Quantifying emissions from spontaneous combustion

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Abstract

Spontaneous combustion can be a significant problem in the coal industry, not only due to the obvious safety hazard and the potential loss of valuable assets, but also with respect to the release of gaseous pollutants, especially CO_2, from uncontrolled coal fires. This report reviews methodologies for measuring emissions from spontaneous combustion and discusses methods for quantifying, estimating and accounting for the purpose of preparing emission inventories.

Acronyms and abbreviations

AAS	atomic absorption spectroscopy
ACARP	Australian Coal Industry Research Programme
AFS	atomic fluorescence spectroscopy
AG DCCEE	Australian Government Department of Climate Change and Energy Efficiency
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BRSC	Beijing Remote Sensing Corporation, China
CCSD	Cooperative Research Centre for Coal in Sustainable Development, Australia
CDM	Clean Development Mechanism
CEN	Comité Européen de Normalisation – European Standards Committee
CFGM	coal-fire gas minerals
CFMIS	Coal Fire Monitoring Information System
CO_2-e	equivalent CO_2, expressed in terms of global warming potential
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CVAAS	cold vapour atomic absorption spectroscopy
CVAFS	cold vapour atomic fluorescence spectroscopy
daf	dry ash free
DOAS	differential optical absorption spectroscopy
ECD	electron capture detection
EDX	energy dispersive X-ray spectrometry
FID	flame ionisation detection
FTIR	Fourier Transform infrared spectroscopy
GC	gas chromatography
GHG	greenhouse gas(es)
GIS	Geographic Information System
GPS	global positioning system
IEA CCC	IEA Clean Coal Centre
IPCC	Intergovernmental Panel on Climate Change
IR	infrared
ISO	International Standards Organisation
ITC	International Institute for Geo-Information Science and Earth Observation, The Netherlands
MODIS	Moderate Resolution Imaging Spectroradiometer
MS	mass spectrometry
Mt	megatonne
NDIR	non-dispersive infrared spectroscopy
NOAA	National Oceanic and Atmospheric Administration, USA
ppb	parts per billion
ppm	parts per million
PRB	Powder River Basin
SEM	scanning electron microscopy
SHT	critical temperature of self heating
TIR	thermal infrared
UNFCCC	United Nations Framework Convention on Climate Change
USGS	US Geological Survey
UV	ultraviolet
VOC	volatile organic compounds
XRD	X-ray diffraction

Contents

1 Introduction

Spontaneous combustion of coal is just that – the unpredicted and instantaneous ignition of coal that is either still underground, in stockpiles or even in transit. Figure 1 shows the classification of different coal fires according to how they occur, their age, location and burning stage. Since spontaneous combustion is unwanted and often occurs without warning, it rarely happens when equipment is available to monitor and quantify emissions with any accuracy. Further, since emissions generally arise from large coal piles or from extended underground coal faces, it is a challenge to obtain total emission values accurately – rather, estimates must be made based on activity data and emission factors. Add to this the fact that the sites of many spontaneous coal fires are remote, abandoned or unsafe to approach, and one can begin to understand why estimates for global emissions from this sector are regarded only as best guesses. Figure 2 shows a bulldozer moving spoils on the Mulga, Alabama gob pile during excavation of a fire break along the base (Stracher, 2012).

The spontaneous combustion of coal results in many of the same types of emissions that arise from coal combustion in power plants but, since there are no control technologies in place, the emission factors are generally higher for spontaneous combustion. The emissions of most concern are commonly CO_2 and CH_4 (as greenhouse gases, GHG), CO, mercury and other toxic substances.

Spontaneous coal combustion is a significant global problem. These fires can be dangerous, leading to death, significant pollution and the forced movement of entire communities. Some remote fires are ignored and left to burn for centuries and there is evidence for coal fires as far back as the Pliocene epoch (Stracher and Taylor, 2004). In the last two millennia the amount of coal lost to natural fires is estimated to be one or two orders of magnitude greater than the total amount of coal used in the last century (Heffern and Coates, 2004). According to O'Keefe and others (2010), the estimate for global mass of coal burnt in coal seam and coal waste stockpile fires vary considerably – from 0.5% to 10% of annual global coal production.

