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Fair design of CCS infrastructure for power plants in Qatar under carbon trading scheme

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Abstract

Qatar is currently the highest emitter per capita and targets emission reduction by exercising tight controls on gas flaring. In order to limit the emission under allowances, the power plants have two options: investing in carbon capture and storage (CCS) systems or buying carbon credits for the excess emissions above their allowances. However, CCS systems are expensive for installation and operation. In this paper, a mixed integer linear programming (MILP) model is developed for the design of integrated carbon capture, transport and storage infrastructure in Qatar under carbon trading scheme. We first investigate the critical carbon credit prices to decide under which price it is more beneficial to invest on CCS systems or to buy carbon credits via carbon trading. Then the fair design of the CCS infrastructure is obtained under two fairness scenarios: the same saving ratio and the game theory Nash approach. Fair cost distribution among power plants in Qatar is obtained by selecting the CO_2 resources (power plants) to be captured with available capture technologies and materials, designing the transportation pipeline network to connect the resources with the sequestration and/or utilisation sites and determining the carbon trading price and amount among power plants. Under different fairness scenarios, the total costs are slightly higher than that from minimising the total cost to obtain the fair cost distribution. Power plants with higher CO_2 emissions determine to install CCS system, while other power plants buy the carbon credits from domestic or international market to fulfil their carbon allowance requirements. The future work includes extending the current model by considering power generation distribution and designing the pipeline network with the selection of pump locations and pipe diameters.

Key words: *CCS; carbon trading; Game theory; mixed integer linear programming (MILP)*

1 Introduction

Increasing greenhouse gas emission (GHG) is considered as one of the main reasons for global warming. Reduction of carbon dioxide (CO_2) emissions from energy system involves reforestation, energy efficiency enhancement, fuel substitution, utilisation of low-carbon technologies and carbon capture and storage (CCS) (Chicco and Stephenson, 2012). One more CO_2 reduction method is known as carbon capture and conversion (CCC), which recovers CO_2 to synthesise useful products through chemical transformation (Taheri Najafabadi, 2015). CCS enables the continued use of fossil fuels which accounts for over 80% of global total primary energy consumption (Anantharaman et al., 2013) and CCS is recognised as an attractive option for CO_2 abatement on a large scale from centralised energy systems. Three main steps are included in CCS: CO_2 capture from gaseous combustion, CO_2 transportation and CO_2 storage in reservoirs. In power generation section, CO_2 emissions can be captured by pre-combustion technique, after combustion technique or the oxyfuel process. CO_2 transportation, which connects the capture and sequestration, can apply carbon pipeline, ships or road tankers. Pipe line transport is ideal for large-scale and long-distance. Captured CO_2 can be stored in sinks with different geological formations, such as deep saline formations, depleted oil and gas reservoirs (with or without enhanced oil recovery) and deep unmineable coal seams (Middleton and Bielicki, 2009a).

The optimal design of the CCS system has been investigated in several recent studies around the world. A toolbox integrating ArcGIS and MARKAL is developed to assess the development of a large-scale CO_2 infrastructure in the Netherlands for 2010-2050 (van den Broek et al., 2009). Three different CCS infrastructure systems are assessed for six EU member states: Begium, Czech Republic, Germany, Netherlands, Poland and Slovakia in (Kjärstad et al., 2011). Middleton and Bielicki (2009b) introduce a comprehensive model, simCCS, to solve for optimal spatial deployment of the CCS infrastructure. It minimises the annual cost by determining the pipeline network between CO_2 sources and sinks. Then a five-step process for developing a candidate pipeline network is introduced based on the simCCS model (Middleton et al., 2012). Tan et al. (2012) present a continuous-time mixed integer linear programming (MILP) model to match CO_2 sources and sinks in CCS systems while considering the storage limitations of the sinks. A multi-period MILP model is also proposed by them (Tan et al., 2013) to match CO_2 sources and inks under the constraints of temporal, injection rate and storage capacity. Weihs et al. (2011) develop an optimisation model for CCS pipeline networks to minimise the network cost with a genetic algorithm. The model is applied to design the CCS network for the south eastern Queensland region in Australia. An optimisation model, InfraCCS model, is described by Morbee et al (2012), which minimises the cost of a CO_2 transport network at European scale for 2015-2050. Non-technological issues, including economies of scale, infrastructure ownership and political incentives, are analysed within the existing CO_2 transport infrastructure in (Brunsvold et al., 2011). What is more, utilisation and disposal of CO_2 is included in a scalable and comprehensive CCS infrastructure model introduced by Han and Lee (2011). Hasan et al. (2014; 2015) design a CO_2 capture, utilisation and sequestration (CCUS) supply chain network to minimise the cost by selecting the source plants, capture processes, capture materials, CO_2 pipelines, locations of utilisation sites and amounts of CO_2 storage.

The major challenge toward large-scale deployment of CCS is its high cost, while carbon trading approach is proposed for emission control from economic incentives. It refers to the trading of emissions of six major GHGs: carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphurhexafluoride (SF6). There are several mandatory emissions trading schemes under operation, which are European Union Emissions Trading system (EU ETS), Regional Greenhouse Gas Initiative (USA), New Zealand Emissions Trading Scheme, Tokyo metropolitan trading scheme and the New South Wales Greenhouse Gas Abatement Scheme (Australia) (Perdan and Azapagic, 2011). Among them, USA has not ratified the Kyoto Protocol (UNFCC, 1998). Uddin and Holtedahl (2013) classify the emission trading schemes into three groups: ‘cap-and-trade’, ‘rate-based’ and ‘project-based’. The international emissions trading under Kyoto Protocol allows for less costly emissions abatement than domestic actions alone. Emission reductions are expected to take place where the cost of reduction is the lowest. The EU ETS is the largest multinational emission trading scheme in the world, and the governments agree on the national emission caps allocating the allowances to their industrial emitters (Rebennack et al., 2009). Compared with the carbon taxation method which has a fixed price, the ETS permits are traded by the market participants and the cost of emissions is determined by market forces (Villoria-Sáez et al., 2016). In the carbon trading system, cap and trade system is commonly used approach where each entity is placed a cap of CO_2 emissions and receives an allowance that is equal to its individual cap value (Chaabane et al., 2012). These entities can sell or buy the allowances if they have lower or higher CO_2 emissions than the cap values on a yearly base. From the cost-effective aspect, the carbon trading system encourages these entities to reduce CO2 emissions by investing in more effective technology or utilising renewable energy (Üçtuğ et al., 2014). These entities often have two options: installing their own CCS system and buying carbon credits for the excess emissions above the allowance. As a result of carbon trading scheme, the cash flows of power plants become dependent on the emission amount during operation and the price of carbon trading (Koo et al., 2011). On the other hand, the CCS installation depends on both internal and external conditions: its own performance effectiveness, economics, emission reduction target and unit price of emission allowance. The carbon trading price can be determined by the supply and demand of the allowances as any commodity market (Li et al., 2015). Allowance allocation is one of the most important policy design issues in emission trading, since the initial allocation of permits affects both fairness and market efficiency. Three major methods are available for allowance allocation: auction, criteria exogenous to the firm receiving the permits and output-based allocation (Liu et al., 2012). In this work, the allowance allocation problem is not considered, while the allowances are assumed to be provided in advance.

'Fairness' is not commonly defined and Mathies and Gudergan (2011) suggest the definition of fairness as the reasonable, acceptable or just judgment of an outcome which the process used to arrive. The fair solution suggests that all game participants can receive an acceptable or 'fair' portion of benefits. Equality, equity and exemption are considered as different but complementary notions of distributive fairness for burden sharing in international climate policy (Ringius et al., 2002). Equality means all players should have equal obligations. Equity means the costs is distributed proportionally. Exemption means the poorest countries just provide moral support instead of material contributions. Responsibilities, capabilities and needs are frequently invoked as interpretations of equity for climate change negotiation (Underdal and Wei, 2015). Five equity criterial are used to locate carbon emission reduction target to model economic performance of interprovincial CO_2 emission reduction quota trading in China, which are CO_2 emissions, energy consumption, population, GDP and per capita GDP (Zhou et al., 2013). Different marginal abatement cost curves across different provinces are constructed and applied in their work. Game theory has been applied to find the 'fair' solution, where the fair solution suggests that all game participants can receive an acceptable or 'fair' portion of benefits. A cooperative game is proposed by Rosenhal (2008) to determine the transfer prices for the intermediate products in the supply chain to allocate the net profit in a fair manner. Nash bargaining framework from cooperative Game theory has been applied for 'fair' solution in different areas, such as resources allocation problems and fair profit sharing among enterprises (Ganji et al., 2007; Gjerdrum et al., 2001; Gjerdrum et al., 2002; Yaiche et al., 2000).

