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ORIGINAL PAPER

Optimization of CO_2 separation technologies for Chinese refineries based on a fuzzy comprehensive evaluation model

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Abstract This study aims at determining the optimal CO_2 separation technology for Chinese refineries, based on current available technologies, by the method of comprehensive evaluation. Firstly, according to the characteristics of flue gas from Chinese refineries, three feasible CO_2 separation technologies are selected. These are pressure swing adsorption (PSA), chemical absorption (CA), and membrane absorption (MA). Secondly, an economic assessment of these three techniques is carried out in accordance with cash flow analysis. The results show that these three techniques all have economic feasibility and the PSA technique is the best. Finally, to further optimize the three techniques, a two-level fuzzy comprehensive evaluation model is established, including economic, technological, and environmental factors. Considering all the factors, PSA is optimal for Chinese refineries, followed by CA and MA. Therefore, to reduce Chinese refineries carbon emission, it is suggested that CO_2 should be captured from off-gases using PSA.

Keywords Chinese refineries · CO_2 emission · Separation technique · Economic evaluation · AHP-entropy method · Fuzzy comprehensive evaluation model

1 Introduction

It is well accepted that carbon dioxide (CO_2), which is considered as the leading source of greenhouse gas (GHG) emissions, results in the climate change. Direct emissions of CO_2 from industry account for approximately 20 % of global CO_2 emissions (IEA 2010). Globally, the petroleum refining industry is one of the largest contributors to anthropogenic CO_2 emissions (IEA 2009; de Mello et al. 2009; Kuramochi et al. 2012). CO_2 emissions from refineries account for about 4 % of the global CO_2 emissions, close to 1 billion metric tons of CO_2 per year (Van Straelen et al. 2010).

China has surpassed U.S. as the world's largest emitter of CO_2. In 2012, China contributed 26.1 % of total world CO_2 emissions, equal to 8,254 million metric tons (Mt) (EIA 2013). On the other hand, the overall goal of the Chinese government is to reduce the CO_2 emissions per unit of GDP by 40–45 % by 2020 from 2005 levels. Nevertheless, with the ever-increasing enlargement of refining scale, the rising demand for high-quality products and the restricted supply of light and sweet crudes, CO_2 emissions of Chinese refineries have increased significantly. In 2012, Chinese crude oil refining reached 468 Mt. Consequently, it was estimated that CO_2 emissions would be around 133 Mt according to the CO_2 emission factor of 0.284 t/t crude oil (Ma et al. 2011). In this paper, a proper mitigation strategy for the Chinese oil refining sector is badly needed to enable China to appropriately implement its climate change policy with consideration of its socio-economic features.

At present, CO_2 emissions of oil refineries can be reduced in three ways. The first option requires energy conservation. The second option requires energy consumption switching to non-fossil fuels such as hydrogen,

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nuclear, biomass, and solar energy. The third option involves CO_2 capture and storage (CCS). However, the nature of oil refining implies that even if a refinery is highly energy efficient, it will consume considerable amounts of energy, and therefore produce considerable amounts of CO_2. The first two measures could reduce the current CO_2 emissions by 9–20 Mt/year, yet a 13–80 % reduction of CO_2 emissions could be achieved by implementing carbon capture (Johansson et al. 2012). Thus, to meet mid- to long-term CO_2 reduction, cost-effective CO_2 separation technologies are the key issue for oil refineries.

Most of the reported studies have focused on technical and economic performance of CO_2 capture technology for power generation, and only a very few studies are about CO_2 capture for the petroleum refining industry (IEA-GHG 2000; Van Straelen et al. 2010; de Mello et al. 2009; Kuramochi et al. 2012; Ho et al. 2011). Specifically, no studies have been reported on Chinese refineries.

The objective of this study is to optimize CO_2 separation technologies for Chinese refineries. Section 2 of this paper reviews CO_2 separation technologies and initially selects available technologies for Chinese refineries. Section 3 introduces the method of economic evaluation and fuzzy comprehensive evaluation. Section 4 presents the results. Section 5 gives the conclusions. The general frame of this study is shown in Fig. 1.

