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Power system planning with emission constraints: Effects of CCS retrofitting

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ABSTRACT

Today, the world's energy needs are still supplied mainly from fossil fuel based resources. This is true for electricity generation as well, thus making the power sector responsible for 45% of greenhouse gas emissions. The present climate crisis has made it necessary to minimise emissions in power generation, with low-carbon energy sources taking on greater significance in recent years. However, most low-carbon sources have inherent problems, like intermittency and high capital expenditure. A suitable alternative is carbon capture and storage (CCS) technology which allows continued fossil fuel-based electricity generation at much lower rates of emission. Two approaches are possible in the deployment of CCS technology. The first is to introduce new power plants equipped for carbon dioxide (CO_2) capture, while systematically shutting down existing coal power plants. Another is to retrofit existing power plants for CO_2 capture. These approaches are compared in this work. The study shows that allowing CCS retrofitting of existing power plants can reduce the overall cost requirement significantly. In addition, a sensitivity analysis is also done to study the effect of nuclear energy on the overall energy mix.

Keywords: Emissions targeting; Power system planning; Carbon capture and storage (CCS); Optimisation; Indian energy sector; Cost minimization

1. Introduction

Sustained economic growth is placing enormous demand on the world's energy resources. Economic development, betterment of living standards, rapid industrialisation, spread of energy access, rise in per capita energy consumption, etc. are the important factors to substantially increase the total demand for energy in general and electricity, in particular. The global primary energy consumption has risen from 435×10^{18} joules in 2002 to 539×10^{18} joules in 2010, which is a 24% increase in just 8 years (EIA, 2012). At the same time, the threat of global warming is making carbon dioxide (CO_2) reduction a pressing issue. Current annual emissions now exceed 30 Gt/y of CO_2, while atmospheric CO_2 levels recently exceeded 400 ppm (UNEP, 2013). This poses a great concern as carbon intense fossil fuels are our major source for electricity generation. It is, therefore, necessary to balance electricity generation and emission reduction.

Carbon dioxide reduction in power generation sector can be achieved in a number of ways. The overall efficiency of power generation can be improved by good housekeeping, reduction of transmission and distribution losses, improved processing scheme, etc. For example, in a conventional coal power plant, 1% efficiency improvement decreases CO_2 emission by 2.5–3% (Boulet et al., 2010). However, such changes have only a limited effect. Installation of renewable energy sources with low or zero carbon emission is another solution to the problem. While very low emissions are possible using renewable sources, these are, in general, capital-intensive and fluctuating in nature. Also, a sudden and complete departure from the fossil fuels is not practical, especially in developing countries where growing populations and rising standards

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Nomenclature

C	cost ($)
CF	capacity factor
CRF	capital recovery factor ($year^{-1}$)
EF	emission factor (t CO_2/MWh)
F_d	total electricity demand (MWh)
F_{rmax}	maximum potential capacity of a power plant (MWh)
f_j	electricity flow from existing power plant *j* to demand (MWh)
f_{jw}	unutilised capacity of existing power plant *j* (MWh)
f_i	electricity flow from new power plant *i* to demand (MWh)
N	total number of plants
P	power plant capacity (MW)
t CO_2	tonnes of carbon dioxide

Subscripts

c	coal
ccs	carbon capture and storage
d	demand
MW	per megawatt
max	maximum
o&m	operation and maintenance

of living result in rapid increases in energy demand. This disadvantage can be overcome with the help of carbon capture and storage (CCS) technologies. These techniques allow the continued use of fossil fuels, while reducing the CO_2 emissions drastically. However, CCS is also capital-intensive. Furthermore, carbon capture (CC) also causes parasitic loads in electricity production, effectively reducing the overall efficiency of power generation (Tan et al., 2009; Cormos et al., 2011). These two factors eventually translate into higher power generation costs. To address the problem of electricity generation at lower emission rates, it is necessary to combine various methods of power generation and emission reduction to obtain an economically viable solution.

