

Carbon Sequestration for Geological Negative Emissions of the Shale Gas Value Chain in China

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors' exploration of the potential for geological negative emissions within China's shale gas value chain, specifically the transformation of shale gas extraction into a carbon sink via CO₂ fracturing and sequestration technologies, is an interesting study. They assess the shale gas industry value chain and conduct a detailed economic feasibility analysis using statistical data. However, several points need attention.

On page 4, in the section "Synergy of carbon sequestration and production enhancement": Line 88, "CO₂ fracturing and CO₂ huff-n-puff serve dual purposes: enhancing production while sequestering carbon. CO₂ fracturing can achieve a carbon sink of 1,406.5 Mt while increasing shale gas production by 4,018 bcm. The CO₂ puff-n-huff technique can create a 610.2 Mt carbon sink with a 499.8 bcm production increase." Missing data sources, add relevant references.

On page 5, in the section "Synergy of carbon sequestration and production enhancement": Line 101, The Carbon Neutrality Coefficient (CNC) is used to measure the carbon reduction potential in comparison with baseline emissions. What does baseline emissions refer to, and what is the specific amount of emissions?

On page 6, in the section "Value chain assessment for carbon footprint and Geological Negative Emissions ": (1) Lines 131 and 137, the CO₂ emission reductions under the Optimized management scenario (OM) and Optimized production scenario are described respectively, but the subsequent calculation schemes only present the leakage reduction of CH₄ (OM) and the incremental production of shale gas (OP), and how CO₂ emission reductions are derived? (2) Line 148, Is the comprehensive plan simply the sum of the CO₂ emission reductions of the other three plans, or is there a different calculation method? If it's a simple sum, will the three methods interfere with or affect each other?

On page 9, in the section "Economic viability across shale gas reservoirs and scenarios ": Line 173, the article mentions that optimizing the production plan can significantly improve economic benefits, but the high costs of CO₂ fracturing technology and CO₂ injection may not be matched by the increased production of shale gas, potentially affecting economic feasibility. Additionally, CO₂ fracturing technology has certain limitations. Can the appropriate regions for implementing the optimized production plan be identified based on the formation conditions?

On page 14, in the section "Life cycle assessment of value chain carbon emissions": (1) Line 334, The statement "The carbon emissions stem from energy inputs, raw materials production, methane leakage, and CO₂ emissions" should clarify whether it includes the CO₂ emissions from the final combustion of shale gas. (2) Line 339, Regarding the calculation of carbon intensity, it is recommended that the authors provide a detailed explanation of how the proportion coefficients for the three stages (upstream, midstream, and downstream) are established. This would help readers better understand the methodology and assumptions behind the carbon intensity calculations.

On page 16, in the section "Assessment of emission reduction potential throughout the shale gas value chain," the authors propose four scenarios for reducing greenhouse gas emissions, two things need to be noted:(1) For the OM scenario, it is suggested that the authors elaborate on the specific process of estimating that methane leakage in China can be reduced by about 40% based on the success of US LDAR program. This would enhance the clarity and credibility of the estimation.(2) In the OP scenario, the authors distinguish the cumulative shale gas production percentage (CPIP) for CO₂ fracturing

technology under different geological conditions (marine, terrestrial, and transitional). This distinction enhances the credibility of the data and reveals the CO₂ sequestration potential in different regions. However, the discussion lacks an exploration of specific challenges that may be encountered during the implementation of these technologies. It is recommended that the authors supplement the discussion with relevant challenges to enhance the study's practicality and reliability.

On page 18, in the section "Techno-economic analysis of emission reduction scenarios": Lines 421 and 427, formulas 9 and 10 are used to calculate the Internal Rate of Return (IRR) and net present value (NPV). Were these formulas derived through deduction or do they cite previous research? If they were derived, please provide the derivation process; if they cite previous research, please specify the relevant references.

Reviewer #2

(Remarks to the Author)

This article is focused on China. At a minimum, the title should include that.

The abstract description I read while agreeing to review does not match the content of the manuscript.

I did read the paper and it is difficult to understand. The authors use many buzz words that I am not familiar with. These could be terms that apply to China.

The figure fonts and figure size are very small. When reading the text and referring to the paper, it is hard to understand and interpret the figures. There is also a lot of information in each figure.

In the methods section, I don't understand why equation (1) is using 30% sequestered while later the authors use 50% sequestered. And the reference is from 2016, which seems like a time when people were not thinking about storage CO₂ in shale gas reservoirs.

The authors should also be consistent when using sequestration versus storage throughout the text.

Reviewer #3

(Remarks to the Author)

The article puts forward a very interesting proposal: transforming shale gas formations themselves into net carbon sinks by applying techniques such as CO₂ hydraulic fracturing, the huff-n-puff method (enhanced recovery with CO₂ injection), and storage in depleted wells. The approach is innovative and is framed within the idea of achieving geological negative emissions—something that could have a transformative impact on the carbon balance of the unconventional gas industry. One of the manuscript's most striking claims is that the potential for net emissions reduction could reach 1.981 billion tons of CO₂ (1.981 Gt CO₂) between 2024 and 2060, which would represent a spectacular climate benefit if validated. However, this ambition contrasts sharply with the scientific execution of the article, which presents significant shortcomings both in its conceptual framing and in its development. The main issues identified are outlined below in an orderly and reasoned manner.

1) The introduction lacks solid and specific references to support its key claims. The concept of geological negative emissions is mentioned as emerging, but no prior scientific literature from countries with mature shale gas industries—such as the US or Canada—is properly cited. As a result, the reader lacks the necessary context to situate this work within the current state of knowledge.

2) Throughout the article, highly ambitious figures for the potential CO₂ sequestration are presented, yet the traceability of those calculations is not clearly or transparently explained. For example, the authors state that a total of 1.98 Gt CO₂ could be stored by 2060 using a combination of technologies, but the assumptions behind this estimate—such as injection coefficients or average recovery factors—are not broken down or justified. This undermines the credibility of the conclusions.

3) The article fails to address emissions associated with methane, both in terms of fugitive leaks and full lifecycle impacts (e.g., indirect emissions from supply chain activities). This is a critical omission, as recent studies have consistently shown that methane leakage is often the key obstacle to achieving carbon neutrality—or net negativity—in shale gas systems. Here, methane is barely mentioned, and certainly not quantified.

4) There is no distinct conclusion section or a clear and concise summary of the key findings. The final ideas are scattered across various parts of the discussion, making it difficult for the reader to extract the article's main contributions, limitations, or policy implications.

5) The structure of the manuscript is confusing. There is no clear delineation between the methodology, results, and discussion sections. Technical concepts, emissions calculations, and interpretative commentary are blended without smooth transitions. This lack of structure makes it harder to follow the line of reasoning and diminishes the overall impact of the work.

6) The mathematical methodology is underdeveloped. While a few formulas are included, there are no worked examples or validation cases to demonstrate the robustness of the models used. For instance, the net capture cost (NCC), net present value (NPV), and internal rate of return (IRR) are all mentioned, but not a single complete numerical example is provided using real or assumed data.

7) The figures are mostly low-resolution maps focused exclusively on China. Although it is logical for the study to focus on

that country, it would be beneficial to include at least some international comparison or broader context, given the global relevance of the topic. Moreover, the maps do not provide sufficient technical detail—such as geological characteristics, pressure, depth, or estimated storage capacity.

8) Internationally comparable economic units are not used. All costs are expressed in yuan per cubic meter, with no conversions to dollars or other widely used benchmarks. This limits the article's accessibility to international audiences and hinders comparison with other studies.

9) More comprehensive visual tools are missing. There are no summary tables that compare the different technologies (CO₂ fracturing, huff-n-puff, injection into depleted wells), nor graphs illustrating CO₂ capture over time or economic profitability curves. This weakens the communicative value of the analysis.

10) Although the manuscript mentions the use of Monte Carlo simulations to assess uncertainty, it does not explain the underlying assumptions, input distributions, or the interpretation of the results. No probabilistic outputs, sensitivity analyses, or uncertainty ranges are shown. This part of the analysis remains underdeveloped and unconvincing.

11) From an editorial perspective, the manuscript requires a thorough review. There are spelling errors, confusing phrases, and misused terms (e.g., "puff-n-huff" instead of "huff-n-puff"). Furthermore, there is some repetition of ideas that could be avoided with more careful editing.

12) The article does not critically analyze the risks, limits, or barriers of the proposal. For example, the possibility of CO₂ leaks, infrastructure costs, social acceptance, or regulatory implications are not discussed. The presentation is overly optimistic and lacks a balanced reflection on potential flaws or uncertainties.

13) The structure of the article urgently needs improvement. There is no hierarchical numbering of sections and subsections that allows the reader to easily orient themselves. The discussion mixes several thematic lines without an easily identifiable order. It is strongly recommended that authors include an outline or "content map" at the beginning of the document, specifying the main sections of the manuscript (e.g., methodology → results → economic discussion → climate implications), and that consistent numbering be used throughout the text (e.g., 1, 1.1, 1.2, 2, 2.1, etc.). This formatting improvement would greatly facilitate understanding of the argument and critical reading of the document.

In summary, the article starts with a very promising idea and addresses a crucial problem with remarkable ambition. However, it needs a thorough revision to fulfill its promise. It lacks methodological rigor, clarity of presentation, risk analysis, and solid references that situate the work within the existing international framework. If these aspects are corrected, the manuscript could make a valuable contribution to the debate on negative emissions in the shale gas industry. In its current state, however, the most reasonable recommendation is a major revision.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Response to Author's Revision

I have carefully reviewed the revised manuscript and the authors' detailed responses to my previous comments. I appreciate the substantial efforts made in addressing the concerns raised in the first round of review. Below is my assessment of the revisions.

Response to Question 1:

The author's note indicates that the data presented in the text are derived from model simulations and offers a comprehensive description of the computational methodologies employed for CO₂ fracturing technology and CO₂ huff-n-puff technique. The revised version successfully clarifies any uncertainties concerning the origin of the data.

Response to Question 2:

The author delineates the baseline emissions within the text and presents precise emission figures for various regions. This approach serves to strengthen the validity of the ensuing calculations related to Carbon Neutrality Coefficient (CNC).

Response to Question 3:

(1) The author provides a detailed explanation of CO₂ fracturing and CO₂ suction technologies, introducing calculation methods for CO₂ emission reductions under optimized management scenario (OM) and optimized production scenario (OP).

(2) The paper further clarifies how CO₂ emission reductions can be derived through leakage reduction of CH₄ (OM) and the incremental production of shale gas (OP).

The author clarifies that these three approaches do not simply add up linearly but exhibit nonlinear technological synergies effects, detailing the interconnections and influencing mechanisms among them.

Response to Question 4:

The author performed a comparative analysis of the costs related to CO₂ fracturing technology alongside the benefits derived from optimized production (OP), thereby systematically assessing the economic feasibility of optimized production scenario. Notably, the advantages of this approach are observed exclusively in the Tarim Basin and Ordos Basin. Future research could investigate potential enhancements to this methodology.

Response to Question 5:

(1) The authors have clarified the rationale for applying U.S. LDAR experience to China, supplemented with references and

similarity between China and the U. S. This provides sufficient justification and improves the credibility of the estimation. (2) The authors have added comprehensive discussions of technical and economic challenges, including leakage risks, induced seismicity, infrastructure costs, and monitoring difficulties. This significantly enhances the practical relevance and reliability of the study.

Response to Question 6:

The authors have clarified that downstream combustion emissions are included and have provided detailed explanations of how carbon intensity is calculated across upstream, midstream, and downstream stages, with supporting references. This strengthens methodological transparency.

Response to Question 7:

The author elucidates the foundational principles underlying the internal rate of return (IRR) and net present value (NPV) calculation methodologies, supplemented by relevant scholarly references. This approach serves to strengthen the validity of the ensuing techno-economic analysis.

Conclusion

The authors have satisfactorily addressed all of my previous concerns. I believe the manuscript is now suitable for publication after minor editorial polishing. I recommend acceptance with minor revisions.

Reviewer #3

(Remarks to the Author)

I thank the authors for addressing all my comments point by point. The manuscript has clearly improved in clarity, structure, and robustness. My only remaining suggestion is to add a brief reflection in the discussion or conclusion on the global applicability of the proposed shale-gas-based decarbonization strategies beyond China, which would further enhance the paper's international relevance.

Reviewer #4

(Remarks to the Author)

This paper is very interesting and well-structured. However, there are some methodological issues, although the study scope is well covered.

1. The carbon sink assessment method. For shale reservoirs, normally, the storage capacity should be included the adsorption or competitive adsorption, this should be applied to CO₂ fracturing, huff-n-puff and CO₂ sequestration. However, the method, particularly for fracturing and huff-n-puff does not explicitly include the approach for this part.
2. The reservoir modeling has demonstrated that the gross and net utilization factors are major concerns for evaluating the life cycle emissions. Especially, for subsurface CCUS like CO₂-EGR and ECBM process. However, this paper has not incorporated these drivers, leading to the inaccurate assessment for supply chain GHG emissions.
3. Multiple studies has demonstrated the methane emissions can significantly affect the GHG emissions. This paper, however, does not include the methane emission estimates for the bottom-up modeling according to equation 9.
4. The TEA part, why transportation of CO₂ is not considered? This would be a major driver in system NPV optimization, that cannot be neglected for most of the time.
5. Defining of the "negative emission" need to specify the system boundary and LCA approach explicitly. However, this paper did not clearly discussing the limitation of negative emission discussion. For example, when CO₂ is sourced from point source, even with successful storage, it can be only claimed as carbon offset not negative emission. Unless CO₂ is captured from air with DAC or BECCS. In addition, the system boundary has to be cradle-to-grave. Unless using the system expansion LCA approach.
6. When linking the TEA and LCA, it is worthwhile to look at the economic and environmental trade-offs. However, authors did not dive into this discussion, leaving the paper structurally incomplete.

Version 2:

Reviewer comments:

Reviewer #3

(Remarks to the Author)

Overall, the manuscript presents a solid and well-supported contribution. In light of the revisions made by the authors and the quality of the evidence provided, I believe the article is ready for publication in Nature Communications.

Reviewer #4

(Remarks to the Author)

Thank you for all efforts from authors. All my comments are addressed. I think this manuscript is in a wonderful shape now.

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Responses to comments

Dear Reviewers,

We sincerely appreciate the thorough and constructive reviews from you. Your insightful comments have been invaluable in strengthening our manuscript. We have undertaken substantial revisions to comprehensively address all concerns raised, particularly regarding methodological rigor, clarity of presentation, risk analysis, and positioning within the international framework.

Major Revisions Overview:

1. Enhanced Methodological Rigor and Transparency:

We have comprehensively revised the Methods section with detailed equations and parameter justifications for CO₂ sequestration calculations, added explicit breakdown of assumptions behind the 1.98 Gt CO₂ sequestration estimate, clarified the rationale for different sequestration rates (30% for CO₂ fracturing vs. 50% for huff-n-puff), incorporated comprehensive uncertainty quantification through Monte Carlo simulations (100,000 iterations), developed transparent calculation frameworks showing how EUR values vary across geological formations, and provided detailed techno-economic modeling with worked examples in supplementary materials to ensure full reproducibility of our results.

2. Strengthened Risk Analysis and Economic Assessment:

The manuscript now integrates comprehensive risk analysis including technical challenges (CO₂ leakage, induced seismicity), operational barriers (infrastructure requirements, source-sink matching), and market uncertainties. We have expanded economic modeling to include sensitivity analyses under different carbon pricing scenarios (Chinese market: \$13.23/t CO₂; European market: \$78.19/t CO₂), quantified how geological heterogeneity affects economic viability across basins, and added detailed discussions of implementation challenges specific to marine, terrestrial, and transitional shale formations, demonstrating that profitability critically depends on both geological conditions and carbon pricing mechanisms.

3. Improved Clarity and Structure:

We have completely reorganized the manuscript with clear separation between Results and Discussion sections, added a visual content map (Figure 1) outlining the three-module research framework, redesigned all figures with enhanced readability and high-resolution graphics, standardized terminology throughout (e.g., "well pad" instead of "well site," consistent use of "sequestration"), converted all economic units to US\$ for international comparability, and created clear subsections in the Discussion addressing implications, barriers, and policy recommendations, ensuring logical flow and easy navigation throughout the manuscript.

4. Solid International Context and References:

The literature review has been substantially expanded to incorporate global perspectives, particularly from U.S. and Canadian shale gas industries. We have added foundational references including Lyu et al. (2021) comprehensive review in Energy & Environmental Science, Edwards et al. (2015) on CO₂ storage capacity in Marcellus shale, Tao & Clarens (2013) estimating U.S. shale sequestration potential, and the U.S. DOE NETL methodology for standardized assessment. The work is now properly positioned within international climate frameworks and CCUS research, with 85 additional recent publications incorporated to ensure our China-specific findings are contextualized within global knowledge.

5. Comprehensive Methane Emissions Analysis:

Responding to critical feedback about methane accounting, we have explicitly integrated fugitive methane emissions throughout the life cycle assessment, with all CH₄ emissions converted to CO₂-equivalent using IPCC AR6 GWP₁₀₀ values. Detailed emission factors for upstream, midstream, and downstream activities are provided in Supplementary Table 13, methane leakage reduction potential through LDAR programs is quantified (40% reduction estimated for China based on U.S. empirical data), and the critical role of methane control in achieving net-negative emissions is emphasized throughout the analysis.

6. Enhanced Visual Communication and Technical Details:

All figures have been recreated at high resolution with improved readability, comprehensive technology comparison tables have been added showing key parameters for CO₂ fracturing, huff-n-puff, and depleted well sequestration, sensitivity analysis tornado charts reveal that shale gas price and carbon credit value are primary economic drivers, and uncertainty ranges are visualized for all major results. Maps now include technical details such as formation depths and geological characteristics requested by reviewers, significantly improving the manuscript's ability to communicate complex technical and economic relationships.

We have provided detailed point-by-point responses to all comments in the accompanying document, with all changes in the manuscript clearly marked using track changes. Where specific requests could not be fully addressed, we have provided thorough explanations and alternative approaches.

We believe these substantial revisions have transformed the manuscript into a more rigorous, clear, and impactful contribution that advances understanding of carbon management opportunities in shale gas systems. The work now provides a solid foundation for evidence-based policy decisions on achieving carbon-negative fossil fuel operations, with clearly articulated uncertainties, risks, and implementation pathways.

Thank you for the opportunity to revise our manuscript. We look forward to your evaluation of our revised submission.

Sincerely,
Sai Liang

Reviewer #1:

The authors' exploration of the potential for geological negative emissions within China's shale gas value chain, specifically the transformation of shale gas extraction into a carbon sink via CO₂ fracturing and sequestration technologies, is an interesting study. They assess the shale gas industry value chain and conduct a detailed economic feasibility analysis using statistical data. However, several points need attention.

[Response]: Thank you for the thoughtful evaluation and for recognizing the importance of our study. We have carefully addressed each of the points requiring attention through substantial revisions, including enhanced technical explanations, additional supporting data, and improved methodological clarity. We believe these revisions significantly strengthen the manuscript and fully address the reviewer's concerns. Point-by-point responses to all specific comments are provided below.

1. On page 4, in the section "Synergy of carbon sequestration and production enhancement": Line 88, "CO₂ fracturing and CO₂ huff-n-puff serve dual purposes: enhancing production while sequestering carbon. CO₂ fracturing can achieve a carbon sink of 1,406.5 Mt while increasing shale gas production by 4,018 bcm. The CO₂ puff-n-huff technique can create a 610.2 Mt carbon sink with a 499.8 bcm production increase." Missing data sources, add relevant references.

[Response]: We sincerely thank you for raising this important point regarding data source clarity. These figures (1,406.5 Mt CO₂ sequestered, 4,018 bcm gas production increase for CO₂ fracturing; 610.2 Mt CO₂ sequestered, 499.8 bcm production increase for huff-n-puff) are original modeling results generated from our study, calculated based on the methodology described in sections 2.2-2.4. However, we recognize that presenting them without clear attribution to our own analysis could cause confusion about whether they were cited from external sources.

