for captured CO_2, supported by robust infrastructure, legal clarity, and investment incentives (European Commission 2024b). Shortly thereafter, the Clean Industrial Deal (February 2025) reaffirmed the role of CCU/S as a strategic technology, explicitly referencing the need to “create a market for captured carbon” and to level the playing field between fossil and fossil-free carbon sources (European Commission 2025). Table 1. summarises the main policies that can influence the deployment of CCU/S technologies.

Table 1. Summary of main EU policies affecting the deployment of CCU/S technologies

Policy Name	**Year**	**Quantified Target**	**Target Period**	**Key Technologies/ Solutions**	**Geographic Scope**
Emissions Trading System (ETS)	2005 (updated 2023)	43% GHG reduction by 2030 (compared to 2005) in covered sectors	From 2005	Emissions trading, carbon pricing, CCU/S	European Union
Paris Agreement	2015	Keep global average temperature rise below 2 °C, aiming for 1.5 °C	2020–2100	Low-carbon technologies, renewable energy	Global
European Green Deal	2019	Reduce EU net GHG emissions by 55% by 2030; achieve climate neutrality by 2050	2020–2050	Renewable energy, energy efficiency, sustainable mobility	European Union
European Climate Law	2021	Legally binding the Green Deal: at least 55% GHG reduction by 2030; climate neutrality by 2050	2021–2050	Renewable energy, energy efficiency, sustainable mobility	European Union
Fit for 55 Package	2021	At least 55% GHG reduction by 2030 (compared to 1990 levels)	2021–2030	Energy efficiency, renewables, industrial decarbonization and transport reforms	European Union
ReFuelEU Aviation	2023	Raise SAF share in EU aviation: 2% by 2025, 6% by 2030, 20% by 2035, 34% by 2040, 70% by 2050	2023–2050	Sustainable aviation fuels (SAF), hydrogen, electric aviation	EU, aviation sector
FuelEU Maritime	2023	Reduce GHG intensity of maritime fuels: 2% by 2025, 6% by 2030, 13% by 2035, 26% by 2040, 59% by 2045, 80% by 2050	2023–2050	Alternative fuels (e.g. biofuels, LNG), energy efficiency	EU, maritime sector

Policy Name	Year	Quantified Target	Target Period	Key Technologies/ Solutions	Geographic Scope
Renewable Energy Directive (RED III)	2023	Increase renewables' share in EU total energy consumption to 32% by 2030	2023–2030	Solar, wind, bioenergy, hydrogen	EU, energy sector
Carbon Border Adjustment Mechanism (CBAM)	2023	Introduce carbon tariffs on high-carbon imports to prevent carbon leakage	2023–2030	Carbon pricing, industrial emission reductions	EU, imports
Net-Zero Industry Act	2024	Increase EU net-zero technology manufacturing; achieve 50 Mt CO_2 storage capacity by 2030	2024–2030	Carbon capture, utilization and storage, renewables, clean technologies	European Union
Industrial Carbon Management Strategy	2024	Support industrial emissions reduction through CCU/S deployment	2024–2050	Carbon capture, storage and utilization, hydrogen, bioenergy	EU, industrial sector
Clean Industrial Deal	2025	Competitiveness and decarbonisation in energy-intensive industries and the clean-tech sector	2025–2030	Roadmap to circular economy, low-carbon technologies	European Union

Source: own edit based on (European Council 2021, European Environmental Bureau 2022, European Commission 2023a, European Commission 2023b, European Commission 2024a, European Commission 2025)

While these instruments structure the strategic environment for EU member states such as France, Sweden, and Austria, comparable efforts are underway across the Atlantic. The United States and Canada – though not bound by EU law – have both articulated ambitious, though differently structured, national carbon management strategies. These countries are not merely responding to domestic emission challenges – they are positioning themselves in a competitive landscape where early leadership in carbon management may translate into technological dominance and export opportunities (Ahn 2023). Despite broad agreement on the importance of CCU/S, the pace, scope, and design of CMS differ markedly across jurisdictions. While some countries – such as Sweden, France, and Canada – have embedded CCU/S deployment within coherent policy frameworks complete with dedicated financing streams and clear legal mandates, others rely on fragmented or regionally varied initiatives, as seen in the United States. These variations reflect differences in political priorities, industrial profiles, and resource endowments.

Thus, while the EU's regulatory environment gives its member states a distinct policy framework, the dynamics of CCU/S strategy development are increasingly shaped by global signals: falling technology costs, competition for project finance, multilateral net-zero pledges, and the need for interoperable infrastructure. National strategies influence – and are influenced by – each other's successes, failures, and innovations. As Clean Air Task Force (CATF) notes, a new era of carbon management is underway, in which regulatory leadership, industrial policy, and climate ambition converge (Clean Air Task Force 2022).

This evolving competitive and cooperative context raises key analytical questions:

- How do national carbon management strategies differ in their scope, tools, and implementation priorities?
- Which elements are commonly present in such strategies?
- How do national contexts (e.g., EU membership, storage geology, industrial profile) shape strategic choices?

