Economic Evaluation of CCUS projects

CO_2捕集、利用与地质封存的经济评价

Ning Wei 魏宁
Institute of Rock and Soil Mechanics,
Chinese Academy of Sciences

Economic Evaluation of CCUS projects

- **Aims of this presentation is to show: 本报告目的：**
- **How to calculate the cost of CCUS technologies**
- ✓ **如何计算CCUS成本**
- **The cost range of CCUS technologies**
- ✓ **CCUS成本范围**
- **how economics can be used to decrease the total cost and make decisions for CCS deployment - several type of early opportunities for CCS deployment**
- ✓ **经济评价如何降低成本与支撑CCUS示范决策-几种早期实施机遇**

CCUS = CO_2 capture, geological utilization and geological storage

Outline

- **Introduction of CCUS**
- ✓ CO_2捕集、地质利用与封存介绍
- **Methodology of economic evaluation**
- ✓ 经济评估方法学
- **Application of economic evaluation**
- ✓ 经济评价的应用

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Introduction of CGS

CCUS system

CO_2 capture+ compression +transportation (pipeline) + geological utilization and storage (CO_2-EOR +Aquifer storage)

CO_2捕集+ 压缩 +管道运输 + 地质利用与封存

CGS = CO_2 geological utilization and storage or CO_2 geological storage

- **CO_2 capture 捕集 5~115US$/t**
- **Dehydration and compression 脱水与压缩 ~10US$/t**
- **CO_2 pipeline transportation 管道输送 1~8US$/t**
- **Aquifer Storage 咸水层 1~10US$/t**
- **EOR cost 20~100US$/bbl**
- **MMV 监测 0.1~0.3US$/t**
- **Revenue from production sales 收益 oil 80~160 US$/bbl**

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Methodology of Economic Evaluation

CCUS economic evaluation - model for different components

➢**Technical-economic model** includes two major parts:经济技术模型主要包含两个部分：

- **Performance model 技术模型**(Equipment, operation and production curve, 设备、建设、人力、运行与维护、生产曲线； can be obtained by empirical, semi-analysis, numerical simulation, and field data，生产曲线可由经验、分析、数值模拟和现场运行资料获取)
- **Economic model 经济模型** (empirical, budget, and financial account， 经验、预算、决算)

The performance model and economic model are decided by the phase of CCUS projects and the purpose of economic evaluation 经济技术模型具体的筛选由CCUS工程的阶段和经济评价的目的决定。

Methodology of Economic Evaluation

The schedule of CCUS projects

Identify candidate sites → Characterize and evaluate site → Prepare site → Operate site → Close site → Post closure →

★Screening/Characterization（2~5years）
-Site Screening
-Exploration Permit
-Site Characterization
-Site Selection
-Project plan and primary design

★Operation phase(20~50y)
-Storage Permission
-Site Design and Construction
-Site Preparation
-Injection/Post-injection
-Monitoring & Evaluation
-Environmental Evaluation

★Phase-Closure/Post-Closure(500~1000y）
- Site Closure Permit
-Decommissioning
-Site Closure Certificate
-Transfer of Liability
-Long-term monitoring and managing

The different stages will use different economic evaluation methodology.
项目不同阶段采用不同的经济分析方法;

Methodology of Economic Evaluation

CCUS economic model- technical components

➢ Economic model for CCUS includes

- CO_2 capture; CO_2 捕集
- CO_2 dehydration and compression; 脱水与压缩
- CO_2 pipeline transportation; 管道输送
- CO_2 utilization and storage: **CO_2-EOR; CO_2 aquifer storage;** CO_2-ECBM, CO_2-EGR, and other geological utilization options; CO_2地质利用与封存：**CO_2增采石油；咸水层封存**、驱替煤层气、增采天然气和其他地质利用类型。



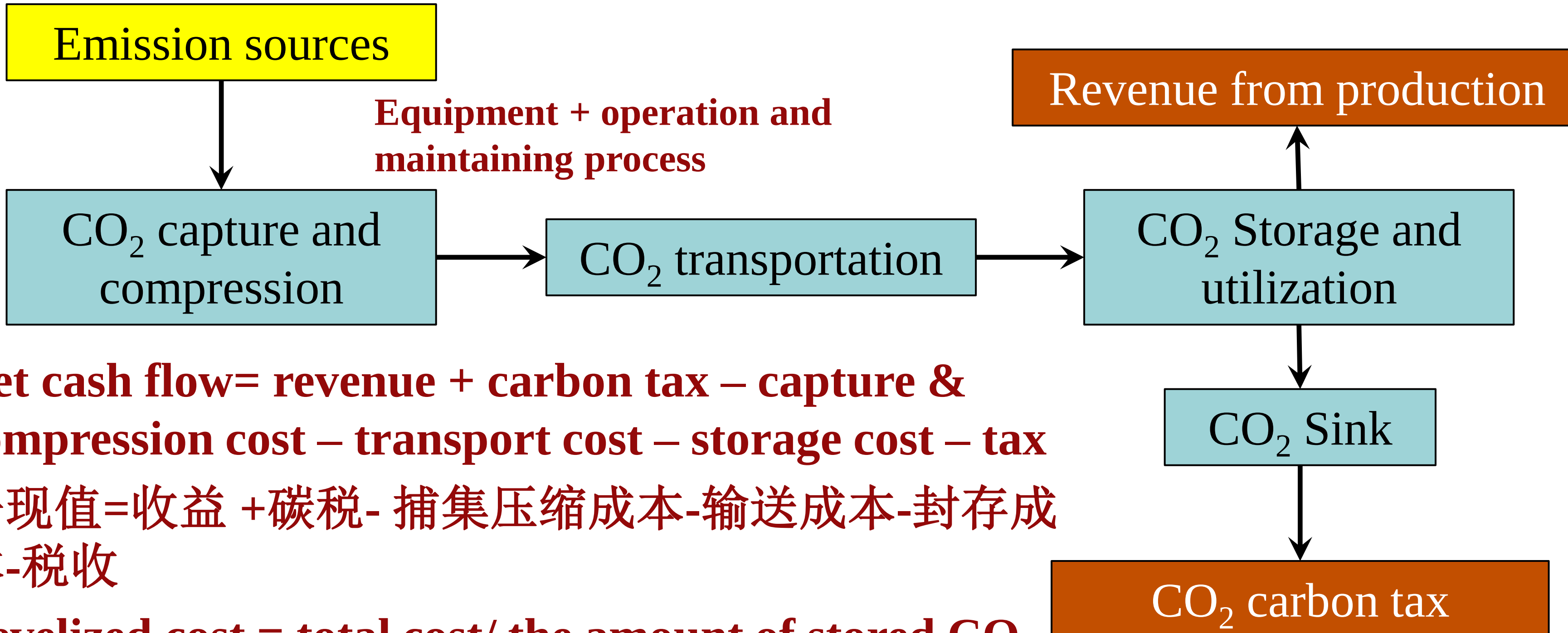

Methodology of Economic Evaluation

Performance model

- Most of the literature has analyses that show economics without projecting cash flow.
- Projecting cash flow allows revenues and costs to change over time
- The effect of tax, inflation and other costs can be changed over time
- 考虑收益、成本、税收、通货膨胀等随时间的变化关系。

Methodology of Economic Evaluation

Main framework of technical-economic model



Net cash flow= revenue + carbon tax – capture & compression cost – transport cost – storage cost – tax

