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Scenario-Based Assessment of CCUS Deployment Pathways for Carbon Emission Reduction in Iran's Energy-Intensive Industries Using an AHP Framework

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ABSTRACT

Iran's industrial transition toward carbon emission reduction technologies, particularly Carbon Capture, Utilization, and Storage (CCUS) technology systems, has been considered in recent years a strategic axis for promoting environmental sustainability and enhancing the efficiency of energy-intensive industries. This study analyzed potential deployment patterns of CCUS technologies by examining three development approaches: gradual, accelerated, and Hybrid Scenarios (HS). The gradual scenario focuses on phased development and the reduction of initial risks; the accelerated scenario seeks the rapid deployment of CCUS infrastructure through extensive investment and policy support; and the HS attempts to provide a sustainable and manageable industrial process by balancing costs, risks, and reliability. In addition, this study examines the technical, economic, and policy challenges associated with CCUS implementation and proposes implementation strategies, including the formulation of supportive policies, the development of CO_2 transport and storage infrastructure, technological capacity building, and the strengthening of public–private partnerships. To evaluate the different pathways, an AHP-based hierarchical model was used to analyze the performance of CCUS applications in power plants, industrial facilities, and refineries using six main indicators: cost, technological attractiveness, technological capability, cultural index, passive defense, and environmental criteria. The results show that the CCUS option achieves the highest scores across all three applications and represents the most efficient option for emission reduction and economic value creation. These findings reinforce the importance of the planned development of CCUS in the country's energy landscape and highlight the need to establish support mechanisms for its commercialization and the expansion of industrial applications.

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1. Introduction

The use of fossil fuels is a major contributor to the production and emission of greenhouse gases. The increasing concentration of greenhouse gases (GHG) in the atmosphere enhances the absorption of infrared radiation emitted from the Earth's surface, thereby leading to global warming. Carbon dioxide (CO_2) is one of the most significant greenhouse gases and plays a crucial role in climate change (Vaddeboina & Puttapati, 2024).

Most of the CO_2 is produced by the energy sector. Therefore, given the growing demand for energy consumption to support global economic development, reducing CO_2 emissions and mitigating climate change require careful consideration. However, with continuously increasing global energy consumption, the limited availability of fossil fuel resources, and rising levels of environmental pollution, it has become essential to replace conventional approaches with innovative methods for utilizing primary energy sources. The application of CO_2 capture technologies is one of the approaches that has been extensively investigated by researchers in recent years (Nath et al., 2024). (Figure 1 shows the CO_2 emission chart and its share in different regions of the world between 1750 and 2024).

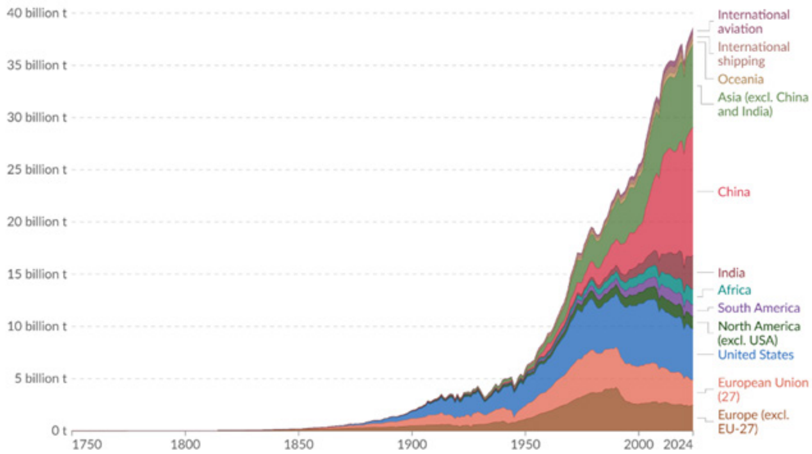

Figure 1. the CO_2 Emission Chart and its Share in Different Regions of the World Between 1750 and 2024 (Our World in Data, 2025)

(Figure 1) traces the evolution of annual CO_2emissions by region between 1900 and 2024 and highlights the major shift in the global distribution of emissions over time. In 1900, global CO_2 emissions reached approximately 1.96 Gt. Emissions were heavily concentrated in Europe and North America. The EU 27 accounted for about 0.71 Gt (36 %), and the United States contributed nearly 0.66 Gt (34 %). Non EU European countries added another 0.49 Gt. Together, Europe and North America dominated global emissions at the start of the twentieth century. At that time, China and India contributed only marginal shares. Emissions rose rapidly during the first half of the century, reaching 5.93 Gt by 1950. The United States then became the largest emitter, producing around 2.54 Gt – equivalent to 43 % of the global total. The EU 27 and non EU Europe remained major contributors, at roughly 1.28 and 1.10 Gt, respectively. In contrast, emissions from both China and India remained below 0.1 Gt each.

A more pronounced geographical shift occurred after 2000. Although the United States remained the largest emitter at that time, with emissions of about 6.02 Gt CO_2, China had already reached 3.64 Gt CO_2, nearly matching the EU-27 at 3.60 Gt. Emissions from the rest of Asia also increased substantially during this period, reflecting rapid industrialisation and economic growth across the region. By 2024, China had become the dominant global emitter, producing approximately 12.29 Gt CO_2, or nearly one-third of total global emissions. Emissions from the United States declined to around 4.90 Gt CO_2, while India increased to approximately 3.19 Gt. At the same time, both the EU-27 and non-EU Europe showed a gradual downward trend, each falling to nearly 2.4 Gt CO_2. Another noticeable change is the growing contribution of international aviation and shipping, which together accounted for more than 1 Gt CO_2 in 2024. Overall, the figure reflects the long-term transition of global emissions from a predominantly Western pattern toward one increasingly centred in Asia, particularly China.

The main program for capturing CO_2 gas is from large producers of this gas, such as power plants, industries, and oil refineries. Capturing CO_2 gas from small and mobile sources in the transportation sector, as well as residential and commercial buildings, is significantly more difficult and costly than capturing it from large-scale emitters. Therefore, it is often overlooked, and the focus is generally on separating gas from large CO_2 emitting sources (Shi & Hu, 2025). An alternative approach to preventing CO_2emissions from these small sources is the use of cleaner energy carriers, such as hydrogen and electricity produced in fossil fuel-based power plants or using renewable energy sources. Owing to concerns about climate change and the gradual warming of the Earth, numerous carbon capture and storage (CCS) projects are currently being implemented worldwide (Alizadeh et al., 2024).

2. Review of Previous Research

(Table 1) lists some previous studies.

Table 1. Review of Some Previous Research

Authors	Focus / Methodology	Key Findings / Conclusions	Reference
Keith et al.	Engineering design and techno-economic assessment of an industrial-scale direct air capture (DAC) facility	Estimated the levelized cost of CO_2 capture and identified the energy and material requirements for capture and regeneration cycles	(Keith et al., 2018)
Bachu	Analysis of geological CO_2 storage options with emphasis on the storage component	Demonstrated that although geological reservoirs have high storage capacity potential, long-term success depends on proper site selection, effective capture mechanisms, and reliable monitoring systems	(Bachu, 2008)
Nagireddi et al.	Systematic review of CCUS technologies; comparison of CO_2 capture, storage, and utilization pathways	Concluded that large-scale deployment of CCUS technologies is not feasible without significant cost reductions and the development of CO_2 transport and storage infrastructure	(Nagireddi et al., 2024)
Wilberforce et al.	Review of recent advances in CO_2 capture technologies	Emphasized that reducing energy requirements for CO_2 recovery and improving long-term operational sustainability are critical for economic viability	(Wilberforce et al., 2021)
Rosanali et al.	Feasibility assessment of CCUS facility installation using net present value methods	Showed how economic feasibility is strongly influenced by capital costs, operating costs, and discount rates	(Roussanaly et al., 2021)
Nink Konk et al.	Evaluation of CCUS technological reserves based on patent analysis	Assessed the state of technological development and innovation trends in CCUS using patent data	(Kang et al., 2021)
Lau et al.	Analysis of the role of CCUS in Singapore's energy transition	Highlighted the strategic importance of CCUS within national decarbonization and energy transition pathways	(Lau et al., 2021)