2 Preliminary selections of CO_2 separation technologies

Currently, the technologies for separating CO_2 from a flue gas include absorption, adsorption, use of membranes, cryogenics, and chemical-looping combustion (CLC) (Figueroa et al. 2008; Yang et al. 2008; Olajire 2010; Mondal et al. 2012). Choosing a suitable technology depends on the characteristics of the flue gas stream and its separation requirements.

CO_2 may be emitted from a variety of sources at a refinery, even over 20 sources of emissions for a complex refinery. The main CO_2 emission sources include furnaces, boilers, catalyst regeneration, and hydrogen manufacturing. Figure 2 shows the CO_2 emissions of a typical Chinese refinery with 12 Mt/year of crude processing capacity (Jiang et al. 2013). The CO_2 concentration of flue gases changes in a wide range. For example, it is 10–20 vol% for catalyst regeneration in fluid catalytic cracking (FCC) (de Mello et al. 2009), and 50–55 vol% for hydrogen manufacturing units (Reddy and Vyas 2009). Table 1 shows the composition of some CO_2 emission sources for the typical Chinese refineries. Table 2 provides a summary of the pros and cons of CO_2 separation techniques. Based on the characteristics of the flue gases, three available CO_2 separation technologies are initially selected for Chinese refineries, as follows:

2.1 Pressure swing adsorption (PSA)

The PSA for CO_2 separation is based on the preferential or selective adsorption of CO_2 on a solid adsorbent at a relatively high pressure by contacting hot gas with solid adsorbent in a packed column. The adsorbed component (CO_2) is then desorbed from the solid by lowering the gas-phase partial pressures inside the column so that the adsorbent can be re-used. From the point of view of technology, PSA can capture CO_2 of almost all concentrations from flue gases. But some studies have proved that at the present commercial development state, PSA is not a suitable technology for bulk capture of CO_2 from postcombustion power plant flue gas (Reiner et al. 1994; Liu et al. 2012). However, due to relatively low energy consumption and easy operation, PSA is a promising technology

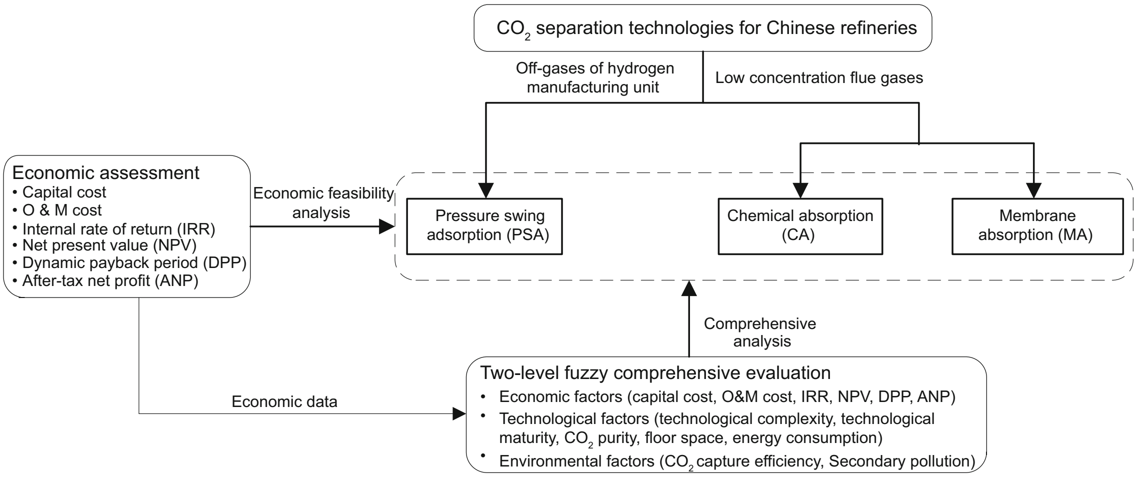

Fig. 1 The general frame diagram of this study

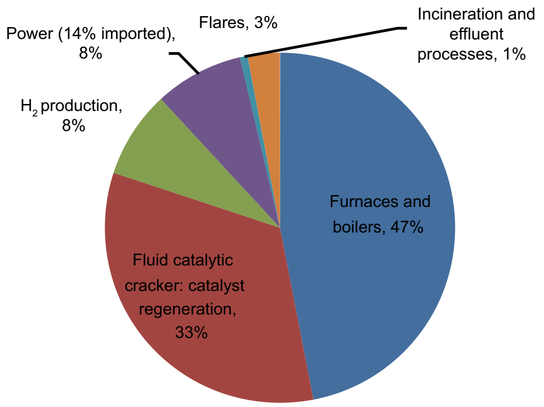

Fig. 2 CO_2 emissions of a Chinese refinery (Jiang et al. 2013)

