

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

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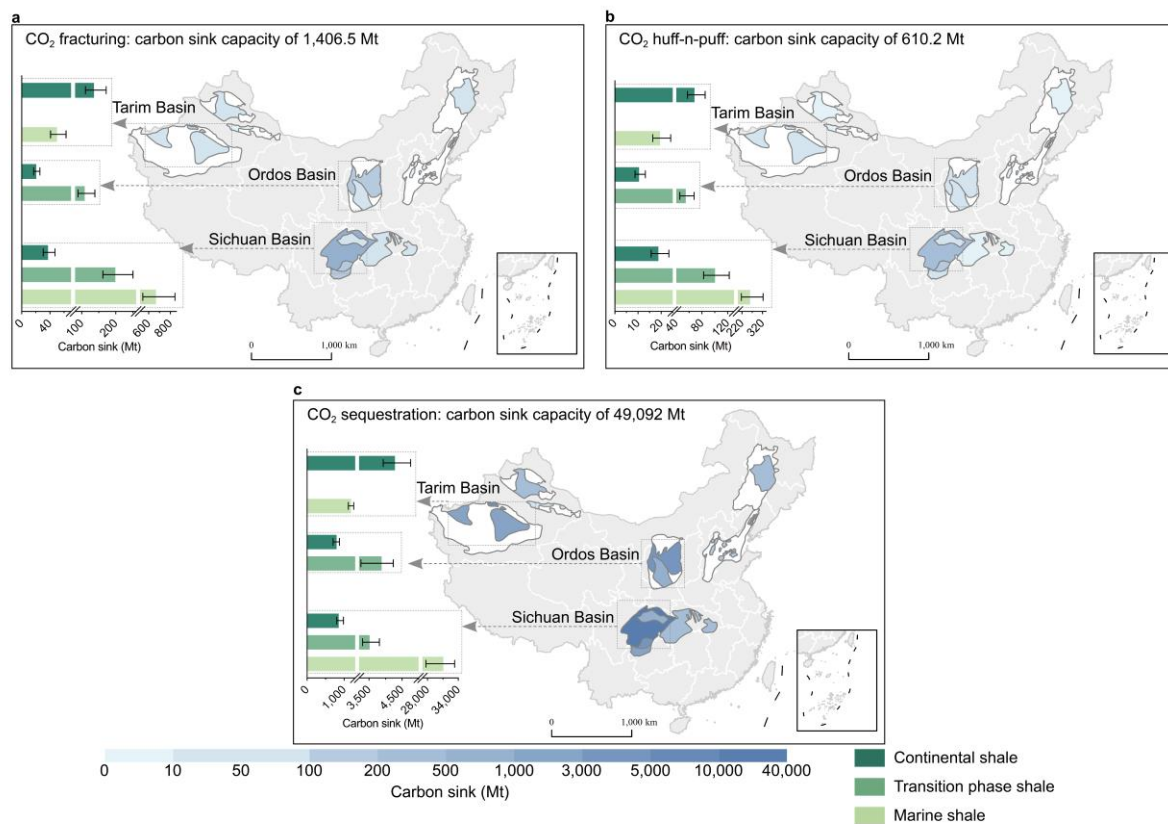
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Supplementary Items List

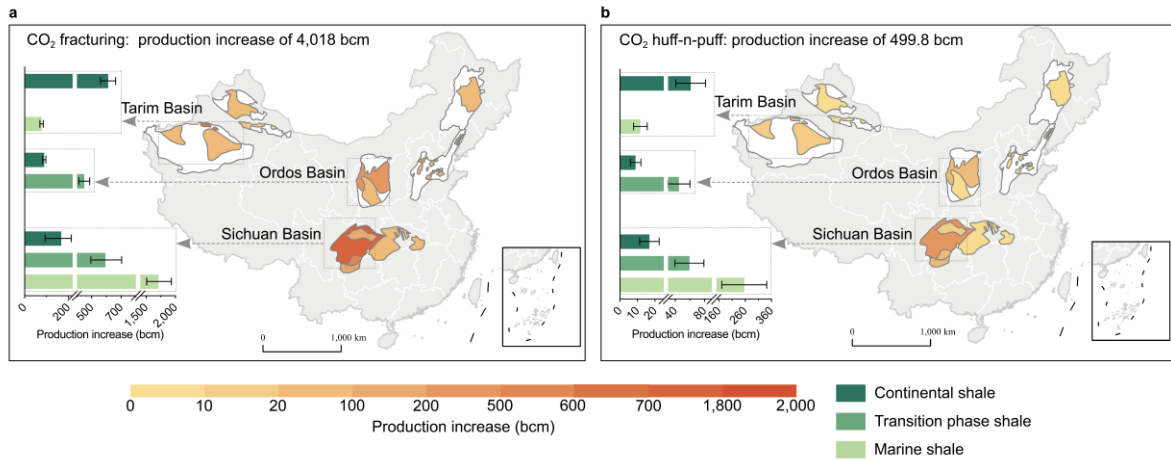
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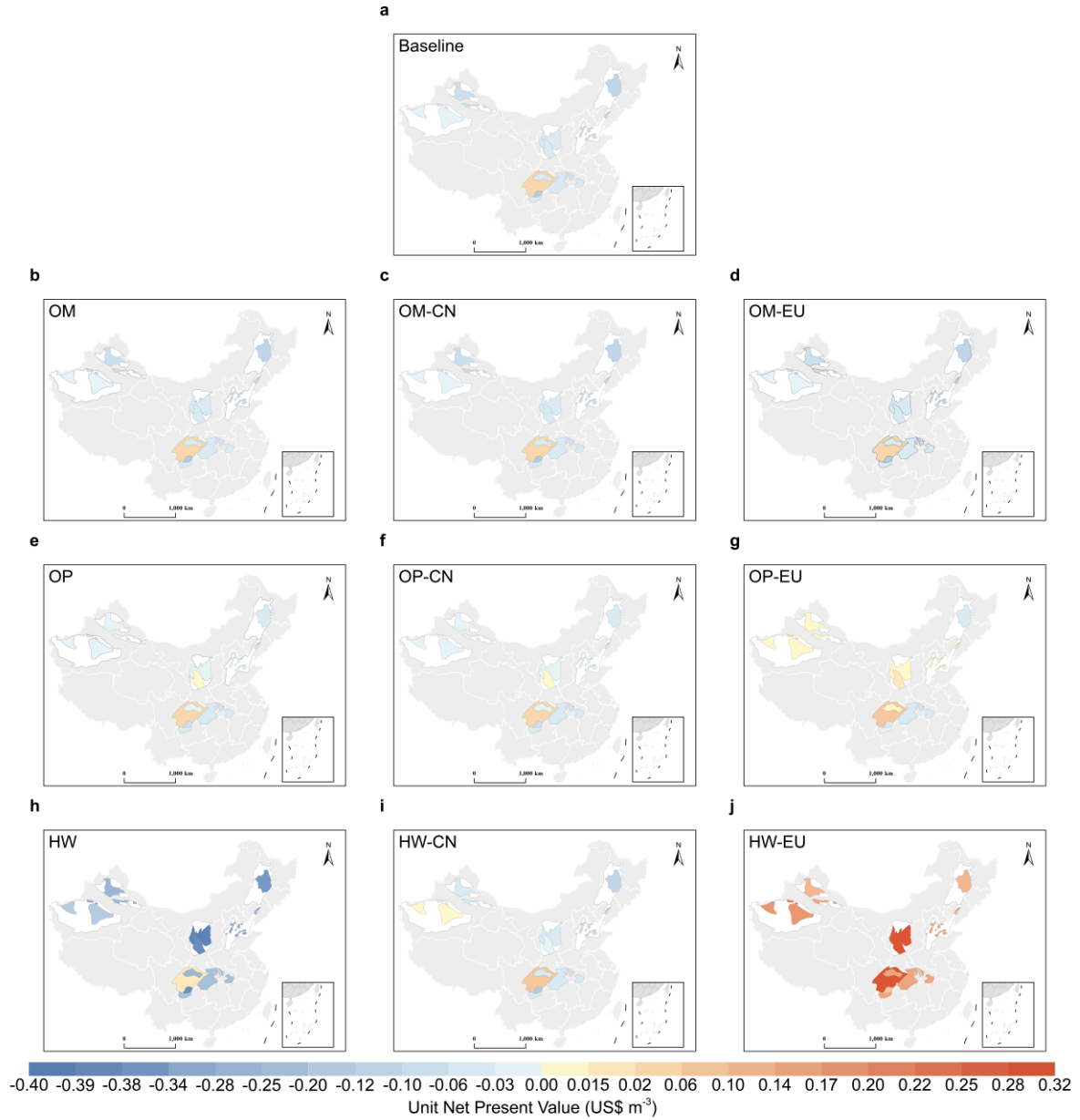
Supplementary Fig. 1 The carbon sequestration potential of different shale gas reservoirs in various regions under different technologies.

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.