Jiang et al.	Policy cycle framework; analysis of China's CCUS policies across three Five Year Plans; comparison with US, Australia, Norway, Japan; evaluation of project data against the 2011 roadmap.	China has a relatively complete CCUS policy but lacks enforceable laws, has low operability, weak market incentives, and insufficient subsidies. Recommends legislation, better regulation, cross provincial cooperation, and green finance.	(Jiang et al., 2020)
Xu & Dai	Applies second best theory to justify CCUS as a necessary mitigation option. Analyzes market distortions (fossil path dependency, energy monopoly, externalities). Compares CCUS with renewables, efficiency, and afforestation. Reviews legal, economic, and social barriers.	CCUS is a second best choice due to renewable bottlenecks and fossil lock in. China has high storage potential (3120 Gt) but lacks specific laws, faces high costs, and low public acceptance. Recommends legislation, carbon tax, liability sharing, and public engagement.	(Xu & Dai, 2021)
Fan et al.	Bibliometric analysis of 968 Web of Science publications (2003 2024) using CiteSpace. Maps co citation networks, keyword clusters, and temporal evolution. Interprets findings through advocacy coalition framework (ACF) and multi level perspective (MLP) on socio technical transitions.	CCUS policy research has evolved through three phases: exploratory, expansion, and rapid growth. The existing literature focuses on several key areas. These include normative frameworks, macroeconomic support mechanisms, regulatory structures, financial incentives, and economic assessments. Nevertheless, significant gaps remain. For example, the Global South is underrepresented. Research collaboration remains fragmented. Moreover, social and institutional dimensions receive insufficient attention. Future work should integrate hydrogen and BECCS pathways. It should also explore digital technologies and participatory governance approaches.	(Fan et al., 2025)
Singh et al.	Employs Fuzzy Analytical Hierarchy Process (FAHP) to prioritise CCUS and renewable energy technologies for India's net zero carbon emission target by 2050. Four evaluation criteria are considered: cost, compatibility with existing and future energy mix, CO_2 reduction potential, and implementation time. Pairwise comparisons are converted into triangular fuzzy numbers with consistency ratio validation, complemented by Business As Usual (BAU) forecasting of energy demand and renewable generation from 1990 to 2050	CCUS demonstrates a substantially higher priority weight (0.981) compared to renewable energy (0.609), indicating that CCUS is the preferred technology for India given its coal dominated energy mix, relatively young coal power plant fleet, and land availability constraints for large scale solar and wind deployment. BAU projections reveal that renewable energy would meet only about 10% of India's electricity demand by 2050, necessitating sustained reliance on fossil fuels.	(Singh et al., 2025)
Xie et al.	LCA and levelized cost assessment of six coal chemical pathways (DCL, ICL, SNG, CTO, CTE, and CTM) with CCUS integration. Evaluation of EOR and DSA storage using carbon balance, transport network, and discounted cash flow analyses.	Without CCUS, carbon footprints range from 3.74 to 11.01 t CO_2/t product, with process emissions contributing over %85 of total emissions. CCUS reduces emissions by %65–36, while DSA storage shows higher mitigation performance than EOR. EOR storage costs range from 582–252 yuan/t, compared with 1,156–896 yuan/t for DSA storage. Raw material costs account for %76–55 of total expenditures.	(Xie et al., 2025)
Colombe et al.	Two-stage stochastic MILP model for CCUS infrastructure planning under policy uncertainty and investor risk aversion. Application to the Texas–Louisiana Gulf Coast considering CO_2 sources, saline aquifers, EOR sites, and pipeline networks.	Current 45Q incentives support economically viable near-term CCUS deployment, enabling nearly 300 Mt CO_2 capture even if incentives end after ten years. Policy uncertainty reduces expected CO_2 capture by up to 16% and has a greater effect than investor risk aversion. Increasing incentives improves capture deployment, although with diminishing returns.	(Colombe et al., 2024)

Although CCUS has been studied from various angles, the literature remains limited. Most studies focus on individual components, such as capture technologies, storage options, transportation, techno-economic performance, or environmental assessment, while fewer studies link these elements to deployment pathways and industrial transition. Some country-level studies have assessed CCUS options in relation to local capacity and national conditions, highlighting the importance of context-specific assessment. Building on this line of research, the present study examines CCUS deployment pathways for power plants, industries, and refineries in Iran, where the main question is not only which option is technically feasible, but also which pathway is more suitable under the current energy and industrial conditions of the country. For this purpose, gradual, rapid, and hybrid development scenarios are compared using an AHP-based multi-criteria decision-making framework.

2.1. Cost of Carbon Capture and Storage

The cost of carbon capture varies depending on the technology and industry, with estimates indicating that this cost ranges from 20 to 140 USD per ton of CO_2 in industrial settings (Adetoye et al., 2018). Some key variables for carbon capture and storage are as follows:

2.1.1. Cost of Carbon Capture and Storage Facilities

The cost of carbon capture in industrial settings, such as iron and steel, refining, pulp and paper, and Industries, ranges from 20 to 140 USD per ton of CO_2 (Adetoye et al., 2018).

2.1.2. Technological Variability: Different Technologies have Different costs

The reaction of CO_2 with amines has the highest costs, whereas calcium looping applied in the cement and pulp and paper industries has lower costs (Adetoye et al., 2018).

2.2. Examples of CCUS Facility Implementation Projects for Hydrogen Production (Blue Hydrogen)

Globally, the implementation of CCUS facilities is one of the most important processes related to clean energy production. Many countries are striving to develop blue hydrogen production to achieve carbon emission reduction goals and transition to sustainable energy. Information on some of these projects is given in (Table 2).

Table 2. CCUS Projects Information (IEA, 2023)

No.	Project Name	Country	Commissioning Year	Primary Feedstock	Technology	CO_2 Capture Capacity (t/year)	Hydrogen Production Capacity (t/year)
1	Port Arthur Project	USA	2013	Natural gas	SMR* +CCUS	900,000	117,700
2	Port Jerome Project	France	2015	Natural gas	SMR+CCUS	100,000	39,000
3	Quest Project	Canada	2015	Natural gas	SMR+CCUS	1,100,000	300,000
4	Sinopec Qilu Petrochemical CCS Project	China	2022	Coal	CCUS	1,000,000	Not reported
5	Al Reyadah CCUS Project (Phase 1)	United Arab Emirates	2016	Natural gas	CCUS	800,000	Not reported
6	Sapio-Mantova Project	Italy	2016	Natural gas	SMR+CCUS	Not reported	1,200

*. Steam Methane Reforming

3. Global and National Status

Numerous CCS projects are currently operational or under implementation worldwide. (Figures 2 and 3) together show that CCS deployment is still concentrated in a limited number of regions and applications. At the regional level, North America accounts for the largest share of operating CO_2 capture capacity, at about 51%, followed by Central and South America at 21%. Australia and New Zealand, Asia Pacific, and the Middle East each contribute relatively small shares, while Europe remains at only 5%. The planned 2030 portfolio is somewhat more distributed: North America still leads, but its share declines to around 45%, whereas Europe rises markedly to about 27%. This suggests that future projects are expected to be less concentrated than the current portfolio, although North America will remain the main hub.A similar pattern is observed by application. Natural gas processing is already the dominant category, representing 38% of operating facilities, and it is projected to increase to 65% in the planned portfolio. Hydrogen is the other notable growth area, rising from 12% to 28%. By contrast, power and heat, industry, direct air capture, and other fuel supply remain minor in both portfolios, each accounting for only about 1-2%. Taken together, the figures indicate that near-term CCS development is still anchored in natural gas processing and hydrogen, rather than in a broader expansion across power generation or direct air capture.