净现值=收益 +碳税- 捕集压缩成本-输送成本-封存成本-税收

Levelized cost = total cost/ the amount of stored CO_2 [$/t]

平准化成本= 总成本/ 封存量 [$/t]

Methodology of Economic Evaluation

- **Net Present Value (NPV) 净现值**

Cash flow is the cash received less the cash spent over lifetime of CCS project. 现金流为收益减成本

$$NPV = \sum_{t=1}^{T} (C^t_{production} + Tax^t_C - Cost^t - Tax^t_{annual})/(1+r)^t$$

- The levelized cost

$$Cost_{Lev} = \sum_{t=1}^{T} Cost^t / M_{CO2}$$

$$Income_{Lev} = NPV / M_{oil}$$

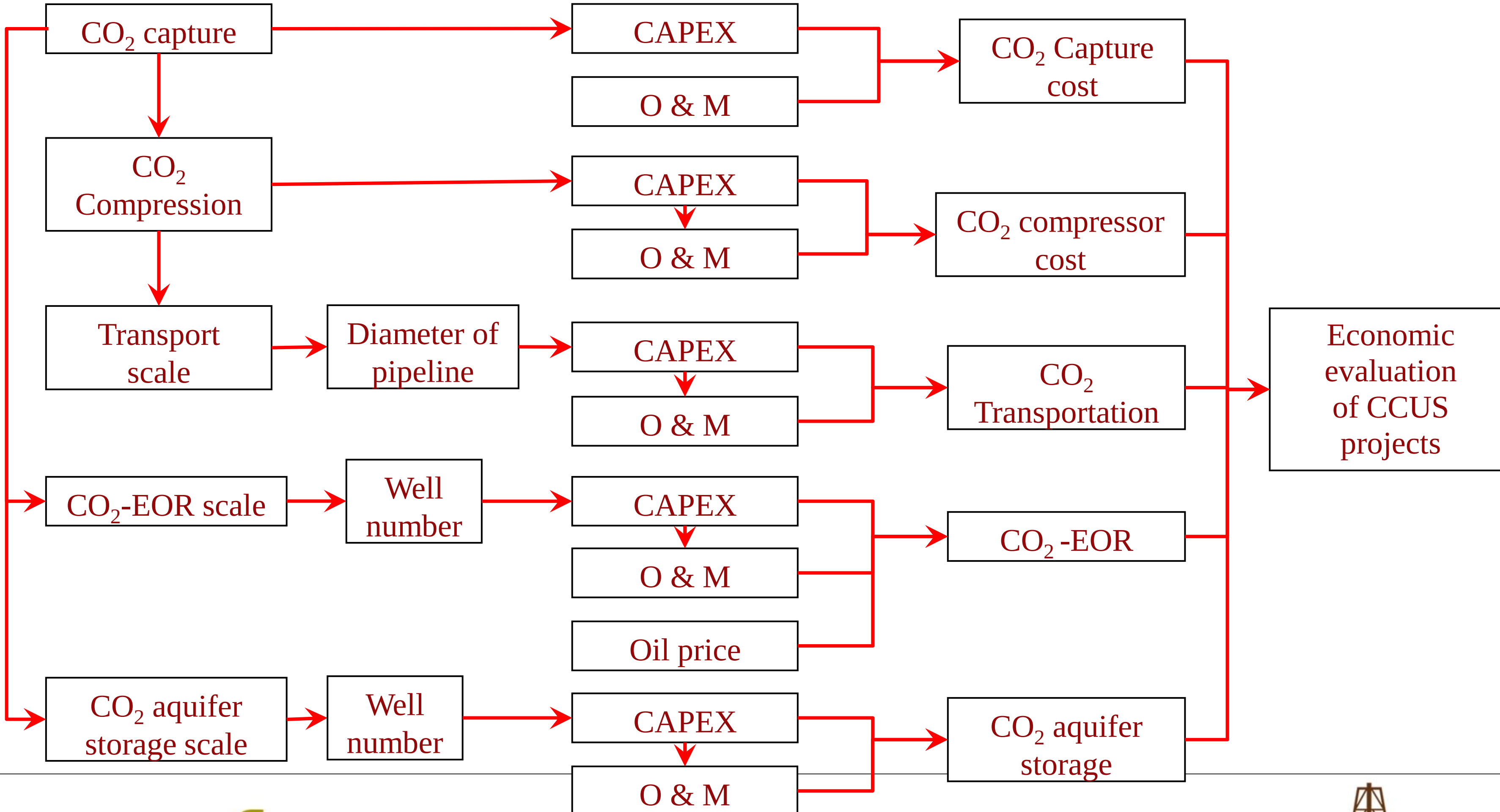
Methodology of Economic Evaluation

- Economic model 经济模型

1. CAPEX and OPEX
   - ✓ 固定投入与运行维护费用
2. Revenue from production
   - ✓ 产品收益
3. Tax policy
   - ✓ 税收政策
4. Net present value or levelized value
   - ✓ 净现值或平准化成本

Methodology of Economic Evaluation

Main framework of economic



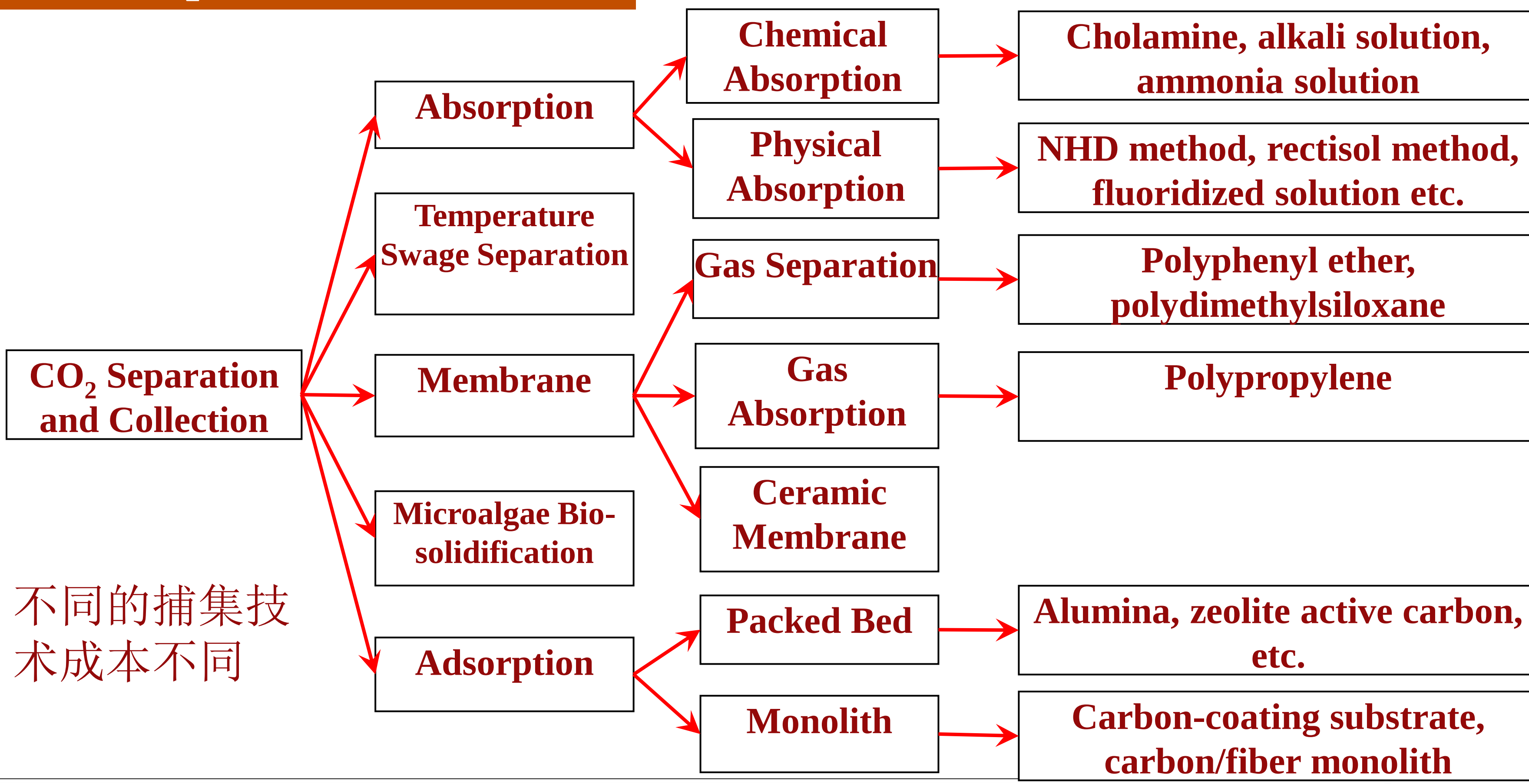
China Australia Geological Storage of CO_2