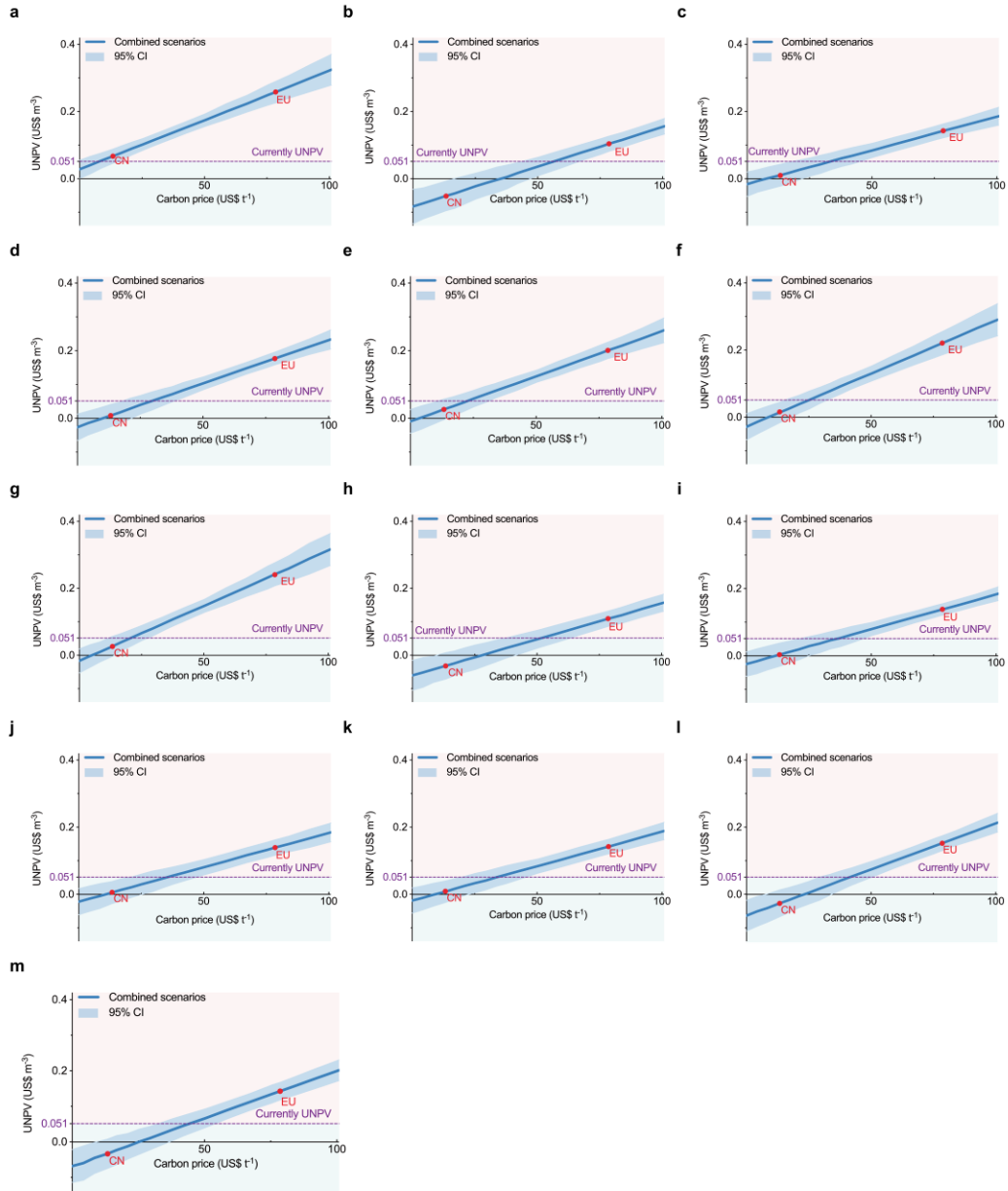
Supplementary Fig. 2 The production increase potential of different shale gas reservoirs in various regions under different technologies.

Figures a and b show the production enhancement potential of different shale gas reservoirs in various regions after applying CO₂ fracturing and CO₂ huff-n-puff technologies, respectively. Among these, the application of CO₂ fracturing technology is the main driving force for production enhancement. The cumulative bar charts in a and b illustrate the production increase potential of different types of shale gas reservoirs in the Sichuan Basin, Tarim Basin, and Ordos Basin, with 95% confidence intervals.



Supplementary Fig. 3 The Unit Net Present Value (UNPV) of different shale gas reservoirs in various regions under different scenarios.

Figure a shows the UNPV of different regions under the baseline scenario. Figures b to d represent the UNPV of different regions under the OM scenario, with c and d showing the UNPV under carbon prices in China (CN) and Europe (EU). Figures e to g depict the UNPV of different regions under the OP scenario, with f and g reflecting the UNPV under carbon prices in China and Europe. Figures h to j illustrate the UNPV of different regions under the HW scenario, with i and j indicating the UNPV under carbon prices in China and Europe.



Supplementary Fig. 4 The variation of Unit Net Present Value (UNPV) of different shale gas reservoirs in various regions under combined scenarios with changes in carbon prices.

The purple dashed line represents the UNPV of the marine shale gas reservoirs currently being developed in the Sichuan Basin, while China (CN) and Europe (EU) indicate the UNPV under the current carbon prices in China and Europe, respectively. Figures (a) to (c) correspond to marine shale, transitional shale, and continental shale in the Sichuan Basin; (d) and (e) correspond to marine and terrestrial shales in the Tarim Basin; (f) and (g) correspond to transitional and continental shales in the Ordos Basin; (h) corresponds to continental shale in the Songliao Basin; (i) corresponds to continental shale in the Bohai Bay Basin; (j) corresponds to continental shale in the Zhuoer Basin; (k) corresponds to continental shale in the Turpan-Hami Basin; (l) corresponds to marine shale in the Yunnan-Guizhou-North Region; and (m) corresponds to marine shale in the Central Yangtze region.

Supplementary Tables

Supplementary Table 1 Geological information of different shale gas reservoirs.

Basins or regions	Sedimentary facies	TRR/10 ¹² m ³	EUR m ⁻³	Depth /m	TOC /%	Clay Mineral Content /%
Sichuan Basin	Marine facies	8.55	118100000	3000	3.2	31
	Transitional facies	0.99	34515600	3000	2.43	48.3
	Continental facies	0.28	51901500	3300	1.62	45
Tarim Basin	Marine facies	0.39	71771100	4000	2.15	25
	Continental facies	1.02	52000000	2500	3.25	45
Ordos Basin	Transitional facies	0.75	47762000	2500	4.91	58
	Continental facies	0.15	50245700	2000	4.6	48
Songliao Basin	Continental facies	0.09	39483000	3200	2.2	39.9
Bohai Bay Basin	Continental facies	0.04	51901500	3900	2.74	23.5
Zhunger Basin	Continental facies	0.08	52000000	4000	3	11.76
Tuha Basin	Continental facies	0.03	52000000	4000	2.1	50.3
Northern Yunnan- Guizhou Region	Marine facies	0.72	52729400	3000	1.75	35
Central Yangtze Region	Marine facies	0.14	52729400	3000	1.53	26.1

The geological characteristics of different shale gas reservoirs exhibit significant variations. Supplementary Table 1 provides a detailed summary of the geological information for various shale gas reservoirs, indicating that factors such as technically recoverable reserves (TRR), depth, total organic carbon (TOC), and clay mineral content have a substantial impact on the CO₂ sink capacity of the reservoirs¹⁻⁴. Additionally, corresponding distribution ranges have been established for depth, TOC, and clay mineral content to better assess their uncertainties.

Supplementary Table 2 National Shale Gas Consumption by Subsector.

Year	Transportation	Chemistry	Industry	Electricity	Household	Others
2012	10.32%	18.39%	31.46%	15.67%	21.84%	2.32%
2013	10.31%	17.91%	33.21%	15.08%	21.24%	2.24%
2014	11.46%	17.12%	33.63%	14.63%	20.81%	2.35%
2015	12.30%	13.42%	32.23%	18.26%	21.29%	2.51%
2016	12.26%	11.72%	32.89%	19.81%	20.87%	2.46%
2017	11.90%	11.12%	35.83%	18.86%	19.95%	2.34%
2018	10.16%	11.54%	39.69%	17.65%	18.77%	2.19%
2019	11.16%	13.39%	38.61%	16.37%	18.46%	2.01%
2020	10.61%	13.79%	36.90%	18.29%	18.63%	1.78%
2021	9.71%	14.20%	38.73%	18.06%	17.56%	1.75%
Future	11.02%	14.26%	35.32%	17.27%	19.94%	2.20%

Due to the lack of data on national shale gas consumption by subsector, this study substitutes data from national natural gas consumption by subsector, sourced from the National Bureau of Statistics⁵. The projected data for future shale gas consumption by subsector is derived from the average of data collected between 2012 and 2021.

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

Basins or Regions	Electricity Emission Factors (kg CO ₂ e kWh ⁻¹)
Sichuan Basin	0.3
Tarim Basin	0.66
Ordos Basin	0.67
Songliao Basin	0.6
Bohai Bay Basin	0.74
Zhunger Basin	0.7
Tuha Basin	0.66
Northern Yunnan-Guizhou Region	0.32
Central Yangtze Region	0.57

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.

Supplementary Table 4 Key technology parameters.

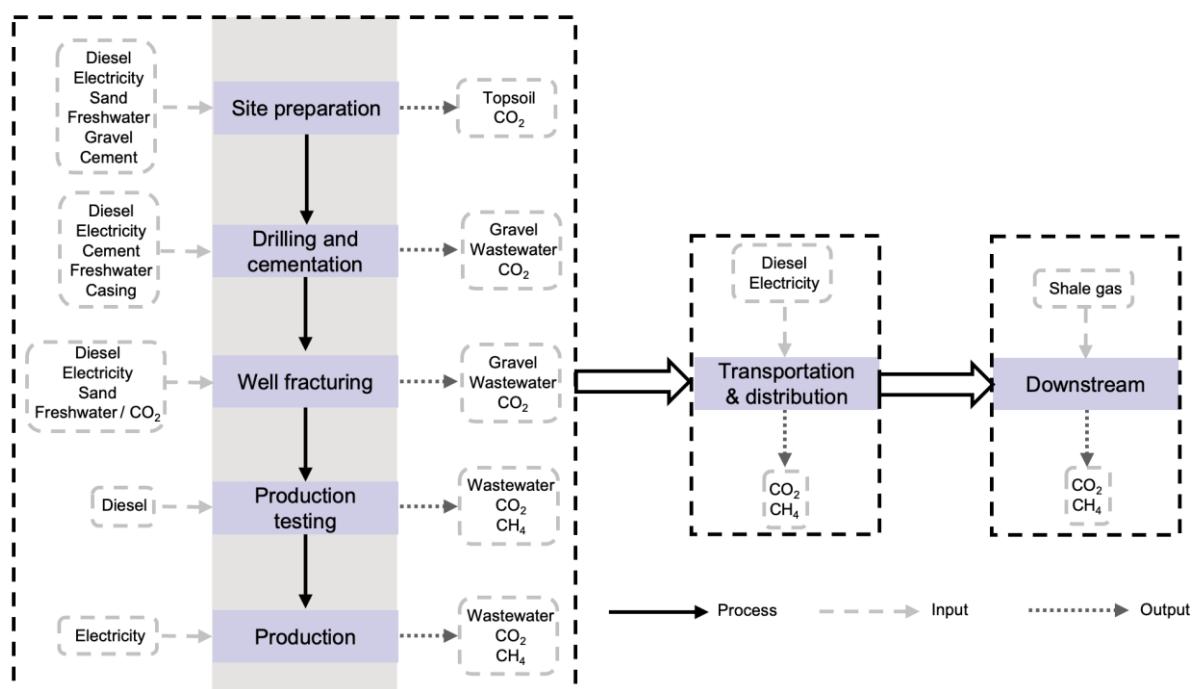
Key CO₂-based technology	Sequestration fraction of injected CO₂/%
CO ₂ fracturing	30
CO ₂ huff-n-puff	50
CO ₂ sequestration	100
Other technology	Carbon emission reduction rate/%
LDAR program	40

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

Supplementary Notes

Supplementary Note 1. Shale gas activity

The shale gas supply chain involves upstream shale gas production, midstream shale gas transport, and downstream shale gas consumption, with Supplementary Fig. 5 delineating the specific processes along with their respective inputs and outputs. In this study, a detailed life cycle assessment was conducted for upstream shale gas, with system boundaries including the site preparation phase, the drilling phase, the hydraulic fracturing and completion phase, and the production phase, which involves the assessment of carbon dioxide emissions, water consumption, and energy inputs. Relevant low-carbon strategies for the shale gas supply chain were also assessed for subsequent scenario-building analyses. Carbon emissions in the midstream and downstream are referenced to carbon emission factors from others' studies due to the lack of relevant data in China. The data in the site preparation stage mainly referred to the survey results of Wang and Chang et al^{7,8}. The Supplementary Note will demonstrate calculations using marine shale from the Sichuan Basin as an example. The calculation process for other shale blocks in several basins are similar.