To address this concern, we have revised the text as follows:

"CO₂ fracturing (before production), CO₂ huff-n-puff (in production), and CO₂ sequestration (in depleted wells). CO₂ fracturing and CO₂ huff-n-puff serve dual purposes: enhancing production while sequestering carbon. Based on our modeling analysis, CO₂ fracturing can achieve a carbon sink of 1,406.5 million tonnes (Mt) while increasing shale gas production by 4,018 bcm. Similarly, our simulations indicate that the CO₂ huff-n-puff technique can create a 610.2 Mt carbon sink with a 499.8 bcm production increase."

2. On page 5, in the section "Synergy of carbon sequestration and production enhancement": Line 101, The Carbon Neutrality Coefficient (CNC) is used to measure the carbon reduction potential in comparison with baseline emissions. What does baseline emissions refer to, and what is the specific amount of emissions?

[Response]: We appreciate this important question regarding the baseline emissions in our Carbon Neutrality Coefficient (CNC) metric.

The baseline emissions refer to the carbon intensity of conventional shale gas extraction without CO₂-based technologies or carbon reduction measures. These baseline values vary by regions due to differences in geological conditions, extraction depths, and EUR

(Estimated Ultimate Recovery) values. For example, in the Ordos Basin, baseline emissions are approximately 0.42 kg CO₂e/m³ of gas produced, while in terrestrial shale formations, they average 0.38 kg CO₂e/m³ (detailed calculations provided in Supplementary Table S3).

To address this concern and improve clarity, we have revised the manuscript as follows:

“The Carbon Neutrality Coefficient (CNC) measures the carbon reduction potential of CO₂-based technologies compared to conventional shale gas extraction baseline emissions. The baseline represents current extraction practices without carbon mitigation measures, with emissions varying by regions (0.38-0.45 kg CO₂e/m³) depending on geological conditions and extraction parameters.”

3. On page 6, in the section "Value chain assessment for carbon footprint and Geological Negative Emissions"

(1) Lines 131 and 137, the CO₂ emission reductions under the Optimized management scenario (OM) and Optimized production scenario are described respectively, but the subsequent calculation schemes only present the leakage reduction of CH₄ (OM) and the incremental production of shale gas (OP), and how CO₂ emission reductions are derived?

[Response]: We sincerely thank you for this constructive feedback, which significantly enhances the clarity of our methodology section.

For the OM scenario: CO₂e reductions are achieved through methane leakage control via timely leak detection and repair programs. Since methane has a GWP₁₀₀ of 28 (IPCC AR6), each cubic meter of prevented methane leakage equals 28 m³ of CO₂e avoided. The CO₂e reduction calculated as:

$$\text{CO}_2\text{e reduction} = \text{CH}_4 \text{ leakage reduction} \times \text{GWP}_{100}$$

For the OP scenario: CO₂ reductions occur through two mechanisms: a. Direct geological sequestration via CO₂ fracturing and huff-n-puff. b. Emission reduction benefits of upstream electrification in shale gas production.

To address this clarity issue, we have:

1. Enhanced the description of CO₂ emission reduction calculations in both scenarios, with the CO₂ fracturing and CO₂ huff-n-puff technologies extensively detailed in the Methods section “**Assessment of carbon sink potentials in shale gas reservoirs**”.

“CO₂ fracturing. During well completion, high-pressure CO₂ is injected to replace water for fracturing, creating fracture networks that facilitate gas recovery. Approximately 70% of injected CO₂ returns during the production, while 30% remains sequestered¹⁶. The cumulative production increase percentage (CPIP) varies with geological formations. In water-sensitive continental and transitional shale gas reservoirs, significant enhancements in shale gas production can be achieved. In contrast, the production increase effect in non-water-sensitive marine shale gas reservoirs is generally modest³⁹.

Based on these, we set CPIP at 60% (55%-65%) for transitional and continental shale and 20% (18%-22%) for marine shale⁴⁰. The production increase can be calculated as:

$$EUR_i = EUR \cdot CPIP \quad (1)$$

where EUR varies across different shale gas reservoirs, with the specific calculation methodology detailed in S5.3 of the **Supplementary Information**. The carbon sink for a single shale gas well using CO₂ fracturing is calculated as:

$$M_{CO_2,F} = V_{CO_2} \cdot n_{stage} \cdot \rho_{CO_2,C} \cdot 30\% \quad (2)$$

where V_{CO_2} is the volume of CO₂ required for a single fracturing stage, n_{stage} is the number of fracturing stages, and $\rho_{CO_2,C}$ is the density of CO₂ during transportation and storage.

CO₂ huff-n-puff. During the typical 20-year production cycle, shale gas wells exhibit a characteristic production decline curve until reservoir depletion occurs. To mitigate this decline and increase the EUR, the CO₂ huff-n-puff technology can be employed. The CO₂ huff-n-puff stimulation is executed over a 6-year period (within years 13 to 18 of the well lifecycle), repeated for 12 cycles. Based on existing experiment and field studies^{41,42}, each cycle comprises one month CO₂ injection (20 t/day), followed by a one-month soaking, and a four-month production. Critically, 50% of the injected CO₂ per cycle undergoes permanent geological sequestration⁴⁰. The CO₂ huff-n-puff yields a CPIP of 3% (2%-4%) for marine shale and 6% (4%-8%) for transitional and continental shale. The method for calculating production increase is shown in Eq. 1."

2. Revised the Methods section “Assessment of emission reduction potential throughout the shale gas value chain” to explicitly state the conversion mechanisms.

“(1) **Optimized Management (OM) scenario.** Shale gas leakage occurs throughout the value chain, from upstream equipment (tanks, compressors, flares)²⁴ to midstream infrastructure (compressor stations, pipelines)^{58,59}, and downstream consumer points. Given the similarity in shale gas production workflows, facility specifications and leakage rate between China and the U.S., we derive China’s methane leakage reduction potential from empirically validated U.S. LDAR programs. Documented implementations in U.S. shale basins demonstrate 36–44% leakage reductions^{20,60}. Through technology applicability adjustments accounting for China’s regulatory maturity and infrastructure gaps, we project a 40% (30–50%) reduction for advanced LDAR deployment in China, directly generating CO₂-equivalent emission reductions derived via the 100-year global warming potential conversion framework defined in IPCC AR6. This estimation approach follows established methodologies for assessing China’s methane mitigation potential⁶¹.

(2) **Optimized Production (OP) scenario.** CO₂ fracturing and CO₂ huff-n-puff technologies deliver synergistic benefits through dual mechanisms of geological CO₂ sequestration and production enhancement, wherein sequestered CO₂ offsets value chain carbon emissions (technical parameters detailed in preceding sections). Facility Electrification further contribute to

*emission reductions, leveraging the inherent advantage of centrally supplied electricity which exhibits markedly lower carbon footprints than on-site diesel generators¹⁸. Significant regional variations in electricity carbon intensity across sedimentary basins, driven by heterogeneity in local grid structures, are documented quantitatively in **Supplementary Table S3**. ”*

3. Added equation (8) to clearly show how carbon intensity incorporates all value chain emissions:

“The carbon footprint of the shale gas value chain is assessed by carbon intensity, measured in g CO₂e/m³, calculated as:

$$I_{i,j} = I_{P,i,j} + I_{T,i,j} + I_{C,i,j} \quad (8)$$

where $I_{P,i,j}$, $I_{T,i,j}$, and $I_{C,i,j}$ represent the carbon intensity of shale gas production, transportation and distribution, and consumption, respectively, across shale gas reservoir i and scenario j . ”

(2) Line 148, Is the comprehensive plan simply the sum of the CO₂ emission reductions of the other three plans, or is there a different calculation method? If it's a simple sum, will the three methods interfere with or affect each other?

[Response]: We sincerely thank you for this insightful comment on the combined scenario. These comments have significantly enhanced the rigor and clarity of the scenario descriptions in this study.

The combined scenario is **not** a simple arithmetic sum of the three individual scenarios. Instead, it exhibits nonlinear technological synergies with important interactions:

Synergistic effects: CO₂ fracturing and CO₂ huff-n-puff technologies enhance the Estimated Ultimate Recovery (EUR) per well, which increases the total available pore volume for geological carbon storage. This creates a multiplicative rather than additive effect.

Capacity constraints: While the enhanced EUR increases total storage capacity, the technologies do compete for the same geological space. CO₂ used in fracturing and huff-n-puff operations occupies pore volume that would otherwise be available for pure sequestration in the abandonment phase.

Temporal sequencing: The technologies are implemented at different stages of the well lifecycle (fracturing, huff-n-puff and abandonment sequestration), creating dynamic interaction rather than simultaneous competition.

To clarify this mechanism, we have revised the scenario description as follows:

“(4) Combined scenario. This scenario integrates the above management strategies through nonlinear synergistic interactions, not merely arithmetic addition. Specifically, CO₂ fracturing and huff-n-puff enhance well EUR, thereby expanding the total geological carbon storage capacity. However, the finite geological storage capacity creates trade-offs: CO₂ injected during fracturing and huff-n-puff operations reduces the volume available for sequestration in depleted wells, requiring optimization to maximize overall

carbon reduction benefits.”

4. On page 9, in the section "Economic viability across shale gas reservoirs and scenarios ": Line 173, the article mentions that optimizing the production plan can significantly improve economic benefits, but the high costs of CO₂ fracturing technology and CO₂ injection may not be matched by the increased production of shale gas, potentially affecting economic feasibility. Additionally, CO₂ fracturing technology has certain limitations. Can the appropriate regions for implementing the optimized production plan be identified based on the formation conditions?

[Response]: We sincerely appreciate the reviewer's insightful comments regarding the regional applicability of production optimization strategies. The concerns about additional expenditures for CO₂ procurement, compression, and injection in CO₂ fracturing and huff-n-puff operations are well-founded and critically impact economic feasibility. Our model has comprehensively accounted for these additional expenditures relative to the incremental revenue from enhanced shale gas production. Consequently, the revised manuscript now incorporates explicit delineation of applicable regions for the optimized production (OP) scenario, with substantive modifications detailed below.

“However, the optimized production (OP) scenario demonstrates more promising results for continental deposits, with significant IRR increases of 4.5% to 7.4% and UNPV improvements of US\$ 0.042 to 0.056 m⁻³. Profitability was achieved only in continental shale formations within the Tarim Basin and Ordos Basin, where favorable geological conditions and CO₂ source proximity offset the technology’s higher implementation costs.”

5. On page 14, in the section "Life cycle assessment of value chain carbon emissions" (1) Line 334, The statement "The carbon emissions stem from energy inputs, raw materials production, methane leakage, and CO₂ emissions" should clarify whether it includes the CO₂ emissions from the final combustion of shale gas.

[Response]: We sincerely appreciate the reviewer’s precise observation. Yes, CO₂ emissions from the final combustion of shale gas are fully included in our life cycle assessment. Specifically, combustion-derived CO₂ is categorized under downstream consumption emissions.

We have revised the text to eliminate this ambiguity:

*“This study employs life cycle assessment to quantify carbon emissions (including CH₄ and CO₂) across China’s shale gas value chain. It includes upstream production, midstream transportation and distribution, and downstream consumption (**Supplementary Figure 5**). The carbon emissions stem from energy inputs, raw materials production, methane leakage, and CO₂ emissions, with the latter primarily arising from downstream shale gas combustion.”*

(2) Line 339, Regarding the calculation of carbon intensity, it is recommended that the authors provide a detailed explanation of how the proportion coefficients for the three stages (upstream, midstream, and downstream) are established. This would help readers better understand the methodology and assumptions behind the carbon intensity calculations.

[Response]: We sincerely thank the reviewer for this important suggestion. Our carbon intensity calculation methodology differs for each stage based on data availability and complexity:

1. Upstream (Production) - Model-based calculation:

The upstream carbon intensity $I_{P,i,j}$ is calculated through detailed bottom-up modeling encompassing five sub-stages:

$$I_{P,i,j} = I_{P1,i,j} + I_{P2,i,j} + I_{P3,i,j} + I_{P4,i,j} + I_{P5,i,j} \quad (9)$$

where $I_{P1,i,j}$, $I_{P2,i,j}$, $I_{P3,i,j}$, $I_{P4,i,j}$ and $I_{P5,i,j}$ represent the carbon intensity during site preparation, drilling and cementation, well completion, production, and decommissioning phase.

Each sub-stage involves multiple calculations for energy consumption, material inputs, and methane leakage (detailed equations provided in Supplementary Information S3).

2. Midstream (Transportation) - Literature-based values:

$I_{T,i,j}$ is derived from published studies specific to China's pipeline infrastructure, accounting for pipeline transmission losses, compression station energy consumption and distribution network characteristics.

Ref:

1. Tong, F., Jaramillo, P. & Azevedo, I. M. L. Comparison of life cycle greenhouse gases from natural gas pathways for medium and heavy-duty vehicles. *Environ. Sci. Technol.* **49**, 7123–7133 (2015).

3. Downstream (Consumption) - Weighted sectoral approach:

$$I_{C,i,j} = \sum (w_k \times EF_k)$$

where w_k represents the consumption share of sector k (industry, transportation, power generation) and EF_k is the sector-specific emission factor.

Ref:

1. Yuan, Z., Ou, X., Peng, T. & Yan, X. Life cycle greenhouse gas emissions of multi-pathways natural gas vehicles in china considering methane leakage. *Appl. Energy* **253**, 113472 (2019).

2. Zhang, Y. *et al.* Life cycle assessment of ammonia synthesis in China. *Int. J. Life Cycle Assess.* **27**, 50–61 (2022).

3. Ling, Y. *et al.* Carbon emissions in China's thermal electricity and heating industry: An input-output structural decomposition analysis. *J. Clean. Prod.* **329**, 129608 (2021).

The revised methodology section now states:

“Life cycle assessment of value chain carbon emissions

*This study employs life cycle assessment to quantify carbon emissions (including CH₄ and CO₂) across China's shale gas value chain. It includes upstream production, midstream transportation and distribution, and downstream consumption (**Supplementary Figure 5**). The carbon emissions stem from energy inputs, raw materials production, methane leakage, and CO₂ emissions, with the latter primarily arising from downstream shale gas combustion. The GHG emission intensities for materials are based on life cycle assessment literature^{16,43–46}, while site data are derived from recent studies^{16,47,48}. The carbon footprint of the shale gas value chain is assessed by carbon intensity, measured in g CO₂e/m³, calculated as:*

$$I_{i,j} = I_{P,i,j} + I_{T,i,j} + I_{C,i,j} \quad (8)$$

where $I_{P,i,j}$, $I_{T,i,j}$, and $I_{C,i,j}$ represent the carbon intensity of shale gas production, transportation and distribution, and consumption, respectively, across shale gas reservoir i and scenario j . Upstream production emissions are calculated through detailed bottom-up modeling. The production carbon intensity $I_{P,i,j}$ encompasses five distinct operational phases:

$$I_{P,i,j} = I_{P1,i,j} + I_{P2,i,j} + I_{P3,i,j} + I_{P4,i,j} + I_{P5,i,j} \quad (9)$$

*where $I_{P1,i,j}$, $I_{P2,i,j}$, $I_{P3,i,j}$, $I_{P4,i,j}$ and $I_{P5,i,j}$ represent the carbon intensity during site preparation, drilling and cementation, well completion, production, and decommissioning phase under shale gas reservoir i and scenario j , detailed in **Supplementary Information S3**.*

*Midstream and downstream emissions employ literature-based approaches due to infrastructure standardization. Transportation and distribution carbon intensity $I_{T,i,j}$ is derived from pipeline network studies specific to China's shale gas infrastructure⁴⁹. Carbon intensity of consumption $I_{C,i,j}$ is calculated using sector-weighted emission factors, accounting for end-use distributions across industry, transportation, and power generation sectors^{50–52}. These values are summarized in **Supplementary Table 13**."*

6. On page 16, in the section "Assessment of emission reduction potential throughout the shale gas value chain," the authors propose four scenarios for reducing greenhouse gas emissions, two things need to be noted.

(1) For the OM scenario, it is suggested that the authors elaborate on the specific process of estimating that methane leakage in China can be reduced by about 40% based on the success of US LDAR program. This would enhance the clarity and credibility of the estimation.

[Response]: We sincerely appreciate the reviewer's suggestion to elaborate on the estimation methodology. This clarification is indeed crucial for establishing the credibility of our projections.

China's shale gas industry has not yet implemented Leak Detection and Repair (LDAR) programs at scale, where existing leakage monitoring primarily focuses on operational safety rather than targeted methane mitigation. Consequently, significant emission reduction potential remains untapped. Given that the United States, the world's largest shale gas producer, has deployed well-established LDAR practices, and considering the similarity in production workflows between the Chinese and U.S. shale sectors, we have

referenced U.S. operational frameworks to inform our estimations. This methodology aligns with the approach adopted by Khanna et al. in their assessment of China's methane abatement potential¹.

1. Khanna, N., Lin, J., Liu, X. & Wang, W. An assessment of China's methane mitigation potential and costs and uncertainties through 2060. *Nat Commun* **15**, 9694 (2024).

To address your request for greater clarity, we have revised the manuscript as follows:

“(1) Optimized Management (OM) scenario. Shale gas leakage occurs throughout the value chain, from upstream equipment (tanks, compressors, flares)²⁴ to midstream infrastructure (compressor stations, pipelines)^{58,59}, and downstream consumer points. Given the similarity in shale gas production workflows, facility specifications and leakage rate between China and the U.S., we derive China's methane leakage reduction potential from empirically validated U.S. LDAR programs. Documented implementations in U.S. shale basins demonstrate 36–44% leakage reductions^{20,60}. Through technology applicability adjustments accounting for China's regulatory maturity and infrastructure gaps, we project a 40% (30–50%) reduction for advanced LDAR deployment in China, directly generating CO₂-equivalent emission reductions derived via the 100-year global warming potential conversion framework defined in IPCC AR6. This estimation approach follows established methodologies for assessing China's methane mitigation potential⁶¹. ”

(2) In the OP scenario, the authors distinguish the cumulative shale gas production percentage (CPIP) for CO₂ fracturing technology under different geological conditions (marine, terrestrial, and transitional). This distinction enhances the credibility of the data and reveals the CO₂ sequestration potential in different regions. However, the discussion lacks an exploration of specific challenges that may be encountered during the implementation of these technologies. It is recommended that the authors supplement the discussion with relevant challenges to enhance the study's practicality and reliability.

[Response]: We sincerely thank the reviewer for the valuable suggestion. This constructive critique has significantly enhanced the rigor and real-world applicability value of our research.

By taking the reviewer's suggestion, we have added comprehensive discussions on potential implementation obstacles in both the Introduction and Discussion sections, as detailed below:

In the Introduction, we now acknowledge key challenges:

“Applying CO₂-based technologies in shale gas operations can generate substantial carbon sink effects, contributing significantly to global carbon neutrality goals^{6,7}. However, large-scale deployment is constrained by formation-specific challenges including economic feasibility barriers^{8,9}, compounded by risks of CO₂ leakage^{9,10} and induced seismicity¹¹. The U.S., as

the world's largest shale gas producer, has conducted reservoir-specific simulations and laboratory-scale explorations of carbon sink potential, evaluating techniques such as CO₂ fracturing and geological sequestration^{12–15}. Nevertheless, existing research predominantly examines isolated processes rather than implementing full value-chain integration assessments, and systematic analysis of CO₂-based technologies' applicability across diverse shale reservoir types remains underdeveloped. China, facing more complex geological conditions, is pioneering integrated CO₂-based technologies including CO₂ fracturing¹⁶, CO₂ huff-n-puff¹⁷, electrification of operations¹⁸, carbon sequestration^{8,19}, and enhanced leak detection programs²⁰, demonstrating enhanced effectiveness in its diverse shale formations. However, systematic assessment of emission-reduction potential across shale gas value chains under varying geological contexts remains challenging.”

