SUSTAINABLE APPLICATION OF RECIPROCATING GAS ENGINES OPERATING ON COAL MINE METHANE GAS

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October 2008

ABSTRACT

Coal provides 25 percent of global primary energy needs and generates 40 percent of the world's electricity, according to the World Coal Institute. The People's Republic of China produces the largest amount of hard coal – an estimated 2.5 billion metric tons in 2006 alone.

The anthropogenic release of methane (CH4) into the environment is a byproduct of the coal mining process and the global warming potential of this methane continues to draw attention globally. Stakeholders responsible for coal and power production are looking for ways to safely and economically mitigate the release of coal mine greenhouse gases.

Sequestering coal mine methane (CMM) as an alternative fuel for reciprocating gas engine generator sets is a mature and proven technology for greenhouse gas mitigation. Prior to commissioning CMM-fueled power systems, the methane gas composition must be evaluated. The project is then developed by utilizing an integrated systems approach.

As with any type of alternative energy, the economics of electric power CMM projects play a major role in the success of the project. Profiles of existing applications that document reliable and efficient utilization of CMM for gas reciprocating engines will be offered to illustrate the success of such systems.

There is considerable opportunity for growth in the Asia-Pacific region for electric power applications using CMM. Caterpillar's experience in this type of power generation has been proven successful at several sites in China and beyond, where the growing economy demands sustainable solutions to meet rising power needs.

INTRODUCTION

The restructuring of China's economy and the resulting rapid growth of both agriculture and industry have contributed to a more than tenfold increase in gross domestic product (GDP) since 1978 – and that figure grows at a higher rate each year. In 2007 alone, the real growth rate of China's GDP was an estimated 11.4 percent. Measured on a purchasing power parity basis, China stands as the second-largest economy in the world after the United States. [1]

With this very swift economic growth comes swiftly increasing demands for power from both industries and consumers – China's energy consumption has more than quadrupled since 1980. In 2006, China's electricity usage reached 2.859 trillion kWh and natural gas consumption was approximately 55.6 billion cubic meters; estimated 2007 oil consumption equaled 6.93 million barrels per day. [1]

China's government recognizes the need for environmental responsibility in the pursuit of greater power production. The government has taken action with official governmental management programs like the nationwide campaign to reduce energy consumption launched in 2006. [2] The Kyoto Protocol, perhaps China's most important environmental commitment, is an international agreement under the United Nations Framework Convention on Climate Change that requires participating developed countries to reduce their greenhouse gas emissions below levels specified for each of them. These targets must be met within a five-year time frame between 2008 and 2012. [3]

One of the ways Kyoto participants pursue this goal is through the Clean Development Mechanism (CDM). CDM allows developed countries to earn and trade emissions credits through projects implemented either in other developed countries or in developing countries where projects are less expensive, which they can use toward meeting their commitments. CDM projects receive Certified Emission Reduction (CER) credits by demonstrating the difference in environmental impact their cleaner processes produce compared to a conventional method that might otherwise have been used, such as burning coal. The greater the reduction of greenhouse gas emissions, the more credits a project may receive. Today, CERs are being traded in the range of US$12 to US$20 per CER. [3]

One of the most promising and effective greenhouse gases used in CDM projects is coal mine methane (CMM), a methane gas formed as a byproduct during coalification that is found within subterranean coal seams. When released during active coal mining, the methane concentration is generally between 25 and 60 percent. Figure 1 below provides a reference point for the composition of CMM compared to other fuel sources. As the table shows, CMM has a higher mix of oxygen and nitrogen than pipeline natural gas and coal bed methane (CBM), which has such a high concentration of methane it can be used in natural gas pipelines with very little treatment. Therefore, CMM requires different equipment considerations when used to power generator sets.

