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Deciding between carbon trading and carbon capture and sequestration: An optimisation-based case study for methanol synthesis from syngas

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ABSTRACT

The economic and technical feasibility of carbon capture and sequestration (CCS) systems are gaining importance as CO_2 emission reduction is becoming a more pressing issue for parties from production sectors. Public and private entities have to comply with national schemes imposing tighter limits on their emission allowances. Often these parties face two options as whether to invest in CCS or buy carbon credits for the excess emissions above their limits. CCS is an expensive system to invest in and to operate. Therefore, its feasibility depends on the carbon credit prices prevailing in the markets now and in the future. In this paper we consider the problem of installing a CCS unit in order to ensure that the amount of CO_2 emissions is within its allowable limits. We formulate this problem as a non-linear optimisation problem where the objective is to maximise the net returns from pursuing an optimal mix of the two options described above. General Algebraic Modelling Systems (GAMS) software was used to solve the model. The results were found to be sensitive to carbon credit prices and the discount rate, which determines the choices with respect to the future and the present. The model was applied to a methanol synthesis plant as an example. However, the formulation can easily be extended to any production process if the CO_2 emissions level per unit of physical production is known. The results showed that for CCS to be feasible, carbon credit prices must be above 15 Euros per ton. This value, naturally, depends on the plant-specific data, and the costs we have employed for CCS. The actual prices ($\approx$5 Euros/ton CO_2) at present are far from encouraging the investors into CCS technology.

1. Introduction

In recent decades, increasing greenhouse gas (GHG) emission is one of the main reasons for global warming with adverse environmental effects such as sea level rise, floods, droughts, etc. Fossil fuel power plants, and many other industries such as iron and aluminium, cement, lime, hydrogen, ammonia and methanol plants have been known as the major emission sources of greenhouse gases, of which the most abundant one in the atmosphere is carbon dioxide, or simply CO_2 (IPCC Fourth Assessment Report, 2007; Soltanieh et al., 2012). Industrial activities account for 40% of global energy-related CO_2 emissions. In 2007 the worldwide figure for CO_2 emissions caused by industrial activities was 7.6 gigatonnes equivalent (Gte) of direct CO_2 emissions whereas the indirect CO_2 emissions due to electricity production for industrial activities were 3.9 Gte (Roddy, 2012). Reduction of fossil fuels (oil, gas, coal) consumption via enhanced energy efficiency, carbon capture and sequestration (CCS), conversion of CO_2 to different products, increasing utilisation of renewable energies and reforestation are effective options to achieve mitigation so as to reach the Kyoto Protocol targets (Chicco and Stephenson, 2012).

Coal-fired power plants are the most common source of electricity production with a global share of 41%. Despite the high level of environmental impact of coal combustion, economic incentives urge many countries towards a coal-dominant energy sector, examples of such countries being U.S.A., China, India and partly Turkey (Cristóbal et al., 2012b). Turkey produces approximately 25% of its electricity through local or imported coal (Capik et al., 2012), and coal is the main energy source of the country as far as local resources are concerned, a situation caused by inadequate natural gas and petroleum reserves. Hence, GHG emissions related to coal utilisation is a significant problem for Turkey, and these emissions must be lowered for a sustainable future. Under these

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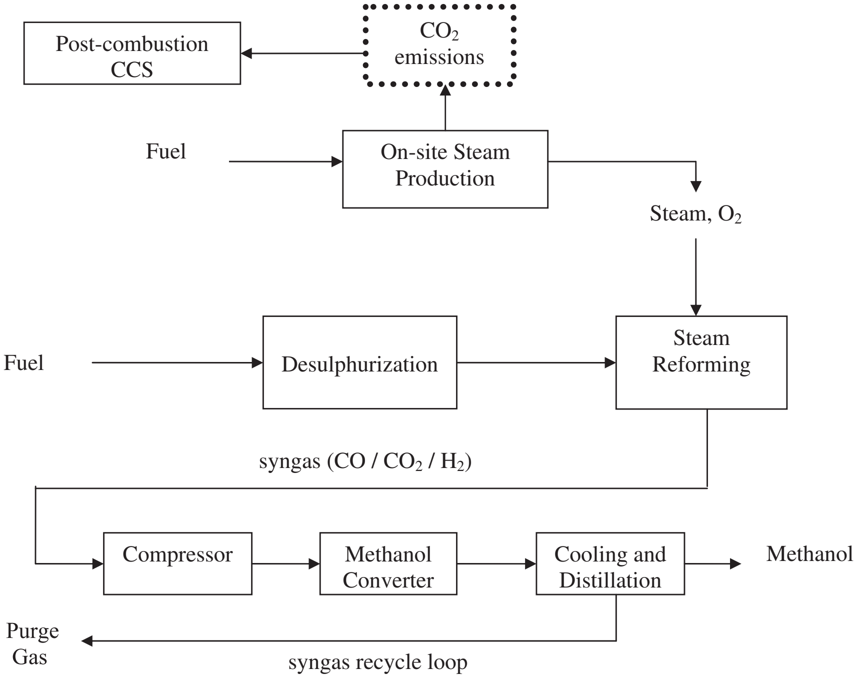