In the Discussion, we provide detailed challenge analysis:

“While formation-specific challenges vary across reservoir types, several fundamental barriers constrain all CO₂ sequestration operations. During CO₂ sequestration, the injection of CO₂ induces pore pressure perturbations, altering the mechanical equilibrium of the reservoir through the effective stress principle. This can potentially activate critically stressed faults or natural fracture systems, leading to microseismic events^{11,15}. Moreover, elevated pore pressure may trigger the reactivation of caprock fractures or shear failure of wellbores, forming leakage pathways that result in small-scale leakage events^{10,11,15}. However, current monitoring techniques face challenges in achieving precise early-stage detection and quantitative characterization of such small-scale leakage occurring beyond wellbore interfaces. Additionally, the challenge to economic feasibility is particularly severe; the full-chain costs – encompassing CO₂ capture, compression, and the deployment of extensive corrosion-resistant pipeline networks to satisfy source-sink matching – pose significant challenges to achieving profitability in the absence of structural subsidies and carbon credit revenue mechanisms^{8,9}. Furthermore, spatial heterogeneity in geological conditions, infrastructure requirements, and operational challenges create uncertainties in both environmental and economic outcomes. These uncertainties affect the reliability of economic forecasts and the effectiveness of carbon reduction strategies.”

7. On page 18, in the section "Techno-economic analysis of emission reduction scenarios": Lines 421 and 427, formulas 9 and 10 are used to calculate the Internal Rate of Return (IRR) and net present value (NPV). Were these formulas derived through deduction or do they cite previous research? If they were derived, please provide the derivation process; if they cite previous research, please specify the relevant references.

[Response]: Thank you for your valuable comment. Equations 9 and 10 (now renumbered as Equations 14 and 17) represent standard financial metrics universally established in corporate finance literature, not novel derivations. These formulas are fundamental tools in investment appraisal, with NPV originating from Irving Fisher's

work on the time value of money and IRR being widely adopted since the 1950s. The Unit Net Present Value (UNPV) in Equation 14 is a straightforward normalization of NPV by technically recoverable reserves, commonly used in petroleum economics to enable cross-project comparisons.

To address this, we have:

1. Added explicit citations to foundational sources:

1 Kruschwitz, L., & Löffler, A. (2006). Discounted cash flow: a theory of the valuation of firms. John Wiley & Sons.

2 Weijermars, R. (2013). Economic appraisal of shale gas plays in Continental Europe. *Appl. Energy*, 106, 100-115.

3 Yuan, J., Luo, D. & Feng, L. A review of the technical and economic evaluation techniques for shale gas development. *Appl. Energy* **148**, 49–65 (2015).

Due to constraints on the number of references imposed by the journal, only ref 3 has been cited.

2. Expanded the methodological context in the manuscript and clarified formula components with detailed variable definitions and calculation procedures as follows:

“The DCF method is a financial valuation approach grounded in the time value of money theory. Its core logic involves forecasting the free cash flow generated by an asset or project and discounting it to its present value using a risk-adjusted discount rate, thereby quantifying its intrinsic value⁶³. Financial profitability metrics such as Net Present Value (NPV), Unit Net Present Value (UNPV), Internal Rate of Return (IRR), and Dynamic Payback Period are all established based on this method. In this study, the DCF method is adopted to evaluate the techno-economic feasibility of multiple emission-reduction scenarios across the shale gas value chain. The UNPV and IRR are selected as profitability indicators to assess the techno-economic performance of different scenarios. UNPV serves as a core metric for evaluating the profitability per unit of shale gas. It is defined as the ratio of the project's NPV to the total production (Q_{total}), calculated as follows:

$$UNPV = NPV / Q_{total} \quad (14)$$

The NPV is calculated by discounting the annual net cash flows (NCF_t) within the shale gas value chain using the industry benchmark discount rate (r_0) and summing the discounted present values. This metric characterizes the absolute profitability of the shale gas value chain. The formula is expressed as follows:

$$NPV = \sum_{t=0}^{t=n} NCF_t \cdot (1 + r_0)^{-t} \quad (15)$$

The NCF_t is calculated as follows:

$$NCF_t = Q_t \cdot f \cdot (P + S_{\text{subsidy}}) - T_t - I_t \quad (16)$$

where Q_t denotes shale gas production in year t ; f represents the proportion of marketable gas output; P is the shale gas wellhead price; S_{subsidy} signifies the shale gas development subsidy, a fiscal incentive provided by the Chinese government, quantified at US\$ 0.013 m^{-3} ⁶⁴. The variable T_t represents the tax cost, encompassing value-added tax, income tax, resource tax, and other applicable levies. I_t denotes the business cost in year t , where I_1 specifically refers to well pad construction investment, including expenditures for drilling, fracturing, and completion activities. The computational specifics regarding T_t and I_t are comprehensively detailed in S5.1, S5.2, and S5.5 of the **Supplementary Information**.

The IRR refers to the discount rate at which a project's cumulative NPV equals zero, reflecting the project's investment return rate. The IRR accounts for the time value of money. A higher IRR indicates better project profitability, making it a key indicator for evaluating project profitability. Its calculation formula is as follows:

$$\sum_{t=0}^{t=n} NCF_t \cdot (1 + \text{IRR})^{-t} = 0 \quad (17)$$

Reviewer #2:

Dear Reviewer,

We sincerely appreciate the time and effort you have dedicated to reviewing our manuscript and providing us with such invaluable constructive feedback. Your insights are crucial for enhancing the clarity, rigor, and readability of our work. We have carefully considered all your suggestions and made corresponding revisions to the manuscript. We hope that these changes effectively address your concerns, and we kindly ask you to review the revised manuscript. Below, we outline our responses to your specific comments and the modifications made:

1. This article is focused on China. At a minimum, the title should include that.

[Response]: We sincerely thank the reviewer for highlighting the need to specify the geographical focus in our title. We fully agree that clearly defining the study area is essential for readers to immediately understand the paper's scope and relevance.

We have revised the title to:

“Carbon sequestration for Geological Negative Emissions of shale gas value chain in China”

We believe this China-specific focus is particularly significant because:

1. **Diversified geological conditions:** China’s shale formations differ substantially from US plays. While US shales are predominantly marine deposits with relatively homogeneous properties, China’s shale resources span marine, terrestrial, and transitional facies, creating more complex but potentially more responsive conditions for CO₂-based technologies.
2. **Enhanced production potential:** Our research demonstrates that CO₂ fracturing technology delivers significantly enhanced production outcomes in Chinese shale formations—markedly surpassing those reported in U.S. shale plays. This disparity stems primarily from the elevated clay content and pronounced water sensitivity characteristic of China's terrestrial and transitional shale facies, which renders CO₂ particularly advantageous as a fracturing fluid.
3. **Global demonstration value:** As the world’s second-largest shale gas producer, China’s successful implementation of negative emissions technologies provides a replicable model for other countries with similar geological complexity, particularly in Asia and South America.

We have also enhanced the Introduction to emphasize China’s technological applications:

“Applying CO₂-based technologies in shale gas operations can generate substantial carbon sink effects, contributing significantly to global carbon neutrality goals^{6,7}. However, large-scale deployment is constrained by formation-specific challenges including economic feasibility barriers^{8,9}, compounded by risks of CO₂ leakage^{9,10} and induced seismicity¹¹. The U.S., as the world’s largest shale gas producer, has conducted reservoir-specific

simulations and laboratory-scale explorations of carbon sink potential, evaluating techniques such as CO₂ fracturing and geological sequestration^{12–15}. Nevertheless, existing research predominantly examines isolated processes rather than implementing full value-chain integration assessments, and systematic analysis of CO₂-based technologies’ applicability across diverse shale reservoir types remains underdeveloped. China, facing more complex geological conditions, is pioneering integrated CO₂-based technologies including CO₂ fracturing¹⁶, CO₂ huff-n-puff¹⁷, electrification of operations¹⁸, carbon sequestration^{8,19}, and enhanced leak detection programs²⁰, demonstrating enhanced effectiveness in its diverse shale formations. However, systematic assessment of emission-reduction potential across shale gas value chains under varying geological contexts remains challenging.”

2. The abstract description I read while agreeing to review does not match the content of the manuscript.

[Response]: We sincerely appreciate your valuable comment on the abstract. We have comprehensively revised the abstract to ensure clear alignment with the manuscript’s structure and findings. Below is a detailed mapping table showing how each abstract sentence corresponds to specific manuscript sections:

1. Abstract Restructuring

“Carbon sequestration in shale gas operations represents a crucial pathway to achieve Geological Negative Emissions, where geological carbon sequestration exceeds life cycle greenhouse gas emissions, for global 1.5°C targets. However, the potential for such emissions reduction in China’s shale gas value chain and its economic viability remain unclear. This study quantifies the potential for transforming China’s shale gas value chain from an emission source to a carbon sink using life cycle assessment, while revealing significant spatial heterogeneity in economic feasibility across distinct shale gas reservoirs. Results demonstrate that synergistic deployment of CO₂-based technologies (fracturing, huff-n-puff, and depleted-well sequestration) can achieve Geological Negative Emissions across the shale gas value chain, with national carbon sink potential reaching 66 billion tonnes of CO₂-equivalents and shale gas production increasing by 4,518 billion cubic meters. Multi-scenario economic assessments reveal that marine shale in Sichuan Basin exhibits inherent profitability, whereas continental reservoirs can reverse negative returns through carbon credit integration or optimized production. As current Chinese carbon market prices provide insufficient incentives, implementing region-specific subsidies and enhancing carbon pricing frameworks could unlock this potential, thereby contributing to national carbon neutrality goals and multiple Sustainable Development Goals.”

2. Table: Abstract-Manuscript Correspondence

Abstract Component	Manuscript Location	Specific Content Match
Opening Statement		

Abstract Component	Manuscript Location	Specific Content Match
"Carbon sequestration in shale gas operations represents a crucial pathway to achieve Geological Negative Emissions..." Research Gap "However, the potential for geological negative emissions in China's shale gas value chain and its economic viability remain unclear."	Introduction (Para 1-2) Introduction (The third paragraph)	Establishes the concept and global context Identifies the knowledge gap
Methodology		
"This study quantifies the potential...using life cycle assessment"	Methods (Life cycle assessment of value chain carbon emissions)	LCA framework description
"...revealing significant spatial heterogeneity in economic feasibility across distinct shale gas reservoirs"	Methods (Techno-economic analysis of emission reduction scenarios)	Economic assessment methodology
Key Findings-Carbon reduction		
"synergistic deployment of CO2-based technologies (fracturing, huff-n-puff, and depleted-well sequestration)"	Results (Synergy of carbon sequestration and production enhancement)	Technology integration analysis
"national carbon sink potential reaching 66 billion tonners of CO ₂ -equivalents"	Results (Fig 2a, CS scenario)	Quantitative carbon sequestration potential
"shale gas production increasing by 4,518 billion cubic meters"	Results (Fig 2b, CS scenario)	Production enhancement quantification
Key Findings-Economic Analysis		
"marine shale in the Sichuan Basin exhibits inherent profitability"	Results (Economic viability across shale gas reservoirs and scenarios, Fig 5)	Basin-specific economic outcomes
"continental reservoirs can reverse negative returns through carbon credit integration"	Results (Economic viability across shale gas reservoirs and scenarios, Fig 5)	Carbon pricing sensitivity analysis
Policy Implications		
"Current Chinese carbon market prices provide insufficient incentives"	Discussion (The first paragraph)	Economic barrier analysis
"implementing region-specific subsidy mechanisms and enhancing carbon pricing framework"	Discussion (The third paragraph)	Policy recommendations

Abstract Component	Manuscript Location	Specific Content Match
"contributing to national carbon neutrality goals and multiple SDGs"	Discussion (The third paragraph)	Broader significance

The revised abstract now clearly aligns with our manuscript structure, providing readers with an accurate preview of our study’s scope, methodology, and key contributions to China’s shale gas decarbonization strategy.

3. I did read the paper and it is difficult to understand. The authors use many buzz words that I am not familiar with. These could be terms that apply to China.

[Response]: We sincerely appreciate your feedback regarding terminology clarity. To enhance accessibility, we have implemented the following revisions:

First, we have standardized our technical terminology to align with international conventions. Throughout the manuscript, we have replaced “well site” with “well pad” to match standard industry usage. For specialized terms that are essential to our analysis, we have added clear definitions at first mention. For example, “shale gas reservoir” is now defined as “a geological formation containing recoverable shale gas resources,” and “CO₂ huff-n-puff” is explained as “a cyclic injection-production process where CO₂ is injected into the formation, allowed to soak, then co-produced with natural gas.”

To further enhance clarity, we have revised complex sentences to use more accessible language without sacrificing precision. Technical concepts are now introduced progressively, with brief parenthetical explanations provided for unavoidable specialized terms. All acronyms are defined at first use, and we have expanded figure and table captions to include definitions of technical terms appearing in visualizations. These comprehensive revisions ensure that our findings on China’s shale gas decarbonization potential are accessible to the broad international readership while maintaining the technical depth necessary for scientific communication.

4. The figure fonts and figure size are very small. When reading the text and referring to the paper, it is hard to understand and interpret the figures. There is also a lot of information in each figure.

[Response]: We sincerely thank the reviewer for highlighting the readability issues with our figures. We have comprehensively redesigned all figures to enhance their accessibility and interpretability.

1. The figure layout has been reconfigured and the bar charts enlarged to enhance data readability.

2. All figures have been updated and uploaded in high-definition (HD) resolution without compression artifacts, ensuring lossless quality throughout the manuscript revision process.

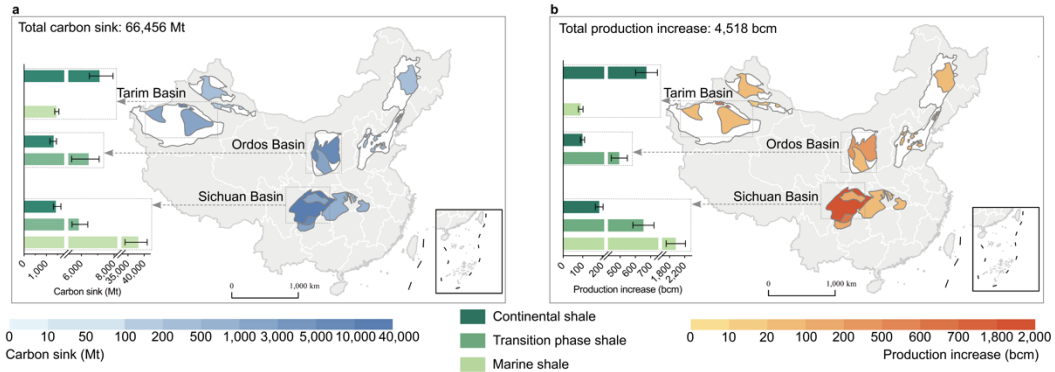


Fig. 2 Carbon sequestration potential and production enhancement in China's shale gas operations by shale gas reservoirs. a, Cumulative carbon sink potential achieved through integrated deployment of CO₂ fracturing, CO₂ huff-n-puff, and CO₂ sequestration technologies across major shale basins; b, Associated production increase potential through combined technology implementation. The cumulative bar charts in a and b illustrate the carbon sink and production increase potential of different types of shale gas reservoirs in the Sichuan Basin, Tarim Basin, and Ordos Basin, with 95% confidence intervals.

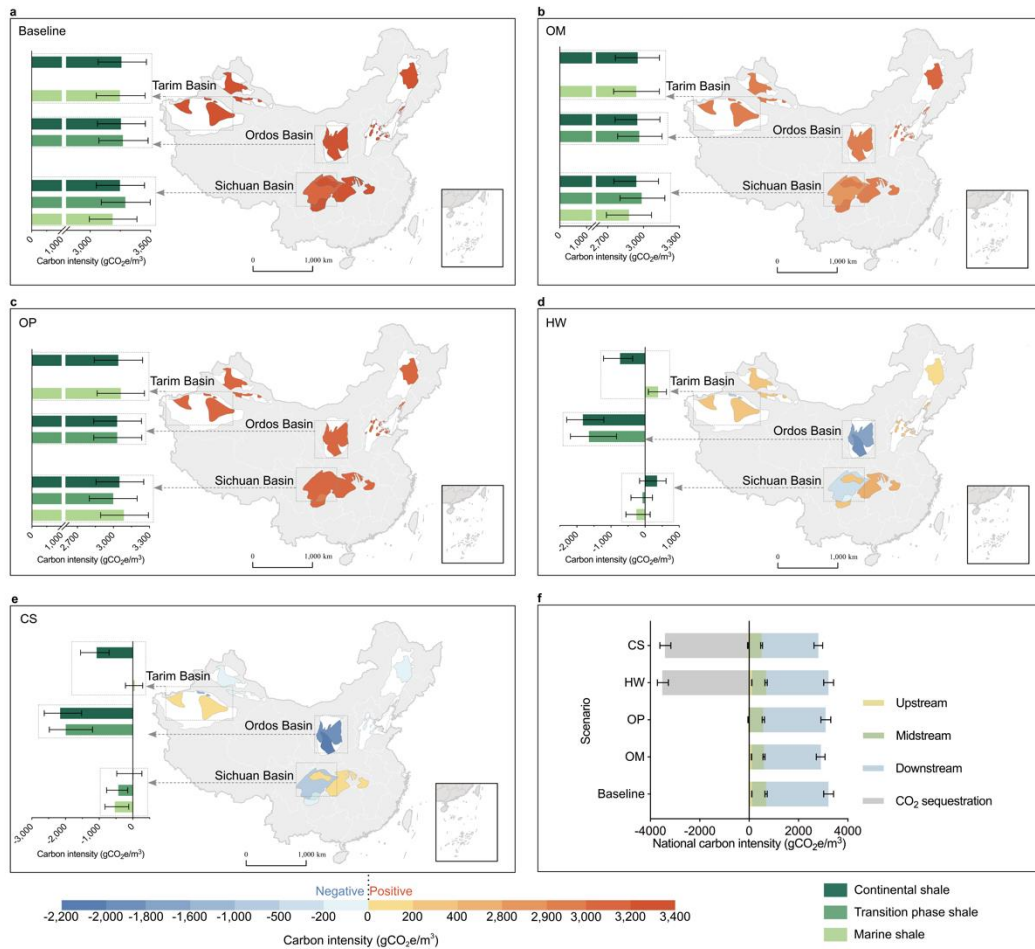


Fig. 4, The carbon intensity of shale gas produced in China's various shale gas reservoirs under different scenarios. a, Business-as-usual emissions per unit of gas produced. b, Optimized management (OM) scenario. c, Optimized production (OP) scenario. d, Depleted well handling (HW) scenario. e, Combined strategies scenario. f, The national average emissions per unit of natural gas production for each scenario (calculated after weighting for each shale gas reservoir). The cumulative bar charts in a-e illustrate the carbon intensity of unitary shale gas produced of different types of shale gas reservoirs in the Sichuan Basin, Tarim Basin, and Ordos Basin, along with a 95% confidence interval.