This study offers a comparative benchmarking of five countries with published national carbon management strategies: the United States of America, Canada, Austria, France, and Sweden. It seeks to identify commonalities, divergences, and best practices in strategy design and implementation.

Through a comparative review of national strategy documents, EU-level policy, and supporting literature, the analysis contributes to both scholarly understanding and policymaking by highlighting what constitutes an effective carbon management strategy in a world where CO_2 has become a traded, regulated, and contested commodity.

2. Methodology

This study employs a structured, comparative approach to benchmark national Carbon Capture, Utilization and Storage strategies in five leading nations – the United States, Canada, Austria, France, and Sweden. By evaluating each country along six dimensions (Political-legal factors, Economic factors, Organizational factors, Technological factors, Ecological factors, and Social factors), common patterns, divergences, and best practices will be compared. Below the key methodological steps are outlined and the selection and analytic framework is justified.

2.1. Nation Selection and Data Collection

The five nations included in this study were selected on the basis that each has published a comprehensive, publicly available, national-level CCU/S strategy. By restricting the sample to countries with formally articulated carbon management frameworks – namely the United States, Canada, Austria, France, and Sweden – it is ensured that the comparative analysis is both grounded in official policy and directly relevant to governments that have committed to CCU/S deployment at the national scale. This criterion allows for consistent coding of factors (e.g. technological priorities, regulatory mechanisms, financing instruments, infrastructure planning), thereby facilitating a transparent benchmarking of mature strategic approaches. The analysis draws on primary source documents, official national CCU/S strategy reports from the U.S. Department of Energy (DOE), Ministry of Natural Resources Canada, the Austrian Federal Chancellery, France's Ministry for Ecological Transition, and Sweden's Energy Agency.

2.2. Analytical Framework

Following a literature review, the results of two studies were identified and merged, thus thematic content analysis was employed: strategy documents were systematically reviewed, according to the influencing factors.

According to Romasheva and Ilinova's study, the following factors are affecting the implementation and deployment of carbon capture and storage (CCS) projects (Figure 1) (Romasheva–Ilinova 2019):

- Political-legal factors: policy and regulatory initiatives in legislation, programming, finance, taxation and management of CCS projects
- Economic factors: influencing the economic feasibility of CCS projects implementation
- Organizational factors: necessary conditions for implementation and trends in energy sector development
- Technological factors: facilitating the exchange of technological experience, technological aspects
- Ecological factors: impacts made on the environment
- Social factors: perception and interest of society in environmental technologies, impacts made on society

According to Storrs et al. (2023), the feasibility of CCU/S technologies is impacted by the following framework of factors (Storrs et al. 2023):

- Institutional factors: describing the political environment and legal infrastructure of the country
- Economic factors: impacting the economic viability of CCU/S, both internally and externally
- Organisational factors: related to how CCU/S initiatives are managed and organised
- Technological factors: impacting the physical, temporal and spatial implementation
- Environmental factors: threatening the environmental value
- Social factors: societies' trust, belief and perception of CCU/S

Figure 1. Classification of factors affecting the deployment of CCS projects including their manageability

Group of Factors	Factors	Manageability * 1	2	3
1. Political-legal factors	1.1 Kyoto protocol and Paris climate agreement (ratification, withdrawal)	V		
	1.2 Climate and energy policies of the country	V		
	1.3 Government programs, strategies for implementation of CCS projects, CO_2 emission reduction roadmaps	V		
	1.4 Detailed CCS specific laws	V		
	1.5 Environmental legislation (environmental protection, water, air and waste quality acts)	V		
	1.6 Standard, limiting CO_2 concentration in gas	V		
	1.7 CO_2 tax	V		
	1.8 Tax preferences for companies implementing CCS projects	V		
	1.9 Carbon capture tax credit	V		
	1.10 Emission trade scheme	V		
	1.11 Direct financial support for CCS projects implementation by different state funds and structures	V		
	1.12 Government support for R&D research	V		
	1.13 International cooperation on CCS projects	V		
	1.14 CO_2 storage permitting process	V		
	1.15 CCS technology promotion institutes and organizations	V		
	1.16 Predictable legal framework	V		
	1.17 Promoting environmentally responsible business	V		
	1.18 Educational tools at all levels of education	V		
2. Economic factors	2.1 Oil prices		V	
	2.2 Capital costs of CCS projects		V	
	2.3 Commercial efficiency of CCS technological schemes		V	
	2.4 Cost of energy required for CCS projects		V	
	2.5 CO_2 prices		V	
	2.6 Private financing of CCS technologies			V
3. Organizational factors	3.1 Level of economic development of the country		V	
	3.2 Focus on traditional energy sources		V	
	3.3 Renewable energy usage		V	
	3.4 Presence of the saline aquifers for CO_2 storage close to the sources of emissions			V
	3.5 Presence of the depleted hydrocarbon reservoirs close to the sources of emissions			V
4. Technological factors	4.1 Advanced centers for CCS technologies promotion (development and implementation)		V	
	4.2 Development and implementation of other environmental technologies		V	
	4.3 Non-maturity of technologies used in different stages of CCS chain		V	
5. Ecological factors	5.1 Significant CO_2 emissions		V	
	5.2 Possibility of CO_2 leaks from geological formations		V	
6. Social factors	6.1 Public acceptance of CCS projects		V	
	6.2 Non-commercial organizations' attitude to the CO_2 storage		V	
	6.3 Employment deficit in the region		V	
	6.4 Public interest in other environmental technologies		V	
	6.5 Impact on economic activity by locals (farming, agriculture, fishery)		V	
	6.6 Monetary burden on taxpayers		V	