中澳二氧化碳地质封存

Refer to all kind of economic model around world.

Methodology of Economic Evaluation

Different CO_2 capture technologies



不同的捕集技术成本不同

Economic model of CCUS

CO_2 capture model

CAPEX

$$C_i = C_{i,ref} \cdot \left(\frac{X_i}{X_{i,ref}} \right)^a$$

O&M cost

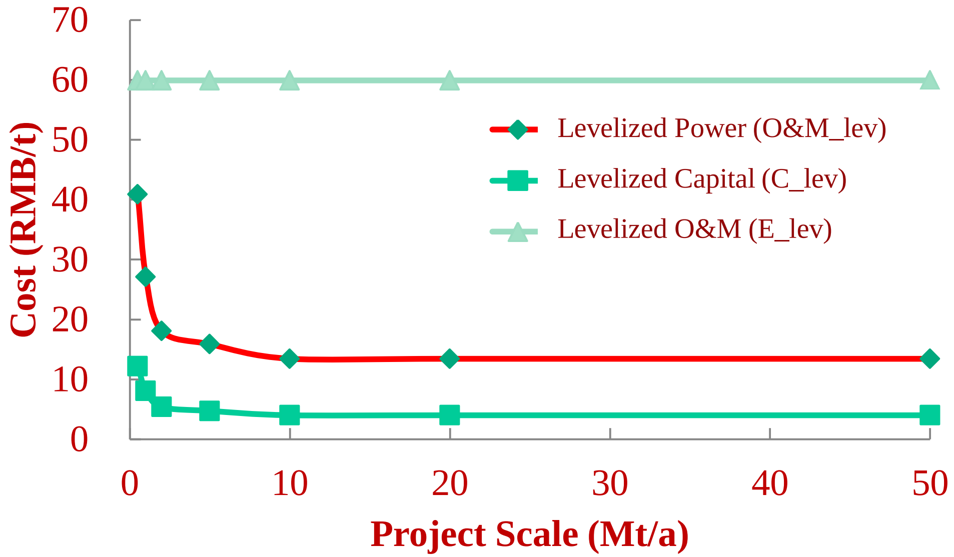
$$C_{capture} = \frac{TCR_a + OMC_a \text{-} C_{sa}}{m_{co_2 \cdot a}}$$

Scale	1Mt	10Mt	20Mt
Capital cost （RMB/tone CO_2）	573.14	455.26	424.77
Discount rate (i)	0.120	0.120	0.120
Levelized capital cost （RMB/t）	73.1	58.1	54.2
Water consumption (t H_2O/t CO_2)	5.5	5.5	5.5
Electronic cost （RMB/t CO_2)	62.7	62.7	62.7
Vapor cost（RMB/t CO_2)	60.0	60.0	60.0
adsorption（RMB/t CO_2)	1.0	1.0	1.0
O&M cost	129.2	129.2	129.2
In total	202.3	187.2	183.4

(20 year， discount rate=0.12, electronic price 0.07US$/kW.h）

Economic model of CCUS

CO_2 Compression cost



(price of electronic = 0.09US$/kW.h)

Relationship between levelized cost and project scale

5 level compressor and pump for the compression process

The total cost for CO_2 compression is about 10~13 US$/t CO_2 for different scale and e price.

采用5级压缩机与1级压缩泵共同实现CO_2压缩， 成本约为10~13 US$/t 。

The energy consumption is really huge.

能量消耗巨大

Economic model of CCUS

CO_2 pipeline transportation

Diameter of pipline

$$D=\frac{1}{0.0254}\left[\frac{\left(32\times F_f\times m^2\right)\left(\frac{1000}{24\times 3600}\right)^2}{\frac{\pi^2\times\rho\times\left(\frac{\Delta P}{L}\right)\times 10^6}{1000}}\right]^{\frac{1}{5}}$$

Iteration

- **Reynold's number**

$$Re=\left(\frac{4\times 1000}{24\times 3600\times 0.0254}\right)\frac{m}{\pi\mu D}$$

- **Manning Coefficient**

$$F_f=\frac{1}{4\left[-1.8\log_{10}\left\{\frac{6.91}{Re}+\left(\frac{12\,\varepsilon/D}{3.7}\right)^{1.11}\right\}\right]^2}$$

parameters	symbol	per unit	parameters	symbol	per unit
pipeline diameter	D	in	pipeline r oughness factor	ε	ft
CO2 mass flow rate	m	tones/day	pipeline length	L	km
Average pressure	P	Mpa	CO2 temperature	T	℃
CO2 viscosity in pipeline	μ	Pa-s	location factor	Fl	
CO2 density in pipeline	ρ	kg/m^3	terrain factor	Ft	

