CHEMICAL ENGINEERING TRANSACTIONS

VOL. 83, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš
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ISBN 978-88-95608-81-5; **ISSN** 2283-9216

DOI: 10.3303/CET2183005

Investment Decision Making for Carbon Capture and Storage Technology in High Efficiency, Low-Emission Coal-fired Power Plant via Dynamic Techno-Economic-Policy Evaluation Framework: Case Study in China

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There are significant uncertainties pertaining to the future of coal power generation across the globe and especially for China. Being one of the largest coal consumers and CO_2 emitters, China aims at addressing its national energy security while ensuring to achieve sustainable operations. In following its commitments to the Paris Agreement and in pursuit of near-zero emissions from power plants, China has actively moved towards high efficiency, low emission (HELE) coal-fired power plants. However, HELE technology alone cannot completely cut carbon emissions, and will require a mature CO_2 emissions reduction technology such as carbon capture and storage (CCS) to significantly reduce the CO_2 emissions within short to medium term. This paper conducts a preliminary evaluation for investment in HELE coal-fired power plant with CCS (HELE-CCS) in China, under the context of the Shenzhen emissions trading scheme. We carry out this preliminary analysis through mixed-integer non-linear programming (MINLP) framework, and by using publicly available power generation and carbon pricing data. Based on hypothetical scenarios, a HELE coal-fired power plant is found to contribute 55 % profit by selling the electricity. However, a substantial CO_2 emissions cost is incurred due to the installation of CCS, leading to a high caution on investment. A more detailed analysis is warranted using real power plant data to confirm real business feasibility of HELE-CCS, including an expansive set of scenarios that also assess relevant appropriate government incentives and subsidies as well as variant financial models.

1. Introduction

Coal is still dominating the world's energy mix even though tremendous initiatives have been conducted to promote renewable and alternative energy resources. This scenario is due to increasing populations and rapid urbanization/industrialization, all which are resulting in enhanced energy demands. High efficiency, low emission (HELE) coal-fired power plants have emerged as one of the technological solutions to overcome this contemporary issue. Nevertheless, HELE technology alone is unable to completely mitigate greenhouse gas carbon emissions. Mature CO_2 emissions mitigation technologies such as carbon capture and storage (CCS) are considered a key to significantly reduce the emissions within short to medium terms. In a joint climate statement with the USA (November's Joint Announcement, The White House, 2016), the Chinese President Xi proclaimed to implement a national Emission Trading Scheme (ETS) (cap-and-trade scheme). This consequently meant that China would become the world's largest carbon market, after the EU ETS. This declaration has sparked interest in studies related to ETSs and their implications on China's economic, political, social, environmental and technology transitions. Deng and Wen (2019) suggested that China should learn from existing international carbon trading policy (e.g. EU ETS, California's cap-and-trade system) to minimize market risks and to ensure a successful implementation of national carbon trading scheme. Prior studies have also proven that preliminary design of carbon emissions schemes such as 'carbon emissions trading only covering the pilots' (Cui et al., 2014) and 'unified carbon emissions trading market' (Song et al.,

Paper Received: 26/06/2020; Revised: 23/09/2020; Accepted: 30/09/2020
Please cite this article as: Abdul Manaf N., Abbas A., 2021, Investment Decision Making for Carbon Capture and Storage Technology in High Efficiency, Low-Emission Coal-fired Power Plant via Dynamic Techno-Economic-Policy Evaluation Framework: Case Study in China, Chemical Engineering Transactions, 83, 25-30 DOI:10.3303/CET2183005