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.

The main facility parameters, material physical properties parameters, etc., used in the shale gas production process are listed in Supplementary Table 5, and these parameters will always be utilized in the subsequent calculations. The physical properties of the materials and the transportation distance are shown in Supplementary Table 6. It is worth noting that the conventional model assumes that diesel generators

provide all electricity used at the well pad. The diesel generators are rated at 100 kW, and it is assumed that the actual power is 80% of the rated power.

Supplementary Table 5 Parameters related to transportation and construction facility.

Facility	Specifications /model	Units	Productivity	Units	Energy intensity	Units	Energy type
Parameters related to transportation							
Truck(soil, sand、 gravel et al.)	8	t	8	t load ⁻¹	0.22	kg km ⁻¹	diesel
Truck(water、 wastewater, CO ₂)	30	t	30	t load ⁻¹	0.302	kg km ⁻¹	diesel
Truck(diesel)	38	t	38	t load ⁻¹	0.306	kg km ⁻¹	diesel
Truck(casing)	40	t	40	t load ⁻¹	0.31	kg km ⁻¹	diesel
Truck(cement)	10	t	10	t load ⁻¹	0.23	kg km ⁻¹	diesel
Parameters related to construction facility							
Grader	120	kW	1429	m ² shift ⁻¹	55	kg shift ⁻¹	diesel
Roller	15	t	7143	m ² shift ⁻¹	43	kg shift ⁻¹	diesel
Bulldozer	90	kW	776	m ³ shift ⁻¹	59	kg shift ⁻¹	diesel
Loader	2	m ³ load capacity	380	m ³ shift ⁻¹	65	kg shift ⁻¹	diesel
Sprinkler truck	4,000	liter capacity	5000	m ² shift ⁻¹	30	kg shift ⁻¹	diesel
Excavator	1.25	m ³ load capacity	571	m ³ shift ⁻¹	54	kg shift ⁻¹	diesel
Concrete mixer	1,500	liter	75	m ³ h ⁻¹	24	kW h ⁻¹	electricity
Concrete pump	80	m ³ h ⁻¹	80	m ³ h ⁻¹	58	kW h ⁻¹	electricity
Cementation truck	336	kW	1.64	m ³ min ⁻¹	31.3	kWh	diesel
Diesel generator*	100	rating power kW	80	kW	20.6	kg h ⁻¹	diesel
Parameters related to drilling and cementation equipment							
Centrifuge	LS1600	-	50	m ³ h ⁻¹	55	kW	electricity
Vibrating screen	ZS-104G	-	150	m ³ h ⁻¹	3.73	kW	electricity
drilling pump	ZJ70/4500LD B	-	9.65	m h ⁻¹	1,176	kW	electricity
mud pump	F-1600	-	38.78	L s ⁻¹	1,180	kW	electricity
Parameters related to fracturing equipment							
	Model	rating power/k W	practical power/kW	Number	Producti vity(m ³ min ⁻¹)	Work time/h	

Fracturing pump trucks	SYL2000 Q-105	1,680	1,121	17	10	347.6
Sand mixing trucks	SHS 10	410	273	2	12	289.7
Instrumentation trucks	SYQ2000	12.4	12.4	1	-	347.6
Manifold truck	SYG140	320	213	2	12	289.7

Supplementary Table 6 Physical parameters related to materials and transportation distance

Material	Density (kg m ⁻³)	Transportation distance (km)
Soil	1,230	10
Gravel	1,553	80
Sand	1,510	50
Water	1,000	5
Bentonite	-	20
Lime and CaCl ₂	-	30
Casing	-	150
Diesel	850	15
Bentonite slurry	1,150	-
Water-based drilling fluids	1,320	-
Oil-based drilling fluids	1,540	-
CO ₂ in transport/storage conditions	1,031.8	150
CO ₂ in flowback or surface conditions	1.808	-

1) Site Preparation Stage

The site preparation phase consists of road maintenance and construction, well pad construction, and ancillary facilities construction. The main parameters of the three parts are shown in Supplementary Table 7.

Supplementary Table 7 The main parameters related to the site preparation stage.

Road maintenance and construction	Length of road maintenance/km	2
	Length of road construction /km	0.25
Well pad construction	The area of the well pad/m ²	8,000
	Freshwater reservoir/m ³	7,500
Ancillary facilities construction	Wastewater sink/m ³	2,200
	Solid waste reservoir/m ³	3,400
	Flare pit/m ³	200

Road maintenance and construction

The Sichuan Basin shale gas resource distribution area has a mature road system, so only a short length of road repair and new construction is needed. According to the research, we make the following assumptions: the length of road repair in the Sichuan Basin is 2 km, the length of the new road is 0.25 km, the repair road only needs to level and compact the existing road, and the new road needs to be paved with gravel. The

width of the road is 6 m and the thickness of the gravel is 8 cm, the construction of the road needs to excavate the topsoil of 20 cm depth firstly, and the topsoil after excavation is transported and disposed of. Combined with the calculations in Supplementary Table 5 and Table 6, the total amount of gravel input in the road maintenance and construction phase is about 186.36 tons (t), the transportation of topsoil is about 369.00 t, and the consumption of diesel fuel is 1,706.92 kg.

Well pad construction

According to the research, the well pad's construction area is 8,000 m². The construction starts with excavating topsoil at a depth of 20 cm, after which gravel with a thickness of 8 cm will be laid and the topsoil transported away. Combining Supplementary Table 5 and Table 6, it can be concluded that the well pad construction consumes 993.92 t of gravel and 6,255.05 kg of diesel.

Ancillary facilities construction

Freshwater reservoir construction

Freshwater reservoir is mainly used to store freshwater from transportation, freshwater reservoir volume of 7,500 m³, the internal laying of waterproof fabric 2,500 m² (subsequent calculations ignored), transportation of topsoil and other construction projects consume a total of 7,065.93 kg of diesel.

Wastewater sink construction

The wastewater pond is used for temporary storage of wastewater generated during the drilling and fracturing stages, and the volume of the wastewater pond is assumed to be 2,200 m³. To prevent seepage of wastewater, the wastewater pond is constructed with concrete, with a thickness of 40 cm at the bottom and 30 cm around the peripheral wall. A concrete partition wall is constructed in the wastewater sink, and it is assumed that 1 m³ of concrete consists of 406 kg of cement, 395 kg of sand, 1,202 kg of gravel, and 191 kg of water. The construction of the wastewater pond requires 164 t of cement, 281 t of sand, 485 t of gravel, and 77 t of water. Supplementary Tables 5 and 6 show that 4,780 kg of diesel fuel was consumed to transport the materials and soil, and 693.08 kg of diesel fuel was consumed by the on-site equipment.

Solid waste reservoir construction

The solid waste reservoir is used to dispose of solid waste generated during the drilling and fracturing stages; in this study, the volume of the solid waste landfill is 3,400 m³; to prevent leakage, it is constructed using concrete with a thickness of 40 cm at the bottom and 30 cm on the surrounding walls. Based on the above assumptions, the construction of the solid waste reservoir consumed 199 t of cement, 341 t of sand, 590 t of gravel, and 94 t of water, and in combination with Supplementary Tables 5 and 6, the transportation of materials and soil consumed 6,301.01 kg of diesel, and on-site equipment consumed 1,035.24 kg of diesel.

Flare pit construction

The flare pit is mainly used for the production testing part of the completion stage, and according to the survey, the volume of the flare pit is 200 m³. The flare pit is constructed with concrete and treated the same way as the solid waste reservoir and wastewater sink. The construction of the flare pit consumed 23 t of cement, 40 t of sand, 69 t of gravel, and 11 t of water, and in combination with Supplementary Tables 5

and 6, the transportation of materials and soil consumed 602.91 kg of diesel, and on-site equipment consumed 68.46 kg of diesel fuel.

Living water use during site preparation

Assuming that the site preparation stage takes 20 days and involves a total of 50 workers with a daily water consumption of 80 L per person and that the water is obtained from a distance of 5 km, this phase consumes a total of 80 t freshwater and 8.05kg of diesel.

Summaries of inputs during the site preparation stage

Supplementary Table 8 summarizes the material inputs for each well pad during the site preparation stage.

Supplementary Table 8 The material inputs for each well pad during the site preparation stage

Input	Road maintenance and construction	Well pad construction	Auxiliary facilities construction	Living water	Total
Cement/t	-	-	386	-	386
Sand/t	-	-	662	-	662
Gravel/t	186.36	993.92	1,182	-	2,362.28
Waterproof fabric/m ²	-	-	2,500	-	2,500
Water/t	-	-	182	80	262
Diesel/kg	1,706.92	6,255.05	20,546.64	8.05	28,516.66

2) Drilling and cementation stage

The drilling and cementation stage consists of drilling and cementing, in which drilling refers to the use of drilling rigs to drill holes into the ground to reach the target rock formation. The drilling process is divided into two parts: a vertical section of about 3 km and a horizontal section of about 2 km. Cementing involves the use of cement slurry and multi-layer casing injected into the drilled holes to stabilize the hole walls and isolate the gas and liquid. The production capacity and the productive life of the shale wells are closely related to the quality of cementing.

