Applied Energy 169 (2016) 912–926

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Temporal multiscalar decision support framework for flexible operation of carbon capture plants targeting low-carbon management of power plant emissions

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HIGHLIGHTS

- Real-time decision support framework for coal power plants with carbon capture.
- Framework consists of multiple time scale levels.
- Revenue maximized under variability in actual electricity and carbon prices.
- Optimized net operating revenue (profit or loss) simulated over full year: 2011 and 2020.
- Framework is competitive asset for carbon trading under emissions trading schemes.

ARTICLE INFO

Article history:
Received 9 October 2015
Received in revised form 7 February 2016
Accepted 8 February 2016
Available online 2 March 2016

Keywords:
Carbon capture
Modelling
Optimization
Flexible operation
Carbon price
Emissions trading scheme

ABSTRACT

A real-time control-optimization framework previously developed across multiple time scales is used for the analysis of power plant net operating revenue when retrofitted with a carbon capture plant. This framework which features high sample frequency commensurate with electricity dispatch and control instrumentation levels is proposed as a decision support tool for flexible operation of the carbon capture plant while considering electricity and carbon price dynamics. This paper presents the results of implementing this framework for operational flexibility of solvent-based post-combustion CO_2 capture (PCC) process in response to power plant dynamic loads (load following and unit turndown). An integrated plant (power plant with PCC) subject to forecast 2020 electricity and carbon prices is shown to generate yearly net operating revenue of approximately 12% of the gross revenue. While, the same integrated plant generates net operating revenue loss of roughly 13% under 2011 electricity and carbon prices. These results underpin the strategy that employs the proposed optimization-based control framework for flexible operation of a PCC plant in the year 2020, because such framework captures financial benefits hidden in the dynamics of electricity load, electricity and carbon price trends, and does so at high temporal resolution.

1. Introduction

Low emissions fossil fuel technologies such as post combustion CO_2 capture (PCC) are expected to play a significant role in combating climate change. Recently, the United Kingdom introduced a 'carbon capture ready' power plant (applicable for a new plant) as a solution towards catastrophic global warming [1]. Most countries are still considering the integration of PCC into existing power plants as an approach to climate change. Thus, the implementation of PCC plant into large-scale industry requires comprehensive managerial studies which cover technical, economic, social, policy, safety and environmental issues/perspectives.

Extensive studies have been conducted related to management strategies of power plants associated with PCC processes. This covers the investment decisions via carbon policies/prices and subsidy [2–10], plant profitability [5,11,12] and fuel switching [13,14]. Brouwer et al. [9] investigated flexible operations of power plants (PC, NGCC and GT associated with CCS) in the future to cope with the economic forecast and future low-carbon electricity system in Netherlands for years 2030 and 2050. An integrated optimization model known as MARKAL-NL-UU and REPOWER was used to predict future power plant portfolios, CO_2 prices and hourly commitment and dispatch of generation units. The analyses indicated that

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http://dx.doi.org/10.1016/j.apenergy.2016.02.052

Nomenclature

AEMO	Australian energy market outlook
CET	carbon emission trading
CCS	carbon capture storage
CE3METL	Chinese energy economy environmental model with endogenous technological change by employing logistic curves
EDF	electricity demand fulfilled
EGCM	electricity generation and CO_2 mitigation
ESP	electrostatic precipitator
ETS	emission trading scheme
EU ETS	European Union Emission Trading Scheme
FGD	wet limestone flue gas desulfuration
GDP	gross domestic product
GT	gas turbine
MINLP	Mixed Integer Non-linear Programming
NGCC	natural gas combined cycle
PCC	post combustion CO_2 capture
PP	power plant
PC	pulverized coal
SCR	selective catalytic reduction
TIMES	Bottom-up partial equilibrium optimization model used to estimate energy dynamics in local, national or multi-regional energy systems over a long term, multi-period time horizon, developed by energy technology systems analysis program (ETSAP)