Economic model of CCUS

CO_2 pipeline transportation

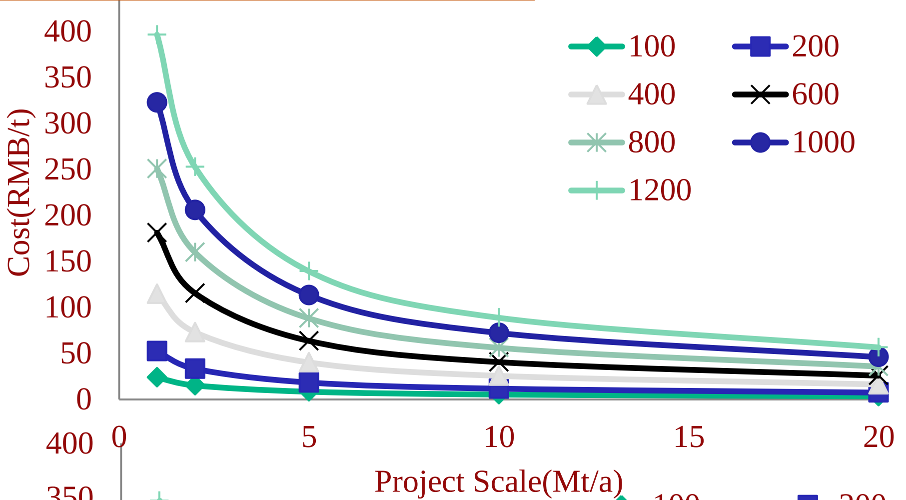
管道成本采用经验方法计算

Empirical method-example from D L. McCollum

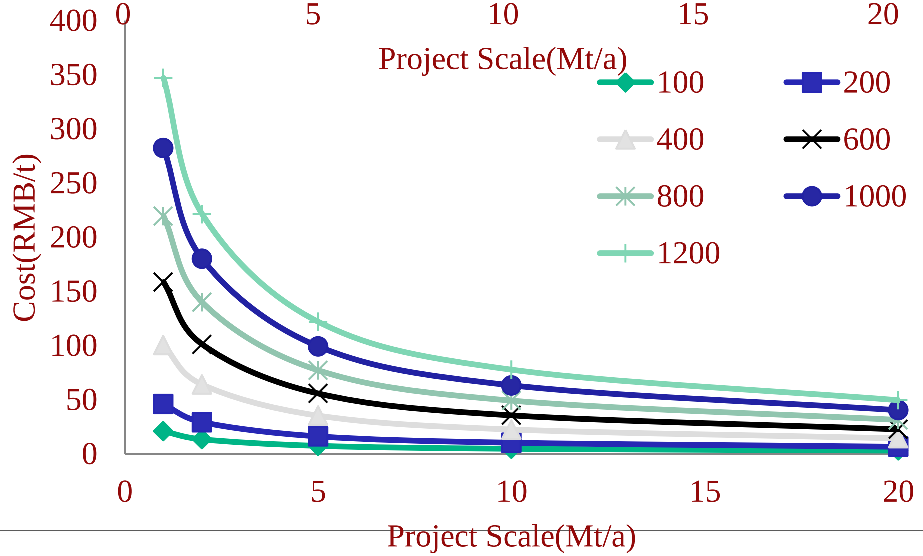
Pipeline capital cost	$C_{cap} = 9970 \times m^{0.35} \times L^{0.13}$
Total pipeline capital cost (modification of location and terrain)	$C_{total} = F_L \times F_T \times L \times C_{cap}$
annualized pipeline capital cost	$C_{annual} = C_{total} \times CRF$
Annual O&M costs	$O\&M_{annual} = C_{total} \times O\&M_{factor}$
Capital cost	$C_{annual} + O\&M_{annual}$
Capital recovery factor	$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$

Economic model of CCUS

CO_2 pipeline transportation



（FL =0.8 and FT = 1.30 (assumed as an approximate average of all terrains)



（FL =0.7 and FT = 1.30 (assumed as an approximate average of all terrains)

Relationship between CO_2 transport distance and levelized cost

Economic model of CCUS

CO_2 aquifer storage

Empirical method-example from D L. McCollum

CO_2 注入速率

$$Q_{CO2/well} = CO_{2injec} \times h \times (P_{down} - P_{res})$$

注入井数

$$N_{well} = \frac{m}{Q_{CO2/well}}$$

渗透系数

$$k_a = (k_h \times k_v)^{0.5} = (k_h \times 0.3k_h)^{0.5}$$

注入温度

$$T_{res} = T_{sur} + d \times (G_g / 1000)$$

CO_2 单井注入性

$$CO_{2injec} = 0.0208 \times CO_{2mobility}$$

注入压力

$$P_{inter} = \frac{(P_{down} + P_{res})}{2}$$

CO_2流动性

$$CO_{2mobility} = \frac{k_a}{\mu_{inter}}$$

井底压力

$$P_{down} = P_{sur} + P_{grav} - \Delta P_{pipe}$$

CO_2 注入压力

$$P_{grav} = \frac{(\rho_{sur} \times g \times d)}{10^6}$$

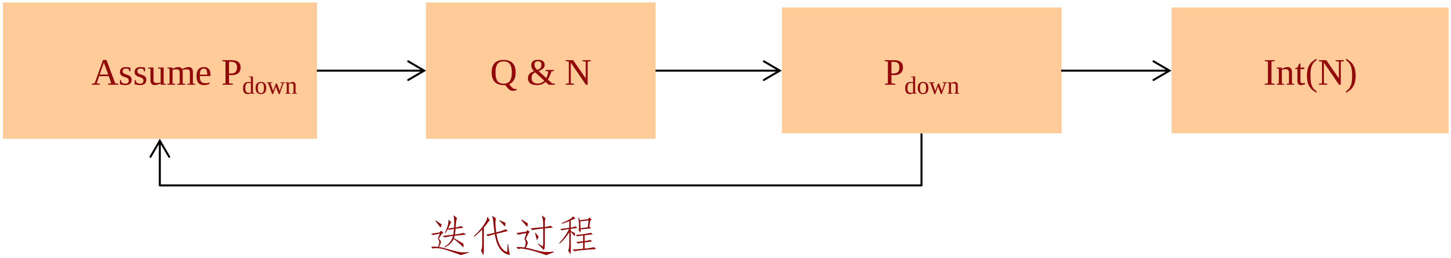
CO_2 流量

$$v_{pipe} = \frac{m \times 1000}{24 \times 3600 \times N} \Big/ \rho \times \pi \times \left(\frac{D_{pipe}}{2}\right)$$

摩擦损失

$$\Delta P_{pipe} = (\rho_{sur} \times g \times F_f \times d \times v_{pipe}{}^2) / (D_{pipe} \times 2 \times g) / 10^6$$