Well drilling

The well drilling process can be divided into four drilling stages: conduit, first, second, and third, where the conduit, first, and second stages are performed in the vertical well section, while the third stage is for the horizontal well section. The composition of the drilling fluids used for each of these stages is different, and Supplementary Table 9 shows in detail the drilling fluids consumed during the drilling of one well⁹. Since this study is based on a cubic meter of shale gas from a single well pad, the material inputs described above must be multiplied by the number of wells per unit of the well pad (6). Similarities in the latter sections will not be repeated. The energy consumption of drilling is mainly related to the depth of the well and the characteristics of the geological layer, and the drilling speed of the Chinese drilling equipment is estimated to be 9.65 m h⁻¹ according to the study of Jiang et al. and the parameters of the Chinese drilling equipment¹⁰. The recycling of drilling fluids is considered in this study, and the main equipment involved are centrifuges and vibrating screens. The working loads of the centrifuges and vibrating screens need to

be obtained by combining the amount of the broken rock and drilling fluid. Combining the diameter of the drill bit and the drilling depth, the amount of broken rock is calculated to be 366.17 m³, while the drilling fluid is about 590.95 m³, totaling 957.12 m³. Combined with Supplementary Tables 5, 6, and 9, it can be calculated that the energy input used for transportation is 1,948.5 kg of diesel, and that used to drive the field equipment is 950,737.67 kg of diesel.

Supplementary Table 9 The drilling fluids consumed during the drilling of one well

Well spud No.	Well interval/m	Drilling fluid	Content					Total/t	Total/m ³
			Water/t	Diesel/t	Bentonite/t	CaO/t	CaCl ₂ /t		
Conductor	50	Bentonite slurry	53.4	-	2.9	-	-	56.3	48.96
First spud	500	Freshwater	225.2	-	-	-	-	225.2	225.2
Second spud	3000	Water-based	226.1	-	26.3	10.2	-	262.6	198.93
Third spud	5000	Oil-based	47.2	93.6	4.5	13.6	22.6	181.5	117.86
Total			551.9	93.6	33.7	23.8	22.6	725.6	590.95

Well cementation

Shale gas wells need to be reinforced with multi-layer casing during the cementing stage, and cement is utilized between the casing and between the casing and the well body. The consumption of casing is calculated as supplementary equation (1):

$$Q_c = \frac{\pi}{4} \times 10^{-9} \sum_1^4 (d_{o,n}^2 - d_{i,n}^2) h_n \quad (1)$$

Where Q_c is the mass of casing/t, $d_{o,n}$ and $d_{i,n}$ are the outer and inner diameters of casing/mm for different cementing stages, respectively, and h_n is the corresponding length of casing/m. The related parameters and casing consumption are shown in Supplementary Table 10. The calculation methods of cement slurry consumption for different cementing stages are different, and the calculation method for the conductor section is as in supplementary equation (2), and that calculation method for first spud, second spud, and third spud is as in supplementary equation (3):

$$V_c = \frac{\pi}{4} \times 10^{-6} \left((d_d^2 - (d_{o,1}^2)) h_1 \right) \quad (2)$$

$$V_c = \frac{\pi}{4} \times 10^{-6} \left(\sum_2^4 (d_{d,n}^2 - d_{o,n}^2) (h_n - h_{n-1}) + \sum_2^4 (d_{i,n-1}^2 - d_{o,n}^2) \times h_{n-1} \right) \quad (3)$$

Where V_c is the volume/m³ of cement slurry, $d_{d,n}$ is the diameter/mm of the drill bit, and $d_{i,n-1}$ is the inner diameter/mm of the last casing. Cement slurry consumption is shown in Supplementary Table 10. The water content of cement slurry is different in different cementing stages, which is 43%, 43%, 43%, and 26%, respectively, and it can be deduced that the amount of freshwater and cement consumed in the process of cementing is 147.6 and 280.1t, respectively. Combined with Supplementary Tables 5 and 6, it is calculated that 10,294.39 kg of diesel is consumed to transport the materials, and 433.24 kg of diesel is consumed to drive the field equipment.

Supplementary Table 10 Casing and cement slurry consumption

Casing	Conduit	Surface casing	Middle casing	Production casing	
Drill diameter/mm	609.6	406.4	311.2	215.9	Total
Outer diameter/mm	508	339.7	244.5	139.7	
Wall thickness/mm	11.1	10.9	11.9	12.7	
Inside diameter/mm	485.8	317.9	220.7	114.3	
Length/m	50	500	3,000	5,000	
Cement slurry density (kg m ⁻³)	1,850	1,850	1,850	1920	
Casing quality/t	6.8	44.2	204.7	198.8	454.4
Cement slurry volume/m ³	4.5	22.3	88.9	111.3	227
Quality of cement slurry/t	8.2	41.3	164.5	213.7	427.7

Living water use during drilling and cementation

Assuming that the drilling and cementation stage takes 55 days and involves a total of 40 workers with a daily water consumption of 80 L per person and that the water is obtained from a distance of 5 km, this phase consumes a total of 176 t of freshwater and 17.71 kg of diesel.

Summaries of inputs during drilling and cementation stage

Supplementary Table 11 summarizes the material inputs for each well pad during the drilling and cementation stage.

Supplementary Table 11 The material inputs for each well pad during the drilling and cementation stage

Input	Well drilling	Well cementation	Living water	Total/t
Freshwater/t	3,311.4	885.6	176	4,373
Bentonite/t	202.2	-	-	202.2
lime/t	142.8	-	-	142.8
CaCl ₂ /t	135.6	-	-	135.6
Diesel/t	1,514.3	10.7	0.02	1,525.0
Casing/t	-	2,726.6	-	2,726.6
Cement/t	-	1,680.8	-	1,680.8

3) Well completion stage

The completion phase includes well cleaning, fracturing, perforation, and production testing processes. The consumption associated with the perforation process was neglected in this study due to the relatively low consumption of materials such as perforation charges. In addition, two scenarios were set up for the fracturing stage in this study, hydraulic fracturing and CO₂-based fracturing, which will be presented in Hydraulic fracturing and CO₂ fracturing section.

Well cleaning

After the cementing operation, shale gas wells require a well cleaning process to meet the requirements for hydraulic fracturing operations. According to investigations, the wellbore cleaning process for shale gas

wells in China consumes approximately 30 m³ of clean water per 1km of well depth¹¹. Considering the average depth of shale gas wells in China is 5 km, the wellbore cleaning process consumes approximately 900.00 t of freshwater at the well pad. Additionally, the transportation of freshwater consumes approximately 90.60 kg of diesel.

The water loss rate during the well cleaning process is estimated to be around 3.5%. Consequently, approximately 868.50 t of wastewater is generated, of which 70% is recycled and reused¹². The remaining 30% of wastewater is transported to the wastewater treatment plant, consuming approximately 104.92 kg of diesel for transportation.

Hydraulic fracturing

Hydraulic fracturing plays a crucial role in the development of shale gas wells. The main materials used in the fracturing process include fracturing fluid and proppants. Currently, the predominant fracturing fluid used in Chinese shale gas wells is slick water, which consists of 99% water. In this study, it is assumed that the slick water is composed entirely of water, and the proppants used are all sand. According to survey results, an average of 1,738.0 t of water and 83.5 t of sand are consumed per stage during hydraulic fracturing. Considering that the average number of fracturing stages in Chinese shale gas wells is 20 (16–24), it can be calculated that each well consumes an average of 34,760.00 t of water and 1,670.60 t of sand. The main equipment used on-site during the hydraulic fracturing process includes 17 fracturing pump trucks, 2 sand mixing trucks, 1 instrumentation truck, and 2 manifold trucks. Detailed parameters for each equipment can be found in Supplementary Table 5. It should be noted that the power of each piece of equipment during the fracturing process is based on actual power⁸. The fracturing pump trucks are responsible for injecting the high-pressure fracturing fluid into the well, while the sand mixing trucks are used to uniformly mix the fracturing fluid and sand. The instrumentation truck provides a centralized workspace for managing and operating instrumentation equipment. Based on a survey by Ren et al., the injection rate of fracturing fluid ranges from 8 to 12 m³min⁻¹¹³. For this study, a rate of 10 m³ min⁻¹ is assumed, and the sand mixing truck operates at a speed of 12 m³ min⁻¹. Calculations show that the on-site fracturing equipment consumes 1,785.70 t of diesel.

CO₂ fracturing

The main sources of CO₂ emissions in the Sichuan and Chongqing regions are the cement, thermal power, and steel industries, which have good carbon sequestration potential¹⁴. In this study, it is assumed that all the CO₂ comes from thermal power plants, and after being captured using the amine chemical method, it is compressed to 2 MPa and transported to the site. The power consumption of the fans and pumps in the capture process is taken as 23.6 kWh per tCO₂, and the energy consumption in the CO₂ compression process is calculated using supplementary equation (4) and (5)¹⁵. W is the work done in the compression process, in kJ kg⁻¹, Z is the compressibility factor (0.9942), R is the universal gas constant (8.3145 J (mol·K)⁻¹), T is the inlet gas temperature of 313.15 K, γ is the heat capacity ratio (c_p/c_v) taken as 1.293759, and M is the molar mass of CO₂ at 44 g mol⁻¹. E is the actual consumed electrical energy, with η_s and η_m representing the isentropic efficiency (80%) and mechanical efficiency (99%), respectively.

$$W = \frac{ZRT}{M} \frac{N_\gamma}{\gamma - 1} [(p_2/p_1)^{\gamma-1/N_\gamma} - 1] \quad (4)$$

$$E = W / (3600\eta_s\eta_m) \quad (5)$$

Currently, China's CO₂ transportation network is underdeveloped, with road transportation by tanker truck still being the main method. During CO₂ transportation, CO₂ needs to be emitted to maintain pressure and undergo cooling, resulting in about a 3% loss¹⁶. Therefore, a 3% CO₂ loss will be considered in the subsequent calculations. Given the distribution of carbon sources, such as cement plants and thermal power plants around the shale gas development base, the CO₂ transportation distance in this study is set at 150 km.