Figure 1: Typical Fuel (CMM) Composition and Physical Properties

Component	Symbol	Units	Pipeline Natural Gas	CBM	CMM*
Methane	CH_4	vol %	92.3	85.9	40.0
Ethane	C_2H_6	vol %	2.5	3.8	---
Hydrogen Sulfide	H_2S	vol %	---	---	---
Oxygen	O_2	vol %	---	2.1	12.6
Nitrogen	N_2	vol %	3.5	8.2	46.8
Others	---	vol %	1.8	0.0	0.6
Lower Heating Value	LHV	MJ/Nm^3	33.2	32.5	13.4
Caterpillar Methane Number	MN	---	80	86	100

*Represents one particular site at one particular time

Methane (CH_4) can be released into the atmosphere through sources where it naturally occurs: landfill decomposition, agriculture, gas and oil extraction systems and coal mining activities. When released into the atmosphere through these and other processes, methane remains in the atmosphere for approximately nine to 15 years. Figure 2 shows past, current and projected amounts of methane released through coal mining activities. [4]

Globally, coal mines emit approximately 400 million metric tons or 28 billion cubic meters of carbon dioxide equivalent annually. About 8% of total anthropogenic methane emissions come from coal mines. This amount is equivalent to consumption of 818 million barrels of oil or the carbon dioxide emissions of 64 million passenger cars. In 2005, U.S. coal mines emitted about 4 billion cubic meters of methane. Between 1994 and 2005, U.S. emissions decreased by over 20%, in large part due to the coal mining industry's increased recovery and utilization of drained gas. China leads the world in coal mine methane emissions with about 14 billion cubic meters of CO_2 emitted annually – a 2004 measurement estimated nearly 200 million metric tons were emitted that year. Aside from the U.S. and China, other leading emitters include Ukraine, Australia, Russia and India. [4]

Figure 2: Methane Emissions [Metric Ton of CO_2 Equivalent (MtCO2eq)] from Coal Mining Activities

Regions	1990	1995	2000	2005	2010	2015	2020
Africa	9.7	10.7	9.3	8.4	8.2	8.2	8.7
China/CPA[1]	152.1	177.3	145.5	162.5	179.5	196.6	213.9
Latin America	5.4	5.3	6.9	7.6	8.4	9.5	10.7
Middle East	0.3	0.3	0.4	0.4	0.4	0.4	0.5
Non-EU Eastern Europe	1.0	1.0	1.9	2.3	3.0	3.9	5.3
Non-EU FSU[2]	142.0	84.4	67.6	59.5	58.6	57.0	55.6
OECD90[3] & EU	188.0	154.3	124.6	123.2	121.5	116.7	116.3
SE Asia	18.1	18.3	20.8	24.3	27.9	33.1	38.5
World Totals	516.7	451.5	376.9	388.1	407.6	425.6	449.5

[1]CPA = Centrally Planned Asia
[2]FSU = Former Soviet Union
[3]OECD90 = Organization for Economic Cooperation and Development (Member States at 1990)

There are several options currently available for CMM mitigation, including reciprocating gas engines, gas turbines, industrial boilers and furnaces, and chemical processing. Other technologies like catalytic systems and fuel cells are also being developed.

As shown in Figure 3, methane is a greenhouse gas with an estimated global warming potential of 21. This means that emissions of methane have an estimated effect on global warming equal to 21 times the effect of carbon dioxide. Implementing methods to use CMM instead of emitting it to the atmosphere will help mitigate global warming, improve mine safety, and productivity and generate revenues and cost savings. Therefore, directing CMM into power generation systems is an excellent way for Kyoto participants to reduce greenhouse gas emissions while generating valuable power for developing areas.