Source: own construction based on Romasheva–Ilinova (2019)
Note: * 1 – it means that the factor can be managed and controlled by various state authorities; 2 – it means that state authorities can partly manage and control factors by creating special condition primarily reflecting the factors of group 1; 3 – it means that factors can't be managed and controlled by various state authorities.

2.3. Limitations

The methodology relies on publicly available strategy documents, simplifying complex policy nuances, which may not fully capture ongoing policy updates or sub-national initiatives. However, accompanying qualitative notes aim to mitigate this limitation by providing context on policy depth and maturity.

3. Discussion and Results

In the following paragraph, the comparative analysis of the carbon management strategies of the United States, Canada, Austria, France, and Sweden will be presented according to the factors influencing the deployment of CCU/S technologies: Political-legal factors, Economic factors, Organizational factors, Technological factors, Ecological factors, and Social factors.

3.1. Political-Legal Factors

The political-legal factors in the carbon management strategies of the United States, Canada, Austria, France, and Sweden are summarized in Table 2.

Table 2. Summary of political-legal factors in the carbon management strategies of the United States, Canada, Austria, France, and Sweden

Country	Legislation & Policies	Incentives & Finance	Governance & Oversight
USA	IRA (2022) and BIL (2021) with $12 B for CCUS; Class VI well regulations.	45Q tax credit ($85–180/t); $12 B grants; DOE loan guarantees.	DOE leads; interagency task forces and state–federal coordination.
Canada	Carbon pricing ($65→$170/t by 2030); Clean Fuel/Electricity regs; CCUS ITC.	ITC, $15 B Growth Fund, $8 B Net-Zero Accelerator; R&D support.	NRCan leads; strong federal–provincial cooperation; Indigenous consultation.
Sweden	EU ETS; SEK 36 B CCS support scheme; planned energy tax relief.	Public subsidy for bio-CCS; relies on EU/state aid; no CCUS tax credit.	Energy Agency is CCS Centre; coordinates permitting, auctions, EU dialogue.
France	Draft CCUS strategy (2023); 4–8 Mt target by 2030; plans for 15-yr CCfDs.	CCfDs under development; early hubs to be publicly supported; EU ETS applies.	Ministries lead with cluster input; regulatory bodies to oversee storage; EU coordination.
Austria	Strategy (2024) lifts CO_2 storage ban; legal reform for pipelines and targets.	No subsidies yet; plans for public–private finance and R&D support.	Strategy by finance/climate ministries; governance council planned; regional collaboration.

Source: own edit based on Natural Resources Canada (2023), Bundesministerium für Finanzen (2024), Fossil Free Sweden (2024), Ministère de l'économie des finances (2024), U.S. Department of Energy (2024)

The U.S. and Canada have the most developed legal frameworks, with sweeping legislation (IIJA, IRA in the U.S.; tax credits and carbon pricing in Canada) to underpin CCU/S. Both emphasize fiscal incentives (45Q tax credit, refundable ITCs, federal funding programs). Sweden's legal approach is centered on strong public support for bio-CCS through state aid rather than carbon pricing (EU ETS provides its price signal). France is just beginning, with a draft strategy setting capture targets and proposing 15-year CCfDs for industrial projects. Austria's strategy is pre-emptive: it has no CCU/S laws yet (storage is currently banned) but recommends lifting bans, transposing EU directives, and setting mandatory capture/transport/storage targets.

On governance, the U.S. relies on DOE-coordinated, multi-agency task forces to streamline permitting and oversight. Canada explicitly integrates federal–provincial collaboration and Indigenous input into its strategy. Sweden created a dedicated CCS Centre (the Energy Agency) to coordinate efforts, reflecting a centralized model. France plans to leverage its cluster approach (industrial regions) with national oversight. Austria's strategy emerged from Ministries of Finance and Climate, with a broad stakeholder process, indicating a top-down but consultative approach. Each country's policy reflects its political system: federal coordination in North America; a national auction scheme in Sweden; EU-aligned regulatory work in France; and a legally cautious, study-driven approach in Austria.

3.2. Economic Factors

The economic factors in the carbon management strategies of the United States, Canada, Austria, France, and Sweden are summarized in Table 3.