The mixing process of CO₂-based fracturing fluid is different from that of water-based fracturing fluid. The high-pressure characteristics of CO₂ liquid allow it to self-drive and carry proppant sand into the mixer without the need for external energy input. Considering the long-term transportation of CO₂ and the pressure loss during proppant transport, the pressure of CO₂ entering the mixer is only 1.4 MPa. The CO₂-based fracturing fluid mixed in the mixer will be injected into the high-pressure pump, which provides the energy required for the fracturing process during the fracturing stage. The specific calculation is given by supplementary equation (6), where E is the energy consumed by injecting the CO₂-based fracturing fluid during the hydraulic fracturing stage, V_f and Δp are the fluid volume and the pressure difference overcome during the fracturing process, respectively, and η_p and η_M represent the efficiencies of the pump and the motor, respectively.

The calculation of the pressure difference overcome during the fracturing process is given by supplementary equation (7), where P_f , P_i , P_p , and P_h represent the fracturing pressure, high-pressure pump inlet pressure, pipeline friction loss, and hydrostatic pressure, respectively. The fracturing pressure gradient is 22.61 MPa km⁻¹, so the fracturing pressure is 67.83 MPa. The high-pressure pump inlet pressure is taken as 1.4 MPa, and it is assumed here that there is no pressure increase during the process of the mixer entering the high-pressure pump.

The pipeline friction loss is calculated according to supplementary equation (8), (9), (10), and (11), where f is the friction factor of the steel pipe used in the fracturing process, L is the total well depth of 5 km, V is the injection velocity, ρ is the average density of the fracturing fluid at the bottom and surface of the well, and D is the pipe diameter.

The Reynolds number Re of the pipeline is calculated based on the dynamic viscosity μ , injection velocity V , pipe diameter D , and the average density ρ of the fracturing fluid at the bottom and surface of the well. Since the value is much greater than 4,000, the fluid is in a turbulent state, and the turbulent friction factor f needs to be calculated considering the pipe roughness¹⁷.

$$E = (V_f \cdot \Delta P) / (\eta_p \cdot \eta_M) \quad (6)$$

$$\Delta P = P_f - P_i + 2P_p - P_h \quad (7)$$

$$P_p = (fLV^2\rho)/(2D) \quad (8)$$

$$Re = VD\rho/\mu \quad (9)$$

$$S = 0.124(\varepsilon/D)Re \quad (10)$$

$$1/\sqrt{f} = 0.868 \ln(0.4587Re/S^{S/(S+1)}) \quad (11)$$

The CO₂ generated during the flow back and test production stages will be recovered and transported to other well pads for reuse. Due to the lack of field data on CO₂ fracturing in China, this study conservatively

estimates that a total of 70% of the injected CO₂ will return to the surface during the flow back, test production, and formal production stages¹⁶. Based on Wilkins' research, the CO₂ generated during the flow back and test production stages accounts for 12.4% of the injected CO₂¹⁶. In this study, the recovered and reused CO₂ is calculated based on this percentage.

The calculations indicate that capturing and compressing CO₂ consumes 23.67 million kWh of electrical energy, while the equipment used during CO₂ fracturing consumes 12.31 million kWh. Transporting CO₂ and sand requires 696.94 t of diesel, resulting in the storage of 66,494.39 t of CO₂ at a single well pad.

Production testing

During the production testing phase, it is necessary to test the functionality of several systems. According to the research by He et al., it is recommended to test 4–5 systems during the pilot production phase, with each system taking approximately 4–6 hours¹⁸. In this study, we assume that the production testing phase will involve testing 5 systems, which will take a total of 25 hours. The average shale gas production during this phase is estimated to be 121,000 (1.2–50.7×10⁴)m³ d⁻¹⁷. The shale gas will be burned with a combustion efficiency of 98% to reduce greenhouse gas emissions, and this phase will produce CO₂ and CH₄. The main components of shale gas in China are shown in Supplementary Table 12.

Based on these assumptions, using supplementary equation (12) and (13), it can be calculated that the CO₂ and CH₄ emissions during the production testing phase will be 1,445.5 t and 10.2 t, respectively. In the supplementary equations, Q_{CO2} represents the CO₂ production (kg), V_{gas} is the shale gas production during the production testing phase/m³, P_{CH4} and P_{CO2} represent the CH₄ content (98.023%) and CO₂ content (0.916%), respectively. D_{CH4} and D_{CO2} represent the density of CH₄ and CO₂ (0.717 kg m⁻³ and 1.964 kg m⁻³), R_C is the combustion efficiency of methane, and F_{CH4} is the emission factor for CH₄ combustion (2.75 kg CO₂e per kg CH₄).

Supplementary Table 12 The main components of shale gas

Gas	CH ₄	C ₂ H ₆	C ₃ H ₈	CO ₂	N ₂	He	H ₂
Proportion/%	98.023	0.47	0.031	0.916	0.469	0.036	0.051

$$Q_{CO2} = V_{gas} \times P_{CH4} \times D_{CH4} \times R_C \times F_{CH4} + V_{gas} \times P_{CO2} \times D_{CO2} \quad (12)$$

$$Q_{CH4} = V_{gas} \times P_{CH4} \times (1 - R_C) \times D_{CH4} \quad (13)$$

During the production testing phase, in addition to shale gas production, there is also a portion of flowback fluid that emerges. According to the research conducted by He et al., the flowback rate during the production testing phase ranges from 1.6% to 11.6%¹⁸. In this study, a flowback rate of 6.6% was adopted. Based on the research by Shi et al., over 90% of flowback water can be recycled. In this study, a recycling rate of 90% was assumed, resulting in a total recovery of 12,388.5 t of freshwater¹⁹.

Living water use during well completion

Assuming that the well completion stage takes 12 days and involves a total of 30 workers with a daily water consumption of 80 L per person and that the water is obtained from a distance of 5 km, this phase consumes a total of 28.80 t of freshwater and 2.90 kg of diesel.

4) Production stage

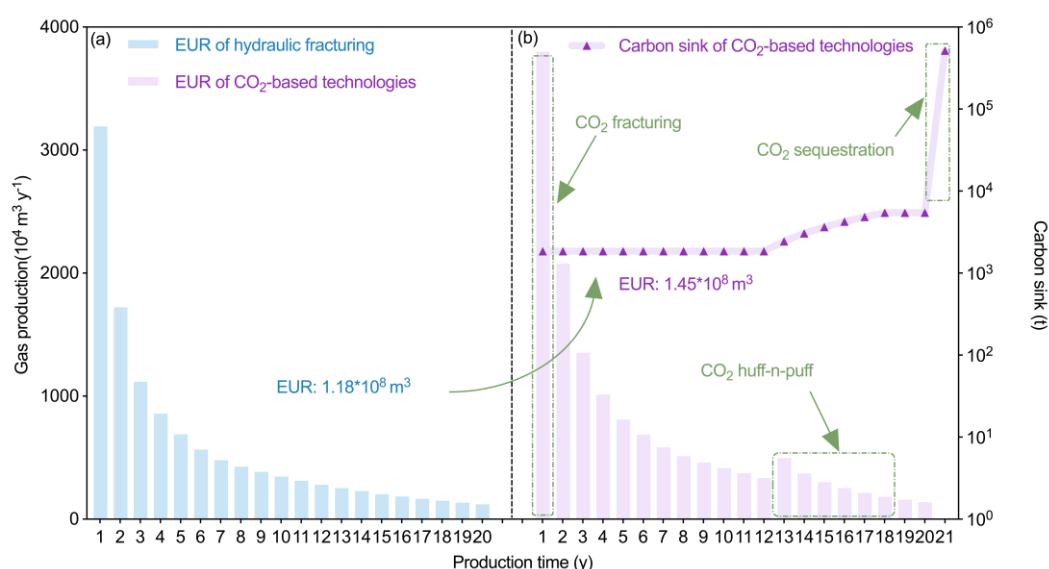
The Estimated Ultimate Recovery (EUR) of shale gas wells during the production stage varies due to the different technological methods. Subsequent research set up two scenarios: one applying conventional hydraulic fracturing and the other applying CO₂ fracturing combined with CO₂ huff-n-puff technology.

Production stage using hydraulic fracturing

The average EUR of shale gas wells developed using conventional hydraulic fracturing techniques over a 20-year life cycle is 118.1 million m³ in Sichuan Basin marine shale^{20,21}. During the production phase, as shale gas is extracted, flowback fluid continues to be brought to the surface. According to the investigation by Ni et al., 28% to 49% of the hydraulic fracturing fluid in the entire lifecycle of shale gas is converted into flowback and produced water²². Considering the flowback rate of 6.6% during the production testing phase, it is estimated that 31.9% of the produced water returns to the surface during the production stage. Of this amount, 90% will be recycled and reused. Therefore, during the production stage, it is expected that 59,877.58 t of freshwater and 6,653.06 t of wastewater are generated. The transportation of wastewater consumes approximately 2,678.96 kg of diesel.

Production stage using CO₂ fracturing and CO₂ huff-n-puff

In this study, the CO₂ fracturing and CO₂ huff-n-puff technique will be used to increase the EUR. Specific annual production and related information can be found in Supplementary Fig. 6. The calculations indicate that capturing and compressing CO₂ consumes 4.75 million kWh of electrical energy, while the equipment used during CO₂ fracturing consumes 3.00 million kWh. Transporting CO₂ requires 134.38 t of diesel, resulting in the storage of 22,248.00 t CO₂ at a single well pad.



Supplementary Fig. 6 Estimated ultimate recovery (EUR) and carbon sink of shale gas wells applying different CO₂-based techniques in Sichuan Basin marine shale. (a) hydraulic fracturing (b) CO₂-based techniques, including CO₂ fracturing, CO₂ huff-n-puff and CO₂ sequestration.

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

6) CO₂ sequestration

Shale gas reservoirs have significant potential for large-scale carbon dioxide storage. After the depletion of shale gas wells, the storage of carbon dioxide at the well bottom can offset the methane and CO₂ emissions over the entire life cycle of the shale gas supply chain, thereby reducing the carbon footprint of shale gas and achieving net zero or even negative emissions for the shale gas supply chain. The storage mechanisms for shale gas wells primarily include structural storage, adsorption storage, and mineralization storage.