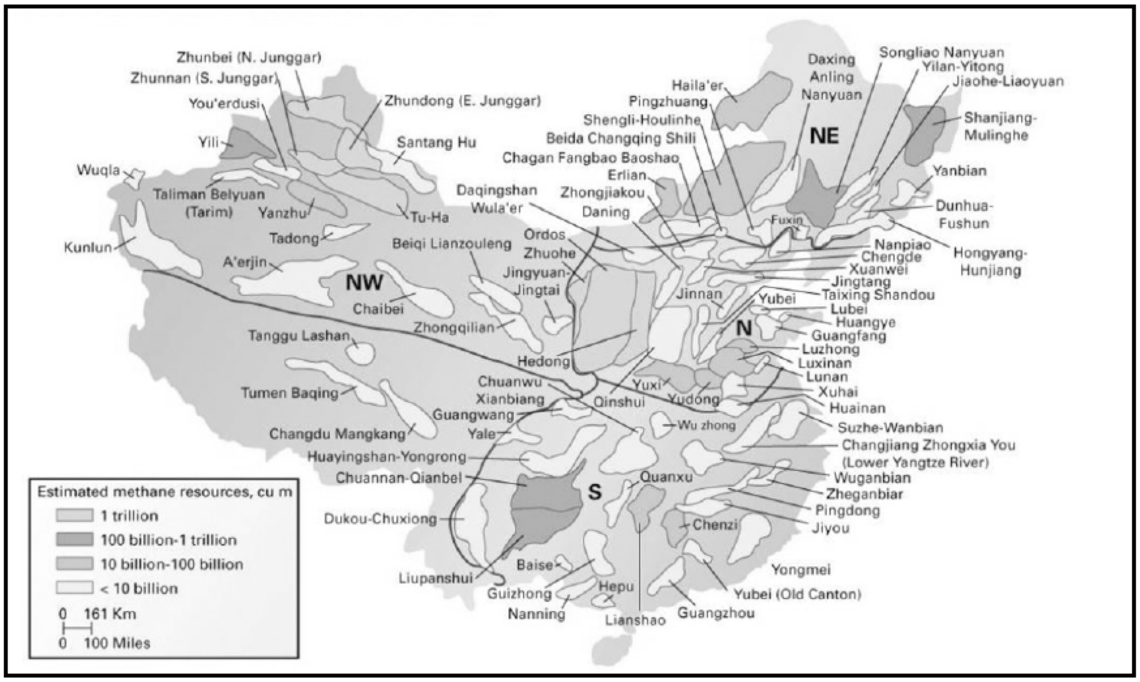
Figure 3: Global Warming Potentials (GWP) and Atmospheric Lifetimes (Years)

Gas	Atmospheric Lifetime	100-year GWP[a]	20-year GWP	500-year GWP
Carbon dioxide (CO_2)	50-200	1	1	1
Methane (CH_4)[b]	12 ± 3	21	56	6.5
Nitrous oxide (N_2O)	120	310	280	170
HFC-23	264	11,700	9,100	9,800
HFC-125	32.6	2,800	4,600	920
HFC-134a	14.6	1,300	3,400	420
HFC-143a	48.3	3,800	5,000	1,400
HFC-152a	1.5	140	460	42
HFC-227ea	36.5	2,900	4,300	950
HFC-236fa	209	6,300	5,100	4,700
HFC-4310mee	17.1	1,300	3,000	400
CF_4	50,000	6,500	4,400	10,000
C_2F_6	10,000	9,200	6,200	14,000
C_4F_{10}	2,600	7,000	4,800	10,100
C_6F_{14}	3,200	7,400	5,000	10,700
SF_6	3,200	23,900	16,300	34,900

Source: IPCC (1996)
[a]GWPs used here are calculated over 100-year time horizon.
[b]The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

Coal accounts for 67.1 percent of total national energy consumption in China. The country is estimated to have over 26,000 mines that produce about 1.4 billion metric tons of coal each year (illustrated in Figure 4). The US Environmental Protection Agency reported in 1996 that underground mining accounted for 95 percent of Chinese coal production. Today, that number is closer to 90 percent.