Table 3. Summary of economic factors in the carbon management strategies of the United States, Canada, Austria, France, and Sweden

Country	Investment incentives	Carbon pricing impacts	Market confidence
USA	45Q credit ($85–180/t); $12 B grants; DOE loan guarantees	No federal price; 45Q & state (CA/OR) credits serve as implicit value; EOR markets	High certainty from IRA/BIL; strong R&D & policy signals; permitting remains a bottleneck
Canada	30% refundable ITC; $15 B Growth Fund CCfDs; $8 B Accelerator; $319 M R&D; CIB pipeline loans	Federal + provincial carbon price ($65→$170/t); emerging CCUS offset credits	High predictability via ITCs, carbon levy; harmonization with US/EU rules enhances investor appeal
Sweden	SEK 36 B bio-CCS subsidy (auctions); no dedicated CCUS tax credit	EU ETS only; negative-emissions counted separately, not used to offset targets	Guaranteed auctions provide revenue clarity; reliance on state aid approvals adds some uncertainty
France	Planned 15-yr CCfDs; pilot hubs via public tenders; limited EU ETS allowances	EU ETS revenues only; strategy avoids reliance on additional carbon pricing	Moderate: CCfDs & legal reforms signal commitment; market still nascent
Austria	No current subsidies; proposes CFDS, feasibility grants; mobilize R&D funds	EU ETS only; envisage general-budget support or future levies; no explicit CO_2 price	Low: legal clarity pending; no domestic projects yet; storage abroad must be assured to build confidence

Source: own edit based on Natural Resources Canada (2023); Bundesministerium für Finanzen (2024); Fossil Free Sweden (2024); Ministère de l'économie des finances (2024); U.S. Department of Energy (2024).

Economic feasibility in the U.S. and Canada is driven largely by strong fiscal incentives and market mechanisms. The U.S. 45Q tax credit and the large Bipartisan Infrastructure Law funds make carbon capture projects significantly more attractive. Similarly, Canada's refundable ITC (worth billions) and Growth Fund Contracts for

Difference are designed to underwrite project revenue. These measures, along with steadily rising carbon prices, create a favorable investment environment. Sweden's approach is different: it absorbs most costs via subsidies. The first auction awarded roughly SEK 20 B of support (from a 36 B SEK envelope) to one BECCS project. This ensures full cost coverage but requires the state to bear nearly all expenses. France's plan relies on long-term CCfDs to guarantee project cash flows, but the exact value of support per ton is still to be defined. Austria's strategy focuses on minimizing overall costs through shared infrastructure (e.g. cross-border pipelines) rather than large upfront spending. A 2024 study (cited by CATF) estimates €12–18 B might be needed for a national pipeline network to transport 5–20 Mt/yr of CO_2. In all cases, the scale of investment needed is high, and governments use policy tools (credits, grants, auctions) to attract private capital.

Across countries, carbon pricing plays a supporting role. Canada's explicit carbon tax adds incentive (it will reach $170/t by 2030), effectively boosting returns from avoided emissions. The U.S. relies on tax incentives and does not impose an economy-wide CO_2 price on industry, though regional programs (like California's LCFS credits) can provide some revenue. Sweden treats BECCS as a compliance measure within the EU ETS (negative emissions), so captured CO_2 earns full ETS credit value rather than being sold back into the market. France and Austria, being in the EU ETS, similarly have to navigate allowance allocations; France's strategy explicitly frames CCU/S as tackling only residual emissions so as not to undermine CO_2 pricing. Ultimately, investor confidence hinges on long-term policy stability, which the U.S. and Canada have bolstered with legislation, while Sweden achieved via legally-backed auctions. France and Austria have recently signaled intent but have less historical certainty, as their strategies are early steps in policy development.

3.3. Organizational Factors

The organizational factors in the carbon management strategies of the United States, Canada, Austria, France, and Sweden are summarized in Table 4.

Table 4. Summary of organizational factors in the carbon management strategies of the United States, Canada, Austria, France, and Sweden

Country	Lead Institutions	Coordination Mechanisms	Energy Sector Context
USA	DOE (FECM, OCED, Labs) + EPA Class VI; interagency (CEQ, USDA, DOD); state permitting	DOE-hosted task forces & White House CCS groups; regional hubs via DOE grants; public-private coalitions	Diverse mix: power, hydrogen, industry; existing EOR pipelines; four DOE use-cases (power, hydrogen, bioenergy, DAC)
Canada	NRCan with Climate/Finance/Energy Ministries; provinces (AB, SK) regulate storage	Federal–provincial tables; industry consortia (CCEMC, CCUS Council); MEA/GCCSI collaborations	Oil & gas (EOR), bitumen, natural gas, cement, ammonia, pulp; Indigenous land projects
Sweden	Swedish Energy Agency as CCS Centre; EPA-equivalent for permits	Fossil Free Sweden platform; CCS Centre dialogues; EU & Nordic consortia	Forestry & bioenergy focus: pulp mills, biomass plants, CHP; BECCS for negative emissions