Supplementary Note 2. Climate change model

In this study, global temperature change is used to assess the time-cumulative impact of historical shale gas activities on China's climate. Additionally, the impacts of shale gas activities are monetized based on the social costs of carbon and methane.

First, 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. Due to the lack of data on the consumption proportions of shale gas in different downstream consumption scenarios, this study used China's natural gas consumption data from 2012—2023 to calculate these proportions. Supplementary Table 14 shows the emission factors for different shale gas production activities, where EF_{CO₂,P}, EF_{CO₂,T}, EF_{CO₂,C}, EF_{CO₂,I}, EF_{CO₂,Hh}, EF_{CO₂,V}, EF_{CO₂,H} and EF_{CO₂,O} are the carbon emission factors for production, transportation and distribution, chemical, industrial, power and heat, transportation, household, and other sectors, respectively.

Supplementary Table 14 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
EF _{CO₂,P}	83.02(61.88–82.85)	33.4828	1.14	This research
EF _{CO₂,T}	576.179(358.17–868.16)	403.325	5.08	25
EF _{CO₂,V}	2,414.808(2,281.73–2,547.89)	1,971.2	13.05	26
EF _{CO₂,C}	4,412.05(3,679.80–5,144.30)	1,971.2	71.79	27
EF _{CO₂,I} , EF _{CO₂,Hh} , EF _{CO₂,H} , EF _{CO₂,O}	2,184.029(2,120.18–2,247.88)	1,971.2	6.26	28

The rise in greenhouse gas concentrations in the atmosphere leads to an increase in radiative forcing, which in turn causes a rise in the global average surface temperature. In assessing the time-cumulative impact of shale gas activities on climate, we use the indicator of global average surface temperature response (ΔT). The relationship between the ΔT and the sustained radiative forcing (RF) is generally:

$$\Delta T = \lambda \cdot \text{RF} \quad (14)$$

Where λ is the climate sensitivity parameter, and the unit of RF is W m⁻². It is worth noting that RF does not include climate effects unrelated to radiative forcing, such as changes in surface albedo due to changes in vegetation cover, and changes in solar activity. The explicit form of the relationship between the two is further provided:

$$\Delta T(t) = \sum_i \int_0^t E_i(s) \text{AGTP}_i(t-s) ds \quad (15)$$

Where $E_i(s)$ are different emission scenarios, which have been described earlier in this study, s corresponds to the emission pulse time, and t corresponds to the response time. AGTP is the global average temperature potential, which is the temperature change at time t caused by the emission of 1 kg at time $t=0$, with units of K kg⁻¹. The expression for AGTP is:

$$\text{AGTP}_i(t) = \int_0^t \text{RF}_i(s) \text{R}_T(t-s) ds \quad (16)$$

Where RF_i is the radiative forcing caused by the emission pulse, and R_T is the temperature response per unit radiative forcing. The specific expressions for RF_i and R_T will be provided later.

$$RF_i = A_i \cdot \exp(-t/\tau_i) \quad (17)$$

$$R_T(t) = \sum_{j=1}^M \frac{c_j}{d_j} \exp(-t/d_j) \quad (18)$$

Where A_i is the radiative forcing per unit increase in atmospheric concentration, and τ is the perturbation lifetime of the gas in the atmosphere. C_j is the climate sensitivity parameter, and d_j is the response time parameter for all terms $j = 1, \dots, M$. The absolute global temperature potentials for methane and carbon dioxide are:

$$AGTP_{CH_4}(t) = (1 + f_1 + f_2) \cdot A_{CH_4} \sum_{j=1}^2 \tau_{CH_4} c_j / (\tau_{CH_4} - d_j) [\exp(-t/\tau_{CH_4}) - \exp(-t/d_j)] \quad (19)$$

$$AGTP_{CO_2}(t) = A_{CO_2} \sum_{j=1}^2 \left\{ a_0 c_j \left[1 - \exp\left(\frac{-t}{d_j}\right) \right] + \sum_{k=1}^3 \alpha_k \tau_{CO_2,k} c_j / (\tau_{CO_2,k} - d_j) \left[\exp\left(\frac{-t}{\tau_{CO_2,k}}\right) - \exp\left(\frac{-t}{d_j}\right) \right] \right\} \quad (20)$$

The radiative efficiency of carbon dioxide is given by supplementary equation (21), where α is the radiative transfer coefficient, $C_{0,t}$ is the reference CO_2 concentration, and ΔC is the change in reference concentration. The CO_2 concentrations for 2012–2023 are from the observed global atmospheric CO_2 concentrations reported by the US National Oceanic and Atmospheric Administration (NOAA), and the CO_2 concentrations for 2023–2112 are from the IPCC RCP SSP2-Baseline baseline scenario^{29,30}.

$$A_{CO_2} = \alpha [\log(C_{0,t} + \Delta C) / \Delta C] \quad (21)$$

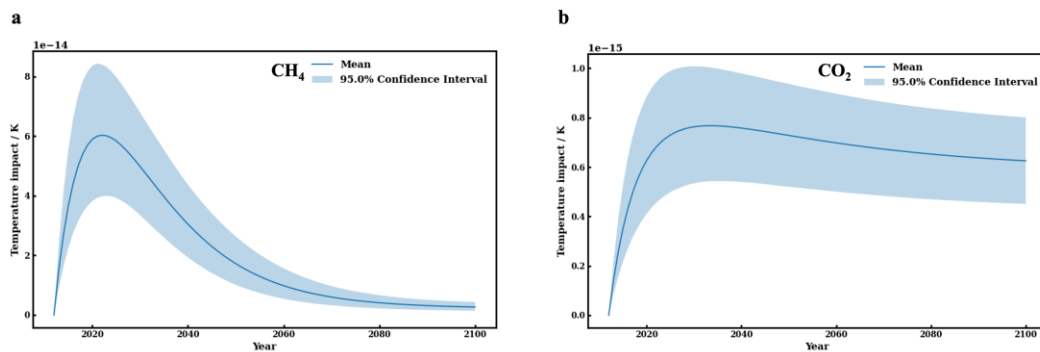
The parameters in the above equations are detailed in Supplementary Table 15, including the definition, distribution, and source of each parameter. We used Monte Carlo simulation to simulate 10,000 realizations for the AGTP functions per kg of CH_4 and CO_2 pulse, the results of which are shown in Supplementary Fig. 7, displaying the mean AGTP and the 95% confidence interval.

Supplementary Table 15 The input parameters, definitions, values, units, and sources in the climate impact model

Parameters	Definitions	Values / Distributions*	Units	Sources
A_{CH_4}	radiative efficiency of CH_4	1.3×10^{-13}	$W \cdot m^{-2} \cdot kg^{-1}$	31
α	radiative transfer coefficient	5.35	$W \cdot m^{-2}$	32
α_k	fraction of CO_2 remaining in the atmosphere after a pulse	k = 0: 0.2173	-	33
		k = 1: 0.2240		
		k = 2: 0.2824		
		k = 3: 0.2763		
$C_{0,t}$	reference mean atmospheric CO_2 concentration	time-varying	ppm _v	29
c_j	climate sensitivity parameters	j = 1: Uniform (0.631±0.2)	$K \cdot W^{-1} \cdot m^{-2}$	34,35
		j = 2: Uniform (0.429±0.18)		
d_j	response time parameters	j = 1: Uniform (8.4±30%)	years	34,35
		j = 2: Uniform (409.5±30%)		
f_1	ozone effect on CH_4 radiative forcing	Normal(0.5, 0.05)	-	32,35,36

f_2	stratospheric water effect on CH ₄ radiative forcing	Normal(0.15, 0.05)	-	35,36
τ_{CH_4}	CH ₄ perturbation lifetime	Normal(12.4, 1)	years	34,35
$\tau_{CO_2,k}$	CO ₂ perturbation lifetime for each term	$\tau_{k=1} = 394.4$	years	33
		$\tau_{k=2} = 36.54$		
		$\tau_{k=3} = 4.304$		

*Uniform distribution is expressed as Uniform (base value $\pm$ error term), where the minimum value is the base value minus the error term and the maximum value is the base value plus the error term. Normal distribution is expressed as Normal (mean, standard deviation).



Supplementary Fig. 7 Absolute global temperature potential from 2012 to 2100 for 1-kg pulses in years 2012 to 2023. (a) CH₄ (b) CO₂. The solid blue line is based on the mean, and the shaded areas are the upper and lower limits based on the 95% confidence intervals.

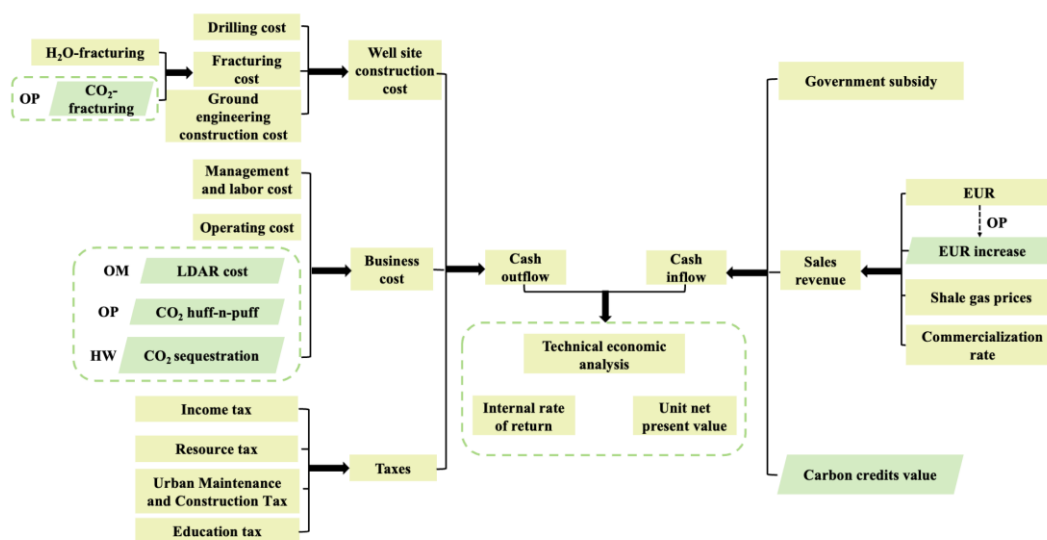
Supplementary Table 16 shows the social costs of CO₂ and CH₄(SCC and SCM), for the years 2012–2023, where 5%, 3% and 2.5% reflect the estimated social costs at the three discount rates, while High Impact (95th Pct at 3%) is the 95th percentile estimate at a 3% discount rate.