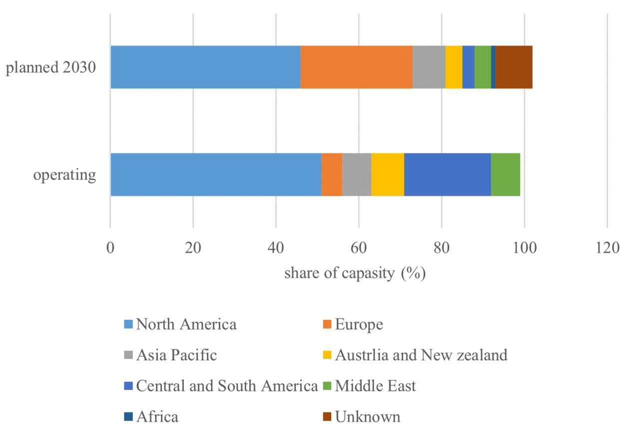

Figure 2. Operating and Planned CO_2 Capture Capacity by Region, Q1 2024 vs. 2030 (IEA, 2024)

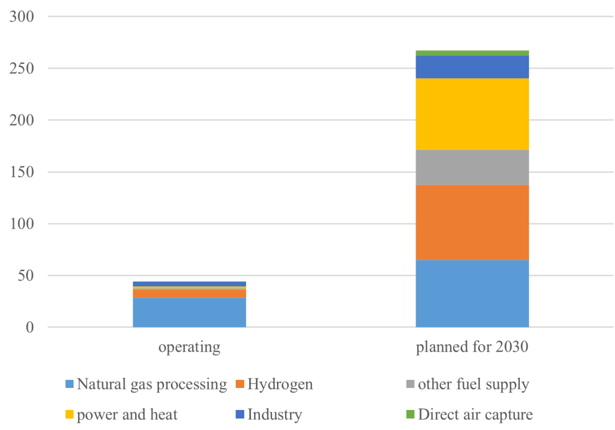

Figure 3. Operating and Planned Facilities with CO_2 Capture by Application (IEA, 2022)

3.1. National Status: Share of Different Sectors in CO_2 Emissions in Iran

The combustion of fossil fuels to produce heat or mechanical work for applications such as transportation fleets or power generation plants constitutes the largest part of energy system operations. During combustion, Carbon and Hydrogen atoms in fossil fuel molecules combine with atmospheric oxygen to form CO_2 and water (H_2O), releasing the chemical energy of the fuel in the form of heat. Carbon dioxide, as the most important product of combustion, plays a significant role in global warming; therefore, it is recognized as the most important greenhouse gas. (Figure 4) shows a clear rise in CO_2 emissions from fuel combustion in Iran over 2000-2025, although the increase is much stronger in some sectors than others. Electricity and heat production remained the main source of emissions during the whole period, increasing from roughly 75 Mt CO_2 in 2000 to more than 200 Mt CO_2 by 2025. The increase becomes noticeably steeper after 2018. This is likely related to the growing electricity demand and the continued dependence of the power sector on fossil fuels. Transport follows the same overall trend, with emissions rising from about 72 Mt to nearly 165 Mt CO_2. Compared with the power sector, however, the transport curve is more gradual and includes a few fluctuations during the mid-2010s. Residential emissions also increased considerably, reaching around 145 Mt CO_2 in 2025, which may reflect both population growth and higher household energy consumption. Industrial emissions show a similar pattern, particularly in the later years of the period, where the increase becomes more pronounced. In contrast, sectors such as Commercial and Public Services, Agriculture/Forestry, and Fishing remained relatively small contributors throughout the study period. Overall, the figure suggests that the recent growth in Iran's CO_2 emissions has been driven mainly by electricity generation, transport, and expanding energy demand in residential and industrial activities.

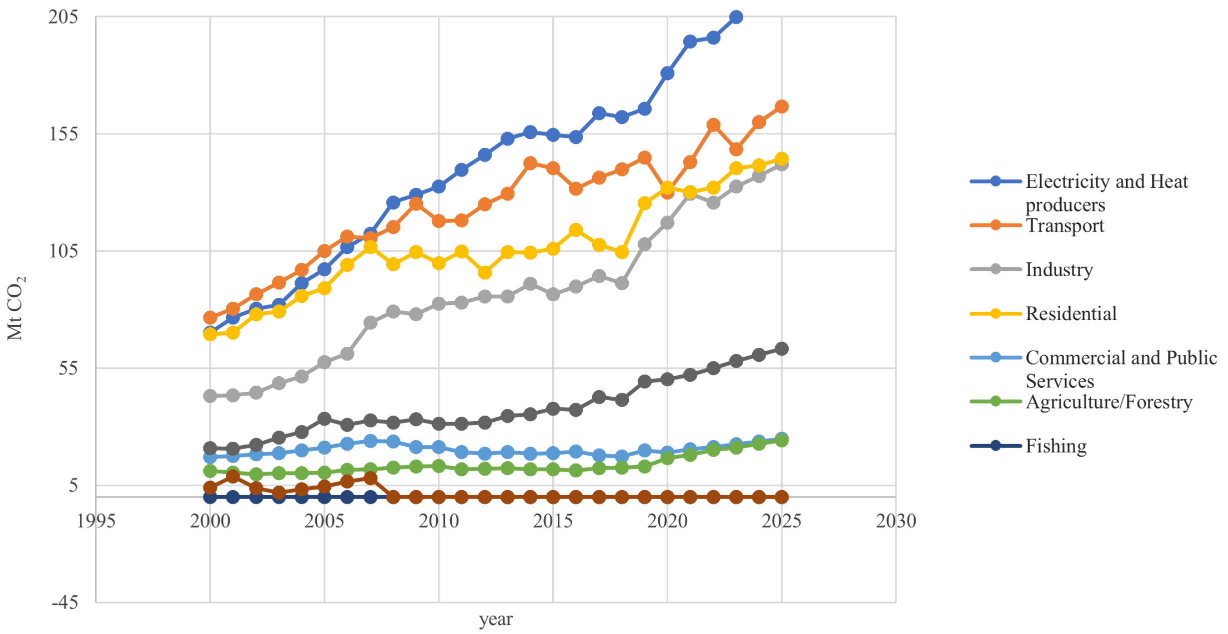

Figure 4. Trend of CO_2 Emissions (Due to Fuel Combustion) in Various Sectors from 2000-2025 (IEA, 2023)

(Figure 5) shows a clear imbalance in sectoral CO_2 emissions in 2025, with most emissions concentrated in a few major sectors. Electricity and Heat producers account for the largest share, reaching nearly 220 Mt CO_2. This value is substantially higher than all other sectors and reflects the continued dependence of the power sector on fossil-fuel-based electricity generation. Transport ranks second, with emissions close to 170 Mt CO_2, remaining about 50 Mt lower than the power sector but still considerably above the rest of the economy. The Residential sector contributes roughly 145 Mt CO_2, while Industry reaches nearly 140 Mt CO_2, indicating that energy consumption in households and industrial activities remains a major source of emissions. Together, these four sectors account for the overwhelming majority of total CO_2 emissions in 2025. In contrast, the remaining sectors contribute much smaller amounts. Commercial and Public Services remain below approximately 20 Mt CO_2, whereas Agriculture and Forestry stay near 25 Mt CO_2. Other energy industries contribute only around 10-15 Mt CO_2. The difference between these sectors and the major emitting sectors is considerable; for example, emissions from Electricity and Heat producers alone are almost ten times larger than those from Commercial and Public Services. This uneven distribution suggests that emission reduction policies in Iran will likely have the greatest impact if they focus primarily on electricity generation, transport, residential energy use, and industrial activities.

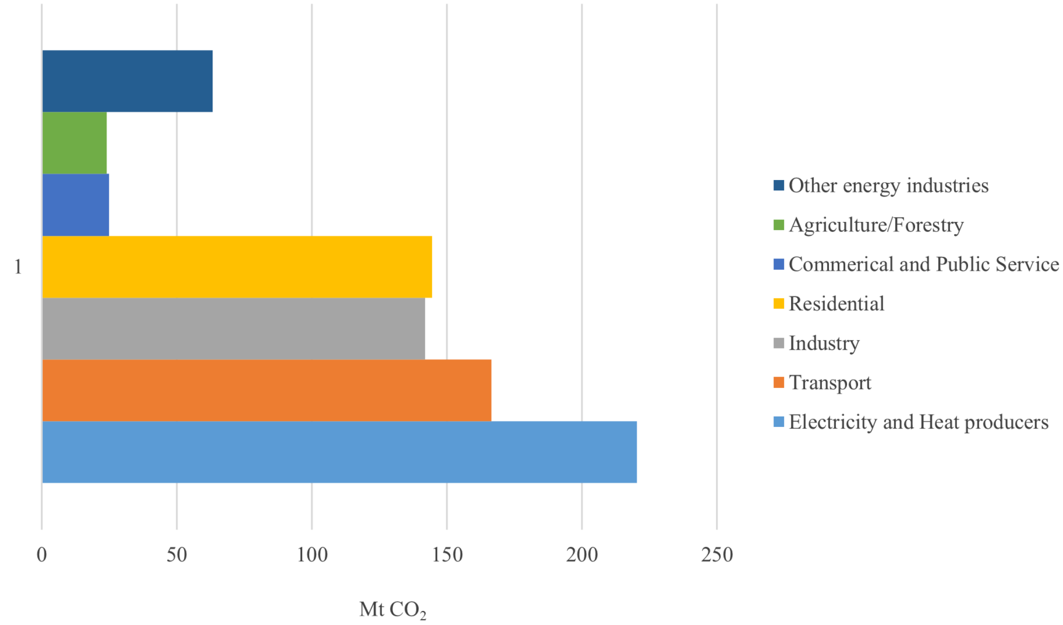

Figure 5. Share of each Consumption Sector in CO_2 Emissions (Due to Fuel Combustion) in 2025

4. Methodology

Designing decision-making scenarios for systems related to CCUS is one of the main pillars of strategic planning for reducing CO_2 emissions. In this section, the basis for designing scenarios is defined not in terms of the type of Hydrogen but in terms of the development and implementation pathways of CCUS technologies. Scenarios, as tools for analyzing technological, economic, and institutional uncertainties, enable the comparison of different industrial transition pathways based on CCUS.