Table 1 Compositions of some CO_2 emission sources for the typical Chinese refineries

Compositions, vol%	FCC	Hydrogen manufacturing
CO_2	16.6	50
N_2	82	–
O_2	0.8	–
H_2	–	30
CO	0.6	–
SO_x, ppmv	20	–
Other combustible gas (e.g., methane, light alkanes & alkenes)	–	20

for capturing CO_2 of high concentration (20–80 vol%) (Ho et al. 2008; Martunus et al. 2012). In oil refineries, most hydrogen manufacturing units use a PSA to recover H_2 from the syngas. PSA can only recover 75–90 % of the overall H_2 in the syngas. PSA off-gas containing CO_2, unrecovered H_2, and combustible gas is usually burned as fuel gas (shown in Table 1). The direct combustion of off-gases would lead to not only energy waste, but also the emission of large quantities of CO_2. Therefore, to maximize overall production and profitability, oil refineries should recover the CO_2 and remaining valuable H_2 in PSA off gas. Reddy and Vyas (2009) have investigated the recovery of CO_2 and H_2 from PSA off gas using the CO_2LDSep^{SM} plant. Beijing Yanshan Petrochemical Company (China) has constructed a PSA unit recovering hydrogen manufacturing off-gases, with which 0.2 Mt food-grade CO_2, 64.8 Mm^3 combustible gases and 36 Mm^3 H_2 can be produced annually. In the study, some relevant data of the PSA is determined based on this industrial application.

2.2 Chemical absorption (CA)

The chemical absorption process, using amine solutions, is a commercialized technology and has been used in natural gas industry for 60 years. It is regarded as a mature process. The most commonly used solvent is monoethanolamine (MEA). Many studies have been reported about CO_2 capture from an existing coal-fired power plant using chemical absorption method based on MEA (Singh et al. 2003; Alie et al. 2005; Aroonwilas and Veawab 2007; Rubin et al. 2007; Abu-Zahra et al. 2007). They all have indicated that CO_2 capture using MEA is the only feasible option in the short term for flue gases with low concentration CO_2. Therefore, in this study, random packed columns and ordinary carbon steel are used to act as the absorber and stripper with anticorrosive fluororubbers and stainless steel internals. Furthermore, 20 wt% MEA is selected to absorb CO_2, and the CO_2 loadings of lean and rich solution are, respectively, set to 0.20 mol-CO_2/mol-MEA and 0.45 mol-CO_2/mol-MEA (Alie et al. 2005). An absorption temperature of 40 °C is used and the average pressure is around 0.01 MPa. The regeneration temperature is 110 °C and pressure is 0.025 MPa. Therefore, based on these operating conditions, the size of absorber and stripper needed can be determined using the model provided by Abu-Zahra et al. (2007).

2.3 Membrane absorption (MA)

MA, that is using a membrane in conjunction with chemical absorption, is considered as a suitable alternative to chemical absorption by many researchers, due to its unique advantages including large interfacial area, good device-modularity, good operational flexibility, and high mass transfer coefficient (Rangwala 1996; Falk-Pedersen and Dannström 1997; Feron and Jansen 2002; deMontigny et al. 2005; Yeon et al. 2005; Yan et al. 2007, 2008, 2011). In addition, membrane CO_2 absorption technology can also solve the operating problems, successfully including entrainment, flooding, and foaming. It means that solvent losses can be reduced substantially, thereby reducing the absorbent makeup cost. However, the barriers in coal-fired power plants are membrane wetting and plugging which degrade CO_2 separation performance. In order to maintain constant CO_2 removal efficiency, membrane modules need to be replaced again and again, and hence the cost of captured CO_2 will be increased (Mavroudi et al. 2003; Wang et al. 2005; Yan et al. 2008, 2011). Because there are no particles in the flue gas of refineries, membrane plugging will not occur. So, in the assessment of MA in this study, only the membrane wetting problem is considered. With higher specific surface area than packings, hydrophobic hollow fiber membrane contactor is used as the permeable barrier between gas and liquid phase, and the CO_2 can be captured by solvents (e.g., MEA) (Li and Chen 2005). Therefore, hydrophobic polypropylene membranes are selected owing to their relatively low price and commercial availability, with an assumption that the working life of the membranes is 5 years. In addition, the only difference between MA technique and CA technique is the