the present market design (2010) of energy based power sector was incompatible for the future low-carbon scenarios. The energy generation from future low-carbon power systems was found to incur an additional cost amounting to approximately 25% of the Baseline scenario (no CO_2 emission cap and government action imposed) due to the price of CO_2. In terms of operational flexibility, pulverized coal power plants associated with CCS featured high capacity factors which required high electricity prices (>€75/MW h) to recover the preliminary investment in 25 years. Whilst, new NGCC and GT plants associated with CCS were found to be unprofitable due to the low capacity factors and its character as the price setters. Huang et al. [10] evaluated the investment decision of abatement technology diffusion in Shenzhen coal-fired power plant (for short and long terms) under regional climate policy ETS. They analyzed scenarios involving three carbon prices (70, 110, and 30 ¥/tonne-CO_2e) for seven (short-term) and nine (long-term) types of abatement technologies based on the change of net present value (ΔNPV). It showed that for a short-term (2013–2015) investment, conversion of condensate pumps featured as a lucrative investment with and without ETS. While, for a long-term (2013–2027) investment, potential abatement technologies provided significant investment benefit subject to ETS. These abatement technologies included conversion of condensate pumps, increase of nameplate capacity, flow passage transformation of steam turbine, transformation for increasing unit safety and economy and intelligent soot blowing system for boilers and steam cooling system. Moreover, various ranges of carbon prices showed significant influence on the abatement technology decision for a short and long-term investment time frames.

Recently, a sophisticated bottom-up integrated optimization model (namely CE3METL and China TIMES) encompassing multiple types of Chinese energy systems (at local, national and multi-regional levels) and abatement mitigation strategies subject to multi-period time horizon was utilized to envisage the future potential of CCS installations in China's power sector [8,15]. Zhu et al. [8] developed three major scenarios which included introduction of various emission constraints, government subsidies and CO_2 utilization to predict future implementation of CCS towards emissions reduction in China. They indicated that the best case for CCS technology diffusion is under CO_2 utilization with no emission constraints. In contrast, imposition of emission constraints on a power plant with CCS negatively impacted CCS deployment in China. In a different study, implementation of CCS appeared to be economically feasible subject to 40–45% of carbon intensity reduction rates. In this scenario, power systems were capable of mitigating almost 47% of CO_2 emissions compared to the reference scenario (reference scenario: carbon intensity reduction at 45%) [15]. These two studies elucidated that the emission constraint and carbon capture profile/rate is of vital importance in determining the investment decision of CCS technology. To date, many studies have used carbon capture rate/profile as a stochastic variable, where the capture rates are predetermined in order to predict the investment opportunity of CCS. This is to ensure that the outcome can accommodate the predetermined capture rate profile. However, in a real application, imposing the emission/carbon constraints on the integrated plant (power plant with CCS technology) may cause interruption in plant operation, making it technically impractical. For instance, a predetermined emission constraint may require intermittent operating revision if the following scenarios are to occur: revamp/abolishment of existing climate change policy due to the major political transition, fluctuation of electricity and carbon prices due to power outage and volatility on commodity markets (abrupt change in carbon/fuel prices). Thus, this present work features a novelty by allowing this integrated plant (power plant associated with CCS technology) to operate optimally and flexibly under prevailing unprecedented economic/energy changes (represented by electricity prices) and climate policy (denoted by the carbon prices) without requiring frequent major technical and operational changes to the plant. Moreover, under this proposed optimal/flexible operation, the power system still generates substantial net operating revenue which is a criterion of principal concern to managerial personnel and technology investors.

In the same line of thought, there were studies used to predict the carbon price/allowance rate corresponding to the plant operation and economic objectives, for instance, in [16,17]. They predicted that the CCS technology faced high investment risk in the future (2030) at a carbon price of or below €47.88/tonne-CO_2 [17] while was profitable at the carbon price between €65 and €115/tonne-CO_2 [16]. These two outcomes were based solely on statistical and hypothetical analyses instead of real circumstances of the country in which CCS technology was to be deployed. Essentially, carbon prices are regulated by the government or international related bodies where these prices are dependent on several uncertainties, for instance, demand in carbon credits, a country's emissions reduction target and GDP levels [18]. Thus, this work fills in the gap in the existing research studies by utilizing a real-time carbon price market (based on historical carbon price data) for targeting the low-carbon management of power plant emissions instead of predicting the carbon price to satisfy business demands as explained earlier.

Seven key uncertainties for innovation of CCS have been identified in [19], with economic and financial viability being one of the key uncertainties indicated. This risk is further influenced by a wide-range of climate policies, for example the Clean Development Mechanism (CDM) defined in the Kyoto Protocol, the European Union Emission Trading Scheme (EU EST) and the Carbon Pricing