Qatar is currently the highest emitter per capita, 79.3 tons per capita (Dargin, 2010), and is concerned with taking responsibility in carbon emission reduction. Fig. 1 presents the GHG emissions by subsector for Qatar in 2012 (Qatar Energy & Industry Sector, 2012), where emission from power and utilities represents 12%. Qatar became the first Gulf Cooperation Council (GCC) member to join the World Bank's Global Gas Flaring Reduction (GGFR) project which targets emission reduction by exercising tight controls on gas flaring. CCS is considered as a solution among others since it will allow Qatar to continue using the cost effective energy sources, fossil fuel, while reducing carbon emissions to the atmosphere. Although there are high emission rates in the Gulf states, the carbon trading are stated as enormous and would cut down the CO_2 emissions while generation revenue for renewable energy projects (Qatar Energy & Industry Sector, 2012).

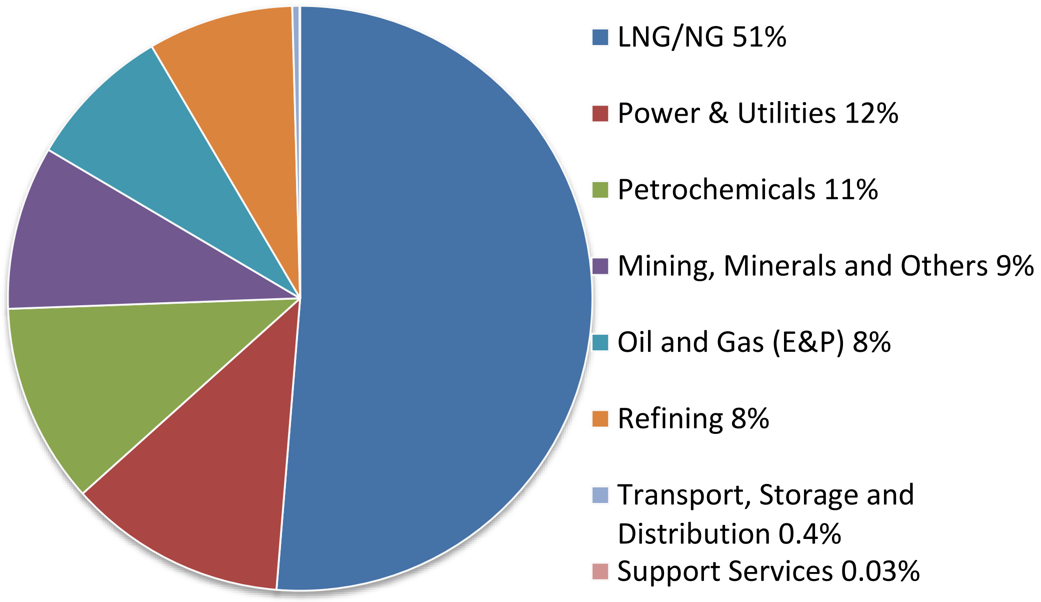


Fig. 1. GHG emission by subsector in 2012 (Qatar Energy & Industry Sector, 2012)

There are some recent works addressing the design of CCS infrastructure with carbon trading effects. Kuby et al. (2011) propose an MILP model to optimise a CCS infrastructure network while considering pricing CO_2 emissions through a tax or a cap-and-trade system. Johnson and Ogden (2011) examine the CCS infrastructure development under the cap-and-trade programme with specific bonus. And the proposed optimisation model analyses if the projected allowance prices will support the CCS deployment without the bonuses. CO_2 allowances are considered in a CO_2 value chain optimisation work for the Norwegian continental shelf (Klokk et al., 2010). Mo et al. (2015) develop a multistage decision model to analyse the time of introducing emission trading system, especially the effects on power plant CCS retrofit decisions, plant CO_2 emissions and net present value (NPV). Carbon trading scheme is also addressed in the studies of supply chain optimisation (Chaabane et al., 2012; Giarola et al., 2012; Zakeri et al., 2015). However, only one site or the total cost is minimised rather than considering the individual cost of each member within the carbon trading network. By applying carbon trading among power plants, the power plants can be taken as collaborative networks. All the power plants have their own objectives and constraints which make them compete with other power plants, but they will obtain better benefits via cooperation. In this work, we design a comprehensive integrated CCS infrastructure under carbon trading, which selects the CO_2 resources (power plants) to be captured with available capture technologies and materials, and designs the transportation pipeline network to connect the resources with the sequestration and/or utilisation sites based on the work of Hasan et al. (2014). The proposed MILP model decides whether it is beneficial for the CO_2 resources to be involved into a CCS system or buy CO_2 credits from other entities. Fair design of CCS infrastructure for power plants in Qatar is determined by determining the carbon trading price and the annual transferred amount among power plants under two fairness scenarios: same saving ratio and game theoretical Nash approach (Gjerdrum et al., 2001).

2 Mathematical model

In this work, a mathematical MILP optimisation model is developed for the fair design of integrated carbon capture, transport and storage infrastructure in Qatar under carbon trading scheme. It determines the emission capture locations and the capture amount of each power plant with CCS. CO_2 transportation pipeline network is obtained between various sources and sinks based on their distances and geographic situations. The locations of the sinks are selected as well as the amount of injection at each reservoir. The carbon credit trading prices and the transferred amounts are determined to obtain fair cost distribution among power plants.

The overall optimisation problem can be stated as follows:

Given (a) for each source (power plant): its location, annual CO_2 emissions without CCS, emission rate based on power output, CO_2 compositions in the flue gas, power generation capacity; (b) capture and compression technologies, corresponding materials and costs; (c) CO_2 pipeline cost based on distance; (d) for each sink (utilisation or sequestration): its type, location, annual CO_2 storage estimation, storage limit and injection costs; (e) CO_2 selling price to the utilisation; (f) available carbon credit trading prices among power plants; (g) carbon credit price from abroad;

Determine (a) CO_2 capture amount of each source; (b) CO_2 capture technology and its corresponding material; (c) sinks to be selected; (d) CO_2 storage amount in each sink; (e) pipeline network connecting source and sink; (f) carbon credits amount to sell/buy for carbon trading among power plants; (g) carbon credit trading prices among power plants; (h) carbon credits amount to sell/buy from abroad;

In order to find the multi-participant strategies which result in optimal, fair cost distribution among power plants within the CCS system.