4.1. Gradual CCUS Development Scenario

In this scenario, the deployment of carbon capture facilities begins in a phased manner and at a small scale. The initial focus is on natural gas-dependent industries and facilities with relatively simple integration capabilities using capture systems. The development of storage infrastructure is carried out as a pilot project, and after performance evaluation, scalability is achieved. The main feature of this scenario is the reduction of technological and economic risks through gradual learning and step-by-step system upgrades. This path is considered particularly suitable for countries with limited financial resources and institutional uncertainty.

4.2. Rapid CCUS Development Scenario

In this scenario, the focus is on the simultaneous and extensive development of CCUS facilities. Large-scale investments are being made in CO_2 transport infrastructure, geological storage reservoirs, and integrated industrial systems. The goal of this scenario is to achieve high capture and emission reduction capacities quickly. This path depends on the existence of stable policy frameworks, extensive financial support, and access to advanced technology.n

4.3. Hybrid CCUS Development Scenario

This scenario is a combination of the two previous paths, where gradual development in the short term is accompanied by targeted investments in the medium and long terms. In this approach, some industries enter the full CCUS phase, whereas other sectors are upgraded in stages.

The main strategy of this scenario is to balance the risk, cost, and speed of emission reduction. (Table 3) compares the three scenarios.

Table 3. Comparison of Three Scenarios

Scenario	Features	Drawbacks	Advantages
Scenario 1: Gradual CCUS Deployment	• Stepwise deployment of carbon-capture facilities; focus on pilot-scale and demonstration projects. • Limited concentration on large-scale industrial clusters. • Moderate pace of infrastructure development aligned with regulatory readiness and policy frameworks.	• Slower reduction of CO_2 emissions. • Longer time required to reach full capture capacity. • Dependence on stable policies and long-term investment guarantees. • Lower competitiveness compared to rapidly evolving international markets.	• Lower technological and economic risk. • Reduced need for large upfront capital expenditures. • Flexibility in adapting to industrial, political, and market conditions
Scenario 2: Rapid CCUS Development	• Accelerated investment and wide deployment of capture facilities across major industrial clusters. • Rapid development of CO_2 transport and storage networks. • Capability to implement CCUS in large point-source emitters.	• Requires extensive capital investment. • Higher technological and operational risks. • Possible regulatory and social-acceptance challenges. • Increased likelihood of market imbalance during early phases.	• Fast reduction of CO_2 emissions. • Quick alignment with global decarbonisation pathways. • Potential to establish competitive advantage in regional energy markets.
Scenario 3: Hybrid CCUS Development	• Combined use of CCUS, CCU, and CCS across major industrial sectors. • Integration with long-term decarbonisation programmes and large-scale projects. • Preservation of existing infrastructure while enabling CO_2 capture in hard-to-abate sectors.	• Increased system complexity; higher coordination requirements. • High capital intensity and long planning horizons. • Elevated risk of technological lock-in if alternatives emerge.	• Creates balance between cost, efficiency, and emissions reduction. • Supports diversification of carbon-management strategies. • Offers socio-economic flexibility for industries undergoing transition.

The gradual, rapid, and hybrid CCUS development scenarios are not treated as separate AHP alternatives. They are introduced to show how the carbon-management option may be implemented under different policy, financial, and technical conditions.

4.1.2. Multi-Criteria Decision-Making (AHP) Assessment for CCUS Pathways

AHP is a decision-making method developed by the American researcher A. L.AHP was proposed by Satty in the 1970s. AHP is a method that models and quantifies the decision-making process of experts regarding complex issues. The basic principle of the AHP method is to decompose the problem into different levels according to the nature of the problem and the overall goal, and then form the structure of an analytical model at several levels. In this study, the open-source software SuperDecisions, which includes the AHP and ANP models and sensitivity analysis, was used (Https://www.Superdecisions.Com).

4.2.1. Model Used

In this study, the AHP framework was applied to evaluate four technology options, including No CC, CCS, CCU, and CCUS, in the power plant, refinery, and industrial sectors. (Figure 6) presents the assessment structure developed for evaluating the implementation of CCUS in power plants for CO_2 capture. The hierarchical model was used to determine the most suitable CO_2 capture pathway in the three selected sectors based on the considered criteria and the results obtained from the AHP analysis. The gradual, rapid, and hybrid development scenarios defined earlier in the study were considered implementation approaches and were therefore not included as separate alternatives in the AHP model. The expert group consisted of industry owners, faculty members, industrial and academic experts, and PhD students affiliated with the Energy Research Center at Shahid Beheshti University.

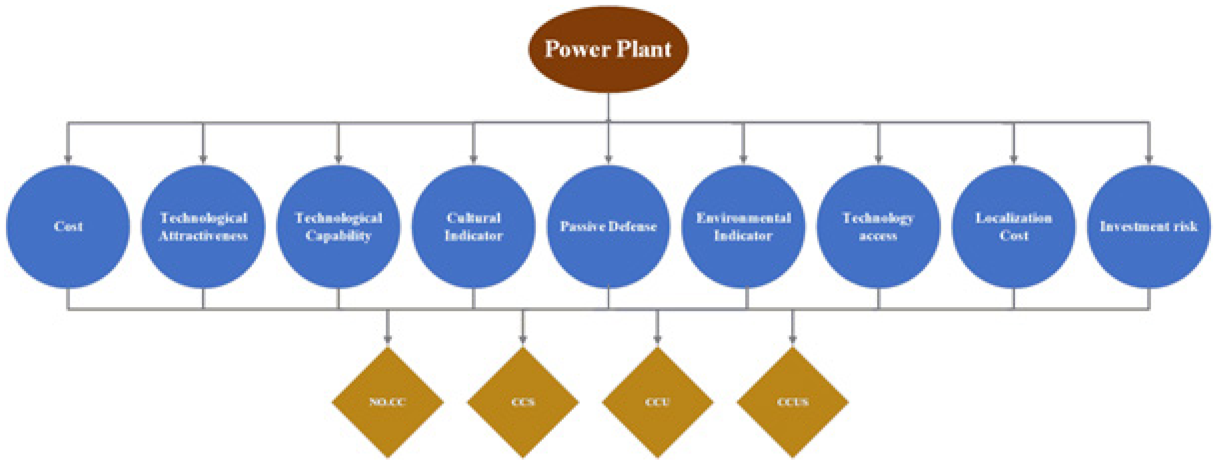

Figure 6. Power Plant Evaluation System Based on AHP

In this study, in the first stage, considering the characteristics of the power plant and various factors affecting its development, nine criterion indicators and four program evaluation indicators were used by the AHP method. The judgment criteria for the performance of a power plant's full-chain technical pathway can be divided into cost, technological attractiveness, technological capability, cultural, passive defense, and environmental indicators. These indicators were examined for four scenarios: No carbon capture (NO.CC), CCS, CCU and CCUS.

4.2.2. Criterion Indicators

This section describes the types of criterion indicators used in the AHP.

- Cost

The cost of goods means calculating the direct costs involved in producing a good or providing a service, which includes labor wages, raw materials, and manufacturing overheads.

- Technological Attractiveness

The strategic or operational importance of a technology for an organization or country determines investment priorities in the relevant sector.

- Technological Capability

Capability includes the level of mastery over technology, from operation to the creation of new methods of use.