Figure 4: China's Coal Basins and Coal Bed Methane Resources

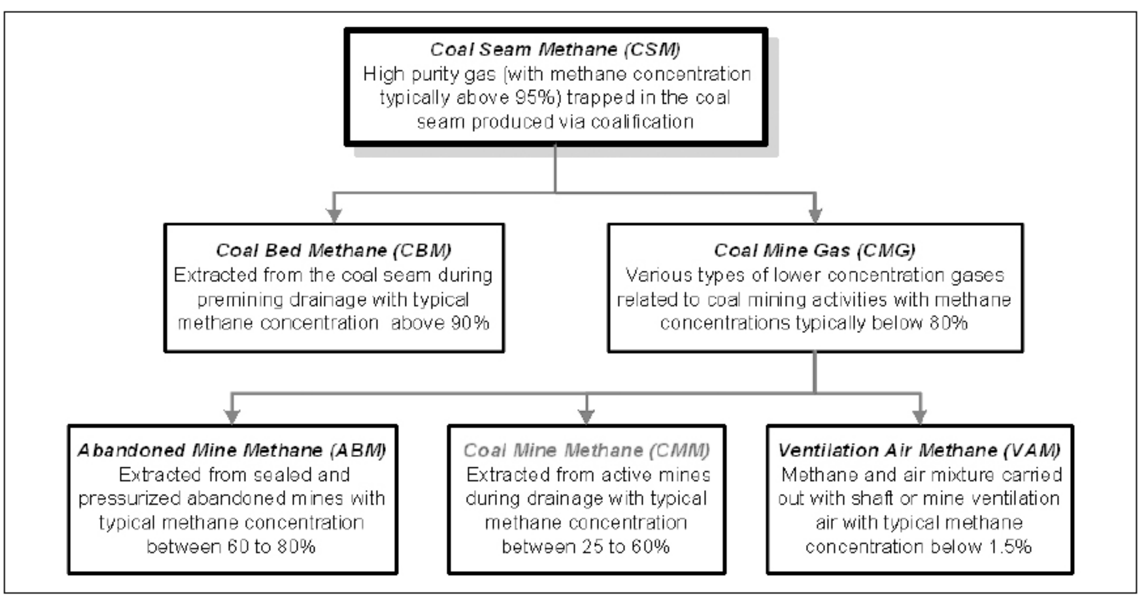


DISCUSSION

System Integration and Technologies

As shown in Figure 5, coal seam methane (CSM) extraction projects come in two basic types: coal bed methane (CBM) and coal gas methane (CGM). Under CGM, there are two other major categories of gases: CMM and ventilation air methane (VAM).

Figure 5: Various Methane Containing Gases Produced During Coal Mining Activities

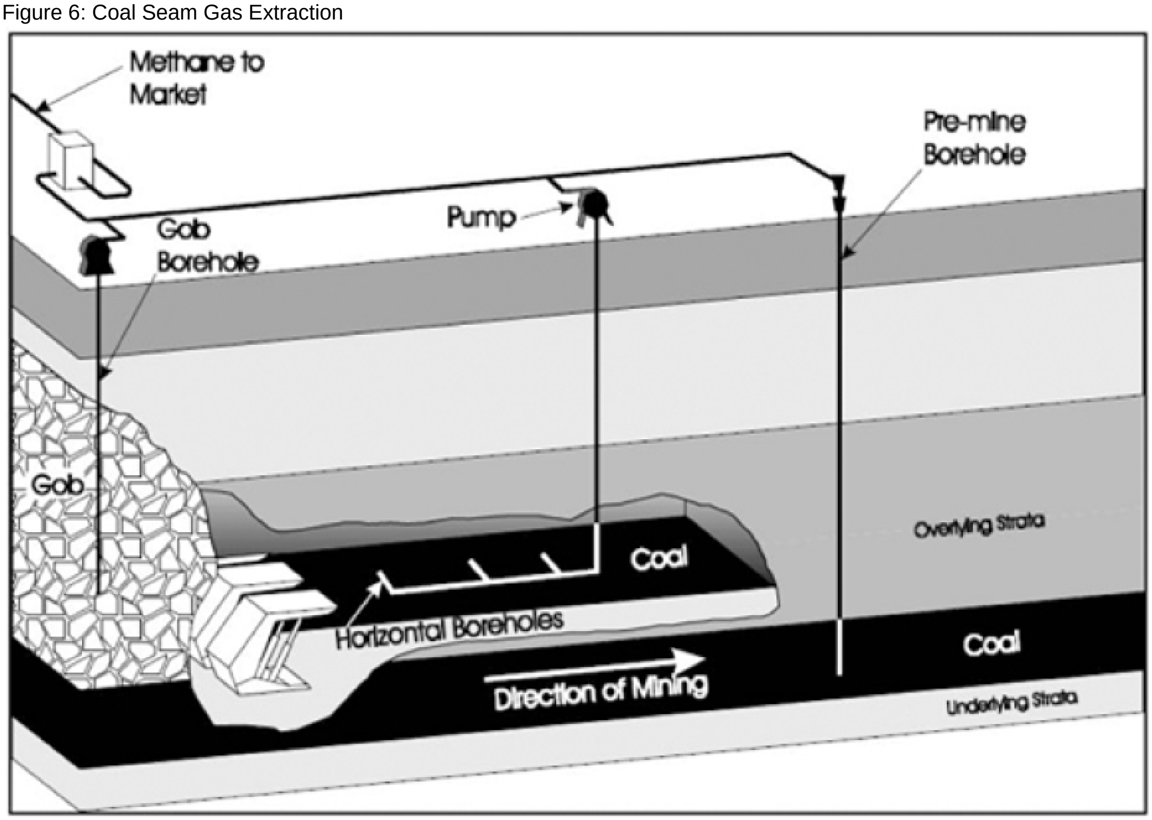


VAM extraction is a necessary part of the process of coal mining. Existing mineshaft air must be ventilated to keep the methane content at acceptable levels for miner safety. While the coal seam is actively mined, a large volume of air is pulled through it to remove the methane. The concentration of methane in the recovered air is typically very low, typically in the 0.3 – 1.5 percent range. Because of the low methane concentration in ventilation air, its beneficial use is difficult.