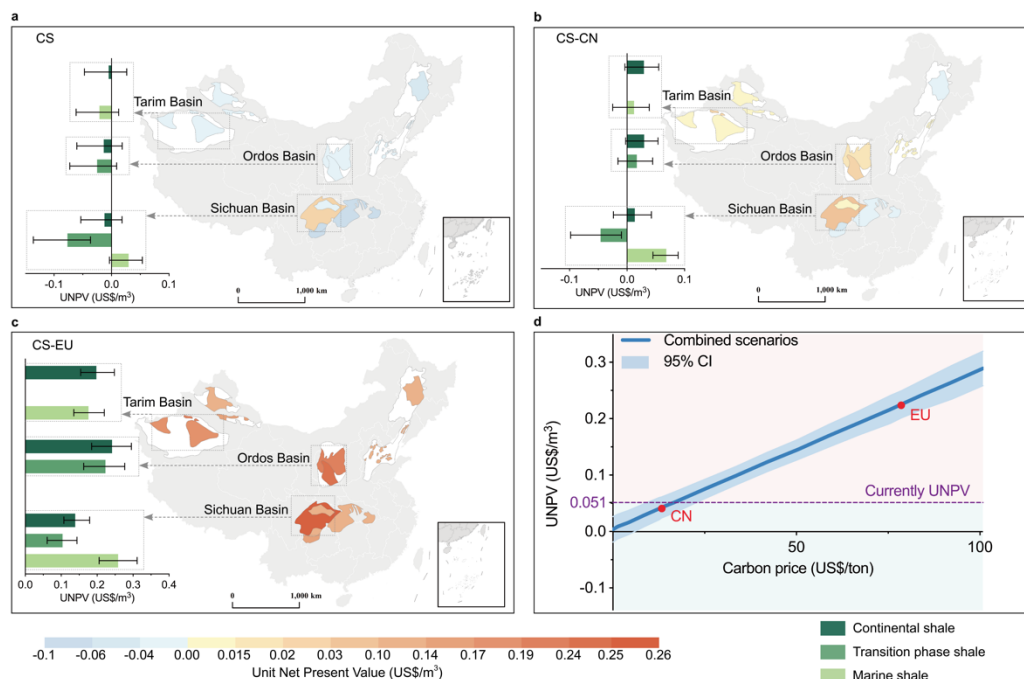


Fig. 5 The Unit Net Present Value(UNPV) of different shale gas reservoirs in various regions under different carbon prices in the combined scenario. a, The UNPV of different shale gas reservoirs in various regions under a comprehensive scenario without carbon subsidies. b, The UNPV of different shale gas reservoirs in various regions under a comprehensive scenario at carbon market prices in China(CN). c, The UNPV of different shale gas reservoirs in various regions under a comprehensive scenario at carbon market prices in Europe(EU). The cumulative bar charts in a-c illustrate the UNPV of different types of shale gas reservoirs in the Sichuan Basin, Tarim Basin, and Ordos Basin, along with a 95% confidence interval. d, The variation in the UNPV of Chinese shale gas reservoirs under a comprehensive scenario with changes in carbon prices.

5. In the methods section, I don't under why equation (1) is using 30% sequestered while later the authors use 50% sequestered. And the reference is from 2016, which seems like a time when people were not thinking about storage CO₂ in shale gas reservoirs.

[Response]: We deeply appreciate the reviewer's insightful observation regarding the sequestration efficiency parameters in Equation (1). It helped us improve the clarifications that substantially enhance the methodological transparency of our revised manuscript.

Clarification of Different Sequestration Rates:

The 30% and 50% sequestration rates apply to distinct technologies with different mechanisms. In CO₂ fracturing, high-pressure CO₂ replaces water during fracturing process to create fracture networks. Approximately 70% of injected CO₂ returns during flowback operations, while 30% remains permanently sequestered within the formation through adsorption and dissolution mechanisms. In contrast, CO₂ huff-n-puff operations, implemented during years 13-18 of well life, achieve 50% sequestration per cycle due to the extended soaking period that enhances CO₂-rock interactions and

displacement processes. We have revised the manuscript to clearly distinguish these process-specific rates and their underlying mechanisms:

“CO₂ fracturing. During well completion, high-pressure CO₂ is injected to replace water for fracturing, creating fracture networks that facilitate gas recovery. Approximately 70% of injected CO₂ returns during the production, while 30% remains sequestered¹⁶. ”

“CO₂ huff-n-puff. During the typical 20-year production cycle, shale gas wells exhibit a characteristic production decline curve until reservoir depletion occurs. To mitigate this decline and increase the EUR, the CO₂ huff-n-puff technology can be employed. The CO₂ huff-n-puff stimulation is executed over a 6-year period (within years 13 to 18 of the well lifecycle), repeated for 12 cycles. Based on existing experiment and field studies^{41,42}, each cycle comprises one month CO₂ injection (20 t/day), followed by a one-month soaking, and a four-month production. Critically, 50% of the injected CO₂ per cycle undergoes permanent geological sequestration⁴⁰. The CO₂ huff-n-puff yields a CPIP of 3% (2%–4%) for marine shale and 6% (4%–8%) for transitional and continental shale. The method for calculating production increase is shown in Eq. 1.”

Regarding the 2016 Reference and CO₂ Fracturing Research Timeline:

We acknowledge the reviewer’s concern about citing a 2016 reference. This particular study by Wilkins and Free employs life cycle assessment to compare environmental impacts of water-based versus CO₂-based fracturing in the Marcellus Shale. By 2016, CO₂ fracturing technology had already undergone three decades of development. The technology trajectory began with Lillies and King’s pioneering field test in 1982, followed by Yost et al.’s pilot project in Devonian shale (1993), Campbell et al.’s full-scale implementation in Lewis shale (2000), and Mazza’s optimization studies in Texas (2004). The renewed interest in CO₂ fracturing post-2010 was driven by water resource constraints and environmental concerns in major shale plays.

Reference:

1. Lillies, A. T. & King, S. R. Sand fracturing with liquid carbon dioxide. in *SPE Production Technology Symposium* (New Mexico, 1982).
2. Yost, A. B., Mazza, R. L. & Gehr, J. B. CO₂ /sand fracturing in devonian shales. in *SPE Eastern Regional Meeting* (Pittsburgh, Pennsylvania, 1993).
3. Campbell, S. M., Fairchild, N. R. & Arnold, D. L. Liquid CO₂ and sand stimulations in the lewis shale, san juan basin, new mexico: A case study. in *SPE Rocky Mountain Regional/Low-Permeability Reservoirs Symposium and Exhibition* (Denver, Colorado, 2000).
4. Mazza, R. L. Field Testing & Optimization of CO₂/Sand Fracturing Technology; Petroleum Consulting Services (US, 2004).

5. Middleton, R. S. *et al.* Shale gas and non-aqueous fracturing fluids: Opportunities and challenges for supercritical CO₂. *Appl. Energy* **147**, 500–509 (2015).

Evolution of CO₂ Storage in Shale Formations:

While early carbon sequestration research focused on conventional depleted reservoirs (Bachu, 2000; Oldenburg *et al.*, 2002), the shale gas boom catalyzed investigation into shale-specific storage potential. The U.S. DOE's National Energy Technology Laboratory developed standardized methodologies for shale CO₂ storage assessment by 2016. Notably, Tao and Clarens (2013) demonstrated that the Marcellus Shale could sequester >50% of U.S. stationary-source emissions by 2030, while Liu *et al.* (2013) validated technical feasibility through reservoir simulations.

Therefore, by 2016, both CO₂ fracturing and shale-based carbon storage were well-established research areas with substantial literature support. The Wilkins and Free reference appropriately captures the state of knowledge at that time, providing validated parameters that remain relevant for our analysis of China's shale gas decarbonization potential.

1. Bachu, S. Sequestration of CO₂ in geological media: criteria and approach for site selection in response to climate change. *Energy Convers. Manag.* **41**, 953–970 (2000).

2. Oldenburg, C. M. & Benson, S. M. CO₂ injection for enhanced gas production and carbon sequestration. in *SPE International Petroleum Conference and Exhibition* (Villahermosa, Mexico, 2002).

3. Lackner K S. A guide to CO₂ sequestration[J]. *Science*, 2003, 300(5626): 1677-1678.

4. Levine, J. S. *et al.* U.S. DOE NETL methodology for estimating the prospective CO₂ storage resource of shales at the national and regional scale. *Int. J. Greenh. Gas Control* **51**, 81–94 (2016).

5. Tao, Z. & Clarens, A. Estimating the carbon sequestration capacity of shale formations using methane production rates. *Environ. Sci. Technol.* **47**, 11318–11325 (2013).

6. Liu, F., Ellett, K., Xiao, Y. & Rupp, J. A. Assessing the feasibility of CO₂ storage in the new albany shale (devonian–mississippian) with potential enhanced gas recovery using reservoir simulation. *Int. J. Greenh. Gas Control* **17**, 111–126 (2013).

6. The authors should also be consistent when using sequestration versus storage through out the text.

[Response]: We sincerely thank the reviewer for identifying this important inconsistency in our terminology. We have now standardized our terminology throughout the entire manuscript.

As suggested, we have now systematically standardized the terminology throughout the manuscript. All references to carbon storage now explicitly use "sequestration" (over ten instances revised). This includes revisions in the abstract, main text, figure captions,

and supplementary materials. For example, we now consistently use "CO₂ sequestration rate" when discussing the percentage of injected CO₂ that remains permanently trapped, and "CO₂ sequestration capacity" when quantifying the potential of shale formations to permanently contain CO₂.

The established acronym Carbon Capture, Utilization, and Storage (CCUS) remains unchanged as it reflects standardized nomenclature within the field and is widely recognized in both academic literature and policy documents. This selective retention ensures our work remains aligned with international conventions while maintaining internal consistency.

Reviewer #3:

The article puts forward a very interesting proposal: transforming shale gas formations themselves into net carbon sinks by applying techniques such as CO₂ hydraulic fracturing, the huff-n-puff method (enhanced recovery with CO₂ injection), and storage in depleted wells. The approach is innovative and is framed within the idea of achieving geological negative emissions—something that could have a transformative impact on the carbon balance of the unconventional gas industry. One of the manuscript's most striking claims is that the potential for net emissions reduction could reach 1.981 billion tons of CO₂ (1.981 Gt CO₂) between 2024 and 2060, which would represent a spectacular climate benefit if validated. However, this ambition contrasts sharply with the scientific execution of the article, which presents significant shortcomings both in its conceptual framing and in its development. The main issues identified are outlined below in an orderly and reasoned manner.

In summary, the article starts with a very promising idea and addresses a crucial problem with remarkable ambition. However, it needs a thorough revision to fulfill its promise. It lacks methodological rigor, clarity of presentation, risk analysis, and solid references that situate the work within the existing international framework. If these aspects are corrected, the manuscript could make a valuable contribution to the debate on negative emissions in the shale gas industry. In its current state, however, the most reasonable recommendation is a major revision.

Dear Reviewer:

We sincerely appreciate your thorough evaluation and recognition of our manuscript's innovative approach to transforming shale gas formations into carbon sinks. Your acknowledgment of the potential transformative impact of achieving geological negative emissions in the unconventional gas industry validates the importance of our research direction. We are grateful for your constructive criticism and the opportunity to strengthen our manuscript through major revision.

In response to your detailed comments, we have undertaken a comprehensive revision addressing each identified weakness:

Methodological Rigor: We have provided complete transparency in our calculation of the 1.981 Gt CO₂ sequestration potential, with detailed breakdowns of assumptions, parameter justifications, and uncertainty bounds. Monte Carlo simulations (100,000 iterations) now quantify confidence intervals for all major findings. The sequestration rates (30% for fracturing, 50% for huff-n-puff) are explicitly justified with mechanistic explanations and literature support.

Clarity of Presentation: The manuscript has been completely restructured with clear separation between Results and Discussion sections, standardized terminology, and improved transitions. All economic units have been converted to US\$ for international accessibility. Complex technical concepts are now introduced progressively with clear definitions.

Risk Analysis: We have added comprehensive discussion of implementation challenges including CO₂ leakage risks, induced seismicity potential, infrastructure requirements, and economic barriers. The analysis now explicitly addresses formation-

specific challenges and includes sensitivity analyses showing how key uncertainties affect outcomes.

International Framework: We have substantially expanded our literature review with additional references, particularly from U.S. and Canadian studies. The work is now properly positioned within the global CCUS research landscape, with explicit comparisons to international projects and methodologies (e.g., U.S. DOE NETL framework).

We believe these comprehensive revisions have transformed the manuscript into a rigorous scientific contribution that maintains its innovative vision while meeting the standards of methodological excellence. We are confident that the revised manuscript now provides a valuable and credible contribution to the critical debate on achieving negative emissions in the shale gas industry. We deeply appreciate your detailed feedback, which has been instrumental in elevating the quality and impact of our work.

1. The introduction lacks solid and specific references to support its key claims. The concept of geological negative emissions is mentioned as emerging, but no prior scientific literature from countries with mature shale gas industries—such as the US or Canada—is properly cited. As a result, the reader lacks the necessary context to situate this work within the current state of knowledge.

[Response]: We sincerely appreciate the reviewer’s insightful critique regarding the insufficient contextualization of geological negative emissions within the established global knowledge base. We have comprehensively revised the Introduction to address this critical gap by incorporating extensive references from mature shale gas industries, particularly the U.S. and Canada.

Our revised Introduction now reads:

“Applying CO₂-based technologies in shale gas operations can generate substantial carbon sink effects, contributing significantly to global carbon neutrality goals^{6,7}. However, large-scale deployment is constrained by formation-specific challenges including economic feasibility barriers^{8,9}, compounded by risks of CO₂ leakage^{9,10} and induced seismicity¹¹. The U.S., as the world’s largest shale gas producer, has conducted reservoir-specific simulations and laboratory-scale explorations of carbon sink potential, evaluating techniques such as CO₂ fracturing and geological sequestration^{12–15}. Nevertheless, existing research predominantly examines isolated processes rather than implementing full value-chain integration assessments, and systematic analysis of CO₂-based technologies’ applicability across diverse shale reservoir types remains underdeveloped. China, facing more complex geological conditions, is pioneering integrated CO₂-based technologies including CO₂ fracturing¹⁶, CO₂ huff-n-puff¹⁷, electrification of operations¹⁸, carbon sequestration^{8,19}, and enhanced leak detection programs²⁰, demonstrating enhanced effectiveness in its diverse shale formations. However, systematic assessment of emission-reduction potential across shale gas value chains under varying geological contexts remains challenging.”

We have now incorporated extensive references from North American research,

drawing particularly on the comprehensive review by Lyu et al. (2021) published in *Energy & Environmental Science*, which synthesizes the current understanding of CO₂ applications in shale gas recovery and sequestration. This seminal work highlights that while CO₂ fracturing creates more complex fracture networks than hydraulic fracturing, leading to enhanced permeability, the technology faces significant deployment challenges including CO₂ leakage risks and induced seismicity concerns.

Our revised Introduction now includes:

1. **Foundational U.S. studies:** Edwards et al. (2015) demonstrated through modeling that CO₂ storage capacity in Marcellus shale wells could reach 0.5–18.7 Mt per well, while Tao and Clarens (2013) estimated that U.S. shales could sequester >50% of national stationary-source emissions by 2030.
2. **Field-scale validation:** Liu et al. (2013) validated CO₂ storage feasibility in New Albany Shale through reservoir simulation, documenting 17–24% enhanced gas recovery with simultaneous CO₂ sequestration. Schaef et al. (2014) provided experimental evidence of CO₂-shale interactions affecting storage integrity.
3. **Technical challenges:** Middleton et al. (2015) identified critical barriers including proppant transport difficulties in CO₂, while Verdon et al. (2013) documented induced seismicity risks from large-scale CO₂ injection based on Weyburn and In Salah projects.
4. **Methodological frameworks:** The U.S. DOE NETL methodology (Levine et al., 2016) established standardized approaches for evaluating shale CO₂ storage resources, providing the foundation for our China-specific assessment.

Added References:

1. Lyu, Q. *et al.* The role of supercritical carbon dioxide for recovery of shale gas and sequestration in gas shale reservoirs. *Energy Environ. Sci.* **14**, 4203–4227 (2021).
2. Middleton, R. S. *et al.* Shale gas and non-aqueous fracturing fluids: opportunities and challenges for supercritical CO₂. *Appl. Energy* **147**, 500–509 (2015).
3. Lackner, K. S. A guide to CO₂ sequestration. *Science* **300**, 1677–1678 (2003).
4. Verdon, J. P. *et al.* Comparison of geomechanical deformation induced by megatonne-scale CO₂ storage at sleipner, weyburn, and in salah. *PNAS*. **110**, E2762–E2771 (2013).
5. Zhang, X., Lu, Y., Tang, J., Zhou, Z. & Liao, Y. Experimental study on fracture initiation and propagation in shale using supercritical carbon dioxide fracturing. *Fuel* **190**, 370–378 (2017).
6. Edwards, R. W. J., Celia, M. A., Bandilla, K. W., Doster, F. & Kanno, C. M. A model to estimate carbon dioxide injectivity and storage capacity for geological sequestration in shale gas wells. *Environ. Sci. Technol.* **49**, 9222–9229 (2015).

7. Liu, F., Ellett, K., Xiao, Y. & Rupp, J. A. Assessing the feasibility of CO₂ storage in the new albany shale (devonian–mississippian) with potential enhanced gas recovery using reservoir simulation. *Int. J. Greenh. Gas Control* **17**, 111–126 (2013).
8. Schaef, H. T. *et al.* CO₂ utilization and storage in shale gas reservoirs: experimental results and economic impacts. *Energy Procedia* **63**, 7844–7851 (2014).
9. Tao, Z. & Clarens, A. Estimating the carbon sequestration capacity of shale formations using methane production rates. *Environ. Sci. Technol.* **47**, 11318–11325 (2013).

2. Throughout the article, highly ambitious figures for the potential CO₂ sequestration are presented, yet the traceability of those calculations is not clearly or transparently explained. For example, the authors state that a total of 1.98 Gt CO₂ could be stored by 2060 using a combination of technologies, but the assumptions behind this estimate—such as injection coefficients or average recovery factors—are not broken down or justified. This undermines the credibility of the conclusions.

[Response]: We sincerely thank the reviewer for this critical insight, which directly enhances the scientific rigor of large-scale carbon sequestration potential assessment. To address this fundamental concern about calculation transparency, we have comprehensively revised our methodology presentation:

1. Enhanced methodological transparency in the main text:

We now explicitly present our calculation framework, acknowledging that geological heterogeneity in reservoir characteristics (e.g., porosity, permeability) fundamentally influences EUR per well across different shale reservoirs. We addressed this variability through parameter decomposition, drawing upon analogous basin-scale data from commercial/test wells in published literature. The revised manuscript specifies:

“The production increase can be calculated as:

$$EUR_i = EUR \cdot CPIP \quad (1)$$

*where EUR varies across different shale gas reservoirs, with the specific calculation methodology detailed in S5.3 of the **Supplementary Information**.”*

2. Provided comprehensive parameter justification:

Section S5.3 now provides complete transparency in EUR estimation methodology as follows:

“S5.3 Estimation of Single Well EUR

The EUR of shale gas single wells is closely related to their economic viability. A higher EUR can reduce the unit cost of shale gas and improve economic efficiency. Various geological conditions, including reservoir characteristics, porosity, and permeability, directly impact single well production. Furthermore, the annual production of shale gas wells exhibits a clear

declining trend, with initial production typically being high but rapidly decreasing over time. Accurately predicting the EUR of shale gas wells is challenging. Common oil and gas production forecasting methods include the Arps decline curve method, analytical methods, numerical simulation methods, and empirical methods. All these approaches require substantial geological or shale gas well data. However, in China, only certain blocks in the Sichuan Basin have achieved commercial shale gas development, leading to a severe lack of relevant information. Therefore, this study obtains initial production data from several commercial and experimental wells across various basins from the relevant literature and uses a model relating initial production to EUR to calculate the EUR of shale gas wells in the target basin, as shown in Eq. S32. EUR represents the ultimate recoverable reserves of a single well in 10^8 m^3 , and IP denotes the initial production of the shale gas single well in 10^4 m^3 . Additionally, the annual production ratio of shale gas wells is substituted with relevant ratios from the marine shale in Sichuan Basin.”

$$EUR = 0.08279 \cdot IP + 0.06367 \quad (S32)$$

Regarding CO₂ fracturing and CO₂ huff-n-puff technologies, large-scale field datasets remain limited. To evaluate their production enhancement effects and injectivity coefficients: We derived results from some studies^[1-2]. Classified CPIP into two distinct categories: Marine shale formations and Transitional/continental shales.

Supplementary Table 18 Key parameter settings for uncertainty analysis

Input	Units	Distribution	Parameter	
CO ₂ fracturing-CPIP for marine shale			18	22
CO ₂ fracturing-CPIP for transitional and continental shale			55	65
CO ₂ huff-n-puff -CPIP for marine shale	%	Uniform	2	4
CO ₂ huff-n-puff -CPIP for transitional and continental shale			4	8

References:

1. Ji, T., Jiang, P., and Xu, R. Technology portfolios optimization to deliver cost-effective shale gas development: Using CO₂ versus water. *Fuel* 335, 127006 (2023).
2. Wilkins, R., Menefee, A. H. & Clarens, A. F. Environmental life cycle analysis of water and CO₂-based fracturing fluids used in unconventional gas production. *Environ. Sci. Technol.* **50**, 13134–13141 (2016).