- Cultural Indicator

The implementation of CO_2 capture technologies in society requires social acceptance, awareness of their dimensions, and the acceptance of existing risks by various social institutions. Studies show that currently, a small percentage of people, even in developed countries, are aware of CO_2 capture technologies in general, and of the risks associated with transmission lines and storage in particular (Praetorius & Schumacher, 2009). Without social acceptance, the processes of transport, utilization, and storage are likely to face opposition and protests from active non-governmental organizations.

- Passive Defense

In the context of this study, Passive Defense refers to the ability of a technology to improve energy-system resilience, limit vulnerability in critical infrastructure, and maintain stable operation in the face of external disruptions. The AHP assessment therefore focused on practical aspects such as robustness, continuity of operation, waste reduction, and resistance to sanctions and supply-chain constraints.

- Environmental Indicator

Many environmental concerns are related to the issue of CO_2 gas leakage from transmission lines and storage reservoirs. The leakage of this gas into the atmosphere causes climate change. Given the global climate change concerns, environmental concerns are the most important challenge for the commercialization of carbon capture, utilization, and storage technologies.

- Technology access

Access to technology is one of the main requirements for the implementation and development of CCUS. The deployment of these technologies depends not only on technical knowledge, but also on the availability of specialized equipment, industrial software, licenses, spare parts, and technical support services. In developing countries, especially under sanction conditions, limitations in technology transfer and restricted access to foreign suppliers can slow down project implementation and reduce operational reliability. For this reason, the level of access to technology can significantly influence the feasibility of CCUS projects and their long-term performance.

- Localization Cost

One of the major challenges associated with advanced carbon management technologies is the cost required for domestic development and implementation. Localization is not limited to manufacturing equipment; it also includes engineering redesign, pilot testing, adaptation to existing industrial infrastructure, workforce training, and the development of local technical capabilities. In countries facing external technological restrictions, a considerable part of the implementation process must rely on internal resources and domestic industries, which can increase overall project expenditures. Consequently, localization cost plays an important role in evaluating the economic viability of CCUS technologies.

- Investment risk

Large-scale CCUS projects generally require long-term investment and substantial financial support. However, economic uncertainty, fluctuations in exchange rates, changes in energy policies, and limitations in international financial cooperation can increase the risks associated with such investments. In addition, delays in technology deployment or uncertainty regarding future economic returns may reduce investor confidence and affect funding decisions. Under these conditions, investment risk becomes an influential factor in the selection and commercialization of carbon capture and utilization technologies.

5. Results and Discussion

This section examines the AHP results for the proposed facility and identifies the preferred carbon-management pathway in each sector. The analysis shows that the criteria were not equally weighted. In the first stage, the criterion indicators were defined, and in the second stage, the expert-group data were used to weight these indicators relative to one another. The intraclass correlation coefficient among experts was 0.825, indicating a stable and reliable level of agreement. The calculations were conducted for three application areas: power plants, industries, and refineries. These calculations were based on the assigned values of the criterion indicators and expert evaluations derived from existing strategies and plans. The previously defined deployment scenarios are then used to provide a practical interpretation of how the preferred options may be implemented under different economic, technological, and policy conditions in Iran.

5.1. Power Pla

Power Plant: Ministry of Energy and the private sector. The results of the power-plant system analysis are presented in (Figure 7). As illustrated, the CCUS alternative achieved the highest ideal priority value (1.000), indicating its superior preference and overall suitability among the evaluated options for the power generation sector. The CCS scenario ranked second with an ideal priority value 0.6529, followed by CCU with a value 0.4871. In contrast, the No.CC alternative exhibited the lowest priority value 0.1884. These findings reveal a strong preference toward integrated carbon management strategies in the power plant sector, particularly approaches incorporating carbon capture, utilization, and storage simultaneously. Furthermore, unlike the refinery and industrial sectors, where CCU demonstrated a relatively stronger position than CCS, the present results suggest that standalone carbon storage strategies are considered more favorable than utilization-oriented pathways in the power generation sector under the selected evaluation criteria.

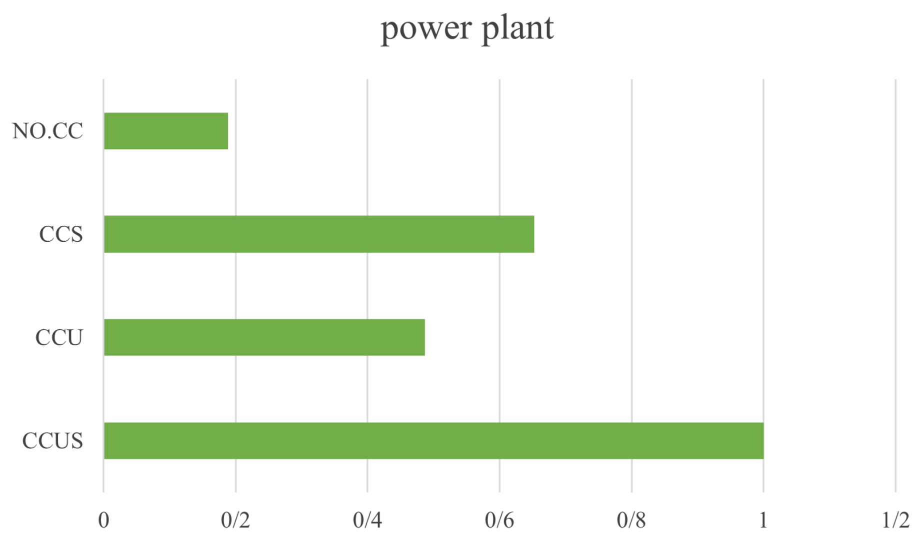

Figure 7. Ideal Priorities of Power Plant Sector Options Obtained from AHP

In this study, the discussion of stakeholders and custodians of different applications is raised differently, and essentially, there is no single custodian to make macro decisions regarding carbon capture and determine the future of these facilities.This means that there are various custodians and stakeholders, and this research proposal is separate for different sectors, so that each custodian can make policies and decisions based on the data. Therefore, the proposal was separated for each sector.

In official documents such as the energy balance sheet, the amount of CO_2 emissions in different sectors has been analyzed and reviewed separately and is not uniform.

5.2. Industry

Industry: Ministry of Industry, Mine, Trade and the private sector. (Figure 8) shows the CO_2 capture implementation potential assessment system for the industry, while the results of the corresponding AHP analysis are presented in (Figure 9). As illustrated, the CCUS option achieved the highest ideal priority value (1.000), indicating the strongest preference and overall suitability among the evaluated industry sector alternatives. The CCU scenario ranked second with an ideal priority value of approximately 0.6377, reflecting a comparatively favorable position relative to the other options. In contrast, the CCS and No.CC alternatives obtained substantially lower priority values, at approximately 0.2897 and 0.3476, respectively. These findings demonstrate a pronounced preference for integrated carbon management strategies combining carbon capture, utilization, and storage within the industrial sector. Furthermore, the higher ranking of CCU compared with CCS suggests that utilization-oriented pathways are considered more advantageous than standalone carbon storage approaches under the selected evaluation framework.

