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Addressing the CO_2 emissions of the world's largest coal producer and consumer: Lessons from the Haishiwan Coalfield, China

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ABSTRACT

China is now the world's largest user of coal, and also has the highest greenhouse gas emissions associated with the mining and use of coal. In the mining sector, the interests of workforce safety coincide with those of GHG (greenhouse gas) management. While the traditional approach to ensuring workforce safety in coal mines was simply to vent the hazardous gases to the atmosphere, thus increasing GHG emissions, recent innovations have seen elements of CCS (carbon capture and storage) being used to simultaneously ensure workforce safety and minimization of GHG emissions. The Haishiwan Coalfield represents a particularly challenging environment for applying this approach, as the coal-bearing strata host both oil shales and a naturally-occurring CO_2 reservoir, disturbance of which could both imperil workers and lead to elevated GHG emissions. A low-carbon, CCS-based model of gas management developed in the Haishiwan Coalfield offers attractive lessons for application to other coal mines, within and beyond China. This approach achieves multiple benefits: energy production, enhanced workforce safety and minimization of GHG emissions. Given the extreme nature of the Haishiwan case, it ought to be even easier to implement these approaches elsewhere.

1. The challenge of greenhouse gas emissions in China

1.1. Introduction

Emissions of GHG (greenhouse gases) are widely accepted to be the principal agent of anthropogenic climate change [1]. The atmospheric concentrations of the principal greenhouse gases carbon dioxide (CO_2) and methane (CH_4) were 391 ppm and 1803 ppb respectively in 2012, exceeding pre-industrial levels by about 40% and 150% respectively [2]. Coal use is responsible for about 40% of global electricity generation as well as 40% of greenhouse gas emissions. It is present in some seventy nations, with the United States, Russia, and China possessing the largest reserves. Coal emits far more CO_2 per unit of energy produced than other fossil fuels: about 30% higher than that of crude oil, and about 70% more than natural gas. Without the implementation of pollution controls, increased coal usage will inevitably result in serious environmental impacts, both in terms of global climate change and through release of other contaminants that have more localized impacts [3]. The greatest potential for reducing the GHG emissons from coal is CCS (carbon capture and storage), which offers CO_2 emissions reductions of 80–90% per unit of energy produced [4]. CCS is being considered as one element of a wider strategy for stabilizing atmospheric CO_2 concentrations. This plan requires that billions of tonnes of CO_2 must be captured worldwide each year, and concentrated and stored to prevent it entering the atmosphere for hundreds to thousands of years [5].

1.2. The case of China

Since China opened its doors to the world in 1978, it has not only been the world's fastest-growing large economy, but also an outstanding exporter and a large recipient of FDI (foreign direct

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investment). China has now become the “workshop of the world”, with demand for its good from all around the world spurring its burgeoning manufacturing sector: China's primary, secondary and tertiary manufacturing industries accounted for10.1%, 46.8% and 43.1% of its GDP in 2010 [6], and manufacturing depends on an adequate supply of affordable energy. Market pressures mean that energy must be cheap and account for only a small proportion of the total cost of manufacturing. This has translated into a huge demand for coal. China has become the world's largest energy producer and consumer. As a primary energy source, in 2012, coal accounts for 68% and 52% of Chinese production and consumption respectively. In 2013, China was consuming 52% of all coal used worldwide, the vast majority of which was produced within China. According to predictions to 2040, coal will continue to dominate energy production and consumption in China for the foreseeable future [7,8].

According to IEA (International Energy Agency) estimates, China's CO_2 emissions in 2011 were 7.95 gigatonnes (Gt) [9]. Coal-related CO_2 emissions are not restricted to final combustion: the process of mining and beneficiation of coal is also CO_2 intensive. In terms of CO_2 emissions per tonne of coal delivered to power stations, China emitted four times as much as the USA, and twice as much as the UK [10]. Fugitive emissions of methane from coal mines further exacerbate the GHG impacts of coal mining *per se*. Global methane emissions from coal mines were estimated to account for approximately 8% of worldwide anthropogenic methane emissions in 2010, and these emissions were projected to rise by 15% over the following 10 years [11]. China's estimated methane emissions from coal mines that same year were more than 295 $MtCO_2e$, greatly exceeding those of the second-greatest emitter, the USA, which released slightly over 68 $MtCO_2e$. Controlling CO_2 emissions without hindering economic development is a major challenge not only for China, but for the many economies worldwide that rely on its goods [12]. As part of a wider initiative to rein-in carbon emissions in the coal-to-energy chain, China clearly needs to reduce the direct and indirect GHG emissions from the process of mining coal. This paper explores how this is currently being approached, using a particularly challenging example to illustrate the feasibility of the approach.