Table 2 Pros and cons of CO_2 separation technologies

Separation technologies	Applicable situations	Pros	Cons
Chemical absorption (CA)	Lower or medium CO_2 pressure	High selectivity	Large loss of absorbent
		Wide application	High energy consumption of regeneration
		Reproducible solvent	
		Quick reaction velocity	Strong corrosiveness
Membrane absorption (MA)	Lower CO_2 pressure	Large contact area	Porous membrane easily wetted or blocked
		No problems of bubbling, flooding and entrainment	Under research
		Better permeability and selectivity	
		Low energy consumption	
		Good modularity	
Pressure swing adsorption (PSA)	Higher CO_2 pressure	Easy process	Low recovery
		Low energy consumption	Big investment
		No pollution and corrosion	Large floor area
		High adaptability and product purity	
Physical absorption	Higher CO_2 and total pressure	Low energy consumption and corrosiveness	Low selectivity and separation efficiency
		Easy regeneration and lower dosage of adsorbent	Higher pressure
Cryogenics	High CO_2 pressure (concentration, ~60 vol%)	Higher separation efficiency and purity	High cost and energy consumption
Membrane technology	Higher CO_2 pressure	Simple device	High selectivity but not high permeability
		No pollution	Not high CO_2 purity
		Low energy consumption	Not resistant to high temperature
		High separation efficiency	Not easily cleaned
Chemical-looping combustion (CLC)	Under research	No NO_x	No large commercial application
		Low energy consumption	
		Low operation cost	

type of absorber. Others are designed as same as CA technique. Because of the constant liquid–gas contact area, the total membrane contact area can be easily scaled-up linearly based on some successful projects or even the experimental results. According to literature (Yeon et al. 2005; Yan et al. 2007, 2008, 2011), the total membrane contact area could be calculated.

3 Methods

3.1 Method for economic evaluation

Many studies on economic evaluation of CO_2 capture from industrial sources have been reported (Abu-Zahra et al. 2007; de Mello et al. 2009; Yan et al. 2011; Meerman et al. 2012). For Chinese refineries, the economic assessments are subject to two generally accepted guidelines: the Economic Assessment Method and Parameters for Capital Construction Projects (NDRC and MOC 2006), the Economic Assessment Method and Parameters for Oil Construction Projects (MOHURD 2010). Although the economic indicators are not the same due to geographic differences, the methodology is similar.

In the study, the economic assessment using cash flow analysis are made up of the following six key economic categories: capital cost, operating and maintenance (O & M) cost, internal rate of return (IRR), net present value (NPV), dynamic payback period (DPP), and after-tax net profit (ANP). The cost model developed in the present study is based on the China-specific guidelines, and the methods for calculating the costs of each category and the data are drawn from the two guidelines (Table 3).

3.2 Method for fuzzy comprehensive evaluation

The evaluation of the optimal CO_2 separation technology for Chinese refineries is influenced by a number of factors, such as economic benefits, environmental policy, technological level, and social impact. However, because of the

Table 3 Cost estimation of CO_2 separation technologies

1	Capital cost	Formulas
1.1	Engineering	$C_1 + C_2 + C_3$
1.2	Miscellaneous	$1.1 \times C_4$
1.3	Budgetary reserves	$(1.1 + 1.2) \times C_5$
1.4	Annual interest	$(1.1 + 1.2 + 1.3)/C_6 \times (1 - C_7)/C_6 \times C_8$
1.5	Liquidity	
	Capital cost	$1.1 + 1.2 + 1.3 + 1.4 \times C_6 + 1.5$
2	**Operating and maintenance (O & M) cost**	**Formulas**
2.1	Materials	
2.2	Fuels & power	
2.3	Wage & Welfare	
2.4	Depreciation	Straight-line depreciation
2.5	Maintenance	
2.6	Miscellaneous	
2.7	Administration	
2.8	Financial	Straight-line amortization
2.9	Sales	
	Annual O & M cost	$\sum 2.i$ (where $2.i$ is 2.1–2.9)
3	**Annual cash flow**	**Formulas**
3.1	Income	
3.2	Cash inflow	3.1
3.3	Construction investment	$(1.1 + 1.2 + 1.3)/C_6$
3.4	Operating cost	$2.1 + 2.2 + 2.3 + 2.5 + 2.6 + 2.9$
3.5	Tax and extra charges	
3.6	Income tax	When $(3.1 - 3.7 - 3.6) > 0$, $(3.1 - 3.7 - 3.6) \times C_9$
3.7	Cash outflow	$3.3 + 3.4 + 3.5 + 3.6$
3.8	Net cash flow	$3.2 - 3.7$