The notation used in the MILP model is given below:

Indices	
i	source, power plant
j	CO_2 capture level
k	carbon trading price levels available between sources
m	capture material
s, s'	sink, site for geological storage or utilisation
t	capture technology
Sets	
TM_i	sets of CO_2 capture technology *t* with capture material *m* that can be used in source *i*
Parameters	
$C_{total}^{\min}$	minimum total cost (\$)
$C_{total}^{\max}$	maximum total cost (\$)
$C_i^{\max}$	maximum cost limit of source *i* (\$)
$C_i^{\min T}$	cost of source *i* from minimising the total cost (\$)
C_{iq}	cost of source *i* at each separable piece *q* (\$)
$\overline{E}_i$	CO_2 emission allowance cap value for source *i* (ton/year)

M_{ij}	CO_2 mass flow rate for source *i* at capture level *j* (ton/year)
N	big number
p^{buy}	CO_2 credit buying price ($/ton)
p^{sell}	CO_2 credit selling price ($/ton)
$p^{utilisation}$	CO_2 utilisation price ($/ton)
P_i	power generation of source *i* (MWh)
$P_i^{\max}$	maximum power generation of source *i* (MWh)
$T_{ii'}^{U}$	upper bound of carbon trading from source *i* to source *i'* (ton/year)
φ_i	power consumption rate of CCS for source i
ε_i	CO_2 emission rate of source i (ton CO_2/MWh)
Variables	
B_i	bought carbon credits from abroad of each power plant *i* (ton/year)
C_i	total cost of each power plant *i* ($/year)
CC_i	carbon capture and compression cost of each power plant *i* ($/year)
CT_i	carbon trading cost of each power plant *i* ($/year)
DC_i	dehydration cost of each power plant *i* ($/year)
E_i	CO_2 direct emissions from source *i* (ton/year)
LC_i	levelised pipeline cost of each power plant *i* ($/year)
LJ_i	levelised injection cost of each power plant *i* ($/year)
r_i	carbon trading price of source *i* ($/ton)
$\bar{r}_k$	carbon trading price at level *k* ($/ton)
RE	revenue from CO_2 utilisation ($/year)
S_i	sold carbon credits to abroad of each power plant *i* (ton/year)
$T_{ii'}$	carbon trading amount from source from source *i* to source *i'* (ton/year)
$\bar{T}_{ii'k}$	linearised carbon trading amount from source from source *i* to source *i'* at *k* price level (ton/year)
TC	total cost ($/year)
δ_i	the cost difference between the target cost and optimal cost of source *i* ($)

ϕ	objective value
λ_{sq}	these are SOS2 special ordered variables (Brooke et al., 2008), where at most two variables can take on non-zero values and the two non-zero values have to be adjacent.
Binary variables	
H_i	1 if source *i* buy carbon credits from other sources or abroad, 0 otherwise.
Y_{ijtms}	1 if source *i* at capture level *j* capture CO2 with technology *t* and material *m* is linked to sink *s*, 0 otherwise.
Z_{ik}	1 if source *i* with transfer price level *k* is selected, 0 otherwise.

2.1 CO_2 balances

The CO_2 emission balance for each power plant is given in Eq.(1), where the total emissions minus the carbon allowance, which is the amount the power plant needs to pay for, equals to the amount captured by the CCS system, carbon credit bought from abroad and other domestic power plants, minus the carbon credit sold abroad and to other domestic power plants. However, for each power plant, it is not allowed to sell carbon credits to other power plant before it reaches its own allowance level. Also carbon credits cannot be bought from other sites and sold to abroad at the same time. The binary variable H_i is introduced to ensure that the above two conditions are satisfied by using the two constraints in Eq.(2) and (3).

$$E_i - \bar{E}_i = \sum_{j,(t,m)\in TM_i,s} M_{ij} Y_{ijtms} + B_i - S_i + \sum_{i'} T_{i'i} - \sum_{i'} T_{ii'} \qquad \forall i \tag{1}$$

$$B_i + \sum_{i'} T_{i'i} \le N H_i \qquad \forall i \tag{2}$$

$$S_i + \sum_{i'} T_{ii'} \le N(1 - H_i) \qquad \forall i \tag{3}$$

2.2 Carbon trading

The carbon trading price is calculated based on the price selection among the available carbon trading price:

$$r_i = \sum_k \bar{r}_k Z_{ik} \qquad \forall i \tag{4}$$

For each sink, no more than one transfer price level can be chosen:

$$\sum_k Z_{ik} \le 1 \qquad \forall i \tag{5}$$

The amount of carbon trading is the sum of amounts traded at each carbon trading price level *k*:

$$T_{ii'} = \sum_{k} \overline{T}_{ii'k} \qquad \forall i, i' \tag{6}$$

The upper bound for the amount of carbon trading transferred between sources is introduced, which limits the transferred amount from each carbon trading level.

$$\sum_{i'} \overline{T}_{ii'k} \leq T^{U} Z_{ik} \qquad \forall i \tag{7}$$

Hence, the total carbon trading cost for each source is:

$$CT_i = \sum_{i',k} \overline{T}_{i'ik} \overline{r}_i - \sum_{i',k} \overline{T}_{ii'k} \overline{r}_k \qquad \forall i \tag{8}$$

2.3 Total cost of each power plant

The cost of each power plant is calculated in Eq.(9), it equals to the overall cost of the carbon capture and storage system, which includes the total system cost, including the dehydration cost, carbon capture cost, CO_2 transportation cost, CO_2 injection cost, and international and domestic carbon trading cost, minus the overall system revenue, which is the international and domestic carbon trading revenue and CO_2 utilisation revenue. The detail calculation of each cost term is given in Appendix A based on the CCUS model proposed in (Hasan et al., 2014).

$$C_i = DC_i + CC_i + LC_i + LJ_i + p^{buy} B_i - p^{sell} S_i + CT_i - p^{utilisation} RE_i \qquad \forall i \tag{9}$$

The total cost of all the power plants is calculated as below:

$$TC = \sum_{i} C_i \tag{10}$$

2.4 Power generation constraints

The CCS technologies are quite energy intensive, e.g. the process of chemical absorption with different solvents needs heat in the reboiler to heat up the solvent, provide heat for desorption and produce steam to strip CO_2 from the solvent. Current post combustion capture technology will reduce the electricity output from power plants by about 20% (Lucquiaud and Gibbins, 2011; Peeters et al., 2007). So when CCS is installed and operated, the total power generation rate would increase to cover the original power output, while the total power generation rate (including the energy consumption for the CCS) should be limited by the power plant designed capacity as:

$$P_i + \varphi_i P_i \sum_{j,(t,m)\in TM_i,s} R_{ij} Y_{ijtms} \le P_i^{\max} \qquad \forall i \tag{11}$$

Because of the energy consumption for CCS, more CO_2 has been emitted based on the total power generation amount:

$$\hat{E}_i = \varepsilon_i (P_i + \varphi_i P_i \sum_{j,(t,m)\in TM_i,s} R_{ij} Y_{ijtms}) \qquad \forall i \tag{12}$$

2.5 Objective functions

If only the total cost TC is minimised in Eq.(13) subject to the constraints in Eqs.(1)-(12) and Eqs.(A.1)-(A.12), the cost distribution C_i may not be distributed fairly and there is possibility that some power plant would sacrifice their own benefits to obtain the mutual benefits.

$$\min \quad TC \tag{13}$$

s.t. $C_i \le C_i^{\max} \qquad \forall i$

However, each single sink yields their own minimum costs and they will bargain for their own benefits, which requires an approach that produces a fair cost distribution subject to similar overall performance. In this work, fair cost distribution is obtained under two fairness scenarios: cost distribution with the same saving ratio and under game theory Nash approach.

Under the same saving ratio, the objective of the problem is to obtain the cost of each power plant close to the fixed target cost. The target cost of each power plant is determined by the ratio of cost savings compared with the current cost value $C_i^{\max}$, which is obtained when no CCS system is available and all power plants bought carbon credits from the international market. $C_{total}^{\max}$ is the sum of $C_i^{\max}$ and $C_{total}^{\min}$ is obtained by minimising the total cost of the whole system while the CCS and carbon trading is allowed. In this way, the cost savings from utilising CCS and carbon trading is distributed with the same saving percentage.

$$\delta_i \ge C_i / C_i^{\max} - C_{total}^{\min} / C_{total}^{\max} \qquad \forall i \tag{14}$$

$$\delta_i \ge C_{total}^{\min} / C_{total}^{\max} - C_i / C_i^{\max} \qquad \forall i \tag{15}$$

$$\min \quad \phi_1 = \sum_i \delta_i \tag{16}$$

The mathematical program in Eq.(16) should be solved subject to the constraints in Eqs.(1)-(12), (14), (15) and Eqs. (A.1)-(A.12).