Fig. 1. Methanol synthesis from syngas.

circumstances, amongst many other options, conversion of CO_2 into a usable product emerges as a promising solution, not only because of its environmental benefits, but also due to the economic gain. At this stage, methanol (CH_3OH) appears as a viable product to be obtained via the CO_2 in the flue gas, as suggested in the work of Sayah et al. (2010).

1.1. *Methanol synthesis*

Methanol is a colourless, light, water-soluble liquid with a mild alcoholic odour. Globally, 70% of the methanol synthesised is used to produce formaldehyde, methyl-tert-butyl ether, and acetic acid. Chloromethanes, methylamines, methyl methacrylate and dimethylterephthalate are also produced from methanol. Paints resins, silicones, adhesives, antifreeze, plastics are some examples of methanol-based products (Cheng and Kung, 1994). Theoretically, methanol has high volumetric energy density compared to conventional batteries; hence, in the future direct methanol fuel cells are expected to replace conventional batteries in laptop computers and mobile phones, mainly due to being lighter in weight and having extended operational lives (Üçtuğ and Holmes, 2011). Methanol can also be used in electricity generation plants as an alternative to natural gas. It provides the same flexibility as natural gas, including the ability to start, stop, accelerate and decelerate rapidly (Olah et al., 2006). The most common method of methanol production is methanol synthesis from syngas. Other methods include direct methane oxidation or biological selective conversion of methane (Olah et al., 2006; Crabtree, 1995).

Methanol synthesis through syngas, which is a mixture of carbon monoxide (CO) and hydrogen (H_2), involves the following chemical reactions (Fielder et al., 2003):

$$CO + 2H_2 \leftrightarrow CH_3OH \tag{1}$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \tag{2}$$

$$CO_2 + H_2 \leftrightarrow CO + H_2O \tag{3}$$

Reaction (1) and (2) are exothermic and lead a reduction in volume. Conversely, reaction (3) is an endothermic reaction and is called “reverse water gas shift reaction” (RWGSR). RWGSR produces CO, which can be utilised to produce more methanol by reacting with hydrogen. It must be stated that the CO_2 in the flue gas can be utilised in either reaction (2) or (3) or in both reactions simultaneously. However, in either case syngas would have to be produced separately; and this can be achieved by reforming or partial oxidation of coal, coke, natural gas or petroleum (Kochloefl, 1997). The flowchart of the methanol synthesis process can be seen in Fig.1.

Although the chemical reactions associated with methanol production from syngas do not cause direct CO_2 emission, 3.8 tonnes of CO_2 per ton of methanol produced are indirectly emitted when the source of syngas is coal (Cifre and Badr, 2007). Some part of these emissions is caused by the on-site production of steam for the reforming process via fuel combustion, whereas the rest are off-site (indirect) emissions. It has been stated that indirect emissions account for approximately 3.5% of the total emissions (Methanex, 1996). Hence, by incorporating the data presented by Cifre and Badr (2007) with the data provided by Methanex Corporation (1996), it was concluded that approximately 3.67 tonnes of CO_2 per ton of methanol are directly released and can be captured on-site during methanol production.

1.2. *Carbon capture and sequestration (CCS)*

CO_2 capture and sequestration (CCS) is attracting increasing attention as an option to reduce GHG emissions. CCS may, in fact, play a substantial role in the smooth and cost-effective transition to a sustainable, low-carbon energy future (Rubin et al., 2007; Turkenburg, 1997). CCS process consists of three steps in general: CO_2 capture, CO_2 transportation and CO_2 sequestration. CO_2 is captured at the source by using different techniques like absorption, adsorption, membrane-based separation or cryogenic separation (Steeneveldt et al., 2006). The captured CO_2 needs to be in liquid or supercritical fluid state in order to be able to be