In CBM, degasification systems, commonly referred to as gas drainage systems, are used. Vertical or horizontal wells are drilled into the coal bed and a vacuum is applied to the well to extract the methane (see Figure 6). Compared to VAM, the quality of the methane in this type of extraction is often very high, with methane content above 85 percent being common, especially from vertical wells drilled into the coal seam well ahead of the actual mining. The balance of the recovered gas primarily consists of air.

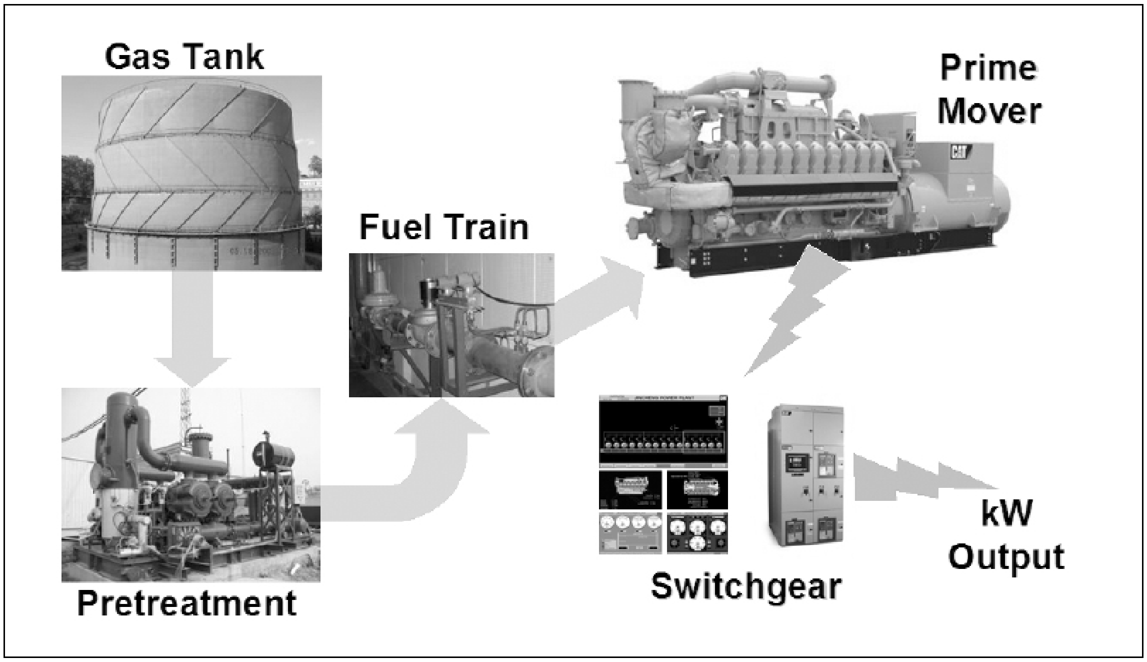
Horizontal wells drilled into the face of the coal seam as it is being mined typically have more air mixed with the methane gas as it is gathered. This gas is generally composed of 25 percent to 60 percent methane with the rest being other resident inert gases such as oxygen and nitrogen. The percent of methane can vary depending on the proximity to, and the amount of, mining activity in the coal seam at the time of extraction.

Figure 6: Coal Seam Gas Extraction



When CMM is removed from the ground, it is held in large tanks until it is pretreated for use in reciprocating gas engines. In China, tanks generally hold approximately 30,000 cubic meters of CMM. Pretreatment includes filtering the CMM for dust and particles through ten micron filters and then one micron filters, drying the gas to below 80 percent relative humidity and sending the CMM through a fuel train, where the pressure is regulated to between five and 35 kPa. After pretreatment, the CMM is sent through to generator sets that are built close to the mining site and managed with switchgear to provide synchronization, voltage checks, loading and unloading of the engines and overall system protection. Figure 7 provides an illustration of a typical layout of a CMM-fueled generator set system.