Country	Lead Institutions	Coordination Mechanisms	Energy Sector Context
France	Ministries of Écologie & Industry; Andra/INERIS; industrial clusters	Four industrial hubs by 2030; implied CO_2 registry; EU-level coordination (Norway, Italy)	Clustered refineries, steel, cement, chemicals; nuclear/gas power; limited coal; CCUS to decarbonize heavy industry
Austria	Finance & Climate Ministries (BMF, BMK); future CO_2 Council; AIT & universities	Inter-ministerial councils; EU networks (ECCSEL); industry associations consulted	Smaller industry: cement, steel, waste incineration; no domestic power CCS; relies on cross-border pipeline integration

Source: own edit based on (Natural Resources Canada 2023, Bundesministerium für Finanzen 2024, Fossil Free Sweden 2024, Ministère de l'économie des finances 2024, U.S. Department of Energy 2024)

Institutional arrangements vary. In the U.S., the federal government (led by DOE) plays the central role in CCU/S strategy and execution. DOE's offices (FECM, OCED, Office of Science, LPO, etc.) collectively fund R&D and demos, while EPA and Interior regulate storage and pipelines. The U.S. strategy explicitly describes interagency task forces for permitting and "CO_2 removal," reflecting strong federal coordination. Canada also has a clear federal champion (Natural Resources Canada) but pushes much of the work through federal–provincial cooperation. Notably, Canada's strategy was developed with consultation from provinces and Indigenous groups, and it envisions federal and provincial governments working in tandem (e.g. joint investments and harmonized regulations).

In Sweden, the single most important body is the Swedish Energy Agency, now formally the "National Centre for CCS," which is mandated to plan, coordinate and promote CCU/S nationally. This reflects Sweden's centralized governance model. The strategy itself was developed by a semi-public body (Fossil Free Sweden) but the Energy Agency will implement it. In contrast, France's approach remains rooted in its ministerial structure. The Environment and Industry ministries lead, with local prefectures (regional authorities) and national research institutes playing roles. France specifically envisions CCU/S deployment via "hubs" or "clusters" in major industrial basins, necessitating coordination between companies and authorities in each region. Austria similarly centralizes initial planning in government ministries. Its carbon management strategy was created by the Finance and Climate/Environment ministries with stakeholder input. Implementation will require cross-sector committees and may build on existing energy research coordination mechanisms.

Across the five countries, the involvement of industry is crucial. The U.S. relies on public–private partnerships (for example, proposed industrial hubs) and expects industry to lead capture projects once the policy is set. Canada actively engages industry and Indigenous communities, treating CCU/S as a nation-building economic sector. Sweden's policy development was industry-driven (through Fossil Free Sweden), and its energy agency will work directly with biomass-based industries. France and Austria are engaging their industrial clusters early to ensure technology and infrastructure plans align with existing manufacturing needs. In all cases, setting up mechanisms (from advisory boards to federal–state tables) to coordinate many stakeholders is seen as essential to guide CCU/S deployment.

3.4. Technological Factors

The technological factors in the carbon management strategies of the United States, Canada, Austria, France, and Sweden are summarized in Table 5.

Table 5. Summary of technological factors in the carbon management strategies of the United States, Canada, Austria, France, and Sweden

Country	Capture Technologies	Infrastructure & Storage	RD&D & Innovation	Technology Readiness
USA	Full suite: post-/pre-combustion, oxyfuel, membranes, cryogenic, chem-looping; strong DAC & bio-CCS pilots	Gulf Coast/TX EOR pipelines; DOE regional hubs; saline & oil-field storage; offshore injection; cross-state rights-of-way	>$500 M/yr via DOE/ARPA-E; labs & pilots (Petra Nova, NET Power, Summit DC); private cost-share	Multiple commercial CCS; DAC at demo scale; bio-CCS proven; focus now on cost reduction
Canada	Amine capture at ethanol, refineries, gas plants; leading DAC & BECCS pilots; labs on mineralization	Enbridge & Weyburn Midale pipelines; NW Corridor plans; proven Alberta/SK reservoirs; saline/basalt tests; ship freight trials	$319 M (2022–28) + $1 B CCUS pillar; CRIN & CarbFix partnerships; university & national lab R&D	Several operational CCS (Boundary Dam, Shand); mature DAC & BECCS scaling; high readiness
Sweden	BECCS focus: pulp mills & biomass plants; CCU (e-fuels, plastics); biochar & forestry sinks	No local storage: planned export via pipeline/ship to Norway/Baltics; Northern Lights study; EU pipeline codes compliance	BECCS optimization funding; KTH & Chalmers pilots; Horizon Europe projects; Fossil Free Sweden collaborations	Low–medium: capture tech mature; no storage connect; pilots pending; first industrial plants needed
France	Amines & oxy-combustion pilots for cement, steel, refineries; CCU e-fuels RD&D; Norway export partnership	Short-term export to Norway/Europe; pipeline network studies; 2030 domestic storage mapping; CO_2 transport framework & ROW planned	Pilot calls (seismic, injection) by 2025; BRGM/IFPEN & Air Liquide R&D; EU projects; R&D tax credits	Nascent: no operational CCS in France; relies on imported/demo testbeds; commercial roll-out awaits permits
Austria	Cement, lime, steel, incinerator emissions targeted; import EU tech; study CCU waste-to-fuel	Must export CO_2 via pipeline (to DE/IT); cross-border corridor scenarios; small "pilot storage" under review; open-access aim	Feasibility studies only; pilot-project funding planned; ECCSEL R&D cooperation; AIT & universities	Essentially zero: no capture units or pipelines; pilot tests planned; heavy institutional push required