3. Implemented rigorous uncertainty quantification:

"This study employs Monte Carlo simulation involving 100,000 iterations to conduct uncertainty analysis of the negative emissions potential and economic viability across the shale gas value chain. Random values were generated following normal, triangular, and uniform distributions, with detailed parameter settings provided in Supplementary Table 18, and the calculation of uncertainties adheres to the principles and methods outlined in the IPCC 2006 guidelines⁶⁵."

This robust framework reveals that our 1.98 Gt CO₂ estimate represents the median value, with a 95% confidence interval of 1.52-2.44 Gt CO₂.

3. *The article fails to address emissions associated with methane, both in terms of fugitive leaks and full lifecycle impacts (e.g., indirect emissions from supply chain activities). This is a critical omission, as recent studies have consistently shown that methane leakage is often the key obstacle to achieving carbon neutrality—or net negativity—in shale gas systems. Here, methane is barely mentioned, and certainly not quantified.*

[Response]: We sincerely appreciate the reviewer’s insightful critique regarding methane (CH₄) emissions in shale gas systems. Addressing this point is indeed critical for a comprehensive carbon accounting framework. Below we clarify our methodological approach.

Our analysis did incorporate fugitive methane leaks and lifecycle emissions (including upstream extraction, midstream transport, and downstream distribution) of methane. All CH₄ emissions were quantitatively assessed and converted to CO₂-equivalent (CO₂e). Documented in Supplementary Table 13 with detailed leakage rates and sources across the value chain. However, we recognize that this was insufficiently highlighted in the main text. **To address this critical omission, we have enhanced the main text to explicitly highlight methane accounting:**

“This study employs life cycle assessment to quantify carbon emissions (including CH₄ and CO₂) across China’s shale gas value chain. It includes upstream production, midstream transportation and distribution, and downstream consumption (Supplementary Figure 5).”

The relevant content within the supplementary materials is presented as follows:

“The CH₄ and CO₂ emissions from upstream, midstream, and downstream shale gas production activities were summarized and calculated. The upstream mainly includes processes such as site construction, drilling, and hydraulic fracturing. The midstream is mainly the transportation and distribution. The downstream consumption stage is divided into chemical, industrial, power and heat, transportation, household, and other consumption based on usage scenarios.”

Supplementary Table 14 *The emission factors for different shale gas production activities*

Parameters	g CO ₂ e/m ³	g CO ₂ /m ³	g CH ₄ /m ³	Data sources
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$EF_{CO2,P}$	83.02(61.88-82.85)	33.4828	1.143	<i>This research</i>
$EF_{CO2,T}$	576.179(358.165-868.162)	403.325	5.084	25
$EF_{CO2,V}$	2,414.808(2,281.726-2,547.890)	1,971.2	13.047	26
$EF_{CO2,C}$	4,412.05(3,679.795-5,144.3)	1,971.2	71.790	27
$EF_{CO2,I}, EF_{CO2,Hh}, EF_{CO2,H}, EF_{CO2,O}$	2,184.029(2,120.180-2,247.878)	1,971.2	6.260	28

References:

1. Tong, F., Jaramillo, P. & Azevedo, I. M. L. Comparison of life cycle greenhouse gases from natural gas pathways for medium and heavy-duty vehicles. *Environ. Sci. Technol.* **49**, 7123–7133 (2015).
2. Yuan, Z., Ou, X., Peng, T. & Yan, X. Life cycle greenhouse gas emissions of multi-pathways natural gas vehicles in china considering methane leakage. *Appl. Energy* **253**, 113472 (2019).
3. Zhang, Y. *et al.* Life cycle assessment of ammonia synthesis in China. *Int. J. Life Cycle Assess.* **27**, 50–61 (2022).
4. Ling, Y. *et al.* Carbon emissions in China's thermal electricity and heating industry: An input-output structural decomposition analysis. *J. Clean. Prod.* **329**, 129608 (2021).
4. *There is no distinct conclusion section or a clear and concise summary of the key findings. The final ideas are scattered across various parts of the discussion, making it difficult for the reader to extract the article's main contributions, limitations, or policy implications.*
- & 5. *The structure of the manuscript is confusing. There is no clear delineation between the methodology, results, and discussion sections. Technical concepts, emissions calculations, and interpretative commentary are blended without smooth transitions. This lack of structure makes it harder to follow the line of reasoning and diminishes the overall impact of the work.*

[Response]: We thank the reviewer for this very valuable comment. Comments 4 and 5 were highly invaluable and pointed to a core structural problem. To comprehensively resolve these structural problems, we have:

1. **Completely reorganized the Results section** to ensure clean separation from discussion. The Results now focus exclusively on presenting quantitative findings with supporting data, while all interpretative commentary has been moved to the Discussion. We added clear transitions between subsections to guide readers through our findings.

“Results

Synergy of carbon sequestration and production enhancement

China's shale gas sector demonstrates exceptional Geological Negative Emissions potential across major basins, advancing climate action goals (SDG 13). Unlike passive carbon sinks, shale gas carbon sequestration provides verifiable active CO₂ removal through geological sequestration, meeting the strict definition of anthropogenic removals outlined by Allen et al. (2024) for effective climate mitigation²⁶. Three primary technologies enable carbon sequestration in the shale gas industry: CO₂ fracturing (before production), CO₂ huff-n-puff (in production), and CO₂ sequestration (in depleted wells). CO₂ fracturing and CO₂ huff-n-puff serve dual purposes: enhancing production while sequestering carbon. Based on our modeling analysis, CO₂ fracturing can achieve a carbon sink of 1,406.5 million tonnes (Mt) while increasing shale gas production by 4,018 bcm. Similarly, our simulations indicate that the CO₂ huff-n-puff technique can create a 610.2 Mt carbon sink with a 499.8 bcm production increase. CO₂ sequestration in depleted wells demonstrates the highest potential, reaching a 49,092 Mt carbon sink (Supplementary Fig. 1 and Fig. 2). The Carbon Neutrality Coefficient (CNC) measures the carbon reduction potential of CO₂-based technologies compared to conventional shale gas extraction baseline emissions. The baseline represents current extraction practices without carbon mitigation measures, with emissions varying by regions (0.38-0.45 kg CO₂e/m³) depending on geological conditions and extraction parameters. Combined implementation of these technologies achieves negative carbon intensity of -437.0 gCO₂e/m³, with national CNC exceeding 110%. This transformation from emission source to carbon sink aligns with China's carbon neutrality goals, with an estimated cumulative carbon sink potential of 66,455.9 Mt CO₂e, equivalent to 4.8 years of China's carbon emissions (13,940 Mt CO₂e in 2022)²⁷, while increasing shale gas production by 4,518 bcm, approximately China's total energy consumption in 2023 (Fig. 2)²⁸. This is attributed to CO₂ fracturing and CO₂ huff-n-puff technologies enhancing the estimated ultimate recovery (EUR) per well, thereby providing more space for subsequent CO₂ sequestration.

Regional implementation of these technologies shows distinct effectiveness patterns, with the Ordos Basin demonstrating the highest potential. Marine-continental transition shales in the Ordos Basin achieve a CNC of 157.5%, while terrestrial shales reach a CNC of 162.8%. These results indicate 57.5% and 62.8% reduction beyond carbon neutrality, respectively. These exceptional results are attributed to the basin's unique geological characteristics and optimal reservoir conditions. The Sichuan Basin shows particularly favourable conditions due to its superior reservoir characteristics, higher EUR values, and low carbon intensity of upstream power. The basin's performance is further enhanced by its well-developed infrastructure and operational efficiency.

These results highlight the substantial potential for synergy between carbon sequestration and production enhancement in China's shale gas industry.

Regional variations in effectiveness underscore the importance of geology-specific implementation strategies. The integration of these three key carbon sequestration technologies with additional systematic emissions reduction measures can further reduce the carbon footprint of the shale gas value chain. The synergistic emission reduction benefits are quantitatively assessed through multi-scenario simulations.”

“Economic viability across shale gas reservoirs and scenarios

The economic feasibility of carbon reduction measures exhibits distinct regional patterns based on geological conditions and operational environment (SDG 8). These basin-specific characteristics create distinct patterns in investment requirements and potential returns. Marine shale in Sichuan Basin shows superior economic viability, driven by favorable geological conditions, established infrastructure, and optimized operational parameters.

Sichuan Basin’s marine shale demonstrates robust economic performance, achieving an Internal Rate of Return (IRR) of 20.1(13.6–27.1)% and a Unit Net Present Value (UNPV) of 0.052 US\$ (0.036–0.066) m⁻³ under baseline scenario. This indicates the strong profitability in this region. In contrast, other basins show negative IRR and UNPV values, reflecting geological constraints. The optimized management (OM) scenario, while reducing emissions per cubic meter of gas to 2,907.3 (2,724.4–3,091.7) gCO₂e and achieving a 9.6(1.1–17.4)% carbon neutrality contribution, yields minimal economic gains with IRR increases of 0.01-0.03%. This suggests limited financial benefits from management optimization alone. However, the optimized production (OP) scenario demonstrates more promising results for continental deposits, with significant IRR increases of 4.5% to 7.4% and UNPV improvements of US\$ 0.042 to 0.056 m⁻³. Profitability was achieved only in continental shale formations within the Tarim Basin and Ordos Basin, where favorable geological conditions and CO₂ source proximity offset the technology’s higher implementation costs.

Carbon pricing demonstrates transformative effects on project economics. Current market conditions present significant challenges. The industrial CO₂ prices at US\$ 40.40 t⁻¹ far exceed the Chinese carbon market price of US\$ 13.23 t⁻¹, limiting technology adoption incentives^{29,30}. With Chinese carbon market prices, the profitability remains limited to Sichuan Basin marine shale, Tarim Basin continental, and Ordos continental blocks. European carbon market prices enable broader profitability across regions, with IRRs ranging from 0.2% to 29.8% and UNPVs between US\$ 0.001 to 0.400 m⁻³ in profitable basins. The Tarim and Ordos Basins continental blocks show particularly strong potential under European carbon pricing conditions, with IRRs of approximately 13.4% and 14.2%, respectively. The launch of the global carbon market at COP29 may accelerate China’s carbon market internationalization, unlocking emission reduction potential³¹. ”

2. We have comprehensively rewritten the Discussion section and distinctly structured it into three subsections that address the reviewer's concerns about scattered ideas and unclear policy implications.

“Discussion

This study provides a systematic quantification of historical carbon emissions from China's shale gas value chain (2012-2023) and delivers the most granular assessment to date of the emission reduction potential across distinct shale gas reservoir types at the full value chain level. The results reveal that the integrated application of CO₂ fracturing, CO₂ huff-and-puff, and geological sequestration in depleted wells enables a fundamental transformation of the value chain from a net carbon source to a net carbon sink while simultaneously enhancing gas production.

The Ordos Basin achieves exceptional results capable of offsetting two years of carbon emissions from the surrounding five provinces³³. The Sichuan Basin's favourable geological conditions enable offsetting 110 years of provincial carbon footprint³³. These results position shale gas operations as vital components of China's carbon neutrality strategy, particularly when integrated with broader industrial decarbonization efforts. This underscores the strategic importance of advancing carbon capture, utilization, and storage technologies in shale gas development as part of China's climate action portfolio. Scenario-based mitigation pathway analysis confirms that both the HW and CS scenarios successfully transform the value chain into a geological negative emissions system. In contrast, OM and OP strategies yield only limited carbon reductions. Economic viability exhibits marked spatial heterogeneity: under the CS scenario, only marine shale projects in the Sichuan Basin maintain unequivocal profitability without carbon pricing support; profitability for other reservoir types (particularly terrestrial and transitional facies) is critically contingent on robust carbon pricing mechanisms. Beyond the naturally profitable Sichuan Basin, additional strategic interventions are required to address varying geological complexities, technological requirements, and operational challenges specific to each basin. This study, underpinned by its developed multi-dimensional assessment framework, provides a replicable scientific methodology for global shale gas resource holders to evaluate reservoir carbon sink potential and design commercially viable negative emission pathways.

While formation-specific challenges vary across reservoir types, several fundamental barriers constrain all CO₂ sequestration operations. During CO₂ sequestration, the injection of CO₂ induces pore pressure perturbations, altering the mechanical equilibrium of the reservoir through the effective stress principle. This can potentially activate critically stressed faults or natural fracture systems, leading to microseismic events^{11,15}. Moreover, elevated pore pressure may trigger the reactivation of caprock fractures or shear failure of wellbores, forming leakage pathways that result in small-scale leakage events^{10,11,15}. However, current monitoring techniques face challenges in achieving precise early-stage detection and quantitative characterization of such small-scale leakage occurring beyond wellbore interfaces. Additionally,

the challenge to economic feasibility is particularly severe; the full-chain costs – encompassing CO₂ capture, compression, and the deployment of extensive corrosion-resistant pipeline networks to satisfy source-sink matching – pose significant challenges to achieving profitability in the absence of structural subsidies and carbon credit revenue mechanisms^{8,9}. Furthermore, spatial heterogeneity in geological conditions, infrastructure requirements, and operational challenges create uncertainties in both environmental and economic outcomes. These uncertainties affect the reliability of economic forecasts and the effectiveness of carbon reduction strategies.

To overcome the final barriers in transitioning shale reservoirs from “carbon sinks potential” to “net-negative emission assets,” there is an urgent need to establish a cross-disciplinary framework for deep technological-policy-financial synergy. On one hand, it is essential to advance technological innovation to accurately predict and mitigate leakage risks while substantially reducing the costs across the entire value chain. On the other hand, it is equally crucial to leverage policy mechanisms, such as designing tailored regional subsidies, implementing carbon credit, and clarifying environmental liability frameworks for sequestration. In parallel, innovative financial instruments must be developed to lower financing barriers and capital costs, thereby providing stable funding support for large-scale commercial projects.”

6. The mathematical methodology is underdeveloped. While a few formulas are included, there are no worked examples or validation cases to demonstrate the robustness of the models used. For instance, the net capture cost (NCC), net present value (NPV), and internal rate of return (IRR) are all mentioned, but not a single complete numerical example is provided using real or assumed data.

[Response]: We sincerely thank the reviewer for identifying this critical gap in our mathematical methodology presentation. We have implemented comprehensive revisions to the method section, encompassing both textual refinement and structural decomposition of equations. Due to length constraints mandated by the journal’s formatting requirements, selected formulae are presented in the Supplementary Information (SI). Accordingly, explicit cross-referencing between the main manuscript and SI has been established to facilitate transparent traceability of computational procedures. Key modifications include:

“The calculation method for carbon emission reduction (Mt CO₂e) across different shale gas plays under various scenarios versus the baseline scenario is as follows:

$$\Delta C_{i,j} = (C_{P,i,b} + C_{T,i,b} + C_{C,i,b}) - (C_{P,i,j} + C_{T,i,j} + C_{C,i,j}) \quad (11)$$

where $C_{P,i,b}$, $C_{T,i,b}$, and $C_{C,i,b}$ represent the carbon emission of shale gas production, transportation and distribution, and consumption under the baseline scenario. Then, the total national carbon emission reduction across scenarios is calculated as:

$$\Delta C_j = \sum_{i=1}^n \Delta C_{i,j} \quad (12)$$

To assess the carbon emission reduction potential across different shale gas plays under various scenarios, we define the carbon neutrality coefficient (CNC):

$$CNC_{i,j} = (I_{i,b} - I_{i,j})/I_{i,b} \quad (13)$$

where $I_{i,b}$ is the carbon intensity of the shale gas life cycle for different shale gas reservoirs under the baseline scenario, and $I_{i,j}$ is the carbon intensity of the shale gas life cycle for different shale gas reservoirs under different scenarios. When the CNC is between 0 and 100%, it indicates that the shale gas value chain has not achieved carbon neutrality; when the CNC equals 100%, the carbon footprint of the shale gas value chain is zero; and when the CNC is greater than 100%, the shale gas value chain can achieve negative emissions.”

“The configuration of multiple scenarios delineates technological pathways for decarbonizing the shale gas value chain. Systematic quantification of the dynamic interactions between regional resource endowments and technological costs remains imperative. Through techno-economic analysis, this study reveals regionally heterogeneous economic viability of emission-reduction technologies. Consequently, it mitigates potential resource misallocation arising from uniform policy implementation and establishes spatially differentiated cost-optimized deployment pathways.

A typical shale gas development project encompasses a 21-year lifecycle, comprising one year of construction followed by 20 years of production⁴⁴. Under the baseline scenario, the cash outflows during the initial year primarily arise from construction costs, including expenditures for drilling, hydraulic fracturing, and surface facility engineering. Throughout the production phase, cash inflows originate from shale gas sales revenue and government subsidies, while outflows consist of continuously incurred business costs and tax costs.

Relative to the baseline scenario, emission reduction scenarios necessitate distinct cash flow considerations. The OM scenario employs LiDAR and Optical Gas Imaging technology for leak detection and repair (LDAR), incurring an incremental cost of approximately US\$ 0.098 m⁻³ ⁶². This investment, however, generates compensatory revenue through recovered methane sales by mitigating fugitive emissions. Concurrently, the OP scenario implements CO₂ fracturing and CO₂ huff-n-puff during Year 1 and Years 13–18, while the HW sub-scenario involves CO₂ sequestration in abandoned wells, requiring expenditures for CO₂ procurement and ancillary energy inputs. The comprehensive CS scenario, integrating all aforementioned technologies, consequently demands holistic cash flow modeling that internalizes these

interdependent cost-benefit structures. To evaluate economic viability across different shale gas reservoirs, we conduct policy sensitivity analyses incorporating variable carbon credit revenues.

The DCF method is a financial valuation approach grounded in the time value of money theory. Its core logic involves forecasting the free cash flow generated by an asset or project and discounting it to its present value using a risk-adjusted discount rate, thereby quantifying its intrinsic value⁶³. Financial profitability metrics such as Net Present Value (NPV), Unit Net Present Value (UNPV), Internal Rate of Return (IRR), and Dynamic Payback Period are all established based on this method. In this study, the DCF method is adopted to evaluate the techno-economic feasibility of multiple emission-reduction scenarios across the shale gas value chain. The UNPV and IRR are selected as profitability indicators to assess the techno-economic performance of different scenarios. UNPV serves as a core metric for evaluating the profitability per unit of shale gas. It is defined as the ratio of the project's NPV to the total production (Q_{total}), calculated as follows:

$$UNPV = NPV / Q_{total} \quad (14)$$

The NPV is calculated by discounting the annual net cash flows (NCF_t) within the shale gas value chain using the industry benchmark discount rate (r_0) and summing the discounted present values. This metric characterizes the absolute profitability of the shale gas value chain. The formula is expressed as follows:

$$NPV = \sum_{t=0}^{t=n} NCF_t \cdot (1 + r_0)^{-t} \quad (15)$$

The NCF_t is calculated as follows:

$$NCF_t = Q_t \cdot f \cdot (P + S_{subsidy}) - T_t - I_t \quad (16)$$

where Q_t denotes shale gas production in year t ; f represents the proportion of marketable gas output; P is the shale gas wellhead price; $S_{subsidy}$ signifies the shale gas development subsidy, a fiscal incentive provided by the Chinese government, quantified at US\$ 0.013 m^{-3} ⁶⁴. The variable T_t represents the tax cost, encompassing value-added tax, income tax, resource tax, and other applicable levies. I_t denotes the business cost in year t , where I_1 specifically refers to well pad construction investment, including expenditures for drilling, fracturing, and completion activities. The computational specifics regarding T_t and I_t are comprehensively detailed in S5.1, S5.2, and S5.5 of the **Supplementary Information.**

7. The figures are mostly low-resolution maps focused exclusively on China. Although it is logical for the study to focus on that country, it would be beneficial to include at least some international comparison or broader context, given the global relevance of the topic. Moreover, the maps do not provide sufficient technical detail—such as geological characteristics, pressure, depth, or estimated storage capacity.