Figure 7: Typical Plant Layout



Caterpillar Inc. currently utilizes a system that begins with CMM composition and stability analyses, which are used to determine the best engine selection for a specific site. Caterpillar's experience in this type of power generation has been proven successful at several sites in China, where the growing economy demands environmentally conscious solutions to new power needs. Caterpillar recently introduced the G3520C low energy fuel generator set for use with CMM and other methane fuels found in landfills, digesters, and low-energy biogas environments. Operating at 50 Hz, the new generator set includes equipment that optimizes the performance of engines in parallel-to-grid, continuous-operation applications.

The generator set was specially designed to handle fuel methane concentration variations typical of CMM operations. The G3520C-CMM package is also designed to efficiently and reliably use fuel gas with lower than typical methane content. Special approval and engine configuration can be made for applications with methane content down to 25 percent. Furthermore, VAM with up to 3 percent by volume of methane can be used as combustion air as long as necessary steps are taken for pretreatment meeting Caterpillar's combustion air specifications.

Equipped with a gas engine control module using ADEM™ III electronic controls, the generator set allows for full engine control from a single source. The advanced Air/Fuel Ratio Control is designed for use without an oxygen sensor, allowing as high as a 19.2 bar BMEP rating that supplies high power density while meeting NOx emission levels of 500 mg/NM3.

An optional NOx level of 250 mg/NM3 is also available through a 54°C separate circuit aftercooler system that can be used with a conventional cooling system arrangement in almost all geographic locations. This option provides greater emissions control for those projects that must meet stricter local regulations or for project owners interested in pursuing carbon trading opportunities.

The Cat® G3520C operates at 1,500 rpm with a continuous rating of 1,966 ekW under standard operating conditions. An open combustion chamber design allows it to operate using low pressure gas supplies of just 5 to 35 kPa (0.7 psi to 5 psi). The low boost pressure requirement reduces the installation cost of fuel treatment systems often found in low-energy fuel environments.

As shown in Figure 8, the generator set can utilize CMM fuel from a range of 25 percent to 100 percent methane, so the equipment remains efficient throughout the life of a coal mining project. In order to compensate the pressure drop across the gas train, the generator set would require a gas supply pressure between 40 to 60 kPa, with less than 0.69 kPa for steady-state or 4.83 kPa for transient per second of fuel pressure rate of change at the entry of the fuel train system.

Figure 8: Fuel Treatment and Specifications for Coal Mine Methane Applications

G3520C — CMM Fuel Specification

Parameters		Unit	Min	Max
Concentration		volume %	25*	100
Supply Pressure at Engine Inlet		kPag	5	35
Supply Pressure at Fuel Train Entry		kPag	40	60
Rate of Change of Supply Pressure	Steady-State	kPad / second		0.69
	Transient	kPad / second		4.83
Particulates (Beta 200)		µm		5
Relative Humidity		%		80

*Requires special approval at this time.