C_1–C_9 are the parameters extracted from the China-specific Guidelines stated above. C_1 is the equipment procurement cost (10^4 Yuan); C_2 is the installation cost (10^4 Yuan); C_3 is the construction cost (10^4 Yuan); C_4 is the miscellaneous fixed asset cost in the proportion of engineering cost, 0.12; C_5 is the budgetary reserves ratio, 0.1; C_6 is the construction period (years); C_7 is the owner's capital–capital cost ratio; C_8 is the loan interest rate; and C_9 is the income tax rate

complexity and uncertainty involved in evaluation, a decision maker must consider these factors in a comprehensive evaluation to avoid one-sidedness. Fuzzy comprehensive evaluation is the process of evaluating an objective utilizing fuzzy set theory. When evaluating an objective, multiple related factors must be considered comprehensively in order to give an appropriate, non-contradicting, and logically consistent judgment (Jorge et al. 2000; Chen et al. 2002; Liang et al. 2006).

In this study, a two-level fuzzy comprehensive evaluation is used as follows.

- Assuming that the objective being evaluated contains n factors, i.e., the factor set is $U = \{U_1, U_2, U_3, \ldots, U_n\}$
- First-level fuzzy evaluation is carried out for each factor $U_k (k = 1, 2, \ldots, n)$ $A_k = \left(a_{k1}, a_{k2}, \ldots, a_{kp}\right)$ is the fuzzy weight vector of each sub-factor in U_k, where a_{kl} is the relative importance of factor l, and $\sum_{l=1}^{p} a_{kl} = 1$.

  The fuzzy appraisal matrix of all p sub-factors:

$$R_k = \begin{bmatrix} r_{k11} & r_{k12} & \ldots & r_{k1m} \\ r_{k21} & r_{k22} & \ldots & r_{k2m} \\ \ldots & \ldots & \ldots & \ldots \\ r_{kp1} & r_{kp2} & \ldots & r_{kpm} \end{bmatrix} \tag{1}$$

where r_{kij} is referred to the fuzzy membership degree of appraisal of factor i. In the study, based on the type of factor i, r_{kij} is defined as (Xie et al. 2012):
For benefit factors:

$$r_{ij} = \frac{x_{ij} - \mathrm{minx_{ij}}}{\mathrm{max}x_{ij} - \mathrm{min}x_{ij}} \tag{2}$$

For cost factors:

$$r_{ij} = \frac{\mathrm{maxx_{ij}} - \mathrm{x_{ij}}}{\mathrm{max}x_{ij} - \mathrm{min}x_{ij}}, \tag{3}$$

where x_{ij} is the eigenvalue of factor i, max x_{ij} and min x_{ij} is, respectively, the maximum, the minimum.
The first-level appraisal result, B_k, can be obtained:

$$B_k = (b_{k1}, b_{k2}, \ldots, b_{km}) = A_k \times R_k \tag{4}$$

- Second-level fuzzy evaluation is implemented for U According to the aforementioned results, the comprehensive appraisal result, B, is calculated as:

$$B = (b_1, b_2, \ldots, b_{\mathrm{m}}) = A \times R = (a_1, a_2, \ldots, a_n) \times \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ b_{21} & b_{22} & \cdots & b_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ b_{n1} & b_{n2} & \cdots & b_{nm} \end{bmatrix} \tag{5}$$

- The priority of evaluated objects can be obtained, and the optimal separation technology for Chinese refineries can finally be determined based on different scenarios.