计算过程



Economic model of CCUS

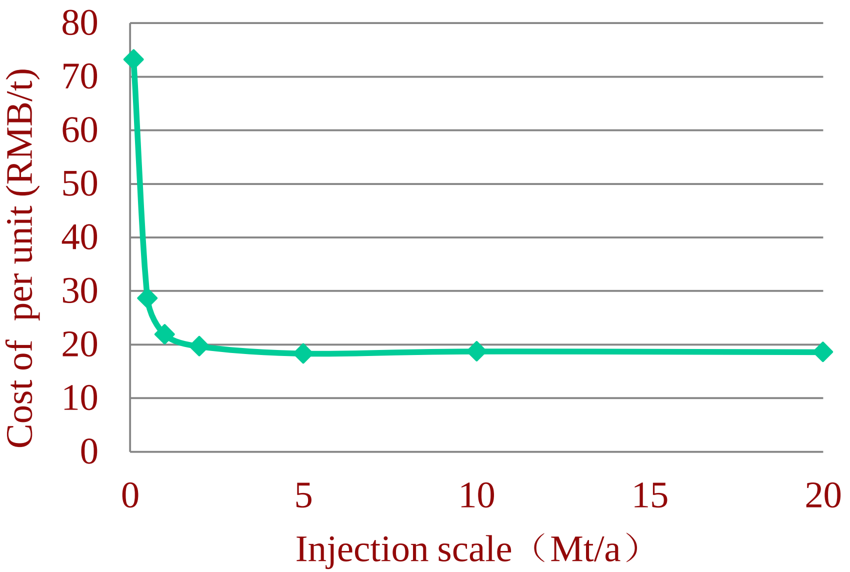
CO_2 aquifer storage

- The flow rate of CO_2 that is delivered to the injection site and the injection rate per well -> Injection well number->the capital cost of equipment->O&M cost-> Levelized costs of CO_2
- Capital cost of injection equipment：
- $C_{equip} = N_{well} \times \{49,433 \times [m / (280 \times N_{well})]^{0.5}\}$
- Drilling cost： $C_{drill} = N_{well} \times 10^6 \times 0.1063e^{0.0008 \times d}$
- Capital cost of site junction： $43,600 \cdot (7389 / (280n))^{0.5}$
- Total capital cost： $C_{total} = C_{site} + C_{equip} + C_{drill}$
- O&M cost： O&M costs due to normal daily expenses ($O\&M_{daily}$), O&M costs due to consumables ($O\&M_{cons}$), O&M costs due to surface maintenance ($O\&M_{sur}$)、 O&M costs due to subsurface maintenance ($O\&M_{subsur}$).
- Cost has been scaled up into year 2005$.
- $O\&M_{daily} = N_{well} \times 7,596$
- $O\&M_{cons} = N_{well} \times 20,295$
- $O\&M_{sur} = N_{well} \times \{15,420 \times [m / (280 \times N_{well})]^{0.5}\}$
- $O\&M_{subsur} = N_{well} \times \{5669 \times (d / 1219)\}$
- $O\&M_{total} = O\&M_{daily} + O\&M_{cons} + O\&M_{sur} + O\&M_{subsur}$

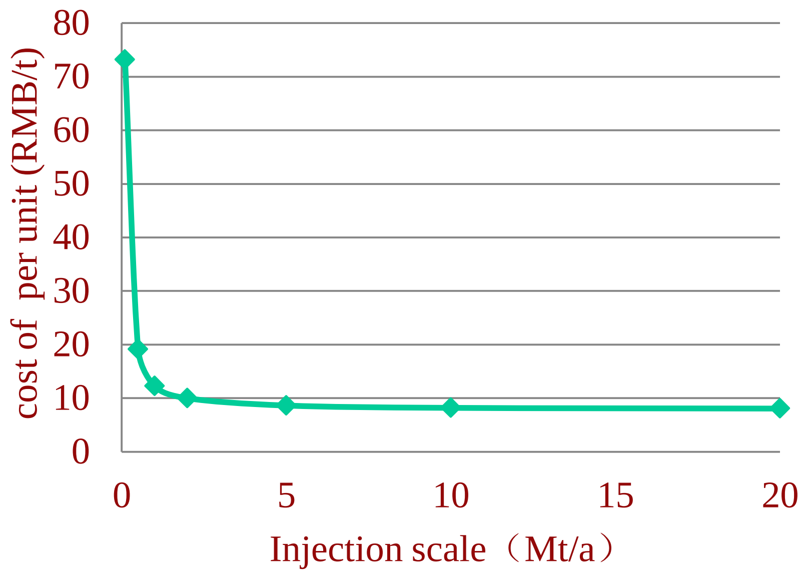
对成本进行中国化！

Economic model of CCUS

CO_2 aquifer storage



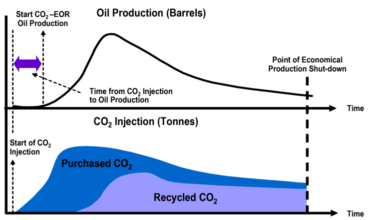
Relationship of CO_2 storage cost and storage scale
The typical parameters of Ordos basin
（injection well： pressure control well=1:0.5，permeability of reservoir 10mD）



Relationship of CO_2 storage cost and storage scale
The typical parameters of Bohai bay basin
（ injection well： pressure control well=1:0.5，permeability of reservoir 100mD）

Economic model of CCUS

CO_2 geological utilization and storage model



Assumed CCUS production curve

Incremental oil recovery and CO_2 storage capacity

Purchased, recycled CO_2 and product production by single phase

Oil production

Recycled CO_2 cost

Purchased CO_2 cost

Oil field properties：
OOIP
Pattern area
Net thickness of "payzone"
Permeability
API gravity
Viscosity
Porosity
Residual oil saturation
Well pattern
CO_2 loss ratio
and so on.

Cost model of single phase (well drilling & completion, connection, and anti-erosion)

CAPEX

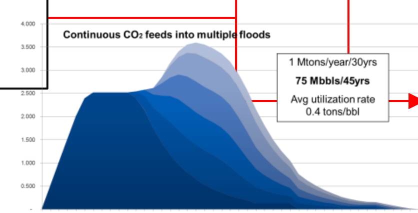
O&M cost

Discount rates
Royalties& Tax rates
Incentives

production recovery and CO_2 storage capacity

Economic of single phase

Assumed production curve of multi-phase CCUS project

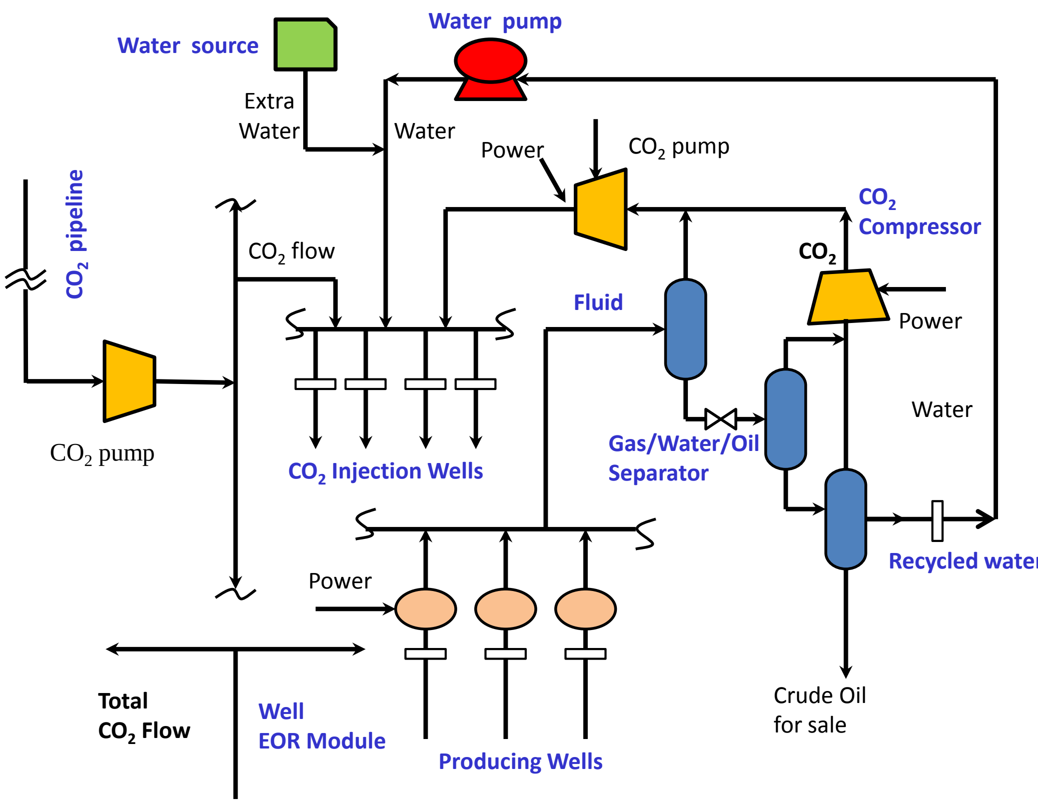


Economic of multi-phase CO_2-EOR project

The cost model mainly follow the economic model by McCoy 2008, but with different performance model.