Source: own edit based on Natural Resources Canada (2023); Bundesministerium für Finanzen (2024), Fossil Free Sweden (2024), Ministère de l'économie des finances (2024), U.S. Department of Energy (2024)

The technological dimension reflects each country's industrial profile and innovation priorities. The U.S. strategy espouses an "all-of-the-above" technology approach. DOE focuses R&D on reducing capture costs (e.g. new sorbents, cryogenic systems) and on diverse applications (power, hydrogen, bioenergy, and CDR). The

U.S. also invests in CO_2 transport modeling and storage monitoring (NETL tools) to inform build-out. Canada likewise is technology-agnostic, funding amines, membranes, DAC, and CDR. Notably, Canada funds a DACCS protocol under its offsets system, signaling support for even early-stage CDR tech.

Sweden's strategy is unique in its singular focus on biogenic sources. It treats BECCS (and related CCU for fuels/materials) as the "industrial sector" for CCU/S. Thus technology efforts center on capturing CO_2 from forest-industry flue gases and converting it into sustainable products (electrofuels, carbon-based goods). No mention is made of DAC or fossil CCS. This fits Sweden's resource base (plenty of biomass and waste).

France emphasizes scaling available technologies in its existing industries. The strategy explicitly plans initial CCU/S hubs for major industrial clusters, which implies retrofitting known capture units (amines, oxygen-blown processes) on large plants. France also notes CCU possibilities (e-fuels from captured CO_2), but these are more speculative. The strategy calls for storage assessment and pilot injections by 2025, indicating a rapid movement toward demonstrating the full chain.

Austria lags technologically. It identifies steel, cement, waste as targets but has no prior projects. Its recent feasibility study on a CO_2 pipeline network and an academic atlas of Austrian CO_2 emissions show preparatory work. The strategy includes promoting R&D and pilot projects in CCU/S/CDR, but acknowledges that deployment requires "cost-effectiveness". In practice, Austria will initially import or adapt technologies from abroad once legal hurdles are overcome.

All five countries stress knowledge sharing: the U.S. engages internationally (Clean Energy Ministerials, DOE labs open to partners), Canada participates in global CCS consortia (GCCSI, CCEMC) and emphasizes lessons from U.S./EU policy. Sweden is active in EU research projects. France is aligning with EU efforts (notably France–Norway collaboration). Austria explicitly calls for EU-wide standardization and cross-border coordination. The diffusion of technology thus leverages both national R&D and participation in global networks.

3.5. Ecological Factors

The ecological factors in the carbon management strategies of the United States, Canada, Austria, France, and Sweden are summarized in Table 6.

Table 6. Summary of ecological factors in the carbon management strategies of the United States, Canada, Austria, France, and Sweden

Country	**Mitigation Role**	**Environmental Impacts**	**Sustainability & CDR**	**Monitoring & Reporting**
USA	Critical for hard-to-abate sectors; IPCC pathways rely heavily on CCS; LTS: ≥400 Mt/yr by 2050; global gigaton ambition.	EPA Class VI & NEPA safeguards; pipeline safety plans; Justice40 hotspot avoidance; mandatory local-benefit reviews.	BECCS, DACCS, mineralization for residual emissions; R&D on direct-air capture; permanence required for CDR crediting.	Well-logging, surface and satellite monitoring; DOE-funded sensor R&D; mandatory data sharing across CCUS programs.
Canada	Integral to net-zero; ~15 Mt/yr by 2030;	Alberta storage site certification; lifecycle	Protocols for DACCS & BECCS	Provincial MRV rules; developing national

Country	Mitigation Role	Environmental Impacts	Sustainability & CDR	Monitoring & Reporting
	CCUS complements deep cuts; BECCS & DACCS explicitly pursued.	GHG accounting for DACCS; integrates CCS with forestry and soils; methane control.	in offsets; sustainable feedstocks; CCU R&D for e-fuels; mineralization studies in labs.	CDR inventory; funded CO_2 sensor/remote-sensing programs; continuous site monitoring.
Sweden	Essential for 2045 net-zero; mandates 11 Mt negative emissions by 2045 via BECCS; biogenic CO_2 focus.	"No replace" stance on emission cuts; biodiversity & land-use safeguards; permanent negative storage; strict EIA vetting.	BECCS-based negative emissions only; EU definitions for residual offsets; bio-CCU products; no DACCS.	EU storage monitoring; auction reporting; climate-law accounting; emphasis on permanence transparency.
France	5–10% of industrial CO_2 by 2030, ~50% by 2050; preserves industry; CCUS only for emissions lacking other solutions.	Early-stage EIAs planned; rigorous seismic/injection studies; net-benefit requirement; manage noise/leak risks.	BECCS & biofuels noted; CCU as long-term e-fuel/chemical option; CDR framing aligned with EU strategy; bio-feedstock safeguards.	Andra geological oversight; GEREP registry expansion; strict credit attribution to avoid double-claiming.
Austria	CCS for unavoidable process CO_2 only; framed as environmental necessity, not policy relief.	Strict storage safeguards; mandatory EIAs for pipelines/injection; require renewable power match to avoid indirect emissions.	BECCS potential acknowledged but secondary; CCS prioritized; sustainable biomass R&D; aligns with EU CDR frameworks.	EU 30+ yr monitoring; adopt ECCSEL best practices; community safety checks included in policy design.