Under game theory Nash approach, the objective is to maximise the product of the deviations of the given maximum cost of each sink. Each sink yields minimum cost while trying to maximise the objective value in Eq.(17).

$$\max \quad \phi_2 = \prod_{i} (C_i^{\max} - C_i) \tag{17}$$

Using the separable programming approach, the objective function is converted to:

$$\max \quad \hat{\phi}_2 = \sum_{i} \sum_{q=1}^{m} \mu_{iq} \lambda_{iq} \tag{18}$$

where $\hat{\phi}_2 = \ln \phi_2$ and μ_{sq} are parameters given by $\mu_{sq} = \ln(C_i^{\max} - C_{iq})$, C_{sq} are taken according to the upper bounds $C_i^{\max}$ and 0.

$$\sum_{q=1}^{m} C_{iq} \lambda_{iq} = DC_i + CC_i + LC_i + LJ_i + p_1 B_i - p_2 S_i + CT_i - p_3 RE_i \qquad \forall i \tag{19}$$

$$\sum_{q=1}^{m} \lambda_{iq}\,{}_{i} = 1 \qquad \forall i \tag{20}$$

$$\lambda_{iq} \geq 0 \qquad \forall i, q \tag{21}$$

The mathematical program in Eq.(18) through (21) should be solved subject to the constraints in Eqs.(1)-(12) and Eqs.(A.1)-(A.12), Eq.(18) being the linear approximation to Eq.(17).

3 Power plants in Qatar

Qatar currently has 29 power plants, including 15 power plants consuming natural gas, 3 consuming oil and 1 using solar radiation (Enipedia, 2015). In this work, 18 power plants are considered and their information is given in Appendix B. The $P_i^{\max}$ values are obtained there by considering the operation hours as 8000 hours per year. It assumes that there are 9 sequestration sites (S1 –S9), which are marked in Fig. 2 along with the 18 power plants. S1-S6 are onshore while S7-S9 are offshore. The proposed model has been implemented for a CCS integrated infrastructure with 18 power plants in Qatar under the following major assumptions:

- There are 9 locations available for CO_2 sequestration, which avoid the agriculture areas and are selected based on population density in Qatar.
- CO_2 composition of flue gas from each power plant is among 4-10% (Hasan et al., 2014).

- The pipeline costs for offshore sinks are 1.5 times of those for the offshore sinks.
- There are no limits for buying carbon credits from abroad for Qatar.
- No carbon credits can be sold to other country.
- Carbon credits can be traded between power plants.

Different carbon capture technologies, including pressure sing adsorption (PSA), vacuum swing adsorption (VSA) and membrane, have their suitable materials. Some alternative materials are given in Table 1, such as monoethanolamine (MEA) and piperazine (PZ), while 13X, AHT, MVY and WEI are known as zeolites. For each combination, it deals with CO_2 capture of feed CO_2 composition within specific range. It also results in different investment and operating costs.

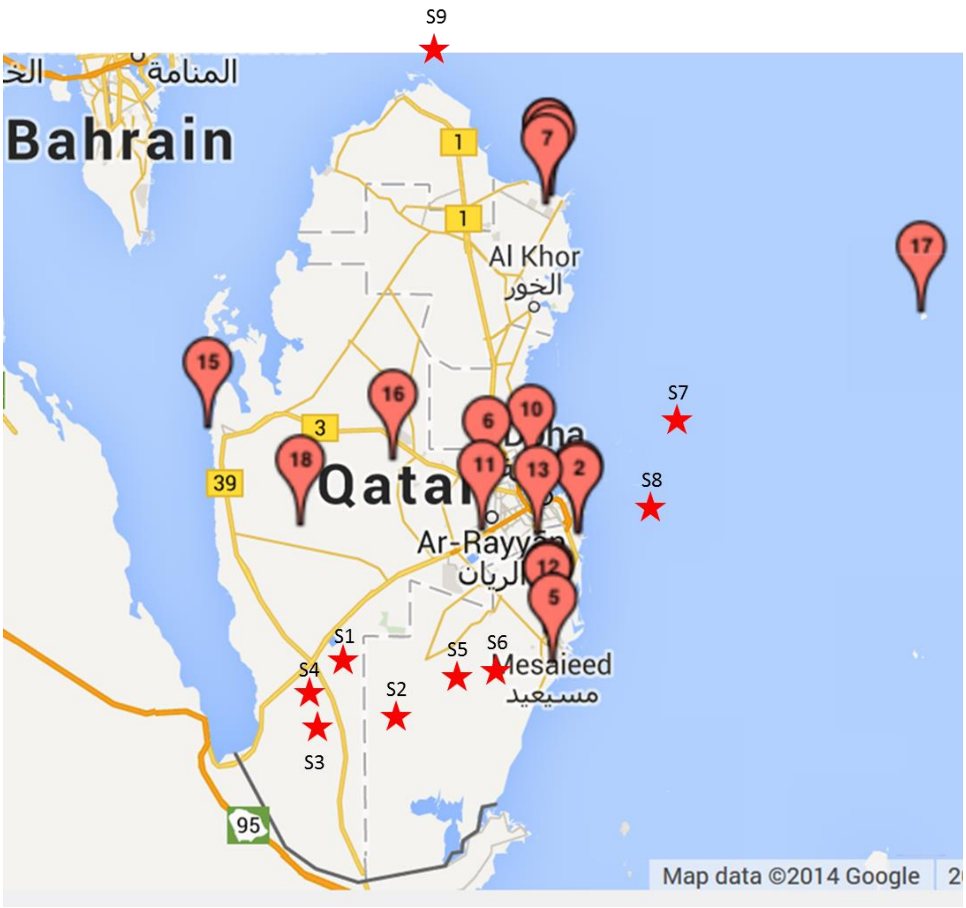


Fig. 2. Power plants and sequestration/utilisation sinks in Qatar (Enipedia, 2015)

Table 1 Carbon capture technology and material (Hasan et al., 2014)

Process	Material	CO_2 composition
Absorption	MEA	0.01-0.7
	PZ	0.01-0.7
	13X	0.1-0.7
PSA	AHT	0.05-0.7
	MVY	0.05-0.7
	WEI	0.05-0.7
VSA	13X	0.1-0.7
	AHT	0.1-0.7
	MVY	0.1-0.7
	WEI	0.1-0.7
Membrane	FSC PVAm	0.3-0.7
	POE-2	0.3-0.7
	POE-1	0.3-0.7

4 Computational results for the indicative example

In this work, different optimal CCS infrastructures are obtained by minimising total cost under four scenarios:

Scenario 1: No domestic carbon trading among power plants

Scenario 2: Domestic carbon trading is allowed but without fairness concern

Scenario 3: Fair cost distribution under the same saving ratio

Scenario 4: Fair cost distribution under Nash approach

4.1 CO_2 capture with different CO_2 caps

CO_2 emission allowance cap values are assumed as 30%, 50% and 70% of the annual emissions of each power plant. Carbon capture amount depends on the CO_2 credit price, the total cost of the CCS system is minimised by considering CO_2 credit price ranging from 1 to 100 \$/ton CO_2. Fig. 3 (A) presents the total optimal costs of the CCS infrastructure for the 18 power plants in Qatar under different CO_2 credit prices together with the total costs without CCS infrastructure. Total captured CO_2 amount is given in (B). As indicated in the two figures, no CO_2 is captured until the CO_2 credit price is over \$ 69/ton. The increase of credit price promotes the CO_2 capture which will save money from buying CO_2 credits from abroad. The total amount of CO_2 to be captured is affected by the carbon emission allowance cap values as shown in (B). (C) presents the total CO_2 credits bought from abroad for the 18 power plants, the lower the CO_2 emission allowance cap values the more amount of CO_2 credits needs to be bought when the carbon credit price is lower than 69 \$/ton. (D) indicates the total carbon credits that can be traded within domestic carbon market under the three emission allowance cap values.