Economic model of CCUS

CO_2-EOR model



Schematic map of CO_2 EOR activities, modified from report by NETL(2011)

National assessment always use statistic data or empirical data, here use China data to escalate the API data.

Major parameters for deterministic economic evaluation

Project Parameter	Deterministic Value
First purchase Oil Price ($/STB)	**90.0**
CO_2 Purchase Price ($/t)	**50.0**
CO_2 recycling Costs($/t)	**23.66**
Discount Rate (%)	12
Ratio of New wells to original wells	**0.15**
Other O&M Costs ($/bbl)	Calculated by model
Amortized CAPEX($/bbl)	Calculated by model
EOR project lifetime (year)	12
HCPV injected	0.5
Ratio of CO_2 to water	1:1
Operating Monitoring & Verification ($/a)	Calculated by model
Closure Cost ($)	0
Taxes & Royalties	
Royalty Rate (%)	12.5
Severance Tax Rate (%)	5.0
Ad Valorium Tax Rate (%)	2.0
CO_2 Tax ($/tonne)	0.00
Real Escalation Rates	
Oil Price (%/year)	2
CO_2 Tax (%/year)	0
CO_2 Cost (%/year)	2
CO_2 Processing O&M Cost (%/year)	2
Lifting O&M Cost (%/year)	2
M &V Cost (%/year)	2
Lease O&M Cost (%/year)	2
Capital Cost Escalation Factors	
Drilling & Completion	2
Production Well Equipment	2
Injection Well Equipment	2
Production Lease Equipment	2
CO_2 Processing Equipment	2
Producer Breakdown	
Existing Producers	n_+
New Producers	0
Producer Workovers	n_+