2018) can provide future insights on the health development of China's emissions trading market. On the other hand, many studies have also been conducted pertaining to the diffusion of CCS technology in China. A real option approach was used by Wang et al. (2016) to analyse the investment decision of CCS by considering net present value and uncertainty factors including carbon price, fuel price, investment cost and government subsidy. Their study found that the increment on carbon price and government subsidy were able to offset the cost of emission reduction and capital cost of integrated plant (power plant integrated with post-combustion carbon capture (PCC)). They suggested that this coincides with increased investment opportunity of CCS towards the transition of clean coal technologies. Similarly, positive investment decision can be obtained if reasonable subsidy is provided to the coal-fired power plant with 20 % carbon emissions reduction based on China scenario in year 2030 (Chen et al., 2016). Recently, Ye et al. (2019) conducted a techno-economic analysis of a 600 MW supercritical plant with and without CCS located in China. They observed that the depreciation rate plays an important role in the economic assessment of carbon costs as well as to the investment option of CCS. High carbon price was required to ensure profitable investment of CCS. Nevertheless, the contribution of the capture and transportation stages towards global warming potential (GWP) will require construction of environmentally sustainable sorbents to ensure positive impact of the CCS technology diffusion in a near future (Zhang et al., 2019). All studies to date have dealt with several important uncertainties (i.e. carbon price, subsidies and so on) all while considering steady state/semi-dynamic scenarios, which increases the possibility to cause bias on the investment decision making. This current work is undertaken to underpin existing studies by demonstrating a framework under dynamic scenario analysis. The scenario involves utilization of time-transient uncertainties (hourly basis) such as carbon price, electricity price and load demand, all in China for the context of the cap-and-trade policy framework in Shenzhen. The present work extends authors' previous work (Abdul Manaf and Abbas, 2019) by also considering capital cost of CCS and cost of CCS control and monitoring system (C & M).

2. Methodology

2.1 Dynamic techno-economic-policy evaluation framework

A genetic algorithm (GA) with mixed-integer non-linear programming (MINLP) optimisation is formulated to predict investment opportunity of CCS based on a Shenzhen China scenario. This optimization-based framework is built on a temporal model of HELE-CCS plant and incorporates economic, environmental and policy dynamic constraints. This techno-economic-policy evaluation framework is adapted and improved from authors' previous work (Abdul Manaf and Abbas, 2019). It comprises an optimization for net load matching mode with the aim (objective function) to maximize plant net profit (economic) as shown in Figure 1.

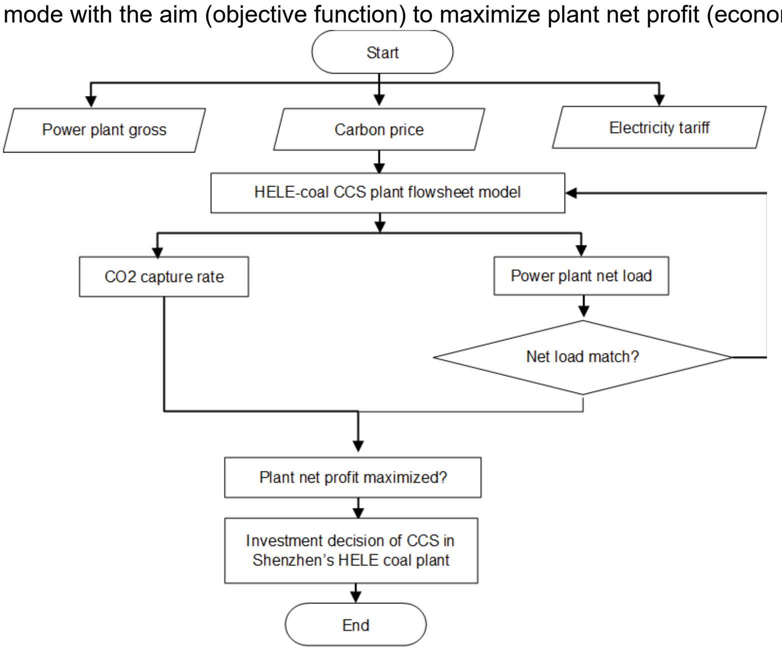

Figure 1: A dynamic techno-economic-policy evaluation framework of HELE-CCS plant

The framework generates two outputs; power plant net load and CO_2 capture rate. These outputs are estimated based on the three inputs fed into the framework which are power plant gross load, electricity tariff and carbon price at 30-min interval time. This framework is implemented in the software Matlab (Mathworks, USA). It involves execution of an optimization algorithm via a single computational technique. The computation time required for one scenario (one full year) is approximately 4–6 d. In this work, the operation of hybrid HELE-CCS plant are simulated under two scenarios of the present (2019) and forecast (2030) years. Dynamic data reflecting Shenzhen's techno-economic-policy uncertainties are quantitatively appraised to examine the CCS investment decision via energy consumption rate (corroborates with power plant net load), CO_2 capture rate and net profit composite.