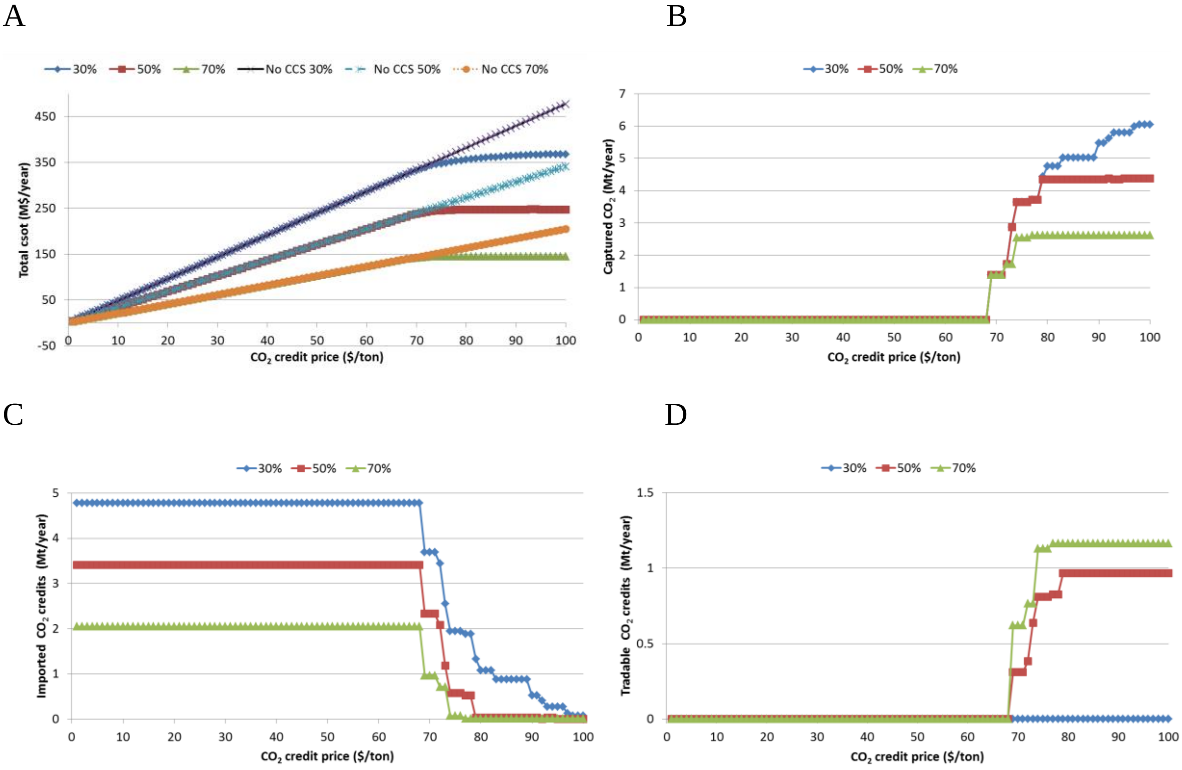


Fig. 3. (A) total cost; (B) total captured CO_2; (C) total imported CO_2 credits and (D) total tradable CO_2 credits for the CCS system

In order to evaluate the fair design of the CCS system in Qatar under CCS and carbon trading, the imported carbon credits is taken as 80 \$/ton, but all the power plants are not allowed to sell carbon credits abroad. There are 8 available carbon trading price levels, from 45-80 \$/ton with even intervals.

The values of $C_i^{\max}$ are given in Table 2, which are obtained by minimising the total cost of the whole system without CCS infrastructure and domestic carbon trading, $C_{total}^{\max}$ is 163.76 M\$/year. $C_{total}^{\min}$ is obtained by minimising the total cost of the whole system with CCS system and domestic carbon trading within Qatar. In this work, CO_2 emission allowance cap values are assumed as 70% of the annual emissions of each power plant. The total annual emissions of all the power plants are 6.84 Mt/year, so the total CO_2 needs to be captured or traded from abroad would be over 2.05 Mt/year because of the extra emissions from utilising CCS.

Table 2 Cost of each power plant under different scenarios

Power plant	$C_i^{\max}$ (M$/year)	Scenario 1 (M$/year)	Scenario 2 (M$/year)	Scenario 3 (M$/year)	Scenario 4 (M$/year)
1	30.65	30.65	29.29	27.28	27.64
2	37.19	35.15	31.25	34.35	37.15
3	20.67	20.67	18.09	18.34	19.19
4	18.97	18.97	16.60	16.79	17.62
5	8.77	8.77	7.68	7.76	7.52
6	8.64	8.63	7.56	7.67	7.26
7	8.58	8.58	7.61	7.60	6.94
8	6.86	6.86	6.00	6.07	5.39
9	4.95	4.95	4.66	4.38	3.71
10	4.64	4.64	4.06	4.11	3.48
11	3.95	3.95	3.45	3.49	2.96
12	3.67	3.67	3.21	3.24	2.75
13	2.01	2.01	1.78	1.77	1.50
14	1.84	1.84	1.61	1.63	1.38
15	1.25	1.25	1.10	1.11	0.94
16	0.60	0.60	0.53	0.53	0.45
17	0.39	0.39	0.34	0.34	0.29
18	0.14	0.14	0.13	0.13	0.11
Total	163.76	161.70	144.94	146.60	146.28

4.2 CCS infrastructure under Scenario 1: no domestic carbon trading

When the total cost is minimised in Eq. (13) subject to the constraints in Eqs.(1)-(12) and Eqs.(A.1)-(A.12), while no domestic carbon trading is allowed, the optimal CCS infrastructure is shown in Table 3. Power plants 2 and 6 choose to have their own CCS, and they transport CO_2 to sinks 8 and 6 individually. The source and sink matches are based on the distance between source and sink, shorter distance is preferred. The CCS technology and material selection is also given in the table, where absorption is selected with MEA as material for plant 2, while PSA with MVY is selected for power plant 6. For both power plants, 40% of their emissions are captured which are the amounts of CO_2 over the assigned carbon trading caps (70%). In total, 0.69 Mt/year CO_2 has been captured, which includes the 30% emissions over the caps and the emissions from CCS utilisation. Furthermore, since the CCS capture efficiency is 90%, more emissions needs to be captured to cover the losses. All other power plants except these two power plants keep buying carbon credit from the international market rather than having their own CCS systems. The cost of each power plant is provided in Table 2, and the total cost is 161.70 M$/year which is 2.06 M$/year less than the cost $C_{total}^{\max}$, 163.76 M$/year, where no CCS is available as shown in the second column. Only the two power plants with CCS reduce their total costs, and all other power plants have the same costs as $C_i^{\max}$

Table 3 CCS integrated infrastructures under different scenarios

Scenario	Power plant	Capture level	Capture Technology	Material	Sink	Total capture amount (Mt/year)
1	2	0.4	Absorption	MEA	S8	0.56
	6	0.4	PSA	MVY	S6	0.13
2	1	1	Absorption	MEA	S9	1.15
	2	1	Absorption	MEA	S8	1.39
	13	1	PSA	MVY	S8	0.08
3	2	1	Absorption	MEA	S8	1.39
	3	1	Absorption	MEA	S8	0.78
	6	1	PSA	WEI	S6	0.32
4	1	0.9	Absorption	MEA	S9	1.03
	2	0.9	Absorption	MEA	S8	1.26
	6	1	PSA	MVY	S6	0.32

4.3 CCS infrastructure under Scenario 2: with domestic carbon trading but no fairness concern

When the total cost is minimised in Eq. (13) subject to the constraints in Eqs.(1)-(12) and Eqs.(A.1)-(A.12), but domestic carbon trading is allowed, the optimal CCS infrastructure is shown in Table 3. Power plants 1, 2 and 13 choose to have their own CCS. Sinks 9 and 8 are selected for CO_2 storage. The three power plants choose to have the capture levels 100%, which are higher than the CO_2 amounts they need to reduce. In total 2.62 Mt/year are captured with absorption and PSA technologies. The cost of each power plant is provided in the fourth column of Table 2, and the total cost is 144.94 M$/year which is about 10% less than that without domestic carbon trading, 161.70 M$/year. However, as shown in Table 4, the costs are distributed without considering the saving ratios, $(C_i^{\max} - C_i)/C_i^{\max}$, which vary among all power plants. Fair cost distribution among power plants is required.