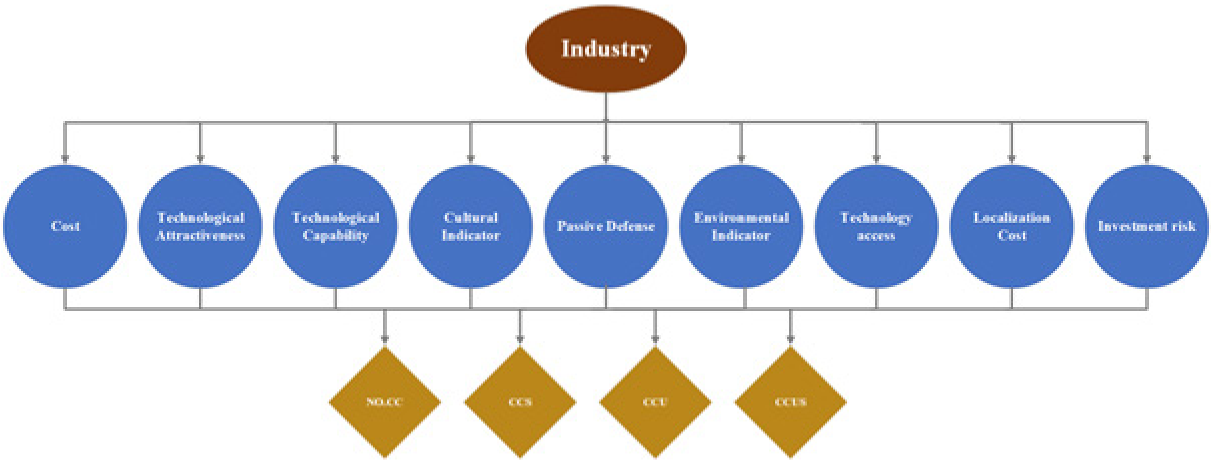

Figure 8. Industry Evaluation System Based on AHP

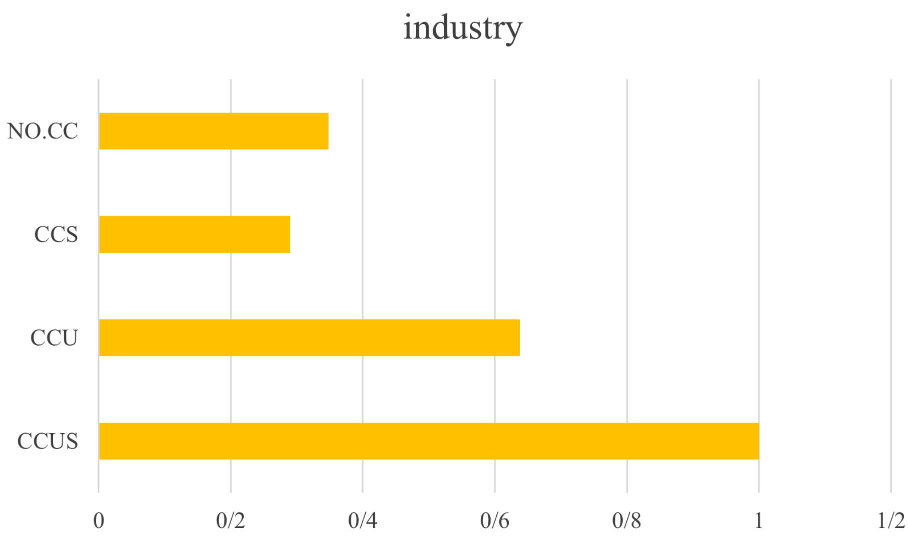

Figure 9. Ideal Priorities of Industry Sector Options Obtained from AHP

5.3. Refinery

Refinery: Ministry of Oil and the private sector. (Figure 10) shows the CO_2 capture implementation potential assessment system used for refineries. The results of the analysis of this system are presented in (Figure 11). As illustrated, the CCUS option achieved the highest ideal priority value (1.000), indicating its superior preference and overall suitability among the evaluated refinery sector alternatives. The CCU option ranked second with an ideal priority of 0.6549, followed by CCS with a substantially lower value of 0.3006, whereas the No.CC scenario exhibited the lowest priority score (0.1401). These findings indicate a strong preference toward integrated carbon capture, utilization, and storage strategies within the refinery sector. Furthermore, the higher ranking of CCU relative to CCS suggests that carbon utilization pathways are considered more advantageous than standalone carbon storage approaches under the selected evaluation criteria.

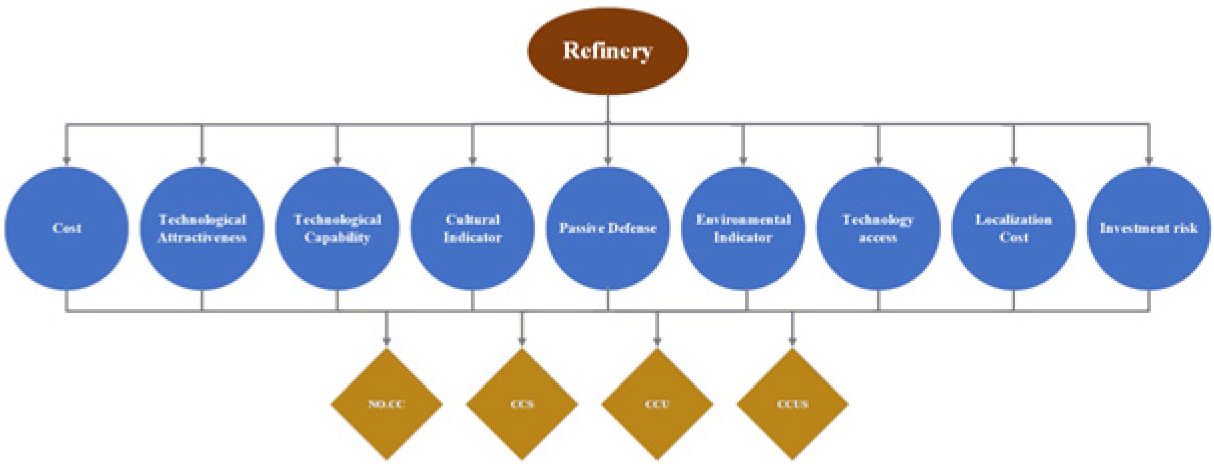

Figure 10. Refinery Evaluation System Based on AHP

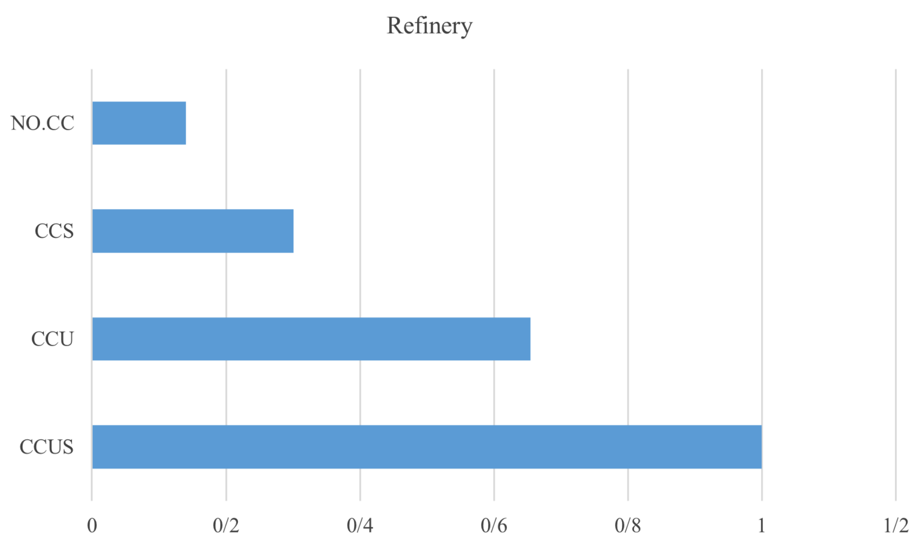

Figure 11. Ideal Priorities of Refinery Sector Options Obtained from AHP

(Figure 12) presents the sensitivity analysis results for the four evaluated alternatives, namely CCUS, CCU, CCS, and NO.CC, across the refinery, power plant, and industrial sectors. Panels (a-d) correspond to the refinery sector, panels (e-h) to the power plant sector, and panels (i-l) to the industrial sector. In all examined cases, CCUS maintains the highest ranking, and no rank reversal is observed within the investigated range of criteria weights. The main differences among the sectors are therefore associated with the degree of sensitivity rather than with changes in the final ranking structure.

The refinery sector, shown in (Figure 12 a-d), exhibits the most stable behavior among the three applications. Variations in criteria weights produce only limited changes in the relative positions of the alternatives. The most noticeable response appears under the cost criterion, where increasing the weight of cost gradually reduces the CCS score, while NO.CC shows a moderate upward trend and approaches CCS near the upper end of the range. In contrast, the environmental, technology-accessibility, and investment-risk criteria produce comparatively small variations, and the ranking order remains unchanged throughout the analysis. Overall, the refinery sector appears relatively insensitive to moderate weighting changes.

A somewhat stronger response is observed in the power plant sector, illustrated in (Figure12 e-h). The effect of the cost criterion is more pronounced in this case, particularly for CCS, whose score declines more visibly as the cost weight increases. At the same time, the difference between CCU and NO.CC decreases slightly. Despite these variations, CCUS consistently preserves its leading position. Under the environmental criterion, the advantage of CCUS becomes more apparent, whereas CCU and NO.CC experience moderate declines. Technology accessibility and investment risk have comparatively limited influence on the overall ranking pattern, and no instability is observed in the decision structure.