4 Results

4.1 Economic evaluation

Three CO_2 separation technologies without considering CO_2 compression and transportation can recover 0.1 Mt/year liquid CO_2. Faced with the restricted downstream demand, CO_2 is usually consumed nearby. Hence, it is assumed for the boundary of the economic evaluation model that around oil refineries there are enough market demands and CO_2 can be completely sold as a commodity. Additionally, Chinese government has established 7 CO_2 pilot emission trading markets in Beijing, Shanghai, Tianjin, Shenzhen etc., and will establish a China national CO_2 emission trading market in the 13th Five-Year Plan. Therefore, some mandatory measures, such as CO_2 emissions taxation, must be taken in the near future in China for refineries as large emission sources. Considering the carbon emissions taxation, CO_2 capture can obtain additional economic benefit. Due to many uncertainties in the pilot carbon market, the CO_2 price may fluctuate greatly, for example, the lowest CO_2 price is 28 Yuan/t and the highest CO_2 price can reach 140 Yuan/t in Shenzhen carbon market. So, in the economic evaluation in this work, a CO_2 price of 140 Yuan/t is used. However, it is worth noting that with the PSA technique, 18 Mm^3/year of H_2 can be recovered simultaneously, and can be sold at a price of 2.0 Yuan/m^3. The common basis for the three techniques is shown in Table 4.

Table 4 Assumptions for economic evaluation with PSA, MA and CA techniques

Items	Value
CO_2 capture efficiency, %	90
CO_2 purity, %	>99
Project working life, years	15
Construction period, years	1
Plant operating time, h/year	8000
Discount rate, %	12
CO_2 sale price, Yuan/t	260
CO_2 transaction price, Yuan/t	140
Owner's capital/capital cost	0.3
Loan interest rate, %	6.55
Income tax rate, %	25

The cost of major equipment for the PSA technique is estimated in terms of investment per unit capacity. Based on the PSA unit of Beijing Yanshan Petrochemical Company (China), the major equipment investment for the PSA technique is estimated to be 243.6 Yuan/t, accounting for approximately 72 % of total construction investment. For the CA and MA techniques, the cost of the absorber and stripper is firstly calculated from the above designs of CA and MA. Then, other costs are estimated in terms of certain proportions. The economic evaluation results for the three CO_2 separation techniques are shown in Table 5.

Table 5 Economic evaluation results for the three techniques

Items	CA	MA	PSA
Capital cost, 10^4 Yuan	3453.3	3613.9	3671.3
O & M cost, 10^4 Yuan/year	3407.1	3397.0	3348.3
IRR, %	17.55	17.75	86.05

Table 5 shows that the capital cost of the PSA technique is the highest, but its other economic indicators are optimal. The reason is that it can simultaneously recover CO_2 and by-product H_2. The capital cost of the MA technique is higher than that of CA. That is because the membrane price is high (about 13 Yuan/m^2), and the membrane needs to be replaced about every 5 years. However, the O & M cost of CA is higher than that of MA, because of lower CO_2 loading capacity, higher solvent losses, and regeneration heat consumption, meaning that using membrane gas absorption process can save the O & M cost in capture of CO_2.

4.2 Fuzzy comprehensive evaluation

4.2.1 Establishment of the factor set

A factor set consists of various factors affecting the evaluation objective. The evaluation objective of this study is to optimize CO_2 separation technologies. Combining experts' knowledge and experience with the actual production condition of Chinese refineries, the factor set

Table 6 Factors for CO_2 separation technologies

Items	Types	Attributes
Economy (C_1)		
IRR (I_1)	Benefit	Quantitative
NPV (I_2)	Benefit	Quantitative
DPP (I_3)	Cost	Quantitative
Capital cost (I_4)	Cost	Quantitative
O&M cost (I_5)	Cost	Quantitative
ANP (I_6)	Benefit	Quantitative
Technology (C_2)		
Technological complexity (I_7)	Cost	Qualitative
Technological maturity (I_8)	Benefit	Qualitative
CO_2 purity (I_9)	Benefit	Quantitative
Floor space (I_{10})	Cost	Qualitative
Energy consumption (I_{11})	Cost	Qualitative
Environment (C_3)		
CO_2 capture efficiency (I_{12})	Benefit	Quantitative
Secondary pollution (I_{13})	Cost	Qualitative

involving economic, technological, and environmental factors has been established (Table 6).