Table 4 Saving ratios $(C_i^{\max} - C_i)/C_i^{\max}$ under Scenario 2

Power plant	Saving ratio	Power plant	Saving ratio	Power plant	Saving ratio
1	4%	7	11%	13	11%
2	16%	8	13%	14	13%
3	12%	9	6%	15	12%
4	12%	10	13%	16	12%
5	12%	11	13%	17	13%
6	13%	12	13%	18	7%

4.4 CCS infrastructures under Scenario 3 and 4: with domestic carbon trading under fairness concerns

The developed MILP models for fair cost distribution are implemented using CPLEX 12.6.3.0 in GAMS 24.7.1 (www.gams.com) (Brooke et al., 2008) on a PC with an Intel(R) Core(TM) i7-4770 CPU, 3.40 GHz CPU and 16.0 GB of RAM. Under the same saving ratio fairness scenario, there are 2,315 equations, 63,111 continuous variables and 17,082 discrete variables and it takes about 156*s* CPU time. Under the Game theory Nash approach fairness scenario, there are 2,315 equations, 63,380 continuous variables and 17,082 discrete variables and it takes 54*s* CPU time.

Under Scenario 3, by applying the proposed model in Eq.(16) subject to the constraints in Eqs.(1)-(12), (14), (15) and Eqs. (A.1)-(A.12), the optimal design of the CCS infrastructure with domestic carbon trading at the same saving ratio is obtained as presented in Table 3. Power plants 2, 3 and 6 choose to have CCS systems with capture level 100%. Power plant 2 and 3 select MEA as absorption material and transport the CO_2 to sink 8. Power plant 6 selects PSA and transport the CO_2 to sink 6. The total cost of the integrated CCS infrastructure is 146.60 M$/year, which is slightly higher than that from Scenario 2 (144.94 M$/year) and about 9% savings than that without domestic carbon trading under Scenario 1. Under the proposed same saving ratio objective, the costs of all the power plants are distributed based on the same saving ratio as shown in the fifth column of Table 2. The cost of each power plant is close to its corresponding assigned target. The differences between the cost and target value of each power plant are presented in Fig. 4. Cost of power plant 2 varies with the biggest δ value among all power plants. The carbon trading prices between power plants and the annual carbon trading amounts are presented in Fig. 5. Power plants 2 and 3 sell carbon credits at the carbon trading prices 65 $/ton and 75 $/ton individually, while both power plant 6 sells carbon credits at 80 $/ton. Power plant 2 sells 224 kton/year carbon credits to power plant 1 and 99 kton/year to power plant 4, which is more than half of its total sold carbon credits (620 kton/year). For power plant 3, it mainly sells the carbon credits to power plant 4 and 5, and the remaining 143 kton/year carbon credits are shared by seven other power plants. Power plants 1 is the only customer of power plant 6. In total 1,108 kton/year of captured carbon emissions are sold as credits by the four power plants with CCS under the domestic carbon trading scheme. Under this scenario, seven power plants in total have imported 107 kton/year carbon credits from abroad at the carbon credits price 80 $/ton. The carbon credits are mainly imported by power plants 8 and 10.

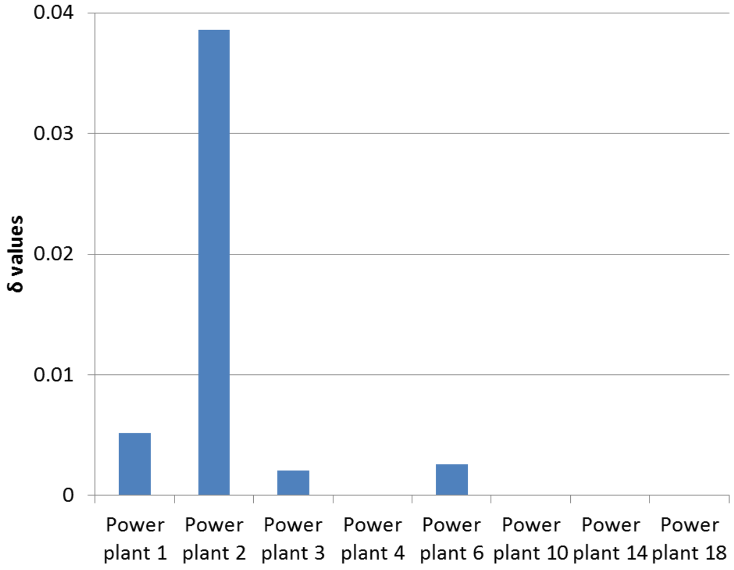


Fig. 4. δ_i value of each power plant under Scenario 3

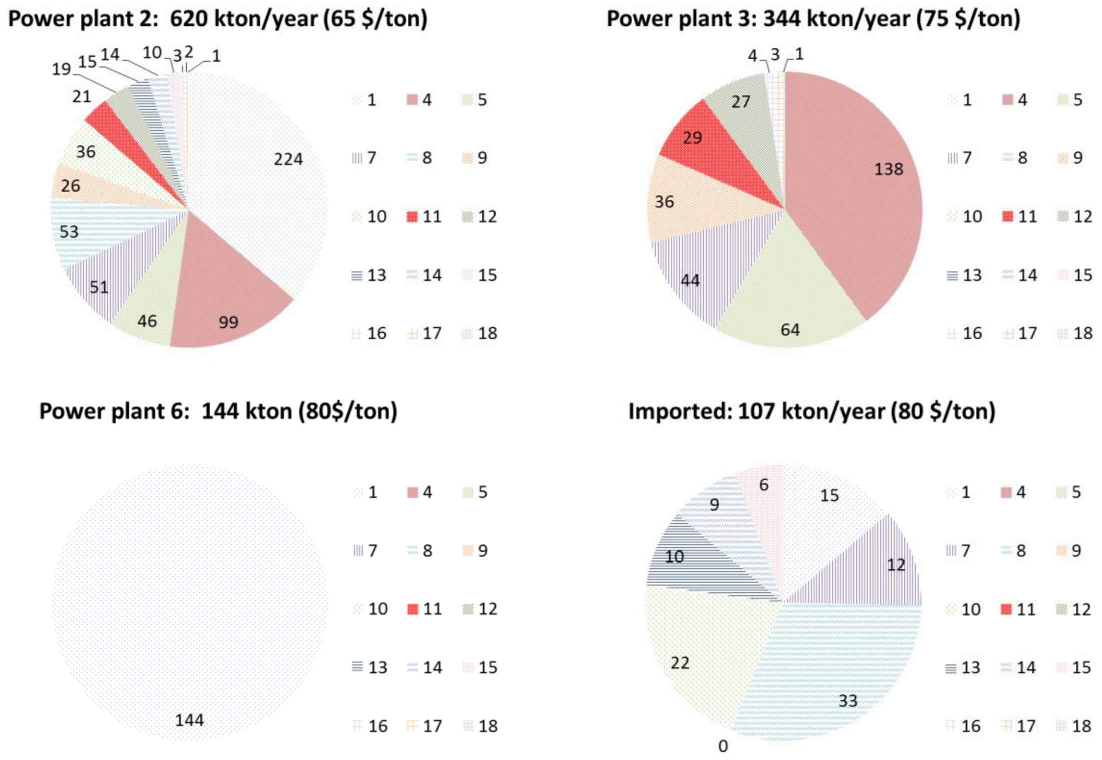
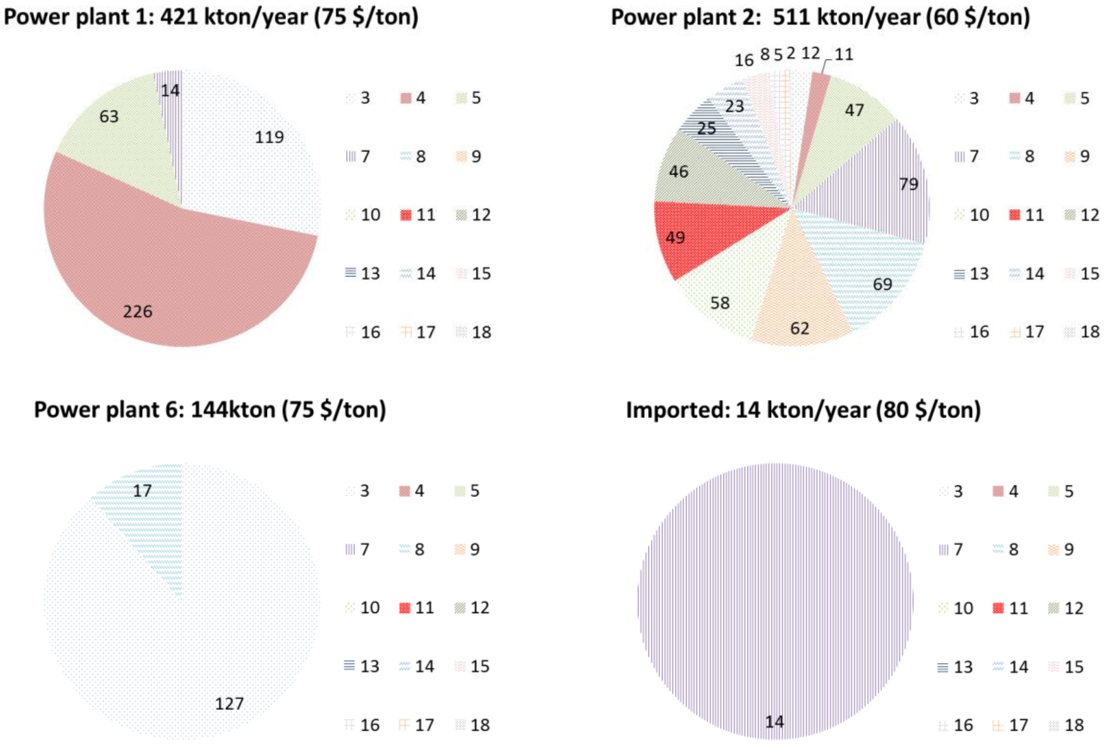