Source: own edit based on Natural Resources Canada (2023), Bundesministerium für Finanzen (2024), Fossil Free Sweden (2024); Ministère de l'économie des finances (2024), U.S. Department of Energy (2024)

All five countries emphasize that CCU/S must yield real climate benefits without shifting burdens. The U.S. strategy and Canada's approach strongly align with the view that CCU/S is for residual, hard-to-eliminate emissions. This is reflected in targets (e.g. France's 4–8 Mt by 2030 and Austria's focus on "unavoidable" emissions). Importantly, every strategy insists on environmental safeguards. In the U.S., pipeline design standards and EPA Class VI permits protect water resources. Canada likewise enforces storage site care (Alberta's CCS regulations) and is developing detailed monitoring (even for direct air projects).

Sweden uniquely stresses that carbon capture should supplement, not replace, emission reductions. It also mandates that biogenic CO_2 capture be used solely to meet climate goals (not counted twice), preserving "market trust" in negative emissions. This reinforces sustainability: biomass feedstock quality and biodiversity considerations are integral (capturing from forest industry residues only). France's draft policy similarly makes CCS a climate tool for residual sources, explicitly warning against using negative emissions as an excuse to continue fossil combustion.

All strategies call for permanent storage and transparency. For instance, Sweden insists that only *permanent* negative emissions are counted. Canada's strategy under development of the national GHG Offset System includes protocols (like DACCS) that ensure carbon is sequestered permanently. The concept of negative emissions is embedded: Canada and Sweden mention BECCS and DACCS as needed for net-zero. Austria's strategy even defines "unavoidable" process emissions that would necessitate CCS.

In practical terms, monitoring and reporting standards are to follow international norms. France plans seismic surveys and pilot injections under EU frameworks. The U.S. DOE supports sophisticated verification (e.g. the Class VI well program). Ultimately, the documents reflect that CCU/S is seen as a critical climate intervention, but one that is contingent on environmental responsibility and actual long-term storage. Public and regulatory trust is tied to these ecological commitments.

3.6. Social Factors

The social factors in the carbon management strategies of the United States, Canada, Austria, France, and Sweden are summarized in Table 7.

Table 7. Summary of social factors in the carbon management strategies of the United States, Canada, Austria, France, and Sweden

Country	Stakeholder Engagement	Community Impacts	Public Perception & Outreach
USA	DOE: community benefit plans, Justice40, public input required.	Jobs for fossil regions; design standards for health/safety.	Mixed views; transparency & outreach are key priorities.
Canada	1,500+ consultations incl. Indigenous groups; outreach planned.	Local jobs & retraining; early projects benefit provinces.	Moderate awareness; Indigenous consent crucial.
Sweden	CCS Centre coordinates; industry–government dialogue ongoing.	Green jobs (e.g. Stockholm); industrial renewal focus.	Low awareness; framed as innovation & national leadership.
France	Public/industry consultations in 2023; transparency planned.	Projects in industrial zones; CCUS framed as job preserver.	Limited debate; strategy tied to decarbonization credibility.
Austria	Strategy calls for awareness campaigns & trust-building.	Regional cohesion focus; cautious acceptance; Green Party supports.	CCS unpopular in past; strategy promotes education & dialogue.

Source: own edit based on Natural Resources Canada (2023), Bundesministerium für Finanzen (2024), Fossil Free Sweden (2024), Ministère de l'économie des finances (2024), U.S. Department of Energy (2024)

Social acceptance and community impacts are treated with varying prominence. In the U.S., equity and community benefits are explicitly integrated into the strategy. U.S. policy mandates that CCU/S projects contribute to local economic development and environmental justice, reflecting learned lessons (and political priorities) on clean energy transitions. In Canada, the strategy highlights inclusive engagement: over a thousand stakeholders including Indigenous peoples and NGOs were consulted. It emphasizes that Northern and Indigenous communities must be involved, although there is no specific "Justice40" equivalent; rather, the approach is via thorough consultations and benefit-sharing.

Sweden's document is less focused on social issues per se, but by promoting BECCS largely from existing industries, it implicitly builds on communities' support for transitioning familiar sectors. The messaging ("Sweden's chimneys as untapped resource") is positive. There is recognition that negative emissions should be credible, which ties into societal trust. Sweden also notes, however, that sustainable biodiversity and materials use must be respected, showing an environmental justice angle to ensure communities get true climate benefits.