4.2.2 Determination of the weight vector

There are dozens of methods to determine a weight, including Delphi (Ma et al. 2003), AHP (Saaty and Shang 2011; Jiang et al. 2012) and entropy (Lai et al. 2012; Khan and Bhuiyan 2014) methods. Each method has its background, significance, merits, shortcomings, and specific areas of application. Combination of different methods can offset the shortcomings of each, integrate their various advantages, and result in an advanced evaluation method (Refat et al. 2011). In this study, the weight of factors is determined by a combination of subjective (AHP) and objective (entropy) methods, that is, the AHP-entropy method takes into account the data and the subjective preferences of decision-makers to achieve a synthesis of subjective and objective and to make the results more realistic and reliable.

4.2.2.1 Determination of the weight vector by AHP method AHP, originally developed by Saaty (1977, 1990, 1994), is a mathematical method for analyzing complex decision problems with multiple criteria and through combination of quantitative analysis with qualitative ones. In this paper, the model is based on the combination of qualitative opinions from experts and references and quantitative analysis from aforementioned economic evaluation, and the results are listed in Table 7.

Table 7 Results of the weight vector by AHP

C	C_1 0.4000	C_2 0.2000	C_3 0.4000	$W_i^{'}$
I_1	0.4149	0	0	0.1660
I_2	0.2592	0	0	0.1037
I_3	0.0501	0	0	0.0200
I_4	0.0848	0	0	0.0339
I_5	0.1609	0	0	0.0644
I_6	0.0300	0	0	0.0120
I_7	0	0.0732	0	0.0146
I_8	0	0.4269	0	0.0854
I_9	0	0.1824	0	0.0365
I_{10}	0	0.0413	0	0.0083
I_{11}	0	0.2762	0	0.0552
I_{12}	0	0	0.5000	0.2000
I_{13}	0	0	0.5000	0.2000

C is the optimization of CO_2 separation technologies for Chinese refineries; $W_i^{'}$ is the weight of the factor set

Table 8 Results of the weight vector by entropy method

Items		E_i	d_i	$W_i^{''}$
Benefit				
I_1	IRR	0.0181	0.9819	0.1212
I_2	NPV	0.0337	0.9663	0.1192
I_5	ANP	0.0022	0.9978	0.1231
I_8	Technological maturity	0.5119	0.4881	0.0602
I_9	CO_2 purity	0.6219	0.3781	0.0467
I_{12}	CO_2 capture efficiency	0.6072	0.3928	0.0485
Cost				
I_3	DPP	0.0960	0.9040	0.1116
I_4	Capital cost	0.4659	0.5341	0.0659
I_6	O & M cost	0.3793	0.6207	0.0766
I_7	Technological complexity	0.5119	0.4881	0.0602
I_{10}	Floor space	0.4555	0.5445	0.0672
I_{11}	Energy consumption	0.5794	0.4206	0.0519
I_{13}	Secondary pollution	0.6126	0.3874	0.0478

E_i is the entropy; d_i is the diversity; $W_i^{''}$ is the entropy weight

4.2.2.2 Determination of the weight vector by entropy method Entropy, first proposed by Shannon, is a concept originating from information theory (Chen et al. 2012). It can calculate the amount of information in the message, which consists of a countable length of character combination. By computing the total probabilities of all the characters in the message, the information entropy of the message is obtained. Generally, the smaller the entropy of a certain factor is acquired, the more weight the factor is given, and vice versa. Table 8 presents the results of the weight vector by the entropy method.

Table 9 Results of the weight vector by AHP-entropy method

Items	AHP	Entropy	AHP-entropy
Economy (C_1)			
I_1	0.4149	0.1962	0.4392
I_2	0.2592	0.1931	0.2700
I_3	0.0501	0.1806	0.0488
I_4	0.0848	0.1067	0.0488
I_5	0.1609	0.1994	0.1731
I_6	0.0300	0.1240	0.0201
Technology (C_2)			
I_7	0.0732	0.2105	0.0791
I_8	0.4269	0.2105	0.4614
I_9	0.1824	0.1630	0.1526
I_{10}	0.0413	0.2348	0.0498
I_{11}	0.2762	0.1813	0.2571
Environment (C_3)			
I_{12}	0.5000	0.5035	0.5035
I_{13}	0.5000	0.4965	0.4965