2. The interdependency of gas emissions and mine safety

2.1. The health and safety imperative in Chinese mining

In the early 21st Century, Chinese coal production increased significantly, from 1299 million tonnes (Mt) in 2000–3050 Mt in 2009, an annual growth rate of 10% [13]. Unlike many other countries, where opencast mining now predominates, underground mining accounts for 95%, of Chinese coal production. Although the death rate per million tonnes of coal produced has been decreasing steadily, the coal industry remains the most dangerous sector, recording more than 2000 deaths every year [14]. The depth of coal mining is typically 600–800 m with an average rate of face advance of 20 m per year. With increasing burial depth of the coal seams, gas pressures and concentrations also increase, which leads to ever greater risks of coal and gas ‘outbursts’ as mines deepen further. An outburst is defined as a violent, simultaneous release of gases and comminuted rock material into a working face or the interior of a shaft. Outbursts in coal mines represent considerable hazards. Apart from impact injuries, the most immediate hazard, and certainly the most perilous, is the unexpected inundation of the ventilation systems with asphyxiating volumes of gas. When methane is the released gas, an explosive hazard can be created, possibly exacerbated by ejected coal dust [15]. To date, coal and/or gas outbursts have been recorded in more than 1040 mines, scattered across most of the mining provinces in China. Out of 2433 Chinese coal mine deaths in 2010, 623 (25.6%) were due to gas-related accidents [16].

Outbursts are only one manifestation of the dangers posed by CMM (coal mine methane), which is a general term for all methane released during and after mining operations. CMM may have formed biogenically or thermogenically, though most methane in deep strata turns to be thermogenic in origin. Methane is primarily stored in coal by adsorption onto the coal surface; thus it is pore surface area that determines the maximum gas holding potential of a coal seam [17]. CMM has long been considered a danger in underground coal mining due to its explosion risk, which poses a serious threat to worker safety and thus productivity. One of the most important duties of ventilation in underground coal mines is to keep methane levels well below the explosive limit by diluting methane emissions that occur during mining. Methane entering a mine can create a localized zone of high concentration in an area of low air velocities and quantities. The concentration of methane in these zones may pass through a range between 5% and 15%, known as the explosive range. In this range, methane can be ignited easily by any ignition source to create a violent methane explosion that may propagate beyond the methane-affected zone by explosion of suspensions of combustible coal dust. In addition to proper ventilation practices, removal of coal mine methane from the mining environments prior to, during, and after coal production by using various in-seam and surface-to-mine borehole designs, has been the key component to alleviate the outburst and explosion threat in mining operations [18]. Pre-drainage of methane is preferable from a GHG emissions reduction perspective, as the methane is obtained in more concentrated form, which is more amenable to separation, use and storage of the CO_2 derived from its use.

Some coal seams contain little methane (e.g. in certain areas of the Illawarra coal measures in New South Wales, Australia), with the predominant coal seam gas being carbon dioxide [19]. Where a mine atmosphere becomes saturated with CO_2, so that the proportion of oxygen drops below the respirable limit, this also poses a mortal hazard to miners [20]. Thus the management of gases for worker safety in coal mines addresses precisely the same gases which are of concern in the context of GHG emissions. Historically, CMM and mine-derived CO_2 have simply been diluted with air and vented to the atmosphere; clearly this approach needs to be amended if a reduction in GHG emissions from mines is to be achieved.

2.2. Coal use and options for minimising CO_2 emissions

Coal fuels almost 40% of the world's electricity and in many countries this figure is much higher: Australia, China, India and South Africa, for example, use their large indigenous supplies of coal to generate most of their electricity. For China, particularly given its large indigenous reserves, continuing use of coal for power generation seems inevitable in coming decades, with coal-fired generation still expected to amount to 70% of total electricity supply in 2030 [21]. This is daunting, as increased coal use has dominated the growth in GHG emissions for energy production: between 1990 and 2011, growth in GHG emissions from power generation was overwhelmingly due to coal use. Beyond the power sector, there are other significant uses of coal in the iron and steel industry (steel, being an alloy of iron and carbon, cannot be made without coal) and in the cement sector. These industries also need to address coal-related GHG emissions whilst keeping costs under control. It seems clear that any further coal usage must be accompanied by CCS (carbon capture and storage).

The greatest potential is offered by CCS which can reduce CO_2 emissions to the atmosphere by 80–90%. CCS technologies enable