The industrial sector results, presented in (Figure12 i-l), show the highest responsiveness to environmental and technology-related criteria. As the weight of the environmental criterion increases, the separation between CCUS and the remaining alternatives becomes more distinct, while NO.CC declines more noticeably. A similar trend is observed for technology accessibility, where CCUS gains additional preference relative to CCS, CCU, and NO.CC. Under the investment-risk criterion, the gap between CCUS and the other alternatives widens slightly, further strengthening its dominant position. Compared with the refinery and power plant sectors, the industrial application therefore demonstrates greater sensitivity to environmental performance and technological feasibility.

Overall, the sensitivity analysis indicates that the ranking structure obtained from the AHP model is stable across all three sectors. Although moderate variations occur among CCS, CCU, and NO.CC under certain criteria, these changes are insufficient to produce rank reversal or substantial instability. The results therefore suggest that the AHP framework provides a reliable basis for evaluating CCUS-related pathways under different sectoral conditions.

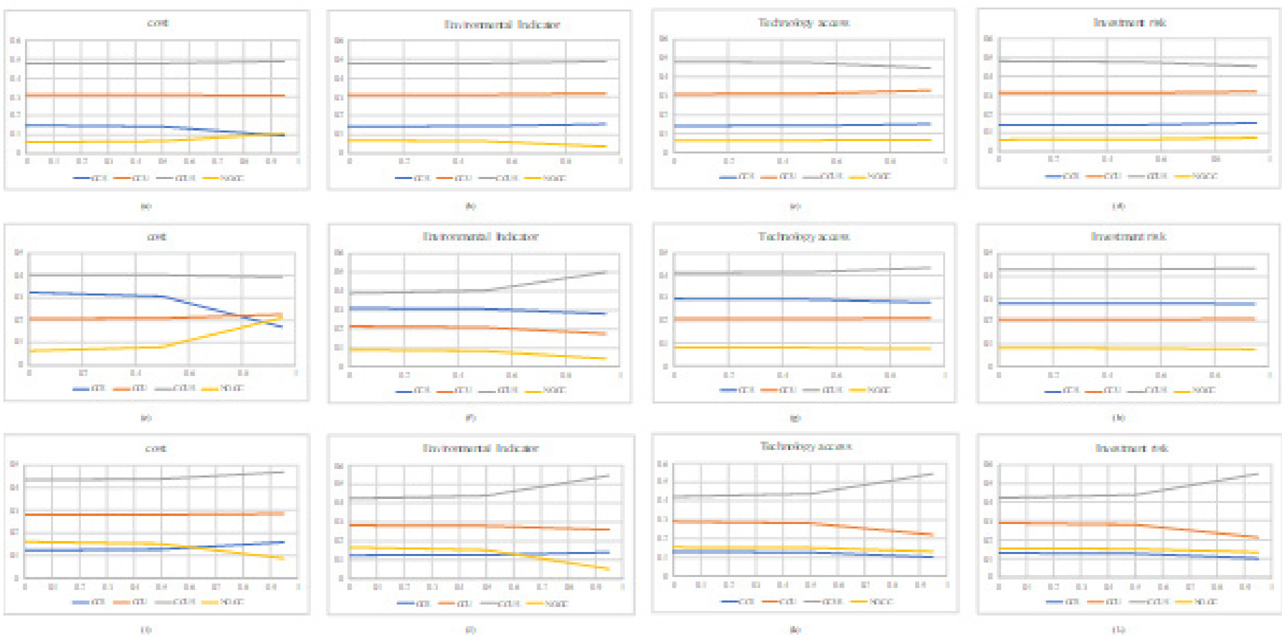

Figure 12. Sensitivity Analyses for the Refinery, Power Plant, and Industry Sectors

6. Analysis of Results

This section presents the results of the hierarchical analyses.

- CCCUS facilities rank first in the three applications because their simultaneous use and storage, owing to no waste, increases the efficiency of the carbon capture process.
- The use of CCU technology in the aforementioned applications is beneficial because of carbon capture and its application in various uses, as mentioned in (Figure 8).
- The CCS process is often more applicable to refineries and industries. One of its uses is for injection into oil wells to compensate for pressure reduction, which is abbreviated as EOR, and it generates revenue in industries.

6.1. Power Plant

Based on existing scenarios, renewable energy is expected to constitute 10% of total power plant capacity; however, at present, less than 1% of installed power plant capacity is based on renewable energy. This is because when the country's primary and non-strategic development plan focuses on the expansion of the natural gas network and the replacement of renewable alternatives with petroleum products, renewable energy fails to gain a significant share in the national economy. Therefore, diversification of the country's energy portfolio appears impractical, as the dominance of natural gas does not allow renewable energy sources to realize their potential. The extensive replacement of natural gas with petroleum products, particularly in the household sector, has resulted in an increase in net energy intensity. Consequently, the heavy dependence of the national energy system on a single dominant fuel has increased vulnerability in terms of energy security, and continued access to low-cost natural gas constitutes a major barrier to the development of renewable energy sources. Therefore, given the current conditions, the dominance of fossil fuels in power plants, and the failure to implement renewable power plants in line with defined targets, the implementation of CCUS projects is considered essential. In the next stage, the utilization of captured carbon for the production of various products can generate a return on investment.

In addition, based on upstream policy documents, CO_2 emissions can be reduced by increasing the efficiency of the country's power plant network through CO_2 capture and storage, expanding the use of renewable energy sources and biofuels, reducing losses in the electricity transmission and distribution network, developing combined heat and power (CHP) and combined-cycle units, optimizing energy consumption in the demand sector, producing biogas, and converting waste to energy. Furthermore, at the national level, by establishing appropriate financial and energy economic mechanisms, such as reducing and gradually eliminating energy subsidies, strengthening the National Environment Fund, and expanding private sector participation, particularly in the energy and efficiency sectors through energy service companies (ESCOs), effective incentive mechanisms can be introduced.

6.2. Industry

Industries generally seek to establish value chains. 19% of carbon pollution comes from industries; therefore, industries can focus on the storage and use of the carbon produced. Supportive and upstream environmental laws can provide incentives for the industry for financing, return on investment, and gas prices, such as Article 27 of the Value Added Tax Law (Green Tax Law).

In general, taxes referred to as green taxes include tax incentives and discounts. These taxes apply to companies whose activities focus on environmental protection and pollution reduction. However, taxes that involve penalties and increased charges within this system include the carbon tax, which is imposed on fossil fuel consumption, tariffs on the import of energy-intensive goods, and mining extraction taxes. In general, this system seeks to reduce the costs associated with environmentally friendly activities and increase the costs of environmentally harmful activities in any form. Therefore, the adoption of CCUS facilities is strongly recommended. Resistance may arise from industries with outdated technologies; however, this can be addressed gradually through the implementation of incentive-based schemes, thereby reducing opposition. In addition, efforts should be made to promote the development of new manufacturing industries with low energy consumption and high efficiency, modernize the structure of existing industrial units, and enhance the economic development of the manufacturing sector.

6.3. Refinery

Preventing reservoir pressure decline is a top priority before implementing any enhanced oil recovery method. Crude oil production is currently experiencing a decline in extraction capacity. Collecting produced gases is a key priority for the upstream oil and gas industry. The same applies to processing or maximising the conversion of associated and flared gases, with due attention to economic and environmental aspects. Consequently, reinjecting these gases into reservoirs is considered an unavoidable necessity. This is because flaring causes environmental pollution and leads to the loss of economic opportunities. As indicated in the analyses and upstream policy documents, CCUS technology is considered the most suitable option for application in refineries. In addition to the reuse of carbon for various applications, such as enhancing both the quantity and quality of refined and petrochemical products with a value-maximization approach, carbon storage is also applied to increase productivity across the oil and gas value chain. Although companies must comply with international commitments, due to sanctions, they are unable to implement such facilities in Iran. Therefore, these technological units must be localized within the country.

7. Critical Interpretation of Results

The superiority of CCUS in the Iranian context does not necessarily imply that technical or economic barriers are absent. Instead, it reflects a lack of sufficiently mature, large scale alternatives that could achieve substantial emission reductions without disrupting the existing hydrocarbon based infrastructure. In other words, the preference toward CCUS appears to be driven more by infrastructural compatibility and transitional practicality than by ideal economic conditions. The sectoral differences observed in the results further suggest that carbon-management pathways cannot be evaluated independently from the structure of the host industry. In refinery and industrial applications, the relatively stronger position of utilization-oriented pathways indicates that the economic value of recovered carbon partially offsets the technological complexity of capture systems. However, this behavior was less pronounced in the power-plant sector, where carbon utilization opportunities remain limited and the economic burden of capture infrastructure becomes more visible. This finding implies that the attractiveness of CCUS is not uniform across sectors and depends heavily on the ability of each sector to internalize the economic value of captured carbon.