Response:

We sincerely appreciate the reviewer's invaluable feedback regarding figure quality and international context. To comprehensively address these concerns, we have implemented the following improvements:

1. Enhanced figure resolution and technical detail: All maps have been recreated at high resolution with enhanced technical information.

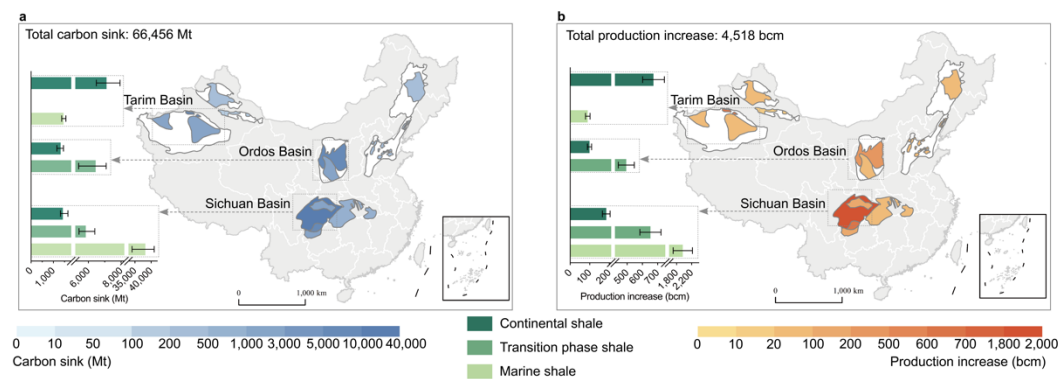


Fig. 2 Carbon sequestration potential and production enhancement in China's shale gas operations by shale gas reservoirs. a, Cumulative carbon sink potential achieved through integrated deployment of CO₂ fracturing, CO₂ huff-n-puff, and CO₂ sequestration technologies across major shale basins; b, Associated production increase potential through combined technology implementation. The cumulative bar charts in a and b illustrate the carbon sink and production increase potential of different types of shale gas reservoirs in the Sichuan Basin, Tarim Basin, and Ordos Basin, with 95% confidence intervals.

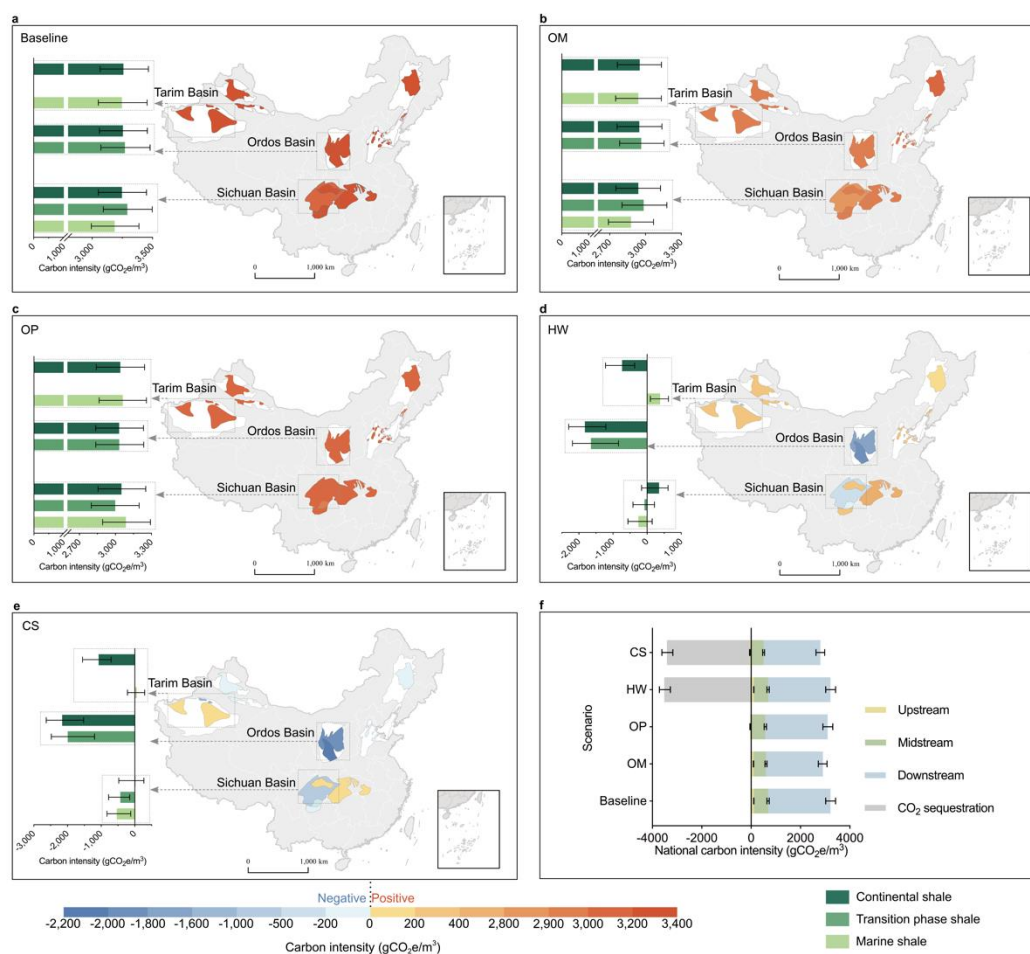


Fig. 4, The carbon intensity of shale gas produced in China's various shale gas reservoirs under different scenarios. a, Business-as-usual emissions per unit of gas produced. **b,** Optimized management (OM) scenario. **c,** Optimized production (OP) scenario. **d,** Depleted well handling (HW) scenario. **e,** Combined strategies scenario. **f,** The national average emissions per unit of natural gas production for each scenario (calculated after weighting for each shale gas reservoir). The cumulative bar charts in a-e illustrate the carbon intensity of unitary shale gas produced of different types of shale gas reservoirs in the Sichuan Basin, Tarim Basin, and Ordos Basin, along with a 95% confidence interval.

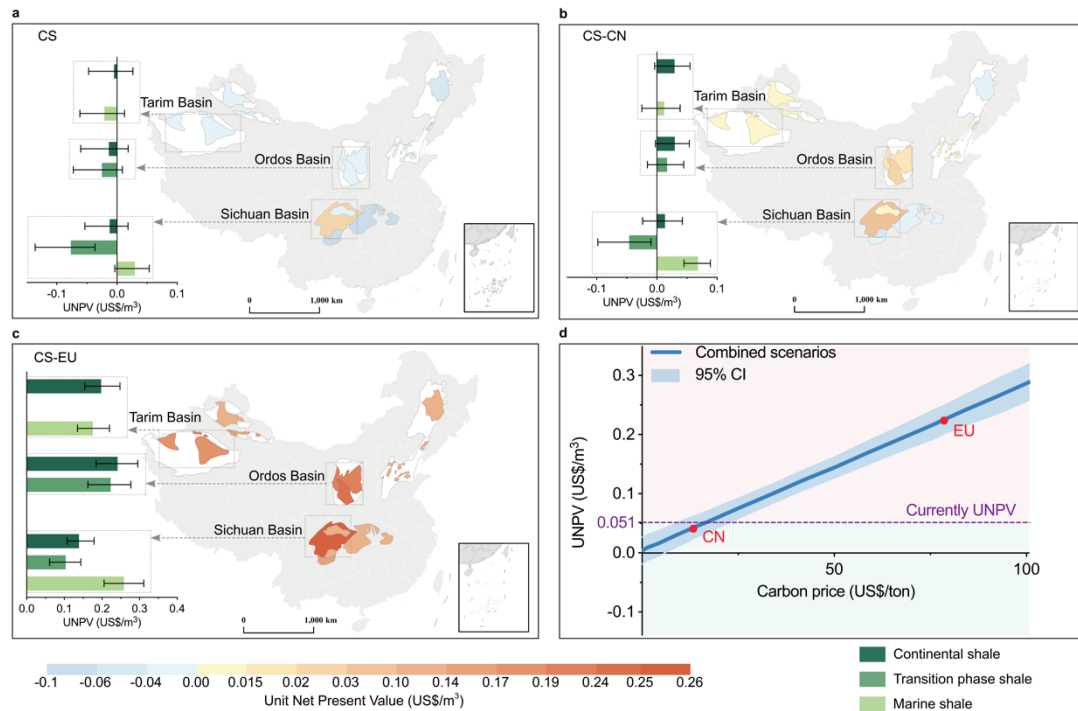


Fig. 5 The Unit Net Present Value(UNPV) of different shale gas reservoirs in various regions under different carbon prices in the combined scenario. a, The UNPV of different shale gas reservoirs in various regions under a comprehensive scenario without carbon subsidies. b, The UNPV of different shale gas reservoirs in various regions under a comprehensive scenario at carbon market prices in China(CN). c, The UNPV of different shale gas reservoirs in various regions under a comprehensive scenario at carbon market prices in Europe(EU). The cumulative bar charts in a-c illustrate the UNPV of different types of shale gas reservoirs in the Sichuan Basin, Tarim Basin, and Ordos Basin, along with a 95% confidence interval. d, The variation in the UNPV of Chinese shale gas reservoirs under a comprehensive scenario with changes in carbon prices.

2. Added global scalability description:

“Given the representativeness of China’s diversified geological contexts of shale gas reservoirs, the findings of this study can provide scientific foundations for achieving Geological Negative Emissions of the shale gas value chain in many regions around the world.”

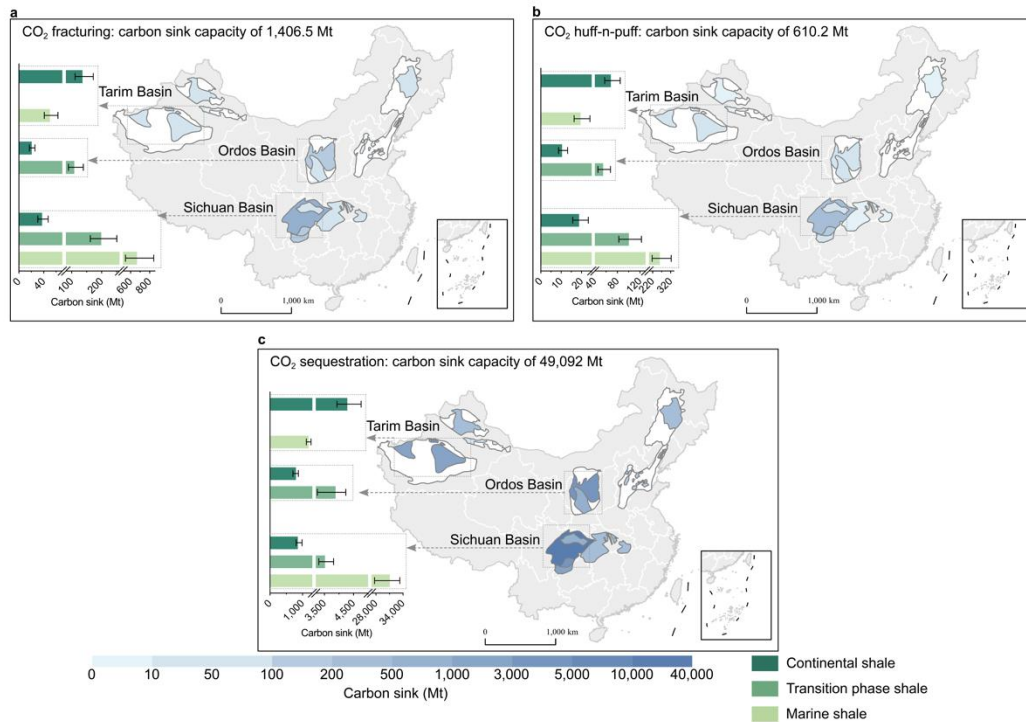
“This study, underpinned by its developed multi-dimensional assessment framework, provides a replicable scientific methodology for global shale gas resource holders to evaluate reservoir carbon sink potential and design commercially viable negative emission pathways.”

3. Estimated carbon storage capacity:

“Supplementary Fig. 1 The carbon sequestration potential of different shale gas reservoirs in various regions under different technologies.

Figure a shows the carbon sequestration potential of different shale gas reservoirs in various regions after applying CO₂ fracturing technology. Figure b illustrates the carbon

sequestration potential of different shale gas reservoirs in various regions after using CO₂ huff-n-puff technology. Figure c demonstrates the carbon sequestration potential of different shale gas reservoirs in various regions after injecting CO₂ into abandoned wells. Among these methods, injecting CO₂ into abandoned wells is the technology with the most significant sequestration potential. The cumulative bar charts in a, b and c illustrate the carbon sink potential of different types of shale gas reservoirs in the Sichuan Basin, Tarim Basin, and Ordos Basin, with 95% confidence intervals.”



8. Internationally comparable economic units are not used. All costs are expressed in yuan per cubic meter, with no conversions to dollars or other widely used benchmarks. This limits the article’s accessibility to international audiences and hinders comparison with other studies.

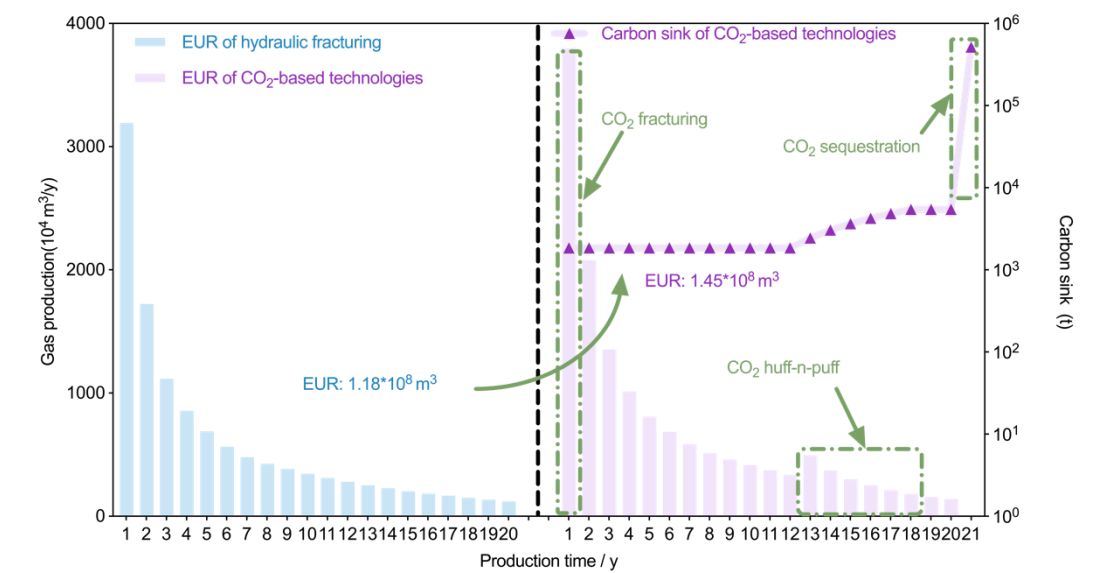
[Response]: We sincerely thank the reviewer for highlighting this critical limitation regarding economic unit standardization. We fully agree that expressing costs exclusively in Chinese yuan impedes international comparability and cross-study benchmarking. To resolve this issue, we have comprehensively revised the manuscript by adopting standardized US\$ units throughout. Additionally, all relevant figures have been rigorously updated to reflect this standardization.

9. More comprehensive visual tools are missing. There are no summary tables that compare the different technologies (CO₂ fracturing, huff-n-puff, injection into depleted wells), nor graphs illustrating CO₂ capture over time or economic profitability curves. This weakens the communicative value of the analysis.

Response:

We sincerely appreciate the reviewer's constructive feedback regarding the lack of comprehensive visual tools. To address this critical gap, we have developed and integrated the following comprehensive visual elements:

1. Added comparative technology summary table (Figure S6, Table S3 and S4 in SI):



Supplementary Fig. 6 Estimated ultimate recovery (EUR) and carbon sink of shale gas wells applying different CO_2 -based techniques in Sichuan Basin marine shale. Blue is EUR applying hydraulic fracturing, and purple is EUR and carbon sink applying CO_2 -based technology.

“Supplementary Table 3 Electricity emission factors in different basins or regions.

Due to the differences in energy structures across various basins, there are significant regional variations in electricity emission factors. Taking the Sichuan Basin as an example, the region is rich in water resources, and the proportion of hydropower generation is relatively high, resulting in a lower electricity emission factor. Furthermore, the electricity emission factors for each basin are derived from a weighted calculation of the emission factors of the provinces they encompass, with data sourced from the Ministry of Ecology and Environment of the People's Republic of China and the National Bureau of Statistics⁶.”

Basins or Regions	Electricity Emission Factors (kg $\text{CO}_2\text{e}/\text{kWh}$)
Sichuan Basin	0.3
Tarim Basin	0.66
Ordos Basin	0.67
Songliao Basin	0.6
Bohai Bay Basin	0.74

Zhungror Basin	0.7
Tuha Basin	0.66
Northern Yunnan-Guizhou Region	0.32
Central Yangtze Region	0.57

“Supplementary Table 4 Key technology parameters.

The key parameters for **CO₂-based carbon sink technologies** and other major **emission-reduction technologies** are presented below.”

Key CO ₂ -based technology	Sequestration fraction of injected CO ₂ /%
CO ₂ fracturing	30
CO ₂ huff-n-puff	50
CO ₂ sequestration	100
Other technology	Carbon emission reduction rate/%
LDAR program	40

10. Although the manuscript mentions the use of Monte Carlo simulations to assess uncertainty, it does not explain the underlying assumptions, input distributions, or the interpretation of the results. No probabilistic outputs, sensitivity analyses, or uncertainty ranges are shown. This part of the analysis remains underdeveloped and unconvincing.

[Response]: We sincerely appreciate the reviewer’s critical observation regarding our inadequate presentation of uncertainty analysis. To address this fundamental weakness, we have completely redeveloped and expanded our uncertainty analysis:

“S6. Uncertainty analysis

Monte Carlo simulations were used to assess the uncertainties associated with emission reduction potential, and economic viability, with 100,000 iterations utilizing Oracle Crystal Ball, with key parameter settings shown in Supplementary Table 18.

In our uncertainty analysis, we employed marine shale data from the Sichuan Basin as a case study in Supplementary Fig. 9. Under the CS scenario without carbon credit revenue, the UNPV is estimated at 0.030 US\$ m⁻³ (0.006–0.050, 95% CI). Key drivers of UNPV include shale gas price, EUR, cost per fracturing stage, and unit operating costs. Among these, the shale gas price constitutes the strongest positive driver.