Kolker and others (2009) suggest that, in China, between 10 million and 200 million Mt of coal reserves (again, somewhere between 0.5% and 10% of total production) are consumed annually by coal fires or are made inaccessible owing to fires that hinder mining operations. The global total could amount to three times the estimate for China. The cost of remediation projects in the USA alone has been calculated at over $1 billion per year, with 90% of that concentrated in the states of Pennsylvania

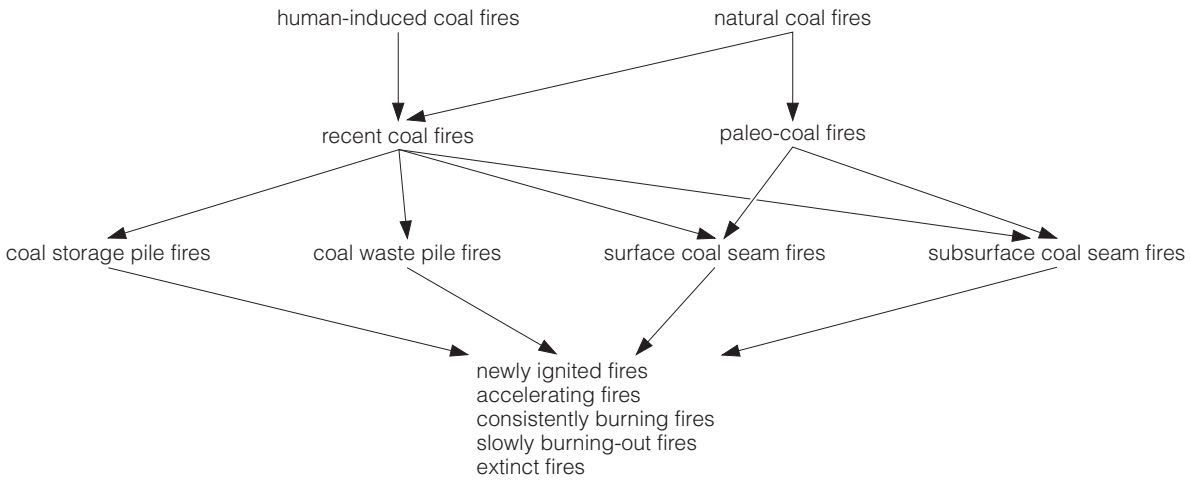

Figure 1 Classification of coal fires according to genesis, age, location and burning stage (Kuenzer and Stracher, 2012)

Figure 2 A bulldozer moving spoils on the Mulga, Alabama gob pile during excavation of an earthen fire break along its base (Stracher, 2012)

and West Virginia, although 15 states have costs exceeding $1 million per year each. Underground fires tend to cost considerably more to extinguish than surface fires and therefore states with more underground mines than open cast tend to have the greatest remediation costs (Kolker and others, 2009).

A recent IEA CCC report (Zhang, 2013) covered the sampling of gases from coal stockpiles, concluding that more research was needed into the formation and control of gaseous emissions. An earlier IEA CCC report (Nalbandian, 2010) dealt with the propensity of coal to self-heat, covering detection, monitoring, prevention and control. The 2010 report discussed methods for measuring emissions from spontaneous combustions but those were methods designed to monitor and control combustion. This new report concentrates only on the measurement and quantification of emissions for the purpose of preparing emission inventories.

2 Sampling and measurement criteria

The previous IEA CCC report by Zhang (2013) deals with emissions from stockpiles undergoing oxidation whereas this report deals with emissions from spontaneous coal combustion. However, these two reports are complementary as it is the oxidation of coal in exposed seams and stockpiles which can lead to spontaneous combustion.

This chapter briefly summarises the chemistry of spontaneous combustion in order to understand why some gases are released during this process. The remainder of the chapter then looks at how each of these gases may be measured and quantified to provide raw data for inventory production. To estimate emissions from sources such as coal fires, inventories require two sets of data:

- an emission factor or rate, relating to the rate of emission of a pollutant from a certain volume or area of coal;
- activity data relating to the volume of coal used, either from weight or volume data or by extrapolation from other data, such as mine surface area.