France and Austria are the least developed socially. France's strategy was only published recently, and although it went to public consultation, it does not detail outreach or community benefits. Its narrative stresses that CCU/S is necessary for climate and industry, implying a social license is conditional on climate gains. Austria's strategy explicitly flags the need to improve public perception and share safety information. Given Austria's prior ban on CCS (reflecting public resistance), the government plans proactive engagement.

All five countries see economic opportunities (jobs, industrial activity) as social benefits of CCU/S. The U.S. and Canada stress retraining fossil fuel workers, while Sweden and France highlight preserving or creating "green industry." Austria expects new high-skill jobs in infrastructure, though it is more cautious. Notably, every strategy warns against using CCS to justify delaying other actions (e.g. fossil phase-out), because that could undermine public trust. In sum, policy documents frame CCU/S deployment as a technical necessity with social safeguards: transparency, consultation and tangible community benefits are viewed as essential for acceptance.

4. Conclusion

This comparative benchmarking of national carbon management strategies for the United States, Canada, Sweden, France, and Austria across six dimensions – political-legal, economic, organizational, technological, ecological, and social – yields the following key findings.

Political-Legal Foundations

All five countries recognize the necessity of clear legal frameworks and supportive policies to enable large-scale CCU/S deployment. The U.S. combines landmark legislation (IIJA, IRA) with agency rule-making (EPA Class VI), while Canada leverages a rising carbon price plus a refundable investment tax credit. Sweden and France, as EU ETS members, rely primarily on EU carbon pricing but have introduced national mechanisms (reverse-auction grants, CCfDs) to fill gaps. Austria is still transitioning from a storage ban to full regulatory enablement. Across the board, durable incentives and unambiguous permitting regimes proved critical to secure investor confidence.

Economic Incentives & Market Signals

Generous, long-duration fiscal incentives – such as the U.S. 45Q credit (up to \$180/t) and Canada's refundable ITC (≈C\$313/t) – are the most powerful drivers of CCU/S project economics. Sweden's large bio-CCS auction and France's 15-year

CCfDs provide similar revenue certainty. Where incentives alone are insufficient, explicit carbon prices (Canada) or EU ETS revenues (France, Sweden, Austria) bolster project viability. Austria's tentative cost-sharing proposals indicate that early-stage funding remains a major barrier wherever dedicated CCU/S subsidies have yet to materialize.

Organizational Leadership & Coordination

Effective CCU/S strategies are underpinned by strong institutional leadership and multi-stakeholder coordination. The U.S. DOE and Canada's NRCan offer centralized policy direction, complemented by interagency and federal–provincial working groups. Sweden's CCS Centre and France's industry cluster consortia exemplify public-private collaboration. Austria's proposed CO_2 Council and inter-ministerial approach illustrate emerging best practices – but remain to be tested in implementation. In every case, formal coordination mechanisms (task forces, tables, auctions) were essential to align technical, regulatory, and commercial actors.

Technological Priorities & Infrastructure

Each strategy tailors its technology mix to national contexts: the U.S. and Canada embrace broad portfolios (point-source CCU/S, DAC, BECCS), Sweden focuses on bio-CCS and natural sinks, France targets industrial hubs with CO_2 transport links, and Austria awaits regulatory clarity before piloting. Across strategies, shared emphasis on transport and storage infrastructure – pipelines, hubs, and cross-border networks – emerged as the linchpin connecting capture to secure sequestration or utilization. Notably, early planning of large-scale networks (e.g. USA midcontinent corridors, France's North Sea pipelines) sets the stage for future scalability.

Ecological Considerations

All five strategies underscore CCU/S as a critical complement to emissions reductions (renewables, electrification) for "hard-to-abate" sectors. Sweden's explicit framing of bio-CCS as negative emissions and Canada's protocol for DACCS highlight emerging ecological ambitions beyond simple capture. France and Austria reference EU "do no significant harm" principles, ensuring CCU/S projects meet rigorous environmental impact assessments. Yet, systematic lifecycle analyses and monitoring plans remain variably detailed, indicating a research gap in harmonized ecological metrics.

Social Acceptance & Equity

Social license is addressed most comprehensively in the U.S. (environmental justice guidance, tribal consultation) and Canada (Indigenous partnerships). Sweden and France discuss stakeholder engagement within their auction and cluster frameworks. Austria's strategy calls for broad advisory councils but lacks explicit community-level commitments. Overall, transparent communication, benefits sharing, and early engagement with local and Indigenous communities are recognized as indispensable to minimize opposition and foster sustained project support.

By synthesizing these dimensions, this study highlights both common success factors (durable incentives, clear governance, early infrastructure planning) and persistent gaps (social equity safeguards, detailed ecological metrics). Addressing these through targeted research and iterative policy refinement will be crucial to scale CCU/S technologies in the pathway to net-zero emissions.

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