Supplementary Table 16 Annual SCC and SCM Values: 2012–2023 (2007 US\$ per t CO₂)

Year	Annual SCC Values				Annual SCM Values			
	5% Average	3% Average	2.5% Average	High Impact (95 th Pct at 3%)	5% Average	3% Average	2.5% Average	High Impact (95 th Pct at 3%)
2012	11	33	53	93	400	940	1300	2600
2013	11	34	54	97	420	970	1300	2700
2014	11	35	55	101	440	1000	1300	2700
2015	11	36	56	105	450	1000	1400	2800
2016	11	38	57	108	470	1100	1400	2900
2017	11	39	59	112	490	1100	1500	3000
2018	12	40	60	116	510	1100	1500	3000
2019	12	41	61	120	520	1200	1500	3100
2020	12	42	62	123	540	1200	1600	3200
2021	12	42	63	126	560	1200	1600	3300
2022	13	43	64	129	590	1300	1700	3400
2023	13	44	65	132	610	1300	1700	3500

Supplementary Note 3. Economic Parameter Estimation for Shale Gas Development

In the investment return analysis of shale gas well pads, the evaluation of investment costs and revenues is a key component. Investment costs primarily include construction investment, operating costs, and other related expenses, all of which directly impact the project's economic viability. Construction investment covers expenses for surface engineering, drilling, and fracturing, while operating costs involve daily operations, labour, and maintenance expenditures. Additionally, other costs, such as taxes, should not be overlooked. Revenue analysis mainly includes shale gas sales and government subsidies, requiring careful assessment of the EUR and sales price of shale gas to accurately predict the project's economic benefits. By conducting a comprehensive analysis of investment costs and revenues, the technical and economic feasibility of different scenarios in various shale gas reservoirs can be clarified.



Supplementary Fig. 8 Economic analysis of shale gas projects under multiple scenarios. The economic evaluation system is based on cash flow analysis, where cash inflows primarily consist of government subsidies, sales revenue, future carbon credit income, and additional revenue from production enhancement through CO₂ treatments. Cash outflows mainly include expenditures for well pad construction, business costs, and taxes, with additional expenses arising under different scenarios.

1) Construction investment

Surface facility engineering costs

The surface facility engineering includes road construction, the development of auxiliary facilities, and the establishment of shale gas storage and processing equipment. Since many of China's shale gas reservoirs are in the mountainous regions of the west, construction costs are higher, typically accounting for about 9% of the total construction investment³⁷. In this study, the cost of surface facility engineering is set at 9.1% of the drilling and completion costs.

The cost of drilling

Drilling costs include vertical well cost and horizontal well cost. Vertical drilling refers to drilling vertically down to the target formation, while horizontal drilling extends horizontally within the target formation

based on vertical drilling, allowing for contact with a larger area of the reservoir and thereby increasing recovery rates. In this study, the calculation of total drilling investment costs is represented by supplementary equation (22),

$$I_{drilling} = I_{vertical} + I_{horizontal} \quad (22)$$

where $I_{vertical}$ represents the cost of vertical drilling, and $I_{horizontal}$ represents the cost of horizontal drilling. The $I_{vertical}$, estimated using the footage method, is as follows:

$$I_{vertical} = C_{vertical} \times L_{vertical} \quad (23)$$

where $C_{vertical}$ represents the unit cost of vertical drilling, set at US\$780 per m. $L_{vertical}$ denotes the length of the vertical well. Due to variations in the burial depth of shale gas resources in different regions, the depth of vertical wells differs.

Horizontal drilling involves higher technical complexity, is more challenging to operate, and requires a larger investment. Directly using the calculation method for vertical wells may lead to significant estimation errors. To estimate the investment more accurately in horizontal wells, this study will utilize data from several wells in the Fuling shale gas block and apply regression methods to estimate the costs. The formula for calculating costs is as follows:

$$I_{horizontal} = a_0 + a_1 \cdot L_{horizontal} + a_2 \cdot L_{horizontal}^2 \quad (24)$$

where $L_{horizontal}$ represents the horizontal length in meters, while a_0 , a_1 , and a_2 are constants, with values of 359.58, 0.2102, and 0.00049, respectively³⁷.

The cost of fracturing

Hydraulic fracturing costs include expenses for fracturing fluids, proppants, fracturing engineering service fees, and fracturing equipment rental fees, among others. These costs can be difficult to obtain, but hydraulic fracturing costs can be determined by factors such as fracturing scale and the number of fracturing stages. The fracturing cost is calculated based on the number of stages and the unit cost per stage, with the unit cost in China being US\$0.2 million per stage³⁸. The calculation of fracturing cost is given by supplementary equation (25), where n_{stage} represents the number of fracturing stages and C_{cost} is the unit cost per fracturing stage.

$$I_{fracturing} = n_{stage} \cdot C_{cost} \quad (25)$$

2) Business cost

The production phase of shale gas is accompanied by the generation of business costs, which mainly include operating costs and management and labor expenses. Operating costs refer to the costs incurred for the operation, maintenance, and production of related facilities for shale gas wells. The calculation of operating costs is expressed by supplementary equation (26), where $C_{operation}$ represents the operating costs, with the operating cost for shale gas projects in China being US\$0.026 m⁻³; C_{manage} represents management and labor expenses, calculated at 0.5% of sales revenue.

$$C_{business} = C_{operation} + C_{manage} \quad (26)$$

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 supplementary equation (27). 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.

$$\text{EUR} = 0.08279 \cdot \text{IP} + 0.06367 \quad (27)$$

4) Estimation of shale gas wellhead price

The price of shale gas is a key parameter for shale gas development projects and has a significant impact on sales revenue. Due to China's energy price regulation policy, the benchmark price for shale gas is set by the government, resulting in relatively stable prices. In China, natural gas is categorized into wellhead prices and city gate prices. In this study, the shale gas price is based on the wellhead price, which is set at US\$0.27 m^{-3} ³⁹.

5) Shale gas development subsidy

China's shale gas subsidy standards can be divided into three phases. The first two phases involve fixed subsidies: US\$0.056 m^{-3} from 2012 to 2015 and US\$0.042 m^{-3} from 2016 to 2018^{40,41}. Starting in 2019, China eliminated fixed subsidies and transitioned to a “more production, more subsidy; winter production, winter subsidy” approach⁴². In comparison to the fixed subsidy standards in the United States, China's subsidy standard has shifted to a non-fixed model, resulting in a dramatic decline. In this study, the calculation of subsidy income is represented by supplementary equation (28), where S_{SG} denotes the subsidy income in US\$, Q_{output} represents shale gas production in m^3 , f is the shale gas commercialization rate at 96%, and S_{subsidy} is the subsidy standard at US\$0.013 m^{-3} ⁴³.

$$S_{SG} = Q_{\text{output}} \cdot f \cdot S_{\text{subsidy}} \quad (28)$$

6) Tax Cost

The taxes payable for shale gas development primarily include the following types: Value-Added Tax (VAT), Income Tax, Resource Tax, Urban and Rural Construction Maintenance Tax, and Education Surcharge⁴⁴. VAT is a tax levied on the value added at each stage of production, circulation, and service provision. While the calculation of VAT does not directly affect the economic viability of shale gas development, the amount of VAT payable serves as a basis for calculating other tax liabilities. The applicable VAT rate for shale gas is 8.5%, and its calculation formula is represented by supplementary equation (29), where t_{VAT} denotes the VAT rate.

$$T_{\text{VAT}} = Q_{\text{output}} \cdot (P_{SG} + S_{SG}) \cdot f \cdot t_{\text{VAT}} \quad (29)$$

Income tax is a tax levied on the taxpayer's income. As shale gas is a specific project supported and encouraged by the state, it is subject to a uniform tax rate of 15%. The calculation formula is represented by supplementary equation (30), where t_{IT} denotes the income tax rate.

$$T_{IT} = (Q_{output} \cdot (P_{SG} + S_{SG}) \cdot f - C_{operation}) \cdot t_{IT} \quad (30)$$

Resource tax is a tax levied to adjust resource rent income, promote the rational development of resources, enhance economic accounting, and improve economic efficiency. Its calculation method is represented by supplementary equation (31), where t_R denotes the resource tax rate for shale gas in China, which is 4.2%.

$$T_R = Q_{output} \cdot (P_{SG} + S_{SG}) \cdot f \cdot t_R \quad (31)$$

The Urban maintenance and construction tax and the education tax are based on the VAT as the tax base. Their calculation formulas are as follows, where t_{UC} is the Urban Maintenance and Construction Tax rate of 7%, and t_E is the Education Surcharge rate of 3%.

$$T_{UC} = T_{VAT} \cdot t_{UC} \quad (32)$$

$$T_E = T_{VAT} \cdot t_E \quad (33)$$

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 Supplementary Tables 5 and 6.

Supplementary Table 17 The electricity prices in different regions

Regions	Electricity prices (US\$ kWh ⁻¹)
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 Note 4. The Trade-off Between Emission Reduction and Economic Performance

Formulating deep emission reduction pathways for the shale gas supply chain requires consideration of the abatement effectiveness and economic feasibility across different scenarios. Supplementary Table S18 summarizes the economic-environmental trade-offs and optimal application contexts for various mitigation strategies under each scenario.

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 -2158.5kg 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 (3186.4–3307.3kg CO ₂ e m ⁻³)	Established economics but declining competitiveness under carbon constraints	Marine shale (Sichuan Basin)

Supplementary Note 5. 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 19.