Economic model of CCUS

CO_2 Flowline

CO_2 Tank

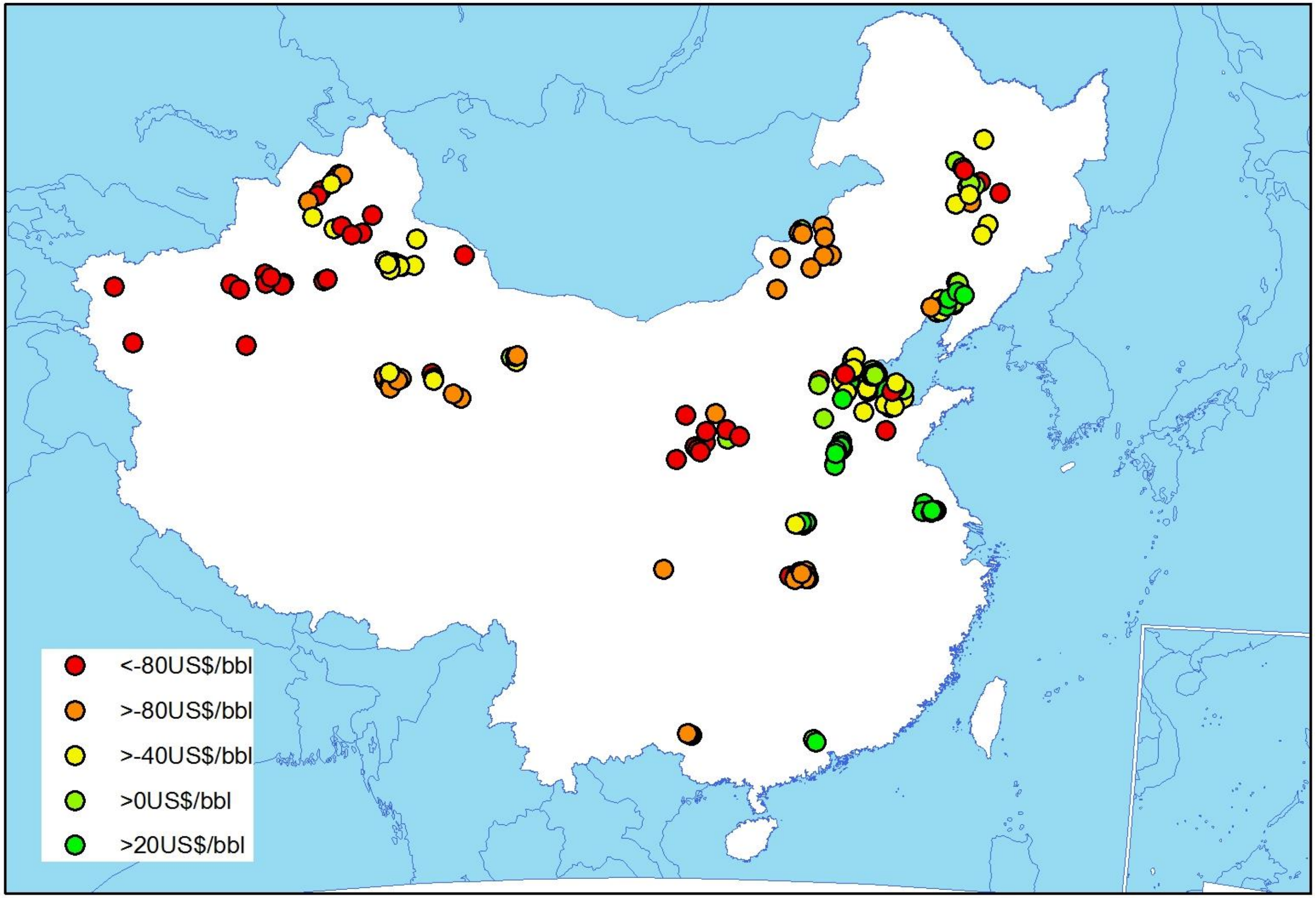
CO_2 separation and compressor

CO_2 Injection well

Production well

Economic model of CCUS

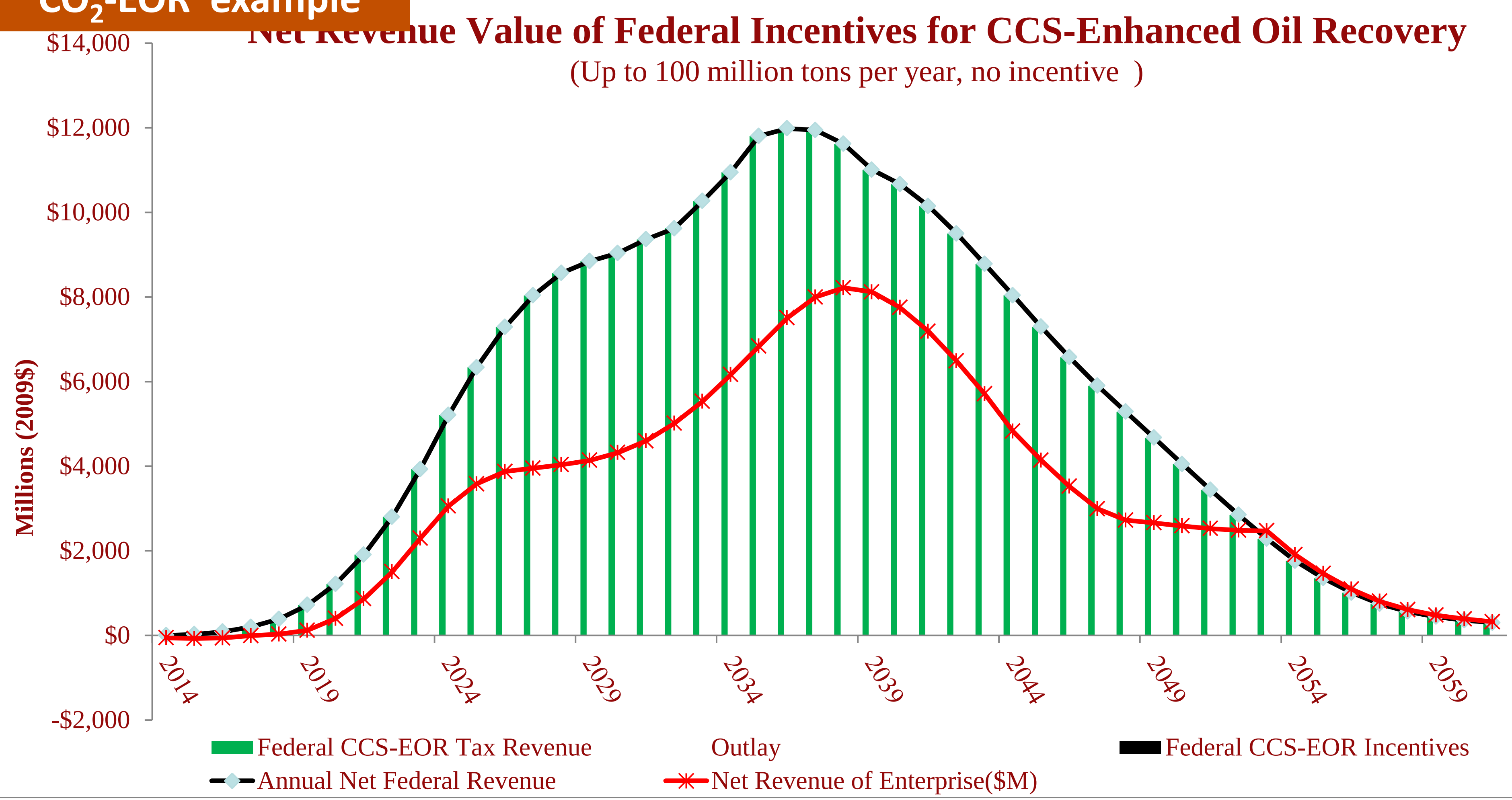
Cost curve of onshore CO_2-EOR in China



The profitable CO_2-EOR are mainly located in the east part of China, Songliao, Bohai Bay, Subei, Nanxiang, and some very small oil field in Sanshui basin.

Economic model of CCUS

CO_2-EOR example



The revenue from CO2-EOR is limited for the following reasons

- Most revenue are for Federal tax; very high crude oil tax;
- Complex geological structure and heavy oil, high CO_2/oil ratio and low recovery of crude oil;
- No incentives for CO_2-EOR projects;

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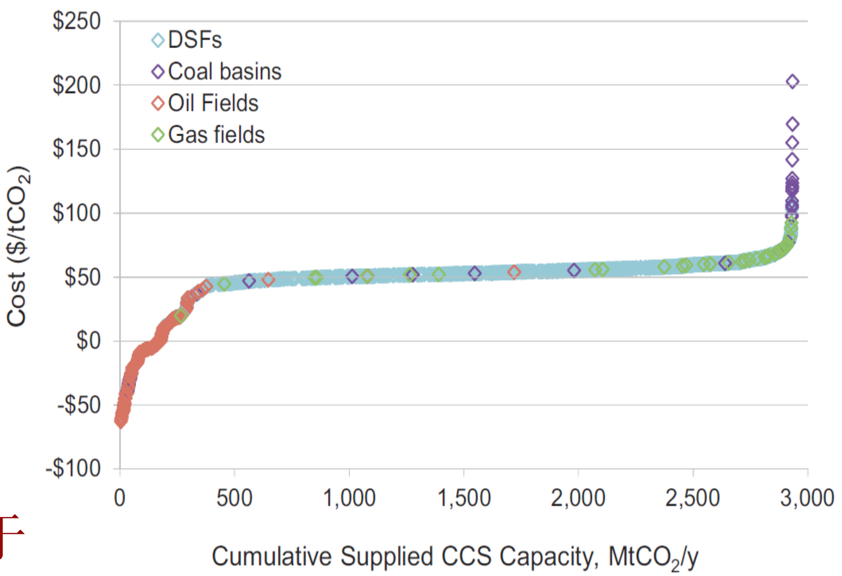
Application of Economic Evaluation

- ➢ **Aims of doing economics**
- • **Assess the economic rang of CCUS projects**
- ✓ CCUS的经济性范围
- • **Assess whether the project is economically viable**
- ✓ 工程的经济性
- • **Select technical components to optimize CCS system**
- ✓ 选择适宜的技术优化CCS技术
- • **Foundation for macro-scale evaluation-link technical and risk to form feasibility study and macro-strategy study.**
- ✓ 宏观研究的基础-和技术与风险联合形成可行性和宏观策略分析

Application of Economic Evaluation

Preliminary results of sources-sinks matching for China

- There are a number of potential opportunities for low and even negative cost storage options;
- 低成本的CCS技术早期机遇；
- The vast majority of storage potential is offered by the large and high capacity deep saline formations at estimated transport and storage costs of less than $10/tCO_2$ (without capture)
- 大多数CCS项目的运输与封存成本低于10US$(不含捕集成本) 和70US$/t.
- However, the properties of geological formation impacts the storage process dramatically, including the technical and cost aspect, further work should be done.