Fig. 5. Carbon trading prices between power plants and annual carbon trading amounts under Scenario 3

Under Scenario 4, the fairness is defined by the game theory Nash approach, the mathematical program in Eq.(18) through (21) are solved subject to the constraints in Eqs.(1)-(12) and Eqs.(A.1)-(A.12). The optimal design of the CCS infrastructure is also given in Table 3. Power plants 1, 2 and 6 choose to have their own CCS systems, where both power plants 1 and 2 select MEA as absorption material while power plant 6 selects MVY as PSA material. The total cost of the integrated CCS infrastructure is 146.28 M$/year. The cost distribution of the 18 power plants is presented in the last column in Table 2. Cost of each power plant has been reduced from the upper bound values, $C_i^{\max}$ as shown in the table. Fig.6 shows the carbon trading prices between power plants and the annual carbon trading amounts. In total the three power plants sell 1,077 kton/year carbon credits to the other power plants which is less than that from scenario 3. These power plants select different carbon trading prices, 75, 60 and 75 $/ton respectively. Power plant 2 has more carbon credits to sell compared with the other two power plants. Power plants 3 and 4 are the main buyers among all the other power plants and about 45% total domestic tradable carbon credits are obtained by them. Power plant 7 solely imports the carbon credits from abroad with the amount of 14 kton/year at the price of 80 $/ton, while all other power plants only buy carbon credits domestically. The two fairness scenarios result in different CCS infrastructures with different carbon trading amounts under different carbon trading prices. Fig. 7 presents the two infrastructures, for both scenarios some carbon credits have to be imported from abroad and power plant 2 and 6 are selected to install CCS and sell carbon credits to other power plants. Meanwhile, sink 6 and 8 are the main reservoirs for CO_2 storage.



Power plant 1: 421 kton/year (75 $/ton)

Power plant 2: 511 kton/year (60 $/ton)

Power plant 6: 144kton (75 $/ton)

Imported: 14 kton/year (80 $/ton)

Fig. 6. Carbon trading prices between power plants and annual carbon trading amounts under Scenario 4

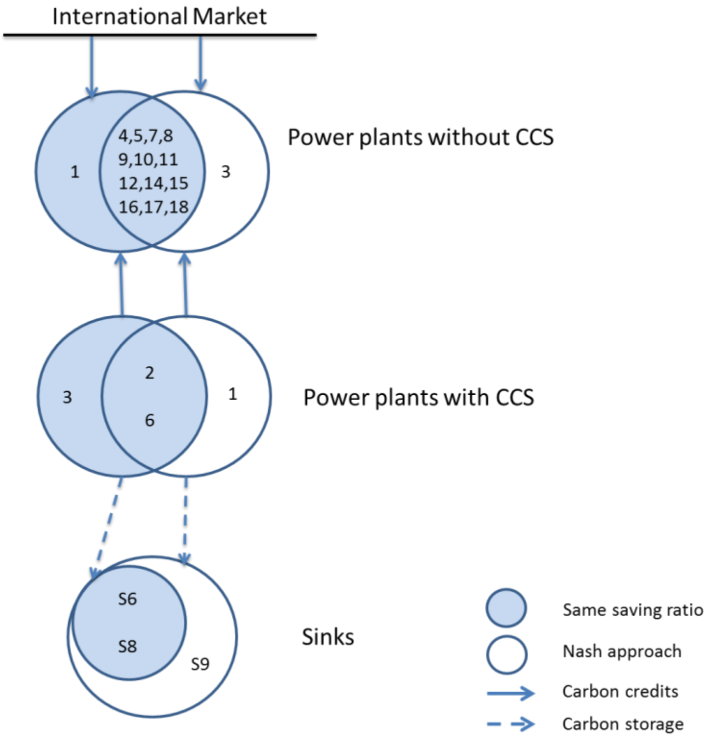


Fig. 7. CCS infrastructures under Scenario 3 and 4

5. Concluding remarks

An MILP model has been proposed for the optimal design of integrated carbon capture, transport and storage infrastructure in Qatar. Under the carbon trading scheme, power plants with higher emission are promoted to invest on the CCS system with higher capture rate and the extra carbon credits can be sold to other power plants. In this way, higher CO_2 capture rate can be obtained domestically rather than buying carbon credits from the international market. The power plants with CCS system can benefit from selling carbon credits and on the other hand the emissions of the other power plants can be limited within the assigned cap with lower expenses. It should be mentioned that the fairness metric used does affect the optimal design of the CCS infrastructure among the 18 power plants. In this work, two alternative fairness metrics have been investigated: same saving ratio and game theory Nash approach. Under scenarios 3 and 4, the total costs are slightly higher than that from minimising the total cost to obtain the fair cost distribution. The cost distributions among the power plants under the two fairness scenarios vary resulting from the selected CCS systems, carbon trading prices and transfer amounts between power plants. Three power plants determine to install CCS systems, while other power plants buy the carbon credits from those power plants or abroad to fulfil their carbon allowance requirements. Meanwhile, power plants with CCS systems obtain economic benefits by selling the credits.

The future work includes pipeline network investigation, such as the location of pumps and connection of pipelines of different sizes. Other emitters, including refineries and chemical factories, can be added as sinks to CCS infrastructure under the carbon trading scheme. Power generation distribution among power plants can also be considered since they have different carbon emission rates. Moreover, optimal CCS design under multi-period will be modelled based on minimising the total cost while considering the operating lives of sources and sinks at different time periods. The installation and operation of the components within the CCS infrastructure will be determined. Environmental issue can also be included to the optimal design of the integrated CCS infrastructure.