2.1.1 Shenzhen cap-and-trade

Shenzhen's ETS pilot is managed and monitored by the National Development and Reform Commission (NDRC) which is responsible for the development of climate change policy in China. Each pilot applied different size of cap and carbon price depending on the type of industries involved and economic structure of the province. Table 1 delineates a cap-and-trade design formulated in MINLP model. Emission penalty is obtained from China Emission Exchange (2014) while other parameters are extracted from the existing information available in other China ETS pilot plants (e.g. Hubei, Beijing). In this work, Shenzhen is selected as a case study since the city is a pioneer in Chinese ETS pilot plant and has the largest historical carbon prices.

Table 1: Preliminary information for the coal-fired power plant imposed with ETS (cap-and-trade)

Project location	Cap (t CO_2/y)	Penalty	Free Allowance by government
Shenzhen	50,000	3 x market price	60 % from the emission cap

2.1.2 Yearly HELE-CCS plant net profit

CCS capital investment cost is extracted from studies conducted by Li et al. (2011). In this work, CCS capital cost component included pipeline (onshore and offshore) and injection costs to illustrate an actual total cost imposed to the investor. Cost of (C & M) is adapted from Jorge (2009). This cost includes service-oriented market and categorized under the service operator. One must take note that the cost assumptions made in this work are intended to reflect expectation of the future, based on the best information available at the time of writing.

2.1.3 Input variables

Three variables (dynamic inputs) are considered in this investment decision evaluation: electricity tariff, carbon price and gross load demand. These three inputs have been selected due to their significant impact towards HELE coal-fired plant operation (supply and demand) and for consideration of CCS installation. Variation of electricity tariff and gross load demand may affect the power plant revenue and operation (Abdul Manaf and Ali Abbas, 2019), while fluctuation of carbon prices can jeopardize the feasibility (in economic aspect) of CCS technology in the long term (Wang et al., 2016). Electricity tariff in China is strictly regulated by the state government andt was charged at low rate and relatively more stable (Fan et al., 2014). This is for public appeasement and to prevent triggering elevation of inflation rates. Shenzhen's electricity tariff for year 2019 is recorded at 52 CNY/MWh (CEIC, 2020) and data for carbon price are extracted from China Emission Exchange (2020). Coal specific cost for 2019 is at 2.5 CNY/GJ (Smil, 1988). Coal price is adopted from old resource due to the credibility of the suggested price to be accommodated with the HELE-coal plant model. Based on the new electricity distribution price, historical electricity tariff for year 2015, 2016 and 2017 are at 143.5 CNY/MWh, 143.3 CNY/MWh and 142.8 CNY/MWh (China Daily, 2015).Due to a scarcity of resources, those aforementioned was adopted to estimate the electricity tariff for year 2030 which is expected to reduce at 0.1 % (based on the percentage difference between 2015 to 2017) from 2019 onwards. This percentage estimation is underpinned with the study conducted by Huang et al. (2015) where they anticipated that the electricity production between 2013 to 2027 will keep stable. Similar assumption is made for forecasting carbon price (2030) since Shenzhen carbon trading scheme is already considered mature enough to sustain the trading process. Forecast carbon price is estimated to be reduced at 0.1 % from present year (2019). Due to limited information in obtaining actual gross load demand in Shenzhen HELE coal plant, plant gross load was estimated by using simple correlation between Shenzhen's temperature (Weather Atlas, 2020) and energy demand, based on the fact that electricity demand is driven by the discomfort created by the temperature difference. This concept is proven based on the study conducted by Staffell and Stefan (2018). These three forecast inputs are considered reliable since those values are estimated from the present/historical trend by assuming minimum fluctuation in Shenzhen's economic portfolio in year 2019 until 2030.

2.2 Investment decision procedure

The main objective of this work is to estimate an investment opportunity of CCS technology for rapid investment decision by evaluating three criteria which are energy consumption rate, CO_2 capture rate and net profit composite. In this work, HELE coal power plant is assumed to has built-in flexibility to be retrofitted with CCS. The investment decision is based on first year operation of CCS by assuming commissioning and testing has been done earlier and 5 % interest rate on the capital cost is incurred for 20 y. Annualized CCS and C&M costs are considered to ensure both costs are deducted from the net revenue of HELE coal-plant at the end of the financial year (assuming December 2019 and 2030). Take note that this study proposes investment decision making based on short term period (one year, in hourly basis). By means, all composited costs of plant revenue are calculated in hourly basis as illustrated in Eq(1).