Dahowski, Li et al, 2012

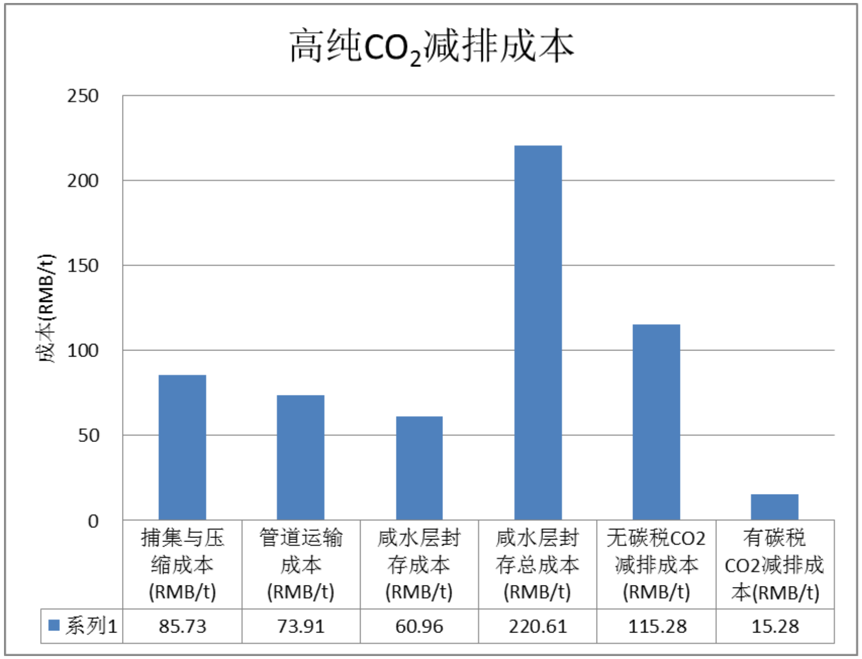
Application of Economic Evaluation

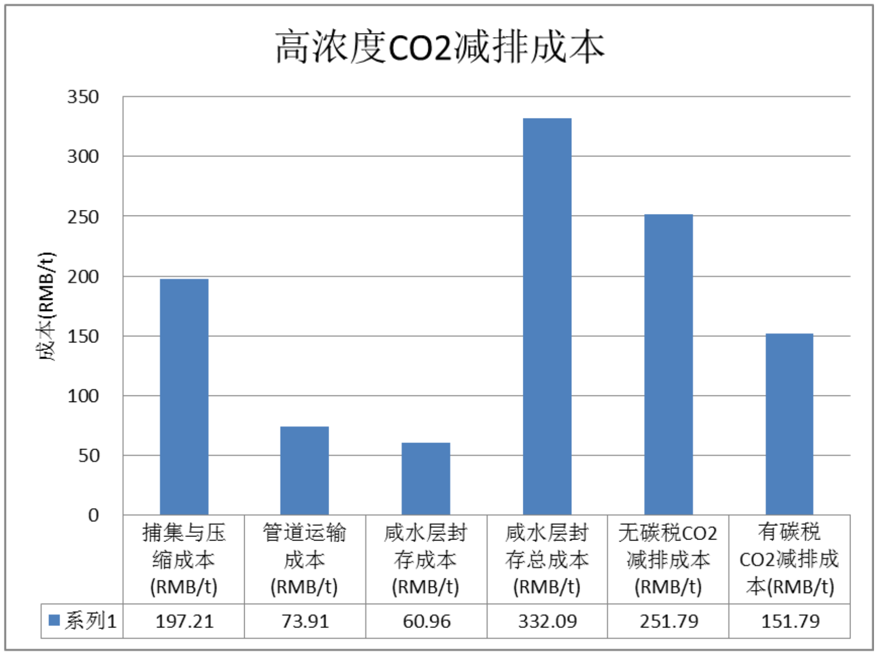
$$NPV = \sum_{t=1}^{T} (C_{production}^{t} + Tax_{C}^{t} - Cost^{t} - Tax_{annual}^{t})/(1+r)^{t}$$

- **Reduce CAPEX 降低固定投入**–cheaper, more efficient equipment
- **Reduce OPEX 降低运行维护费用**–more efficient equipment, less energy demand
- **Reduce energy penalty 降低能源消耗**–use improved solvent, heat and process integration
- **Reduce Tax of CCUS projects;降低税收**
- **Reduce discount rate;降低折现率**
- **Increase CO_2 captured 增加捕集率**–improve capture efficiency and the scale effect
- **Reduce CO_2 emitted 降低CO_2排放**–improve process efficiency in CCS projects
- **Increase energy efficiency 增加能效**–heat and process integration
- **Increase production revenue 增加产品收益-** such as oil and gas production.
- **Increase Carbon tax 增加碳税**

Application of Economic Evaluation

Suitable aquifer sites with oil fields



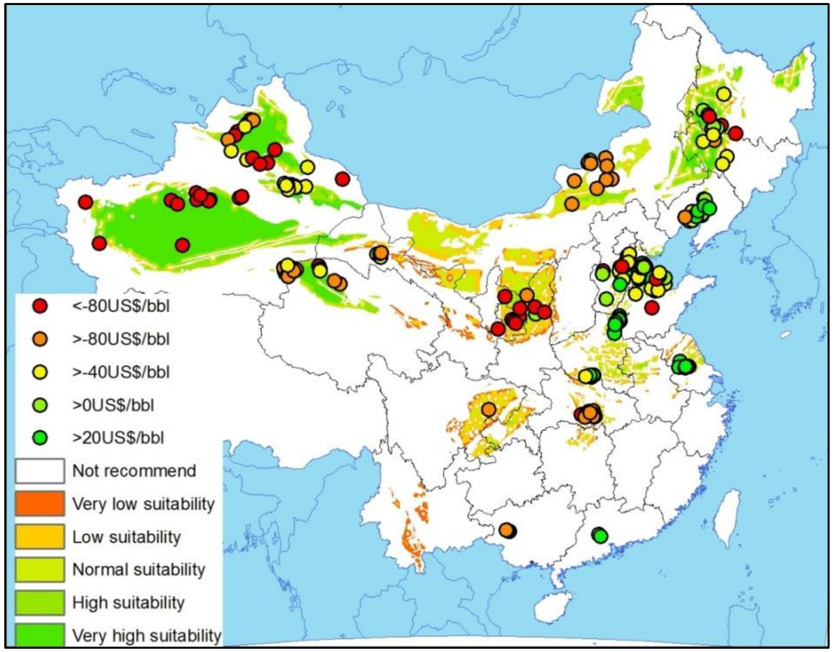


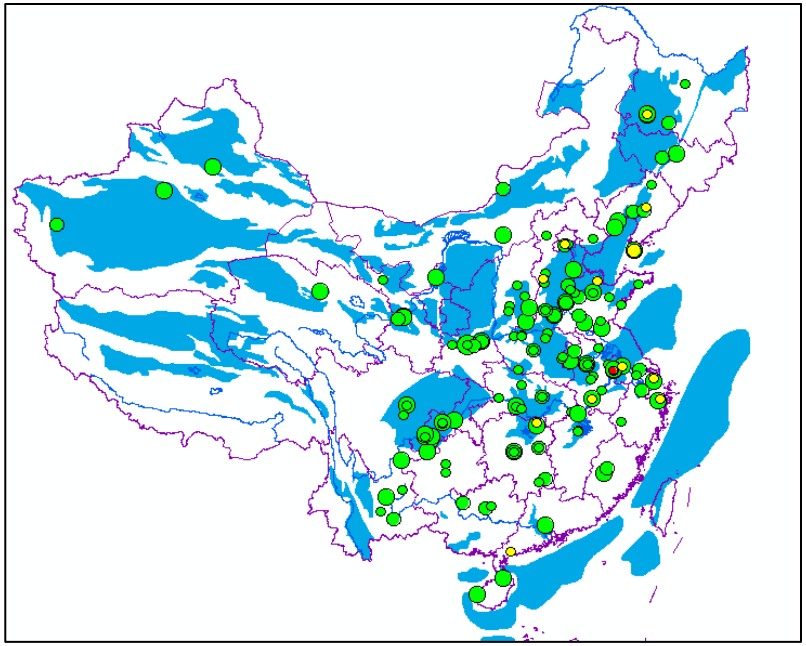
With high purity emission sources and EOR, the total cost of CCUS will be much lower.

结合高浓度排放源和EOR，可降低CCUS工程的整体成本。

Application of Economic Evaluation

Early opportunities of CCS deployment





- High purity sources, including coal chemistry, methanol et al. Those high purity sources have good proximity with storage sites
- The combination of high purity emission sources with CO_2-EOR /aquifer sites is an preferred pairs for early deployment of CCUS projects.

Economic model of CCUS

The economic evaluation of CCUS enable us to analysis

- **Cost and NPV of CCUS projects;**
- **The cost range of CCUS technologies;**
- **Low cost CCUS technologies with selection of technical components and optimization of CCUS system;**
- **Finding of early opportunities for CCS deployment.**

Thank you！

Email: Nwei@whrsm.ac.cn