4.2.2.3 Determination of the weight vector by AHP-entropy method The combined weights are determined by Eq. (6), and the results are shown in Table 9.

$$a_i = \frac{(\omega_i' \times \omega_i'')}{\left(\sum_{i=1}^{m} \omega_i' \times \omega''\right)} \tag{6}$$

4.2.3 Determination of the fuzzy appraisal matrix

Based on Eqs. (1), (2), and (3), the fuzzy appraisal matrix for the economic, technological, and environmental factors is obtained as follows:

$$R_{C1} = \begin{bmatrix} 0.0000 & 0.0029 & 1.0000 \\ 0.0000 & 0.0061 & 1.0000 \\ 0.0000 & 0.0224 & 1.0000 \\ 1.0000 & 0.2633 & 0.0000 \\ 0.0003 & 0.0000 & 1.0000 \\ 0.0000 & 0.1718 & 1.0000 \end{bmatrix},$$

$$R_{C2} = \begin{bmatrix} 1.0000 & 0.0000 & 0.3333 \\ 1.0000 & 0.0000 & 0.3333 \\ 1.0000 & 0.0000 & 0.7538 \\ 0.0000 & 1.0000 & 0.2500 \\ 0.5000 & 1.0000 & 0.0000 \end{bmatrix},$$

$$R_{C3} = \begin{bmatrix} 1.0000 & 0.6296 & 0.0000 \\ 0.0000 & 0.6667 & 1.0000 \end{bmatrix}$$

4.2.4 Results and analysis

(1) Results of first-level fuzzy comprehensive evaluation
According to Eq. (4), the following results of the single-level fuzzy evaluation are obtained:

- For the economic factors, $B_1 = [0.0489 \quad 0.0203 \quad 0.9512]$. The order of the economic benefit of the three techniques is PSA>CA>MA.
- For the technological factors, $B_2 = [0.8217 \quad 0.3069 \quad 0.3076]$. The order of the technological level is CA>PSA>MA.
- For the environmental factors, $B_3 = [0.5035 \quad 0.6480 \quad 0.4965]$. The order of the environmental benefit is MA>CA>PSA.

(2) Results of two-level fuzzy comprehensive evaluation
The B_1, B_2, and B_3 constitute the fuzzy appraisal matrix of second-level factor, that is,

$$R_C = \begin{bmatrix} 0.0489 & 0.0203 & 0.9512 \\ 0.8217 & 0.3069 & 0.3076 \\ 0.5035 & 0.6480 & 0.4965 \end{bmatrix}.$$

The economic, technological, and environmental factors all belong to benefit attribute, and based on the AHP-entropy method, the weigh vector is $A = [0.3247 \quad 0.3664 \quad 0.3089]$. The overall fuzzy comprehensive evaluation is $B = A \times R_C = [0.3942 \quad 0.3220 \quad 0.6349]$. The order of the three separation technologies is PSA>CA>MA.

5 Conclusions and implications

Chinese refineries should prefer PSA, due to its unique advantage of recovering both CO_2 and H_2. With the increasing amounts of heavy and high-sulfur crude oils to be processed, demand for H_2 in Chinese refineries is rising. The recovery of hydrogen from manufacturing off-gases with PSA can not only reduce total emissions from refineries, but also expand their production and profitability. On the other hand, MA, if the obstacle of the membrane wetting is overcome, will be the most promising alternative to chemical absorption to capture CO_2 from oil refinery flue gas in the future. In addition, the methodology presented might be beneficial to decision-making for CO_2 capture projects in oil refineries in other countries. The result is important for evaluating the deployment of CCS in Chinese refining sector.

Utilization of technological options for separation and/or capture of CO_2 from flue gases will make Chinese refining industry realize their target of emission reduction in the future. However, without mandatory cuts, incentives, and a major technological break-through, the high costs impose restrictions on the implementation of carbon capture at Chinese refineries. There are a lot of uncertainties about which technologies could lead to real improvements and which have no real prospects for reducing the cost of capture. On the other hand, the use of the captured CO_2 as a secondary product appears to be attractive. The utilization includes producing chemical substances through the application of organic chemistry, biofuels, etc., or injecting pure captured CO_2 underground for enhanced oil recovery (EOR), enhanced gas recovery (EGR), and enhanced coalbed methane (ECBM), although this is not mentioned in the paper.

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