$$D_t = \prod(P_c, P_e, P_f) = Max\{\int P_e * (Q_e - Q_p) * dt - \int (P_c * Q_c) * dt - \int (3 * P_c * Q_{ce}) * dt - HELE_{op} - CCS_{op} - CCS_{cap} - C\&M_{cap}\} \quad (1)$$

where Π depicts annual revenue of HELE coal-plant, P_e, P_c and P_f denote time-dependent electricity tariff, carbon and coal prices. The Q_e, Q_p, Q_c and Q_{ce} represent electricity output, total power penalty, CO_2 emissions below allowable cap and CO_2 emission exceeding allowable cap.. $HELE_{op}$, CCS_{op}, CCS_{cap} and $C\ \&\ M_{cap}$ represent, coal plant operating cost, CCS operating cost, annualized CCS capital cost and annualized cost of C & M. All costs in 2030 are calculated based on the economic projection cost method via inflation rate. To drive CCS deployment towards zero emission from HELE coal plant, the improved evaluation framework is designed to maximize annual plant revenue by meeting the energy demand (gross load).

3. Result and discussions

3.1 Energy and CO_2 capture performance of HELE-CCS plant

In this work, investment decision is made based on the performance of HELE-CCS plant on technical terms such as energy and CO_2 capture performance, on yearly basis. Energy performance is reflected by the reboiler thermal duty of retrofitted plant, where steam is extracted from the HELE turbine system to assist in the desorption regeneration process. Whilst CO_2 capture performance is evaluated based on yearly amount of CO_2 captured. Both criteria are appraised based on the trend and demand of uncertainties in key dynamic variables (e.g. carbon price, electricity tariff and load demand) in year 2019 and forecast year 2030. As illustrated in Figure 2, HELE coal plant emits almost the same amount of CO_2 in present and forecast years while only capturing approximately 25 % of the CO_2 emissions.

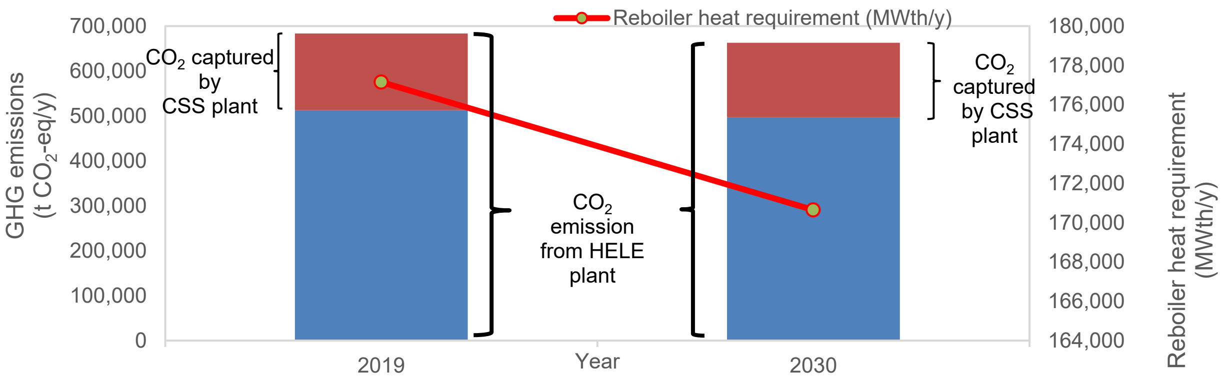

Figure 2: Energy and CO_2 capture performances of HELE coal-CCS plant

This is due to the similarity of the dynamic variables featured in both years. There is enhanced energy performance in HELE-CCS plant in year 2030 operation compared to present operation reflected in 4 % improvement. Based on this prediction, it is relevant to take a negative investment decision for CCS-retrofitted since the plant unable to give significant operational (technical) and environmental contribution to HELE coal plant.

3.2 Net profit composite HELE coal-CCS plant

Plant's net profit composite is used to determine investment decision of CCS from short term economic point of view as illustrated in Figure 3. It can be observed that HELE coal plant contributed approximately 55 %

profit from selling the electricity (CoE: cost of electricity) subjected to electricity and fuel costs at contemporary and forecast market conditions. While cost of CO_2 emission features predominant composition (averaged 40 %) from the net profit composite which lead to negative continuity of the CCS project installation subsequently showed deficit in net profit of plant in year 2019 and 2030.

