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Modelling and optimization of CO_2 abatement strategies

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ABSTRACT

Burning coal is one of the most economical ways of generating electricity but is the most damaging in terms of carbon emissions. Conversely, renewable energy (RE), which produces no carbon emissions, has drawbacks such as intermittency, a lower electricity conversion rate and high cost. In this study, a mixed integer linear programming (MILP) optimisation model under carbon constraints is developed to address these issues. The model is able to determine the most economical low carbon power generation mix to satisfy the forecast electricity demand in Iskandar Malaysia (IM) for the year 2025 while being reliable and having less impact on the environment. The model includes fuel-switching, RE power generation and implementation of carbon capture and storage (CCS). The applicability of the model is tested and compared for scenarios of business as usual (BAU) and various CO_2 emission reduction targets (CO2Em).

1. Introduction

Emissions of greenhouse gases are the major cause of climate change in the world. Climate change has already resulted in observable and catastrophic consequences for human health as well as the economy. A cost of US$ $2-4 \times 10^9$ per year has been estimated for direct damage to health (WHO, 2013), and a death toll of 100 million people by 2030 was estimated in a report that was commissioned by 20 governments (Koebler, 2012). This estimated death toll would place death resulting from climate change as one of the leading causes of death in the globe.

The major contributor of greenhouse gas emissions is CO_2, which is mostly due to the combustion of fossil fuels (coal, natural gas, and oil) in the energy sector, as shown in Figs. 1 and 2 (Metz et al., 2005). Thus, global interest in sustainable energy has increased to mitigate the effects of climate change while simultaneously fulfilling the every-growing energy demands of all countries. The energy supply has direct and indirect interactions with the environment (Ko and Chang, 2008), and climate change mitigation requires a significant reduction of CO_2. Thus, proper planning and policy formulation for sustainable energy growth is of utmost important and urgently needed. The keys to reducing CO_2 are avoidance, reuse, minimisation and mitigation (Klemeš et al., 2012). CO_2 mitigation can be achieved by a variety of measures (IEA, 2007): improving energy efficiency (reusing the heat from hot steam to generate electricity), developing alternative energy sources with less or no CO_2 emissions (using renewable energy (RE) sources such as biomass and solar energy or the replacement of coal with natural gas), or applying CO_2 mitigation technologies (such as CCS).

Because the energy generation sectors are still very dependent on fossil fuels, a rapid move away from fossil fuels is likely not possible. Generally, the most dominant fuel used in power generation is coal, as coal resources are abundant and coal-fired power plant technology is very mature (Ko and Chang, 2008). However, natural gas-fired power plant technology is also mature. Thus, it is possible to reduce CO_2 emissions by switching fuel usage (Othman et al., 2009) from coal to natural gas (Delarue and D'haeseleer, 2008) because the combustion of natural gas emits less CO_2 than that produced by coal combustion. Nonetheless, although natural gas is cleaner, the price of natural gas is far higher than that of coal.

Another option for reducing dependence on fossil fuels is the use of RE (Cong, 2013). RE sources have been recognised as an essential effort in reducing carbon dioxide (CO_2) emission globally (Arnette and Zobel, 2012). Although their intermittent properties and relatively higher cost (Baños et al., 2011) make RE sources less competitive and limit their ability to replace traditional energy generation, RE offers several advantages such as reduction of CO_2 emissions into atmosphere and lower operating cost (Sahu et al., 2013). With continual improvements in RE, such as improvements in energy conversion efficiency and decreases in maintenance costs, RE could be included in national energy grid transmission.

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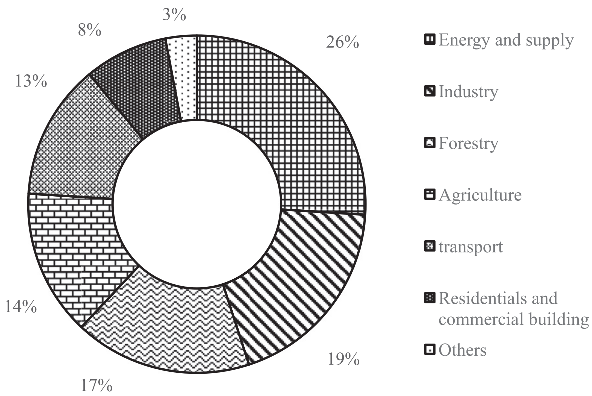

Fig. 1. Sources of CO_2 emission (Metz et al., 2005).

As part of a strategy to manage CO_2 emissions, carbon capture and storage (CCS) technology has gained the attention of researchers worldwide. CCS prevents the emission of CO_2 from large CO_2 sources into the atmosphere. CCS is achieved by capturing CO_2 from pre-combustion, post-combustion and oxy-fuel combustion plants by installing flue gas scrubbing technology to separate and capture most of the CO_2 (Rubin et al., 2012). The CO_2 capture process can effectively capture 80–90% of the CO_2 from plant exhaust gases. The captured CO_2 is subsequently sequestrated for secure storage in various sinks (geological reservoirs, saline aquifers, or depleted oil or gas fields) via transport by pipeline, truck and ship. By preventing large CO_2 emissions into the atmosphere, CCS enables the continued usage of fossil fuels for power plant combustion. However, there are two major drawbacks of CCS technology. The first one is the increment in capital and variable costs of plants due to the required additional equipment. The second drawback is the additional power required for the CO_2 capture process. Because the power required is drawn from the power plant output, the overall power generation and thermal efficiency of the plant will be reduced (Tan et al., 2009).