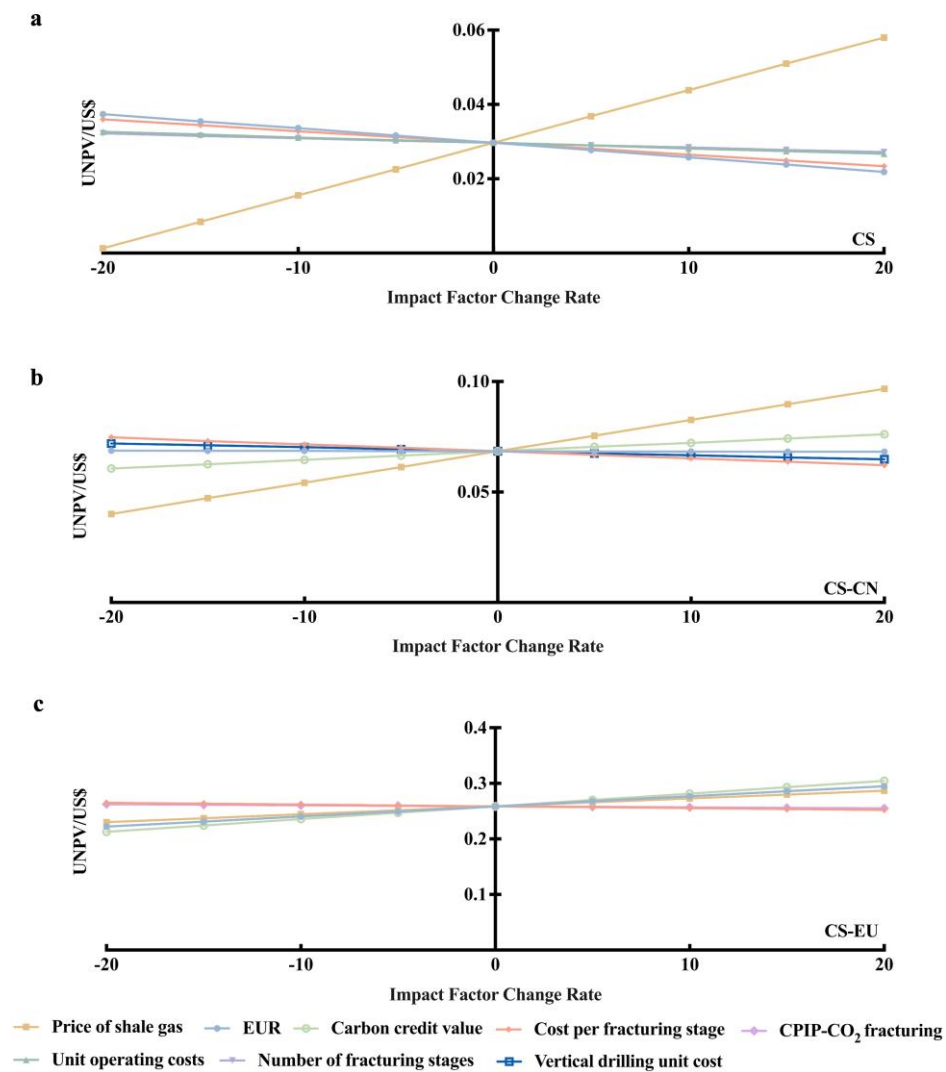
When incorporating Chinese carbon credit revenues under the CS scenario, UNPV rises to 0.068 US\$ m⁻³ (0.045–0.088, 95% CI). Here, shale gas price and carbon credit value emerge as the two primary positive drivers. Under the CS scenario with European carbon credits, UNPV reaches 0.259 US\$ m⁻³

(0.212–0.304, 95% CI), with carbon credit value, EUR, and shale gas price ranking as the top three positive contributors.

Notably, without carbon credit revenue, EUR exerts a negative influence on UNPV. This occurs because higher EUR expands subsurface CO₂ storage requirements, necessitating additional expenditure to procure CO₂ for sequestration in the absence of credit monetization. Although EUR remains negatively correlated under China's carbon credit regime, its adverse impact diminishes. Conversely, under Europe's carbon credit framework, EUR transitions to a positive driver, underscoring the critical role of carbon credit revenue streams.”

Supplementary Table 17 Key parameter settings for uncertainty analysis

Input	Units	Distribution	Parameter		
EUR	m ³	Normal	EUR	0.1EUR	
EF _{CO₂,T}			518.56	576.18	633.80
EF _{CO₂,U} (weighting of downstream)	gCO ₂ -eq/m ³	Triangular	2274.44	2527.16	2779.88
CO ₂ fracturing-CPIP for marine shale			18		22
CO ₂ fracturing-CPIP for transitional and continental shale			55		65
CO ₂ huff-n-puff -CPIP for marine shale	%	Uniform	2		4
CO ₂ huff-n-puff -CPIP for transitional and continental shale			4		8
Methane leakage reduction rate (OM scenario)			30		50
Shale gas price	US\$	Normal	0.27		0.014
Operating cost	US\$ m ⁻³	Normal	0.026		0.0028
Government subsidy	US\$	Normal	0.013		0.0013
Vertical drilling unit cost	US\$	Triangular	702.07	780.08	858.09
Cost per fracturing stage	US\$	Triangular	183,890	204,322	224,754
Number of fracturing stages per well	-	Triangular	18	20	22
Carbon credit value in China	US\$ t ⁻¹	Triangular	12.40	13.23	14.07
Carbon credit value in Europe		Triangular	60.14	78.19	96.23



Supplementary Fig. 9 Sensitivity analysis of UNPV for marine shale gas in the Sichuan basin under distinct carbon credit frameworks. a, CS Scenario without carbon credit incentives; b, CS under China's carbon credit regime; c, CS under Europe's carbon credit mechanism.

11. From an editorial perspective, the manuscript requires a thorough review. There are spelling errors, confusing phrases, and misused terms (e.g., “puff-n-huff” instead of “huff-n-puff”). Furthermore, there is some repetition of ideas that could be avoided with more careful editing.

[Response]: We sincerely appreciate the reviewer's meticulous evaluation of the manuscript's editorial quality. Their identification of linguistic inconsistencies, including terminology misuse, spelling errors, and repetitive phrasing, provides fundamental guidance for enhancing the manuscript's scientific rigor and readability. We fully acknowledge these issues could undermine the clarity of our technical contributions and have implemented comprehensive revisions accordingly.

1. The misused terms like puff-n-huff have been corrected.
 2. The redundant contents have been removed, such as the repeated China's production data in the Introduction and redundant descriptions in the Methodology section.
12. *The article does not critically analyze the risks, limits, or barriers of the proposal. For example, the possibility of CO₂ leaks, infrastructure costs, social acceptance, or regulatory implications are not discussed. The presentation is overly optimistic and lacks a balanced reflection on potential flaws or uncertainties.*

[Response]: We sincerely appreciate the reviewer's critical assessment regarding the need for balanced risk analysis. We fully acknowledge that mitigating such oversights is essential for credible technology evaluation. We have added the barriers of the research.

Introduction

“Applying CO₂-based technologies in shale gas operations can generate substantial carbon sink effects, contributing significantly to global carbon neutrality goals^{6,7}. However, large-scale deployment is constrained by formation-specific challenges including economic feasibility barriers^{8,9}, compounded by risks of CO₂ leakage^{9,10} and induced seismicity¹¹. The U.S., as the world’s largest shale gas producer, has conducted reservoir-specific simulations and laboratory-scale explorations of carbon sink potential, evaluating techniques such as CO₂ fracturing and geological sequestration^{12–15}. Nevertheless, existing research predominantly examines isolated processes rather than implementing full value-chain integration assessments, and systematic analysis of CO₂-based technologies’ applicability across diverse shale reservoir types remains underdeveloped.”

Discussion

“While formation-specific challenges vary across reservoir types, several fundamental barriers constrain all CO₂ sequestration operations. During CO₂ sequestration, the injection of CO₂ induces pore pressure perturbations, altering the mechanical equilibrium of the reservoir through the effective stress principle. This can potentially activate critically stressed faults or natural fracture systems, leading to microseismic events^{11,15}. Moreover, elevated pore pressure may trigger the reactivation of caprock fractures or shear failure of wellbores, forming leakage pathways that result in small-scale leakage events^{10,11,15}. However, current monitoring techniques face challenges in achieving precise early-stage detection and quantitative characterization of such small-scale leakage occurring beyond wellbore interfaces. Additionally, the challenge to economic feasibility is particularly severe; the full-chain costs – encompassing CO₂ capture, compression, and the deployment of extensive corrosion-resistant pipeline networks to satisfy source-sink matching – pose significant challenges to achieving profitability in the absence of structural subsidies and carbon credit revenue mechanisms^{8,9}. Furthermore, spatial

heterogeneity in geological conditions, infrastructure requirements, and operational challenges create uncertainties in both environmental and economic outcomes. These uncertainties affect the reliability of economic forecasts and the effectiveness of carbon reduction strategies.”

13. The structure of the article urgently needs improvement. There is no hierarchical numbering of sections and subsections that allows the reader to easily orient themselves. The discussion mixes several thematic lines without an easily identifiable order. It is strongly recommended that authors include an outline or "content map" at the beginning of the document, specifying the main sections of the manuscript (e.g., methodology → results → economic discussion → climate implications), and that consistent numbering be used throughout the text (e.g., 1, 1.1, 1.2, 2, 2.1, etc.). This formatting improvement would greatly facilitate understanding of the argument and critical reading of the document.

[Response]: We sincerely thank the reviewer for the thoughtful feedback on improving the manuscript's structure. We agree that enhancing navigability is essential for reader comprehension and have implemented key revisions to address this concern.

1. Structural Clarity and Content Map

As suggested, we have added a "Content Map" at the beginning of the manuscript to outline the logical flow of the paper. This now clearly defines the sequence of sections.

“This study analyzes the climate impacts of the entire shale gas value chain from 2012 to 2023 using life cycle assessment (LCA) and climate impact models, identifying key intervention points and technologies for emission reduction strategies across the entire value chain in the future. Integrating Discounted Cash Flow (DCF) analysis with LCA, this study assesses the economic feasibility of multiple emission-reduction scenarios in diverse shale gas reservoirs, with particular emphasis on carbon sequestration potential and enhanced gas recovery efficiency across CO₂-based technologies (Fig. 1).”

We have also created a new Figure 1 that visually presents our research framework with three clearly delineated modules:

- Module 1: Carbon sequestration potential of CO₂-based technologies
- Module 2: Historical carbon footprint assessment (2012-2023)
- Module 3: Multi-scenario techno-economic analysis across regions

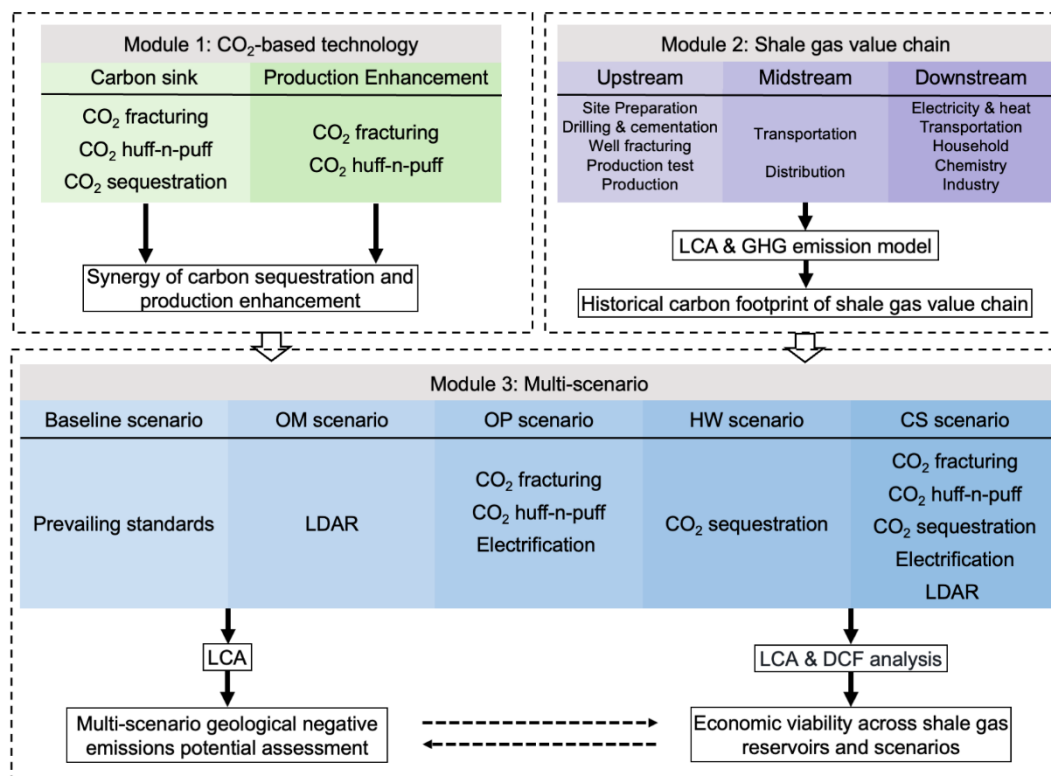


Fig. 1 The research framework of this study. The framework comprises three modules: Module 1 assesses the carbon sequestration potential of CO₂-based technology and production enhancement; Module 2 evaluates the historical carbon footprint of the shale gas value chain; Module 3 quantifies multi-scenario geological negative emissions potential across regions and their techno-economic viability.

2. Hierarchical Numbering: Alignment with Journal Guidelines

We appreciate the reviewer's suggestion regarding hierarchical numbering (e.g., 1, 1.1, 1.2). After careful consideration and consultation with the Nature Communications Guide to Authors, we note that the journal's formatting guidelines specify the use of section headings without numerical hierarchies. The guide states that "*section headings are to be used, and subheadings should appear in the 'Results' and 'Methods' sections*" without mentioning numbering systems.

To maintain compliance with journal requirements while addressing the reviewer's concern about navigability, we have comprehensively reorganized the manuscript with clear section titles, logical content flow, and improved transitions between sections. The Results section now features distinct subsections including "Historical carbon footprint evolution (2012-2023)," "Regional heterogeneity in emission profiles," "Technology-specific carbon reduction potential," "Economic viability across scenarios," and "Uncertainty analysis." Similarly, the Discussion follows a clear thematic progression from "Implications for carbon-negative shale gas development" through "Technology deployment strategies and barriers," "Policy recommendations for scaled implementation," "Global relevance and transferability," to "Limitations and future research directions." We have enhanced navigation through bold subsection headings for visual hierarchy, clear topic sentences at the beginning of each paragraph,

summary boxes highlighting key findings for each section, and cross-references between related sections. These structural improvements significantly enhance manuscript readability while adhering to Nature Communications formatting requirements, ensuring readers can easily navigate and understand our complex multi-faceted analysis.

Reference:

Brief guide for submission to Nature Communications

<https://www.nature.com/ncomms/submit/guide-to-authors>

Responses to comments

Dear Reviewers,

We sincerely appreciate the thorough and constructive reviews you provided. Your insightful comments have been invaluable in strengthening our manuscript. We have undertaken targeted revisions to address the remaining concerns raised in this second round of revision.

Major Revisions in This Round:

1. Clarified Carbon Accounting Framework and Assessment Methodology

Following Reviewer 4's critical feedback, we have explicitly defined our system boundary as cradle-to-grave within the shale gas value chain and clarified that "negative emissions" refers to net carbon sequestration within the operational boundaries of the value chain, not global atmospheric carbon removal. We refined our carbon sink assessment methodology to distinguish between empirical approaches for production scenarios and mechanism-based modeling for permanent sequestration in depleted wells, with all calculations anchored to technically recoverable reserves to ensure realistic capacity estimates.

2. Enhanced Methodological Transparency and Economic-Environmental Analysis

We clarified that methane emissions are explicitly incorporated throughout our bottom-up framework and added detailed documentation of CO₂ transportation costs in the Supplementary Information. To address the structural gap in linking TEA and LCA, we added comprehensive discussion of economic-environmental trade-offs across different technological pathways, including a decision framework mapping performance characteristics and optimal application contexts for each strategy.

3. Strengthened Global Applicability

We added discussion on the global applicability of our framework, emphasizing its replicable methodology while acknowledging region-specific factors that determine successful implementation, thereby enhancing the manuscript's international relevance.

All changes are clearly marked using track changes, and detailed point-by-point responses are provided in the accompanying document. We believe these revisions have successfully addressed all remaining concerns.

Thank you for the opportunity to revise our manuscript.

Sincerely,
Sai Liang

Reviewer #1:

Response to Author's Revision

I have carefully reviewed the revised manuscript and the authors' detailed responses to my previous comments. I appreciate the substantial efforts made in addressing the concerns raised in the first round of review. Below is my assessment of the revisions.

Response to Question 1:

The author's note indicates that the data presented in the text are derived from model simulations and offers a comprehensive description of the computational methodologies employed for CO₂ fracturing technology and CO₂ huff-n-puff technique. The revised version successfully clarifies any uncertainties concerning the origin of the data.

Response to Question 2:

The author delineates the baseline emissions within the text and presents precise emission figures for various regions. This approach serves to strengthen the validity of the ensuing calculations related to Carbon Neutrality Coefficient (CNC).

Response to Question 3:

(1) The author provides a detailed explanation of CO₂ fracturing and CO₂ suction technologies, introducing calculation methods for CO₂ emission reductions under optimized management scenario (OM) and optimized production scenario (OP).

(2) The paper further clarifies how CO₂ emission reductions can be derived through leakage reduction of CH₄ (OM) and the incremental production of shale gas (OP).

The author clarifies that these three approaches do not simply add up linearly but exhibit nonlinear technological synergies effects, detailing the interconnections and influencing mechanisms among them.

Response to Question 4:

The author performed a comparative analysis of the costs related to CO₂ fracturing technology alongside the benefits derived from optimized production (OP), thereby systematically assessing the economic feasibility of optimized production scenario. Notably, the advantages of this approach are observed exclusively in the Tarim Basin and Ordos Basin. Future research could investigate potential enhancements to this methodology.

Response to Question 5:

(1) The authors have clarified the rationale for applying U.S. LDAR experience to China, supplemented with references and similarity between China and the U. S. This provides sufficient justification and improves the credibility of the estimation.

(2) The authors have added comprehensive discussions of technical and economic challenges, including leakage risks, induced seismicity, infrastructure costs, and monitoring difficulties. This significantly enhances the practical relevance and reliability of the study.

Response to Question 6:

The authors have clarified that downstream combustion emissions are included and have provided detailed explanations of how carbon intensity is calculated across

upstream, midstream, and downstream stages, with supporting references. This strengthens methodological transparency.

Response to Question 7:

The author elucidates the foundational principles underlying the internal rate of return (IRR) and net present value (NPV) calculation methodologies, supplemented by relevant scholarly references. This approach serves to strengthen the validity of the ensuing techno-economic analysis.

Conclusion

The authors have satisfactorily addressed all of my previous concerns. I believe the manuscript is now suitable for publication after minor editorial polishing. I recommend acceptance with minor revisions.

[Response]: We sincerely appreciate your thorough evaluation of our revised manuscript and your constructive feedback throughout the review process. We are pleased that our revisions have successfully addressed all your concerns.

Regarding Question 4, we acknowledge your observation about regional applicability as a valuable direction for future research. The current constraints in the Tarim Basin and Ordos Basin reflect complex interactions between geological characteristics, infrastructure availability, and economic parameters. Future work could explore optimization strategies through technological innovations and refined geological characterization.

Following your recommendation for minor editorial polishing, we have carefully proofread the manuscript and performed language polishing to ensure it meets the journal's publication standards.

We sincerely appreciate your valuable time and guidance.

Reviewer #3:

I thank the authors for addressing all my comments point by point. The manuscript has clearly improved in clarity, structure, and robustness. My only remaining suggestion is to add a brief reflection in the discussion or conclusion on the global applicability of the proposed shale-gas-based decarbonization strategies beyond China, which would further enhance the paper's international relevance.

[Response]: We sincerely appreciate your positive assessment of our revisions and your recognition of the improvements. Your constructive feedback throughout this process has been invaluable.

We fully agree that addressing global applicability strengthens the paper's international relevance. Following your recommendation, we have added the following reflection to the **Discussion section**:

“This study, underpinned by its developed multi-dimensional assessment framework, provides a replicable scientific methodology for global shale gas resource holders to evaluate reservoir carbon sink potential and design commercially viable negative emission pathways. The proposed integrated strategy for carbon sequestration and enhanced recovery in shale reservoirs holds potential for global applicability; however, its successful implementation largely depends on the geological suitability of target regions, the availability of established CO₂ source-sink matching infrastructure, and a supportive policy landscape.”

This addition contextualizes how our China-focused findings can inform decarbonization strategies in other shale gas regions worldwide, while acknowledging the critical role of region-specific geological, infrastructural, and policy factors. We believe this enhancement significantly broadens the paper’s contribution to the international research community.

Reviewer #4:

This paper is very interesting and well-structured. However, there are some methodological issues, although the study scope is well covered.

1.The carbon sink assessment method. For shale reservoirs, normally, the storage capacity should be included the adsorption or competitive adsorption, this should be applied to CO₂ fracturing, huff-n-puff and CO₂ sequestration. However, the method, particularly for fracturing and huff-n-puff does not explicitly include the approach for this part.

[Response]: We sincerely appreciate your insightful comment regarding the carbon sink assessment methodology. Your observation about the role of adsorption and competitive adsorption mechanisms in CO₂ storage is highly pertinent and provides an important opportunity to clarify our methodological approach.