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Appendix A: CCUS supply chain model based on the work of Hasan et al. (Hasan et al., 2014)

The additional notations are given as:

Sets:

U	sets of utilisation sink

Parameters:

C^{base}	base cost for CO_2 pipeline capital cost calculation ($/km)
CCR	capital charge rate per year of total ownership of cost
d_s	the well depth of sink *s* (km)
F_i	total flue gas flow rate from source *i* (mol/s)
IC_{ijtm}	investment cost of source *i*, with capture level *j*, using capture technology *t* with material *m* ($/year)
L^{base}	base length for CO_2 pipeline calculation (km)
L_{is}	direct distance between source *i* and sink *s* (km)
$M_i^{source\min}$	minimum CO_2 capture capacity for source *i* (ton/year)

M^{base}	CO_2 base flow for pipeline capital cost calculation (ton/year)
$M_s^{\sin k\max}$	maximum designed capacity for sink *s* (ton/year)
$M^{well\max}$	maximum injection capacity of a well (ton/year)
m_1, m_2	cost parameter for well construction and injection
n_{tm}	capture and compression investment cost factor for technology *t* material *m*
n'_{tm}	capture and compression operation cost factor for technology *t* material *m*
$n_{ij}^{injection}$	the number of wells required for injecting CO_2 from source *i* at capture level *j*
OC_{ijtm}	operation cost of source *i*, with capture level *j*, using capture technology *t* with material *m* ($/year)
$OM^{pipling}$	operation and maintenance cost rate per year of TOC for pipelines ($/year)
P^D	dehydration cost per ton of CO_2 ($/ton)
q_{tm}	capture and compression investment cost factor for technology *t* material *m*
q'_{tm}	capture and compression operation cost factor for technology *t* material *m*
R_{ij}	source *i* CO_2 capture level *j*
x_i	flue gas CO_2 composition from source *i*
$\alpha, \beta, \gamma, n, q$	model parameters for different capture technologies with different materials, which are estimated using the maximum likelihood parameter estimation for the best fit.
η	CO_2 flow rate scaling factor
η^{CCS}	CO_2 capture efficiency
ν	distance scaling factor

A.1 Cost of flue gas dehydration

All saturated flue gases from stationary sources are assumed to be dehydrated using the TEG-absorption. Extra cost included in the CO_2 capture and compression cost based on the flue gas. The cost is computed based on a saturated flue gas from a power plant.

$$DC_i = \sum_{j,(t,m)\in TM_i,s} M_{ij} Y_{ijtms} P^D / \eta^{CCS} \qquad \forall i \tag{A.1}$$

A.2 Cost of CO_2 capture and compression

The optimum investment and operation costs for different capture technologies can be calculated based on the flue gas CO_2 composition and respective technology, including absorption, membrane, PSA and VSA processes. CO_2 is captured from the dehydrated feed and compressed for sequestration at 150 bar. The investment cost (IC) and operating cost (OC) can be calculated as:

$$IC_{ijtm} = \alpha_{tm} + (\beta_{tm} x_i^{n_{tm}} + \gamma_{tm})(F_i R_{ij})^{q_{tm}} \quad \forall j, i, (t,m) \in TM_i \tag{A.2}$$

$$OC_{ijtm} = \alpha'_{tm} + (\beta'_{tm} x_i^{n'_{tm}} + \gamma'_{tm})(F_i R_{ij})^{q'_{tm}} \quad \forall j, i, (t,m) \in TM_i \tag{A.3}$$

The total cost for CO_2 capture and compression is:

$$CC_i = \sum_{j,(t,m) \in TM_i, s} (IC_{ijtm} + OC_{ijtm}) Y_{ijtms} \qquad \forall i \tag{A.4}$$

The conversion from flue gas flow rate to CO_2 mass flow rate is given below:

$$M_{ij} = F_i R_{ij} x_i \eta^{CCS} * \frac{44 * 3600 * 24 * 365}{10^6} \quad \forall i, j \tag{A.5}$$

A.3 Cost of CO₂ transportation

The total levelised piping cost is calculated based on the distance between the sources and sinks as:

$$LC_i = \sum_{j,(t,m) \in TM_i, s} (CCR + OM^{piping})[C_{base}(\frac{M_{ij}}{M^{base}})^{\eta}][L_{is} \times 10^3 (\frac{L_{is}}{L^{base}})^{\nu}] Y_{ijtms} \qquad \forall i \tag{A.6}$$

A.4 Cost of CO₂ injection

The cost of CO_2 injection for sequestration includes the levelised costs of CO_2 injection and construction of new walls.

$$LJ_i = \sum_{j,(t,m) \in TM_i, s} (CCR + OM^{injection})(m_1 d_s + m_2) n_{ij}^{injection} Y_{ijtms} \qquad \forall i \tag{A.7}$$

The number of wells required for injecting CO_2 from source *i* at level *j* as:

$$n_{ij}^{injection} = \frac{M_{ij}}{M^{well\,\max}} \qquad \forall i, j \tag{A.8}$$

A.5 Revenue from CO₂ utilisation

The revenue from CO_2 utilisation comes from selling high purity CO_2 to the prospective CO_2 utilisation sites.

$$RE_i = \sum_{j,(t,m) \in TM_i, s \in U} M_{ij} Y_{ijtms} P^{utilisation} \qquad \forall i \tag{A.9}$$

A.6 Related constraints

For each source, at most one technology with one material can be selected over different CO_2 recovery levels and it can only be transferred to no more than one sink.

$$\sum_{j,(t,m) \in TM_i, s} Y_{ijtms} \le 1 \qquad \forall i \tag{A.10}$$

The total amount of CO_2 stored in each sink needs to be limited within its designed capacity.

$$\sum_{j,i,(t,m)\in TM_i} M_{ij} Y_{ijtms} \leq M_s^{\sin k \max} \qquad \forall s \tag{A.11}$$

For each source, the captured amount of CO_2 should be over the minimum capture unit capacity:

$$\sum_{j,(t,m)\in TM_i} M_{ij} Y_{ijtms} \geq \sum_{j,(t,m)\in TM_i} M_i^{source\min} Y_{ijtms} \qquad \forall i \tag{A.12}$$

Appendix B: Power plants in Qatar (Enipedia, 2015)

	Power plant	Capacity (MW)	Fuel_types	Output (MWh)	CO_2 (Mt)	Maximum output (MWh)	Carbon emission rate (kg CO_2/MWh)	Lat	Lon	X_{co2} (%)
1	"Ras Laffan-a Powerplant"	756	Natural Gas	3711940	1.28	6048000	344.83	25.92	51.55	6
2	"Ras Abu Fontas B1 Powerplant"	985	Natural Gas	3490870	1.55	7880000	444.02	25.20	51.62	5.6
3	"Ras Abu Fontas A Powerplant"	626	Natural Gas	1850900	0.86	5008000	464.64	25.21	51.62	5.2
4	"Ras Laffan-b Powerplant"	1025	Natural Gas	1688810	0.79	8200000	467.79	25.92	51.55	4.8
5	"Umm Said Refinery Powerplant"	128	Natural Gas	734945	0.37	1024000	503.44	24.92	51.56	4.4
6	"Al-wajbah Powerplant"	301	Natural Gas, Oil	723120	0.36	2408000	497.84	25.30	51.40	8
7	"Ras Laffan Rasgas Powerplant"	330	Natural Gas	718016	0.36	2640000	501.38	25.89	51.54	4
8	"Qafco Works Powerplant"	-	-	563471	0.29	676165	514.67	24.99	51.55	4
9	"Ras Laffan Qatargas Powerplant"	187	Natural Gas	396416	0.21	1496000	529.75	25.91	51.56	4
10	"Ras Abu Aboud Powerplant"	-	-	369993	0.19	443992	513.52	25.32	51.51	4
11	"Saliyah Powerplant"	134	Natural Gas, Oil	310524	0.16	1072000	515.26	25.21	51.39	4
12	"Mesaieed Qvc Powerplant"	-	-	286768	0.15	344122	523.07	24.99	51.55	4
13	"Doha South Super Powerplant"	67	Natural Gas, Oil	149590	0.08	536000	534.80	25.19	51.52	10
14	"Umm Said Qapco Powerplant"	-	-	136098	0.08	163318	587.81	25.00	51.55	4
15	"Dukhan Field Powerplant"	44	Natural Gas	90051	0.05	352000	555.24	25.42	50.75	4
16	"Maersk Qatar Powerplant"	-	-	40943	0.03	49132	732.73	25.35	51.18	4
17	"Halul Terminal Powerplant"	-	-	25319	0.02	30383	789.92	25.67	52.42	4
18	"Abu-samra Powerplant"	-	-	10503	0.01	12604	952.11	25.22	50.97	4