Tan et al. (2010) has developed a fuzzy integer programming model for planning of grid-wide CCS retrofits in the power generation sector to fulfil the grid-wide emission limit. However, RE as one of the promising option for emission reduction has not been considered in his work. With the extension of his technique, this paper discusses an optimization model to determine the optimal low carbon power generation mix that incorporates fuel-switching, RE sources and CCS technology. A case study of Iskandar Malaysia's (IM's) power generation system is used to gain insight with the changes of CO_2 emission reduction targets, the increment in electricity demand required and the cost of the implemented technologies. These insights are particularly useful for enabling government decisions on future sustainable electricity generation and meet environmental challenges.

2. Research methodology

Various tools have been used for energy planning system that minimise CO_2 emissions, including Geographic Information Systems (GIS), Microsoft Excel and Aspen Plus, as shown in Table 1.

In this work, a mathematical model is developed and executed using the General Algebraic Modelling System (GAMS, 2011). GAMS version 23.9.4 is used, while the models are solved with ILOG CPLEX 10.1 solver. ILOG CPLEX is an advanced algorithm structure that uses a branch and cut algorithm to effectively solve complex optimisation problems.

2.1. Objective function

Eq. (1) presents the objective function of the deterministic MILP model is to minimise the total cost of the energy-generating system with constrained CO_2 emissions, as follows:

$$
\begin{aligned}
&\text{Minimum total cost}(i,j,o,k,l)\\
&= \overbrace{\sum_{i\in F}\sum_{j}\sum_{l}\text{capital}_{ij}\times\text{capacity}_{ijl}\times x_{ij}}^{\text{capital cost of existing and new fossil fuel power plants without carbon capture}} + \overbrace{\sum_{i\in R}\sum_{o}\sum_{l}\text{capital}_{io}\times\text{capacity}_{iol}\times y_{iol}}^{\text{capital cost of RE power plants}}\\
&+ \overbrace{\sum_{i\in FK}\sum_{j}\sum_{k}\sum_{l}\text{capital}_{ijk}\times\text{capacity}_{ijkl}\times z_{ijkl}}^{\text{capital cost of new fossil fuel power plants with carbon capture}} + \overbrace{\sum_{i\in F}\sum_{j}\sum_{l}\text{fix}_{ij}\times\text{pow}_{ijl}}^{\text{fixed cost of existing and new fossil fuel power plants without carbon capture}}\\
&+ \overbrace{\sum_{i\in R}\sum_{o}\sum_{l}\text{fix}_{io}\times\text{pow}_{iol}}^{\text{fixed cost of RE power plants}} + \overbrace{\sum_{i\in FK}\sum_{j}\sum_{k}\sum_{l}\text{fix}_{ij}\times\text{pow}_{ijkl}}^{\text{fixed cost of new fossil fuel power plants with carbon capture}}\\
&+ \overbrace{\sum_{i\in F}\sum_{j}\sum_{l}\text{var}_{ij}\times\text{pow}_{ijl}\times\text{opt}_{l}}^{\text{variable cost of existing and new fossil fuel power plants without carbon capture}} + \overbrace{\sum_{i\in R}\sum_{o}\sum_{l}\text{var}_{io}\times\text{pow}_{iol}\times\text{opt}_{l}}^{\text{variable cost of RE power plants}}\\
&+ \overbrace{\sum_{i\in FK}\sum_{j}\sum_{k}\sum_{l}\text{var}_{ij}\times\text{pow}_{ijkl}\times\text{opt}_{l}}^{\text{variable cost of new fossil fuel power plants with carbon capture}} + \overbrace{\sum_{t}\text{CO}_2\text{captured}\times\text{transport}_{t}}^{\text{transportation cost}} + \overbrace{\sum_{s}\text{CO}_2\text{captured}\times\text{sequest}_{s}}^{\text{sequestration cost}}\\
&+ \overbrace{\sum_{i\in F}\sum_{j}\sum_{l}\text{pfuel}_{j}\times\text{fuelad}\times\text{HR}_{ij}\times\text{pow}_{ijl}\times\text{opt}_{l}}^{\text{fuel cost of existing and new fossil fuel power plants without carbon capture}} + \overbrace{\sum_{i\in F}\sum_{j}\sum_{k}\sum_{l}\text{pfuel}_{j}\times\text{fuelad}\times\text{HR}_{ij}\times\text{pow}_{ijkl}\times\text{opt}_{l}}^{\text{fuel cost of new fossil fuel power plants with carbon capture}}\\
&+ \overbrace{\sum_{i\in R}\sum_{o}\sum_{l}\text{amount}_{io}\times\text{pRE}_{o}}^{\text{RE supply cost}}
\end{aligned}
$$