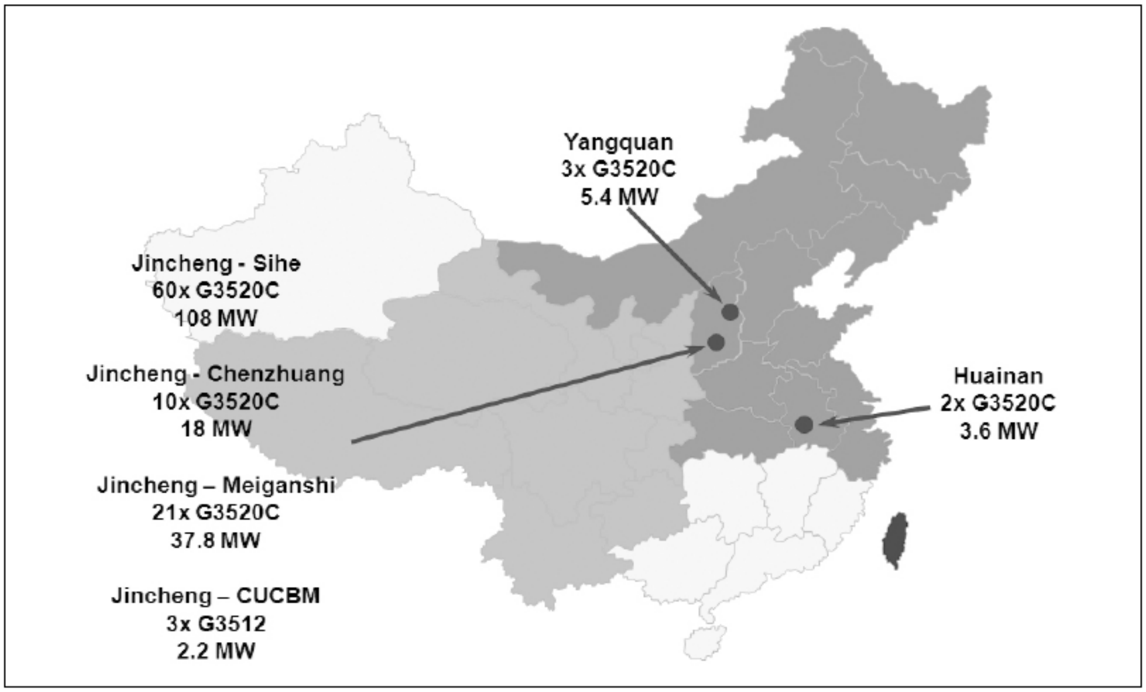
Consideration for Project Development

CMM power plant development typically requires 12 to 18 months from start to completion. Duration very much depends on the site accessibility and the preparation and complexity of the power plant. For mobility and ease of installation, some generator set manufacturers offer containerized sets, which can shorten the completion period.

When considering CMM generator set projects, perhaps the most important decision is choosing a generator set manufacturer. The manufacturer should support customers with design, service, logistical and technical support, and financing. An understanding of local needs and economics and the ability to provide fast, direct service and support are crucial to the success of CMM generator set projects. The manufacturer and dealership staff must also be highly qualified to meet customers' needs for any project, including those like CMM plants with unique needs. A manufacturer that provides financing support and payment options can also be helpful when considering the capital investment required.

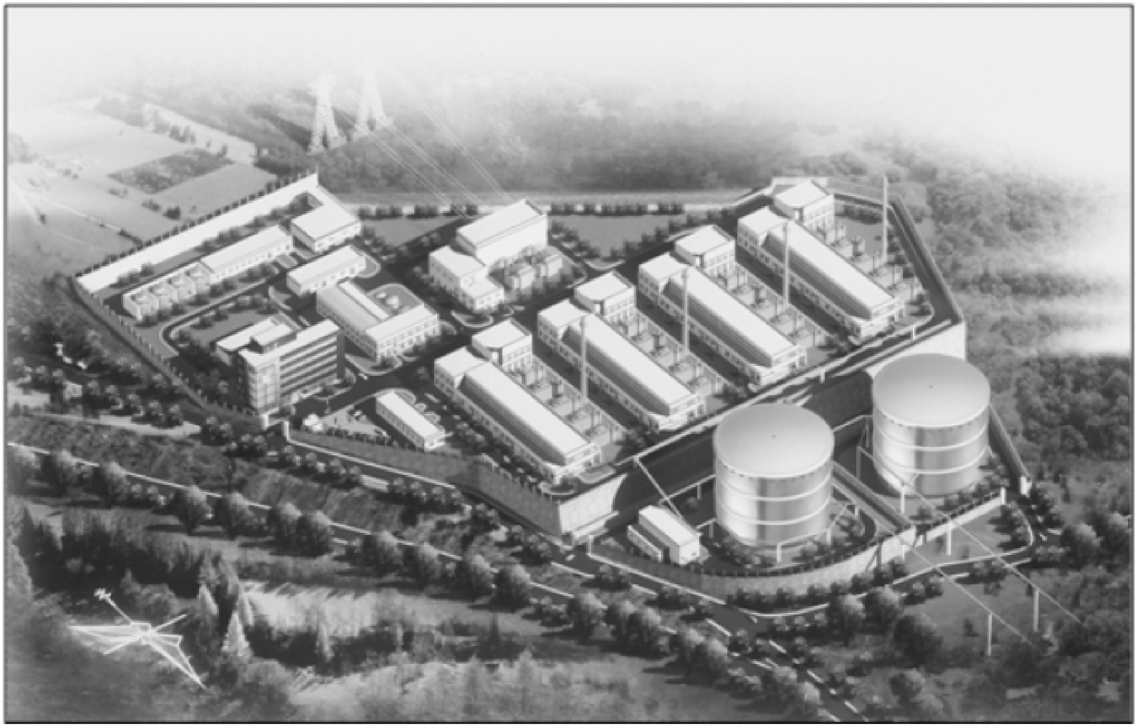
Existing Installations and Future Growth Potential
There are several existing CMM fuel projects in China that have demonstrated the potential for this green energy and its associated economic benefits (see Figure 9).