We fully agree that, from a physicochemical mechanism perspective, injected CO₂ interacts with organic matter in shale through adsorption during all three processes: CO₂ fracturing, CO₂ huff-and-puff, and CO₂ sequestration. However, our assessment methodology deliberately distinguishes between these processes based on their operational characteristics and long-term sequestration outcomes.

For CO₂ fracturing and CO₂ huff-and-puff, the well remains in production after CO₂ injection rather than being permanently sealed. During subsequent production, declining reservoir pressure causes partial desorption of previously adsorbed CO₂, which is then co-produced along with natural gas. The net CO₂ sequestered over the well’s lifecycle represents a dynamic balance among adsorption, desorption, and production processes. Theoretical calculations based solely on initial adsorption capacity would significantly overestimate actual long-term sequestration. Consequently, we adopt an empirical approach grounded in field data and observed flowback rates to estimate the net carbon sink more accurately. This methodology is consistent with established practices in the literature (Ji et al., 2023; Wilkins et al., 2016).

In contrast, CO₂ sequestration in depleted wells involves permanent well closure after injection, with no subsequent production. Under these conditions, all storage mechanisms, including structural trapping, adsorption, and mineralization, can achieve their full theoretical potential and provide permanent sequestration. Therefore, we employ mechanism-based modeling to explicitly quantify each contribution (Equations 3-7), including adsorption capacity calculated through competitive adsorption selectivity (Equation 5 and 6).

We appreciate the Reviewer's comment, which helps clarify this important aspect of our assessment framework. We believe this methodology provides a more robust and realistic evaluation of carbon sink potential across the shale gas value chain.

References:

1. Ji, T., Jiang, P., and Xu, R. (2023). Technology portfolios optimization to deliver cost-effective shale gas development: Using CO₂ versus water. *Fuel* 335, 127006. <https://doi.org/10.1016/j.fuel.2022.127006>.
2. Wilkins, R., Menefee, A.H., and Clarens, A.F. (2016). Environmental Life Cycle Analysis of Water and CO₂-Based Fracturing Fluids Used in Unconventional Gas Production. *Environ. Sci. Technol.* 50, 13134–13141. <https://doi.org/10.1021/acs.est.6b02913>.

2.The reservoir modeling has demonstrated that the gross and net utilization factors are major concerns for evaluating the life cycle emissions. Especially, for subsurface CCUS like CO₂-EGR and ECBM process. However, this paper has not incorporated these drivers, leading to the inaccurate assessment for supply chain GHG emissions.

[Response]: We sincerely appreciate this insightful comment regarding reservoir utilization factors in lifecycle emissions assessment. Your concern about the importance of gross and net utilization factors for subsurface CCUS processes is well-founded and provides a valuable opportunity to clarify a critical aspect of our modeling framework.

Our model is fundamentally based on the **net utilization rate** concept rather than idealized maximum reserves (gross utilization rate). Specifically, our sequestration capacity calculations are anchored to technically recoverable reserves, which is the volume of shale gas that can be realistically extracted under current technological and economic conditions, rather than total original gas-in-place. This approach inherently accounts for net utilization efficiency, as CO₂ fills only the pore space vacated by recoverable shale gas production. Unrecoverable gas volumes remain inaccessible for CO₂ injection and therefore do not contribute to practical storage capacity. This methodology aligns with established reservoir engineering principles and field observations from China's commercial shale gas operations (Nie et al., 2020; Li, 2022; Zhang et al., 2022; Sun et al., 2021).

Thanks to the reviewer, we recognize that this critical modeling assumption was not explicitly articulated in the original manuscript and have therefore added clarification to enhance transparency. To address this concern, we have added the following text to the **Methods** section:

“The total sequestration capacity is:

$$M_{CO_2,T} = M_{CO_2,S} + M_{CO_2,A} + M_{CO_2,M} \quad (7)$$

It is critical to emphasize that the total CO₂ sequestration potential is driven by the technically recoverable shale gas reserves, not the total original gas-in-place. This aligns with the net utilization rate concept, as the pore space associated with unrecoverable gas remains inaccessible for CO₂ injection and thus does not contribute to the practical storage capacity.”

References:

- (1) Nie, H.; Li, D.; Liu, G.; Lu, Z.; Hu, W.; Wang, R.; Zhang, G. An Overview of the Geology and Production of the Fuling Shale Gas Field, Sichuan Basin, China. *Energy Geosci.* **2020**, *1* (3–4), 147–164. <https://doi.org/10.1016/j.engeos.2020.06.005>.
- (2) Li, S. Distribution Characteristics, Exploration and Development, Geological Theories Research Progress and Exploration Directions of Shale Gas in China. **2022**.
- (3) Zhang J.; Shi M.; Wang D.; Tong Z.; Hou X.; Niu J.; Li X.; Li Z.; Zhang P.; Huang Y. Fields and directions for shale gas exploration in China. *Nat. Gas Ind. B* **2022**, *9* (1), 20–32. <https://doi.org/10.1016/j.ngib.2021.08.014>.
- (4) Sun, C.; Nie, H.; Dang, W.; Chen, Q.; Zhang, G.; Li, W.; Lu, Z. Shale Gas Exploration and Development in China: Current Status, Geological Challenges, and Future Directions. *Energy Fuels* **2021**, *35* (8), 6359–6379. <https://doi.org/10.1021/acs.energyfuels.0c04131>.

3. Multiple studies has demonstrated the methane emissions can significantly affect the GHG emissions. This paper, however, does not include the methane emission estimates for the bottom-up modeling according to equation 9.

[Response]: We sincerely appreciate this important comment. Your emphasis on the significance of methane emissions for accurately evaluating the climate impact of shale gas is well-founded and aligns with our modeling approach. We appreciate the opportunity to clarify this point.

Our bottom-up modeling framework explicitly incorporates methane emissions across all key operational phases. As referenced in Equation 9, methane emissions are specifically quantified and included in the carbon intensity calculations for **well fracturing and flowback, production testing, gas production, and well maintenance stages**. The methodology and comprehensive data sources for these estimates are detailed in **Supplementary Information S3**.

Specifically, our assessment accounts for methane leakage rates derived from field observations in China’s natural gas operations (Chen et al., 2017), which serve as appropriate proxies given the operational similarities between shale gas and conventional natural gas production. Additionally, hydraulic fracturing emissions are estimated based on the methodology developed by O’Sullivan and Paltsev (2012), which indicates that fracturing-related emissions constitute approximately 3.6% of total

production emissions. The resulting methane emissions total 809.62 tonnes (with a breakdown across stages shown in Supplementary Table 13), contributing significantly to the overall greenhouse gas footprint calculation.

The relevant text from our Methods section states:

“This study employs life cycle assessment to quantify carbon emissions (including CH₄ and CO₂) across China’s shale gas value chain. The system boundary of the life cycle inventory model includes upstream production, midstream transportation and distribution, and downstream consumption (Supplementary Figure 5).”

And from Supplementary Information S3.5:

“S3.5. Leakage of shale gas

Shale gas leakage is commonly observed throughout the entire life cycle of shale gas production. However, the specific leakage rates for shale gas production in China have not been disclosed. Since the production processes of shale gas and natural gas are similar, leakage rates for natural gas can be used as a reference. Chen et al. conducted a study that calculated the emission factors for CH₄ and CO₂ at various stages in the Shunan gas field. For details, please refer to Supplementary Table 13²³. Additionally, the emissions from the hydraulic fracturing process were estimated based on the research conducted by O’Sullivan et al., which showed that emissions from hydraulic fracturing account for 3.6% of the total emissions associated with shale gas production²⁴. By considering these factors, the calculated methane and CO₂ leakage amounts are 809.62 t and 193.39 t, respectively.”

Supplementary Table 13 The emission factors for CH₄ and CO₂ at various stages

Stage	Component	Well drilling	Well fracturing and flowback	Production testing	Gas production	Well maintenance	Total
Emission factor(t/10 ⁹ m ³)	CH ₄	0	39.70	1.85	605.51	495.52	1,142.58
	CO ₂	0	9.48	252.14	6.54	4.76	272.9
Emission/t	CH ₄	0	28.13	1.31	429.06	351.12	809.62
	CO ₂	0	6.72	178.67	4.63	3.37	193.39

References:

(23)Chen, G.; Yang, S.; Lv, C.; Zhong, J.; Wang, Z.; Zhang, Z.; Fang, X.; Li, S.; Yang, W.; Xue, L. An Improved Method for Estimating GHG Emissions from Onshore Oil and Gas Exploration and Development in China. *Sci. Total Environ.* **2017**, 574, 707–715. <https://doi.org/10.1016/j.scitotenv.2016.09.051>.

(24)O’Sullivan, F.; Paltsev, S. Shale Gas Production: Potential versus Actual Greenhouse Gas Emissions. *Environ. Res. Lett.* **2012**, 7 (4), 044030. <https://doi.org/10.1088/1748-9326/7/4/044030>.

4. The TEA part, why transportation of CO₂ is not considered? This would be a major driver in system NPV optimization, that cannot be neglected for most of the time.

[Response]: We sincerely appreciate this important observation regarding CO₂ transportation costs in our techno-economic analysis. We agree that transportation costs represent a major driver in system NPV optimization and should never be overlooked.

Our initial description of this aspect in the main manuscript and the Supplementary Information was indeed unclear, leading to misunderstanding. We would like to take this opportunity to clarify that in our techno-economic analysis model, the cost of CO₂ transportation has been considered. We recognize that this critical cost component was not sufficiently highlighted in the original manuscript, which may have created ambiguity about our modeling approach.

To address this concern and enhance transparency, we have added a dedicated subsection (S5.7) in the Supplementary Information to explicitly document the CO₂ transportation cost methodology:

“S5.7 Cost of CO₂ fracturing, huff-n-puff, and sequestration

In calculating the CO₂ fracturing huff-n-puff, and sequestration costs, we considered the procurement and transportation costs of CO₂, as well as the energy input costs for the subsequent fracturing operations. The cost of industrial-grade CO₂ is about US\$40.4 t⁻¹, while the cost of diesel is US\$1003.0 t⁻¹. The electricity prices vary slightly by regions, ranging from US\$0.067–0.11 per kW·h, as detailed in Supplementary Table 17. Details regarding CO₂ transportation infrastructure parameters and transport distance are summarized in Tables S5 and S6.”

Supplementary Table 17 The electricity prices in different regions

Regions	Electricity prices (US\$/kWh)
Sichuan Basin	0.097
Tarim Basin	0.067
Ordos Basin	0.086
Songliao Basin	0.11
Bohai Bay Basin	0.096
Zhunger Basin	0.075
Turpan-Hami Basin	0.067
Northern Yunnan-Guizhou Region	0.082
Central Yangtze Region	0.11

Supplementary Table 5 Parameters related to transportation and construction facility.

[illegible]

Truck(water , wastewater, CO ₂)	30	t	30	t/load	0.302	kg/km	diesel
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Supplementary Table 6 Physical parameters related to materials and transportation distance

Material	Density (kg/m ³)	Transportation distance (km)
CO ₂ in transport/storage conditions	1,031.8	150

5. Defining of the “negative emission” need to specify the system boundary and LCA approach explicitly. However, this paper did not clearly discussing the limitation of negative emission discussion. For example, when CO₂ is sourced from point source, even with successful storage, it can be only claimed as carbon offset not negative emission. Unless CO₂ is captured from air with DAC or BECCS. In addition, the system boundary has to be cradle-to-grave. Unless using the system expansion LCA approach.

[Response]: We sincerely thank you for the insightful comments, which are crucial for enhancing the quality and rigor of this manuscript. We deeply appreciate the opportunity to address this fundamental conceptual issue.

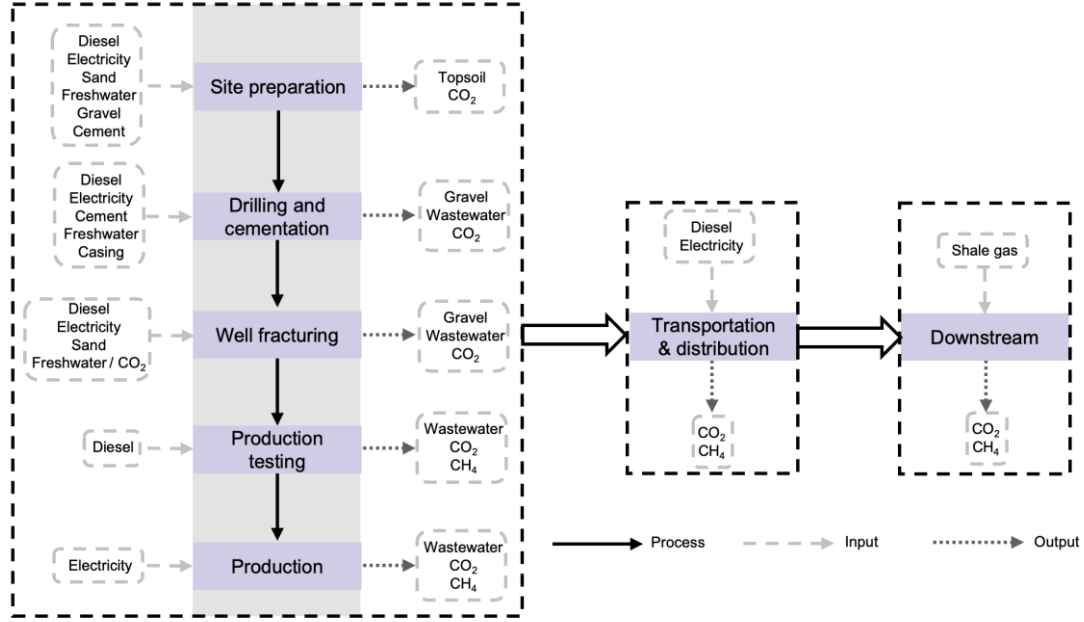
We fully agree with your assessment that the source of CO₂ is critical in determining whether genuine atmospheric carbon removal can be claimed. From a global carbon cycle perspective, only CO₂ captured directly from the atmosphere and permanently stored can constitute true negative emissions. CO₂ sourced from industrial point sources, even when successfully sequestered, represents carbon offsetting rather than net atmospheric removal.

The system boundary of our study is explicitly confined to the shale gas value chain itself, from wellhead to end-user consumption (cradle-to-grave). Our objective is to evaluate how CO₂ utilization and geological sequestration can enable the shale gas sector to achieve **net-zero or carbon-neutral status within its own operational boundaries**, rather than claiming net removal of atmospheric carbon at a global scale. This distinction is fundamental to interpreting our results correctly.

To address this critical clarity issue, we have made the following revisions:

(1) Explicit system boundary and functional unit definition (Methods section):

*“This study employs life cycle assessment to quantify carbon emissions (including CH₄ and CO₂) across China’s shale gas value chain. The system boundary of the life cycle inventory model includes upstream production, midstream transportation and distribution, and downstream consumption (**Supplementary Figure 5**). The functional unit selected for this study is one cubic meter of shale gas produced at the well pad over its full life cycle. The carbon emissions stem from energy inputs, raw materials production, methane leakage, and CO₂ emissions, with the latter primarily arising from downstream shale gas combustion. The GHG emission intensities for materials are based on life cycle assessment literature^{21,50–53}, while site data are derived from recent studies^{21,54,55}. ”*



Supplementary Fig. 5 Schematic diagram of shale gas supply chain: key processes and material flows. The shale gas value chain encompasses multiple stages from well pad construction to final consumption, involving numerous stakeholders. The upstream segment includes processes such as well pad construction, drilling, fracturing, and production testing. The fracturing process is divided into two technical pathways: hydraulic fracturing and CO₂ fracturing. Downstream consumption involves various scenarios, including power generation, transportation, and household use.

(2) Clarified definition of "negative emissions" with explicit limitations (Methods section):

"To assess the carbon emission reduction potential across different shale gas reservoirs under various scenarios, we define the carbon neutrality coefficient (CNC):

$$CNC_{i,j} = (I_{i,b} - I_{i,j}) / I_{i,b} \quad (13)$$

where $I_{i,b}$ is the carbon intensity of the shale gas life cycle for different shale gas reservoirs under the baseline scenario, and $I_{i,j}$ is the carbon intensity of the shale gas life cycle for different shale gas reservoirs under different scenarios. When the CNC is between 0 and 100%, it indicates that the shale gas value chain has not achieved carbon neutrality; when the CNC equals 100%, the carbon footprint of the shale gas value chain is zero; and when the CNC is greater than 100%, the shale gas value chain can achieve negative emissions. **It is important to note that this negative emission status is defined specifically to the value chain itself, meaning that the amount of CO₂ sequestered within the system boundary exceeds the direct emissions generated by the chain.**"

(3) Refined terminology in the Discussion section:

"Discussion

Conventional shale gas energy supply is a significant source of net greenhouse gas emissions, presenting a strategic conflict with carbon neutrality goals. To address this contradiction and explore a sustainable pathway, this study provides a systematic quantification of historical carbon emissions from China's shale gas value chain (2012-2023) and delivers the most granular assessment to date of the emission reduction potential across distinct shale gas reservoir types at the full value chain level. Building on this analysis, we propose a novel integrated value-chain management model. By incorporating key technologies such as CO₂ fracturing, CO₂ huff-and-puff, and geological sequestration in depleted wells, this model fundamentally transforms the system from a net carbon source into a net carbon sink while simultaneously enhancing gas production, thereby offering a resolute pathway for aligning shale gas development with carbon neutrality objectives. ”

6. When linking the TEA and LCA, it is worthwhile to look at the economic and environmental trade-offs. However, authors did not dive into this discussion, leaving the paper structurally incomplete.

[Response]: We sincerely thank you for this valuable observation. We fully agree that a systematic exploration of the economic-environmental trade-offs revealed by our integrated TEA-LCA framework represents a critical analytical dimension that strengthens the practical relevance and policy implications of this work.

To address this gap, we have expanded the **Discussion section** with the following additions:

(1) Economic-environmental trade-offs across technological pathway:

“The integrated analysis framework reveals a fundamental tension between maximizing environmental benefits and maintaining economic viability across different emission reduction strategies. Our analysis identifies a clear trade-off: the HW (CO₂ huff-and-puff in water-based fractured wells) and CS (dedicated CO₂ sequestration) scenarios achieve the most ambitious environmental outcomes, transforming the shale gas value chain into a geological carbon sink with negative emissions, but impose substantial economic penalties due to high CO₂ procurement costs, transportation logistics, and energy-intensive injection operations. Conversely, the OM (operational modifications) and OP (optimized production) strategies deliver modest but cost-effective carbon reductions with favorable economic returns across most reservoir types, yet fall short of achieving carbon neutrality. This trade-off exhibits pronounced spatial heterogeneity driven by geological and infrastructure factors. For marine shale formations in the Sichuan Basin, characterized by superior reservoir quality, high CO₂ adsorption capacity, and established industrial infrastructure, the HW/CS pathways remain economically viable even without carbon pricing support. However, for terrestrial and transitional facies in basins such as Ordos and Songliao, the economic feasibility of negative-emission pathways is critically contingent on robust carbon pricing mechanisms or policy incentives that internalize the climate externalities (Supplementary Table 18).”

(2) Decision framework table in Supplementary Information:

We have added Supplementary Table 18 that systematically maps the trade-off space across different strategies.

Supplementary Table 18 Economic-environmental trade-offs and optimal application contexts for different emission reduction strategies

Strategy	Environmental performance	Economic performance	Optimal application context
HW/CS	Negative emissions (69.7 to -2158.5 kg CO ₂ e/m ³)	High cost; NPV positive only with carbon pricing or in high-quality marine reservoirs	Marine shale (Sichuan Basin); regions with strong carbon pricing policies
OM/OP	Moderate reduction (3.1–9.5% emission reduction)	Improvement in profitability	All shale, especially in transitional and continental shale; cost-constrained scenarios
Baseline	High emissions (3186.4–3307.3 kg CO ₂ e/m ³)	Established economics but declining competitiveness under carbon constraints	Marine shale (Sichuan Basin)