A great deal of work has been done in this area. For example, Elkamel et al. (2009) postulated a mixed integer linear programming (MILP) model for finding the least cost energy mix given a carbon dioxide reduction target. The model was applied to a power system operated by Ontario power generation in Canada. The study brought out the importance of fuel balancing in emission reduction. Muis et al. (2010) carried out a study on Malaysian energy sector with emission targeting constraint using mixed integer linear programming (MILP). The objective was to minimise operating cost of all existing power plants, retrofit cost of existing power plants, annualised capital cost and operation and maintenance (O&M) cost of new power plants. The new power plants considered are renewable or fossil fuel based with integrated gasification combined cycle (IGCC) technology. The constraints considered were those imposed by demand, availability of fuel, and power plant availability. It was observed that IGCC, biomass and nuclear power plants dominate the energy mix for 30% emission reduction. At 50% emission reduction, landfill gas became competitive viable option. However, solar energy was found to be unsuitable due to high capital cost and low conversion efficiency. A similar study was done on the Chinese power sector by Han et al. (2011). An MILP model was proposed to study the power sector in 2020 with 2005 as base year. It was concluded that a 40–45% reduction in emission intensity is possible by shifting from carbon intense fuels to renewable based power generation. Shammakh and Mohammed (2011) proposed an MILP model for sulphur dioxide (SO_2) targeting in power sector and applied to Ontario power generation, Canada. Three options were considered for reducing SO_2 emission; namely, fuel switching, fuel substitution, and conventional flue gas desulphurisation. Various MILP based models have also been developed to study emission constrained energy sector planning, e.g., market allocation model (Watcharejyothin and Shrestha, 2009; Shrestha and Rajbhandari, 2010; Mondal et al., 2010), integrated resource planning model (Shrestha and Marpaung, 2002, 2005; Srivastava et al., 2003).

Pinch analysis was first extended to the carbon constrained energy sector planning by Tan and Foo (2007). Carbon emission pinch analysis (CEPA) methodology was applied to the Irish electricity sector (Crilly and Zhelev, 2008, 2010) and to the New Zealand's energy sector (Atkins et al., 2010). Lee et al. (2009) extended the CEPA to target the amount of low carbon resources. The limitation of graphical pinch analysis, as the accuracy of the solution depends on visual resolution, has been overcome by a tabular and algebraic approach, called cascade technique, by Foo et al. (2008). In addition, Sahu et al. (2013) has applied pinch analysis to the problem of grid wide deployment of CCS and Krishna Priya and Bandyopadhyay (2013) used the concept of prioritised cost to solve the problem of emission constrained power system planning.

Carbon capture (CC) units with various technologies like oxy-fuel combustion, pre combustion capture, post combustion capture, chemical looping combustion, etc. are available. However, CC imposes an energy penalty on the generation process as a certain amount of energy is needed to meet the needs of a CCS plant. The capture and sequestration process acts like a parasitic load on the power system (Tan et al., 2009; Cormos et al., 2011). An improved discrete mathematical formulation of the same problem has been proposed by Tan et al. (2010), while a simplified continuous one was proposed by Pekala et al. (2010). These works detailed which power plants should be retrofitted with which type of CCS unit. The characteristics of CCS sinks like availability, maximum injection rate possible and capacity are not accounted for. These were addressed using MILP models by Tan et al. (2012, 2013) and Lee and Chen (2012). Recently, Lee et al. (2014) developed a unified model that simultaneously considers grid implications along with source–sink matching via a discrete-time MILP formulation.

In this paper, an optimisation model for low-carbon power generation planning is developed. The next section of this paper is the problem statement where in the model formulation is explained. The model is essentially non linear as both the installed capacity and capacity factor of power plants are allowed to vary. Carbon capture is modelled with the help of a parasitic loss. It is followed by a case study on the Indian electricity sector. For this, 2007 is considered as base year and the target year is 2020. An optimum energy mix that meets both energy and emission targets at the minimum cost is to be determined. The key aspect of this study is an investigation as to how carbon capture technology should be implemented. Two cases are considered here. The first scenario deals with CC as essentially a technology applicable only to new power plants. This assumes that no existing power plant is likely to be retrofitted. The second case allows for the possibility of retrofit. The case study also contains a sensitivity analysis on various parameters after which the paper concludes.