Another important observation is that CCS alone did not emerge as the dominant option despite its recognized environmental performance. This may indicate that under Iranian conditions, experts place greater importance on integrated and economically productive carbon-management pathways than on isolated storage strategies. Unlike studies conducted in regions with established transport and storage networks, the Iranian context is characterized by infrastructure limitations, sanctions, financing uncertainty, and localization challenges, all of which alter the practical feasibility of standalone storage projects. Therefore, the present findings suggest that the prioritization of CCUS in Iran is linked not only to emission reduction objectives, but also to the need for compatibility with existing industrial, economic, and energy-system realities.

8. Outlook

CCUS technologies have reached the operational stage in most parts of the world and the Middle East; however, in Iran, this technology has not yet progressed to the pilot stage. Given the presence of thermal power plants, industrial facilities, and abundant oil and gas resources, there is significant potential to utilize these facilities to reduce greenhouse gas emissions and recover carbon for various applications.For example, urban pollution is a critical issue associated with power plants, as they significantly contribute to air pollution in urban areas. Therefore, government agencies must allocate financial resources to address urban pollution and ensure clean air, as pollution directly affects public health. Consequently, the application of CCUS technology can be evaluated as an opportunity to reduce air pollution and mitigate human health risks.

Another application of this technology is the reduction of the gas network imbalance problem. In winter, there is a gas network imbalance problem within the country, and during this season, many power plants near cities use mazut fuel. Here, CCUS units gain strategic value, in addition to economic value. Approximately 60897 million cubic meters of gas per year are consumed by power plants, out of 548.5 million cubic meters of gas produced daily. If mazut is used as fuel in different seasons, this mazut, along with the use of a CCUS facility, becomes a valuable process that simultaneously reduces gas consumption, and the carbon produced can be utilized. Another way to use CO_2 is through CO_2-to-fuel processes, where carbon can be converted into liquid fuels, stored, and its methane used. Therefore, rapid action must be taken, and laws must be enacted to achieve CCUS technology.

Public demand for the government to enact strict environmental regulations aimed at reducing greenhouse gas emissions and moving toward a net-zero carbon program, along with economic engagement of the private sector, reducing government ownership across various applications, realigning the pricing of petroleum derivatives, eliminating hidden energy subsidies, promoting social acceptance of such technologies, imposing carbon penalties across different sectors, and implementing coherent energy policies and commercialization mechanisms, can significantly contribute to the development and advancement of carbon capture technologies. Ultimately, the creation of an optimized energy–environment market through energy policy reform, reducing the role of state-owned enterprises, moving toward cross-sectoral regulation, strengthening private sector participation, and attracting foreign investment in this field can represent a major breakthrough.

9. Conclusion

The results of this study show that the assessment of carbon emission reduction options was conducted using a multi-criteria decision-making framework based on expert judgment and demonstrates acceptable statistical consistency. The level of agreement between experts was calculated using the Intraclass Correlation Coefficient (ICC). The obtained ICC value was 0.751, which, based on standard statistical criteria, indicates a "good" to "acceptable" level of agreement between expert assessments and suggests that the input data to the AHP process are not unduly dispersed and that the ranking results are statistically reliable.This ICC value was directly extracted from the statistical analysis of expert judgments presented in the report and was used as an indicator of the robustness of the AHP results. Based on this validated decision-making framework, the CCUS option received the highest final score compared to other emission reduction options in all three sectors: power plants, industrial facilities, and refineries. This result indicates that, from the experts' perspective, CCUS is not only technically feasible, but also a priority option in terms of its compatibility with the country's current energy structure and its potential for accelerated CO_2 emission reduction.A review of the international benchmark projects introduced in the report also reinforces this prioritization. The operational capacity of successful CCUS projects worldwide generally ranges from approximately 0.1 to 1.3 million tons of CO_2 per year; for example, the Quest project in Canada, with a capacity of about 1.1 $MtCO_2$/yr, the Sturgeon project with 1.3 $MtCO_2$/yr, and the Port Arthur project in the United States with approximately 0.9 $MtCO_2$/yr, are among the established industrial examples. The existence of this capacity spectrum indicates that the deployment of medium- to large-scale CCUS projects, particularly in concentrated emission sources, has reached a level of technical and operational maturity.Accordingly, the report concludes that the design and implementation of a pilot or initial phase of CCUS in the country, with a capacity of approximately 0.5 to 1.0 million tons of CO_2 per year, can be aligned with international experience and play an effective role in the practical demonstration and localization of this technology. From an economic perspective, the data presented in the report show that the cost of CO_2 capture in existing industrial projects is approximately \$20 to \$140 per ton of CO_2. However, the report considers it feasible to reduce the average capture cost by approximately 50% by 2030, citing technological learning effects, scaling up, and improvements in process design. This implies that if the pilot phase transitions to an industrial scale and benefits from synergies between capture, transportation, and storage units, CCUS can evolve from a high-cost solution into a competitive option within the emission reduction policy portfolio. Finally, the report's findings emphasize that the success of CCUS as a transitional strategy depends on its alignment with the country's macro-level energy policies. In a context where the current share of renewable energy in electricity generation capacity is reported to be less than 1%, while a target of increasing it to 10% is under discussion, the development of CCUS can, as a complementary measure, offset emissions resulting from the high consumption of natural gas in power plants and industrial sectors. The quantitative findings therefore demonstrate that CCUS, combined with structural reforms in electricity generation and energy efficiency improvements, represents a limited but viable option. It can achieve significant CO_2 emission reductions in the short to medium term. Importantly, this can be done without causing major disruption to existing infrastructure.

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ارزیابی سناریوهای به‌کارگیری واحدهای CCUS برای کاهش انتشار کربن در صنایع انرژی‌بر ایران با استفاده از روش AHP

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چکیـــــده

گذار صنعتی ایران به‌سوی فناوری‌های کاهش انتشار کربن، به‌ویژه سامانه‌های جذب، استفاده و ذخیره‌سازی کربن (CCUS)، در سال‌های اخیر به‌عنوان یکی از محورهای راهبردی برای ارتقای پایداری محیط‌زیست و بهبود کارایی صنایع انرژی‌بر مطرح شده است. این مطالعه الگوهای محتمل برای استقرار واحدهای CCUS را در قالب سه سناریوی تدریجی، سریع و ترکیبی بررسی می‌کند. در سناریوی تدریجی، توسعه مرحله‌ای، کاهش ریسک‌های اولیه و انطباق تدریجی با الزامات فنی و اقتصادی مدنظر است. سناریوی سریع بر استقرار فوری زیرساخت‌های CCUS از طریق سرمایه‌گذاری گسترده، مشوق‌های مالی و حمایت‌های سیاستی متمرکز است. سناریوی ترکیبی نیز با ایجاد توازن میان هزینه‌ها، ریسک‌ها، زمان‌بندی و قابلیت اطمینان، دستیابی به فرآیندی صنعتی پایدار، مقبول و قابل مدیریت را دنبال می‌کند. در ادامه، چالش‌های فنی، اقتصادی، نهادی و سیاستی اجرای واحدهای CCUS تحلیل شده و راهبردهایی مانند تدوین سیاست‌های حمایتی هدفمند، توسعه زیرساخت یکپارچه حمل‌ونقل و ذخیره‌سازی دی‌اکسید کربن، ارتقای ظرفیت فناورانه داخلی، انتقال دانش فنی و تقویت همکاری میان دولت، بخش خصوصی و نهادهای پژوهشی پیشنهاد می‌شود. برای ارزیابی مسیرهای مختلف، از یک مدل سلسله‌مراتبی مبتنی بر AHP استفاده شده است تا عملکرد واحدهای CCUS در نیروگاه‌ها، صنایع انرژی‌بر و پالایشگاه‌ها بر پایه شش شاخص هزینه، جذابیت فناوری، توانمندی فناورانه، شاخص فرهنگی، الزامات پدافند غیرعامل و معیارهای محیط‌زیستی سنجیده شود.

واژگان کلیدی: سامانه‌های جذب، استفاده و ذخیره‌سازی کربن، گذار صنعتی، تحلیل سلسله‌مراتبی(AHP)، الگوهای استقرار