Figure 9: Existing Caterpillar Coal Mine Methane Projects in China



Sixty Cat G3520C generator sets with low energy fuel packages run on CMM at the Sihe mine in Jincheng, Shanxi province (as illustrated in Figure 10). When fully commissioned, the sixty generator sets will produce over 108 MW of electric power. Additionally, the exhaust heat will be recovered and used to drive steam turbines to produce an additional 12 MW of electric power. The eventual production target is a combined 120 MW with jacket water heat recovery for hot water production. This project is the largest of its kind in the world.

Figure 10: Jincheng Coal Mine Methane 120 MW Power Project



In the City of Yangquan in central eastern Shanxi province, a large CMM fuel project utilizes Cat generator set equipment and that of two other manufacturers. This allowed the customer the opportunity to best evaluate the performance of both the hardware and the technical aftermarket support. The Cat equipment includes three G3520C-CMM gas engines running at 1,800 ekW each at 40% electrical efficiency. The generator sets are grid parallel and operate continuously.

Figure 11 is a summary report based on the evaluation made on Caterpillar G3520C performance at the Yangquan site comparing performance and service. Some of the most important findings are that the Cat generator sets had the least amount of downtime and lowest operating and maintenance cost of the three power systems. Furthermore, Caterpillar is the only supplier at the site with local service when technical or parts support was needed.

Figure 11: Yangquan Summary Matrix

Manufacturer		**Caterpillar**
Model		G3520C
Rated Power	ekW	1800
Reliability		High
Availability		High
Stability		High
Control Interface	Language	Chinese
Derates	Summer (ekW)	None
	Ext. Ancillaries (ekW)	None
Noise Level	Mechanical (dBA)	112
	Exhaust (dBA)	115
Minimum CH_4 for Stable Operation	%	30
Fuel Flexibility		User/self adjustable
Voice of Customer	Reliability	Lowest downtime with most reliable and stable operation
	Production vs. Downtime	2007 production targets reached
	Support	Local service and support staff are experienced and fast responding

While China has several newer successful installations, there are other CMM generator set projects that have been proven successful and efficient in the long-term. One such mature project has been running continuously for over ten years on Australia's southeastern coast.

The Appin and Tower project (shown in Figure 12) is one of the largest coal seam gas energy systems in the world and one of the world's largest reciprocating engine-generator installations of any kind. The Appin and Tower project consumes 600,000m^3 of coal seam gas per day from two separate mines in New South Wales, Australia. Supplementing with natural gas when necessary, the Appin and Tower project uses more than 90 Cat G3516 lean burn generator sets, each of which produces 1,030 kW of continuous power. As of the summer of 2008, most of the units had completed 80,000 running operating hours.

Figure 12: Appin and Tower Coal Seam Energy Project

After more than a decade of operation, the Appin and Tower energy facilities have exceeded expectations for return on investment from the sale of electricity to Integral Energy's grid. The project demonstrates the viability of coal seam gas as a significant source of supply to help meet China's growing need for clean, efficient energy.

CONCLUSIONS AND RECOMMENDATIONS

With the Chinese government's implementation of new policies to drive a cleaner and more sustainable environment, mitigating CMM through generator sets is likely to offer mine owners an opportunity to benefit from the investment. This form of distributed generation is a mature and proven technology used to mitigate methane migration and create power from an available resource.

ACKNOWLEDGEMENTS

This paper would not have been possible without support from the staff of Gelia Wells and Mohr.

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ABOUT

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For more than 80 years, Caterpillar Inc. has been making progress possible and driving positive and sustainable change on every continent. With 2011 sales and revenues of $60.1 billion, Caterpillar is a technology leader and the world’s leading manufacturer of construction and mining equipment, clean diesel and natural gas engines and industrial gas turbines.

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LEXE0025-01 October 2008