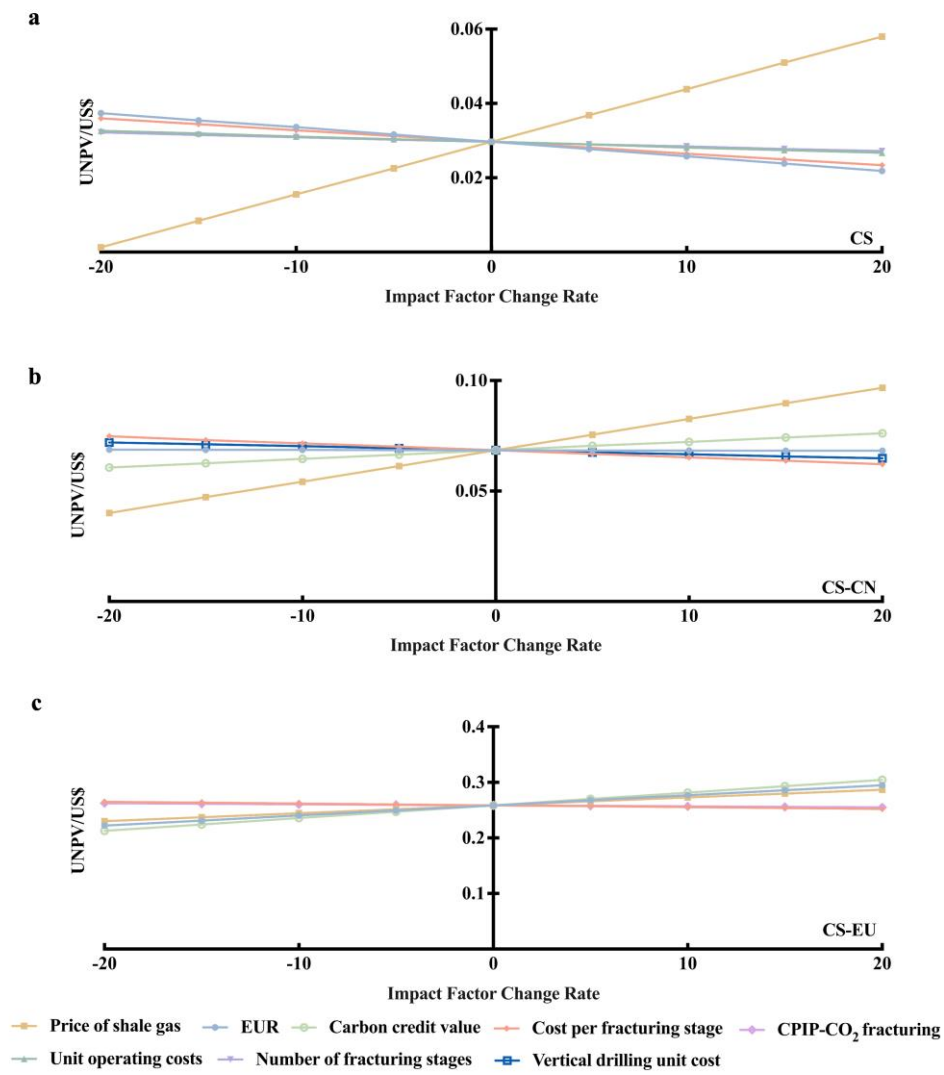
In our uncertainty analysis, we employed marine shale data from Sichuan Basin as a case study in Supplementary Fig. 9. Under the CS scenario without carbon credit revenue, the UNPV is estimated at US\$0.030 m⁻³ (0.006–0.050, 95% CI). Key drivers of UNPV include shale gas price, EUR, cost per fracturing 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 US\$0.259 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 19 Key parameter settings for uncertainty analysis

Inputs	Units	Distributions	Parameters		
EUR	m ³	Normal	EUR	0.1EUR	
EF _{CO2,T}	gCO ₂ -eq m ⁻³	Triangular	518.56	576.18	633.80
EF _{CO2,U} (weighting of downstream)			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 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.

Supplementary References

1. Nie, H. *et al.* An overview of the geology and production of the Fuling shale gas field, Sichuan Basin, China. *Energy Geosci.* **1**, 147–164 (2020).
2. Li, S. *et al.* Distribution characteristics, exploration and development, geological theories research progress and exploration directions of shale gas in China. *China Geol.* **5**, 110–135 (2022).
3. Zhang J. *et al.* Fields and directions for shale gas exploration in China. *Nat. Gas Ind. B* **9**, 20–32 (2022).
4. Sun, C. *et al.* Shale Gas Exploration and Development in China: Current Status, Geological Challenges, and Future Directions. *Energy Fuels* **35**, 6359–6379 (2021).
5. National bureau of statistics. Total natural gas consumption by sector. *National data* <https://data.stats.gov.cn/easyquery.htm?cn=C01> (2024).
6. Announcement by the Ministry of Ecology and Environment and the National Bureau of Statistics on the release of carbon dioxide emission factors for electricity in 2021. *Ministry of Ecological Environment of the People's Republic of China* https://www.mee.gov.cn/xxgk2018/xxgk/xxgk01/202404/t20240412_1070565.html (2024).
7. Wang, J., Liu, M., McLellan, B. C., Tang, X. & Feng, L. Environmental impacts of shale gas development in China: A hybrid life cycle analysis. *Resour. Conserv. Recycl.* **120**, 38–45 (2017).
8. Chang, Y., Huang, R., Ries, R. J. & Masanet, E. Shale-to-well energy use and air pollutant emissions of shale gas production in China. *Appl. Energy* **125**, 147–157 (2014).
9. Shi, W. *et al.* Water use for shale gas development in China's Fuling shale gas field. *J. Clean. Prod.* **256**, 120680 (2020).
10. Jiang, M. *et al.* Life cycle greenhouse gas emissions of Marcellus shale gas. *Environ. Res. Lett.* **6**, 034014 (2011).
11. liu, li, Yu, X., Zhang, L. & Zhu, N. Water resources risk study for shale gas exploration and development. *Energy Conserv* 31–33 (2023).
12. Shi, W. *et al.* Water use for shale gas development in China's Fuling shale gas field. *J. Clean. Prod.* **256**, 120680 (2020).
13. Ren, Y., Qian, B., Zhang, J. & Qiao, L. Practice and understanding of industrial fracturing for shale gas of Longmaxi Formation in Changning region. *Oil Drill. Prod. Technol.* **37**, 96–99 (2015).
14. Shao, M., Xu, W., Guo, Y. & Zhu, T. CO₂ source-sink matching study between shale gas reservoirs and anhydrous fracturing media. *Clean Coal Technol.* **22**, 116–122 (2016).
15. Damen, K. Reforming fossil fuel use the merits, costs and risks of carbon dioxide capture and storage. (Utrecht University, 2007).
16. 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).
17. Sonnad Jagadeesh R. & Goudar Chetan T. Turbulent flow friction factor calculation using a mathematically exact alternative to the Colebrook–White equation. *J. Hydraul. Eng.* **132**, 863–867 (2006).
18. He, X. Optimization and Application of Production—Oriented Shale Gas Testing Technology in Fuling. *J. Jiangnan Pet. Univ. Staff Work.* **27**, 4 (2014).
19. Shi, W. *et al.* Water use for shale gas development in China's Fuling shale gas field. *J. Clean. Prod.* **256**, 120680 (2020).
20. Shi, J. *et al.* Impact of different production evaluation cycles on investment returns of shale gas projects. *Sino-Glob. Energy* **26**, 36–42 (2021).
21. Jiang, X., Sun, Q., Zhao, Q. & Wang, T. Production characteristics and economic benefit classification methods of shale gas wells in south sichuan province. *Sino-Glob. Energy* **26**, 43–50 (2021).

22. Ni, Y. *et al.* Origin of flowback and produced waters from Sichuan basin, China. *Environ. Sci. Technol.* **52**, 14519–14527 (2018).
23. Chen, G. *et al.* An improved method for estimating GHG emissions from onshore oil and gas exploration and development in China. *Sci. Total Environ.* **574**, 707–715 (2017).
24. O’Sullivan, F. & Paltsev, S. Shale gas production: potential versus actual greenhouse gas emissions. *Environ. Res. Lett.* **7**, 44030 (2012).
25. 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).
26. 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).
27. Zhang, Y. *et al.* Life cycle assessment of ammonia synthesis in China. *Int. J. Life Cycle Assess.* **27**, 50–61 (2022).
28. 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).
29. Lan, X., Tans, P. & Thoning, K. W. Trends in globally-averaged CO₂ determined from NOAA Global Monitoring Laboratory measurements. <https://doi.org/10.15138/9N0H-ZH07> (2023).
30. Riahi, K. *et al.* The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Change* **42**, 153–168 (2017).
31. Shine, K. P., Fuglestvedt, J. S., Hailemariam, K. & Stuber, N. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Clim. Change* **68**, 281–302 (2005).
32. Myhre, G. *et al.* Anthropogenic and natural radiative forcing. in *Climate Change 2013: The Physical Science Basis* (Cambridge University Press, 2013).
33. Joos, F. *et al.* Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chem. Phys.* **13**, 2793–2825 (2013).
34. Boucher, O. & Reddy, M. S. Climate trade-off between black carbon and carbon dioxide emissions. *Energy Policy* **36**, 193–200 (2008).
35. Boucher, O. Comparison of physically- and economically-based CO₂-equivalences for methane. *Earth Syst. Dyn.* **3**, 49–61 (2012).
36. Collins, W. J. *et al.* Global and regional temperature-change potentials for near-term climate forcers. *Atmospheric Chem. Phys.* **13**, 2471–2485 (2013).
37. Yuan, B. Research on investment and financial risk issues of shale gas development--taking a shale gas block in China as an example. (China University of Petroleum (Beijing), 2018).
38. Peng, F. Shale gas fracturing project cost control example study. *Bus. Manag.* **26**, (2014).
39. Natural gas spot prices. *Chongqing Petroleum and Gas Exchange* <https://www.chinacqpgx.com/jgzs> (2024).
40. Liu, J. *et al.* Subsidy analysis and development trend forecast of China’s unconventional natural gas under the new unconventional gas subsidy policy. *Energy Policy* **153**, 112253 (2021).
41. Li, Y., Li, Y., Wang, B., Chen, Z. & Nie, D. The status quo review and suggested policies for shale gas development in China. *Renew. Sustain. Energy Rev.* **59**, 420–428 (2016).
42. Ministry of Finance. *Notice on the Issuance of the Interim Measures for the Management of Special Funds for Clean Energy Development.* (2020).
43. Ma X. A compendium and comparative study of shale gas support policies in China and the U.S. *Technol. Econ. Petrochem.* **39**, 1–5, 35 (2023).
44. Xia, L. & Luo, D. A method for calculating economic critical depth of shale gas resources in China via break-even analysis. *J. Nat. Gas Sci. Eng.* **21**, 1091–1098 (2014).