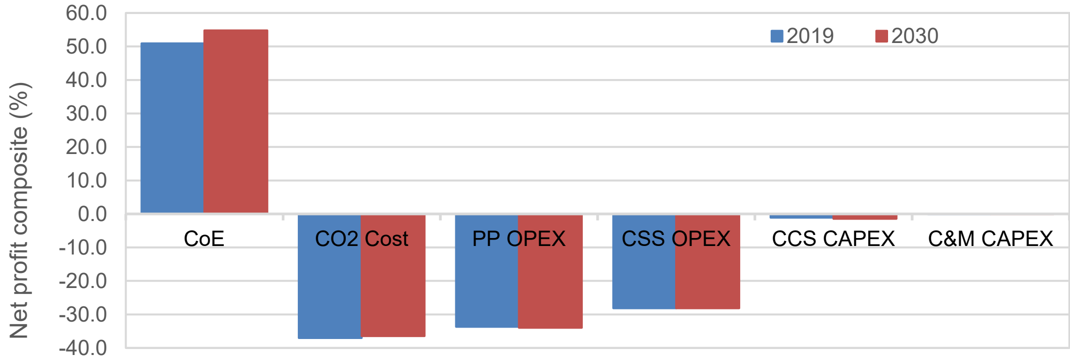

Figure 3: Net profit composite of HELE coal-CCS plant.

3.3 Cap and trade profile of HELE coal-CCS plant

Reliability of CCS investment option is conducted via policy evaluation such as cap and trade scheme. Figure 4 shows cap and trade profile in 2019 and 2030.

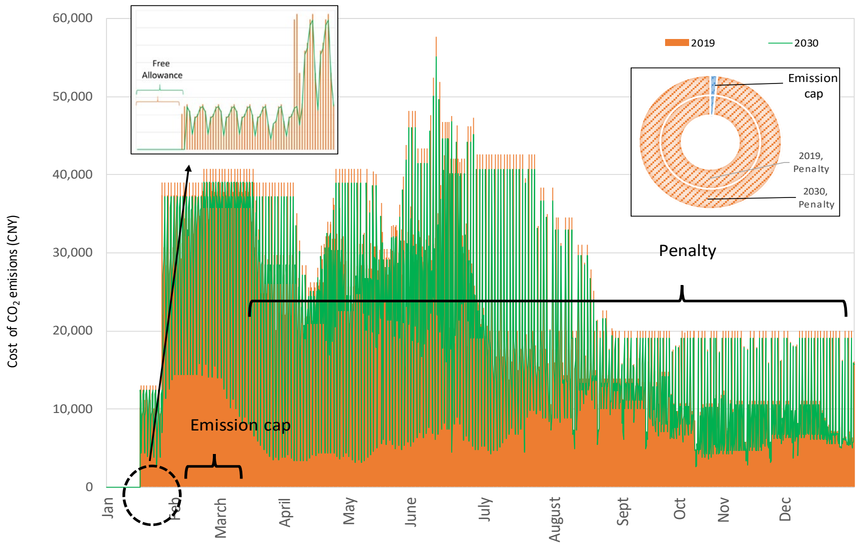

Figure 4: Cost of CO_2 emission based on cap and trade scheme for HELE coal-CCS plant

It can be seen that HELE coal plant reached 60 % free allowance and emission cap in the month of January and February in 2019 and 2030. Based on this projection, HELE coal plant requires to pay huge amount of carbon credit with enormous penalty due to the excessive amount of CO_2 emissions throughout the year, which render negative investment opportunity for CCS plant underpinning the analysis from net profit composite (Section 3.2). These circumstances influence by several aspects such as low carbon price and electricity tariff. It is anticipated that to encourage CCS installation, carbon price should be high enough to motivate maximum capacity of CCS plant (e.g. at > 90 % capture rate) between 99 CNY/t (Cui et al., 2014) and 293 CNY/t (USD 41/t) (Hu and Zhai, 2017).

4. Conclusions

Based on the contemporary and forecast hypothetical scenarios (2019 and 2030), CCS has negative investment opportunity due to insignificant capture percentage (25 %) and energy performance (4 %) and imposition of substantial cost of CO_2 emission. This is due to uncompetitive carbon price and electricity tariff at point of time, CCS operation being unable to achieve profitable operation in 2019 and 2030. To ensure a positive investment of CCS in the future and relevancy of this technology towards sustainable development goal, a pragmatic approach is required. For instance, government can provide subsidy, tax reduction as well as maximizing the carbon price.

Acknowledgments

Authors wishing to acknowledge financial support from Universiti Teknologi Malaysia through Tier 2, project no Q.K130000.2643.15J77.2

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