The data produced from the methods discussed in this chapter can be used as emission factors for the production of emission inventories. Chapter 3 concentrates on the activity data needed to complete the calculations.

2.1 Chemistry of spontaneous combustion

Coal formed over millennia due to extreme temperatures and pressures. During mining, covering layers of soil or rock are removed and coal is immediately exposed to reduced physical pressure allowing the coal to expand and air to move into the seam. Percolation of air through the coal seam can result in a measurable rise in temperature as a result of adsorptive, absorptive and chemical processes. Gases which had previously been either held in the internal surface of the organic matter (adsorption) or within the molecular structure of the coal (absorption) are released and can start to react. These physical and chemical changes within the coal result in the production of heat and, unless the heat is allowed to dissipate, the increasing temperature increases the rate of coal oxidation and self-heating continues, leading eventually to spontaneous combustion.

Materials such as coal which are prone to spontaneous combustion have a critical temperature of self-heating (SHT). If the temperature of the coal reaches the SHT before any equilibrium is attained (through dissipation of heat) then the oxidation accelerates until combustion occurs. And so spontaneous combustion relies on three factors (Pone and others, 2007):

- the reaction between the coal and gaseous reactants which result in self-heating;
- the transport of the gaseous reactant into the coal bed;
- the rate of heat energy dissipation from the coal bed.

The reactions which cause spontaneous combustion can be summarised as follows (Pone and others, 2007):

$$\text{coal} + \text{oxygen} \rightarrow \text{oxycoal} + \text{heat} \rightarrow \text{gas products}$$

Pone and others (2007) have summarised the four stages of oxidation:

- O_2 is physically adsorbed at around –80°C up to 30–50°C when adsorption becomes negligible. The adsorption produces heat as a byproduct of the modified surface energy of the coal;
- chemical absorption (chemisorption) becomes significant at 50°C causing the formation of unstable compounds of hydrocarbons and oxygen known as peroxy-complexes;
- as the SHT of the coal is reached, the peroxy-complexes decompose at an accelerating rate releasing more O_2 for further oxidation (50–120°C, but typically 70°C). At higher temperatures

the peroxy-complexes decompose faster than they form and gaseous products are released – CO, CO_2, water vapour, oxalic acids, aromatic acids and unsaturated hydrocarbons. Together these gases give a characteristic smell known as 'gobstink';

- when the temperature exceeds 150°C, combustion accelerates rapidly.

O_2 consumption is rapid to begin with, as it is involved in chemisorption, but this reduces over time to reach equilibrium, unless the SHT is reached in which case combustion will occur. It is therefore suggested that spontaneous combustion could be avoided by monitoring the gradual increase in oxidation as a function of temperature.

It is not just exposure to air that can cause spontaneous combustion – water can have a surprising effect on coal heating. Water will, at first, cause the coal to swell as it is absorbed and then shrink as the water evaporates. This exposes more coal surface area as the coal structure changes and can lead to higher rates of oxidation and self heating. And so, although water may help reduce spontaneous combustion in some situations by reducing the temperature (via evaporation), it can also cause an increase in coal temperature via the heat of adsorption as coal removes water vapour from the air. The balance of these effects will determine whether spontaneous combustion occurs. Over and above this, water will directly interact with pyrite in the coal:

$$FeS_2 + (7/2)O_2 + H_2O \rightarrow FeSO_4 + H_2SO_4$$

And so water can actually promote spontaneous combustion under some circumstances (Stracher and Taylor, 2004).

The factors leading up to spontaneous combustion are numerous and complex. Figure 3 shows the most important factors involved at open cut coal mine sites. Everything from the type of coal, through the way it is mined to the meteorological conditions can all play a role in whether spontaneous combustion will actually occur (Carras and Leventhal, 2001).

Since the start of mining activities, miners have been aware of the potential hazards of explosions and potential fires when working with coal. Methane and hydrogen released from seams can easily be ignited by electrical equipment, explosives or even sparks from machinery. Natural events such as lightning or bush fires can also ignite coal fires. As a result of this potential hazard, monitoring systems were developed initially only as warning systems and not as quantification systems. 'Coal-fire detector' gases are commonly CO, H_2, C_2H_4, C_3H_6 and C_2H_2, which are released sequentially as

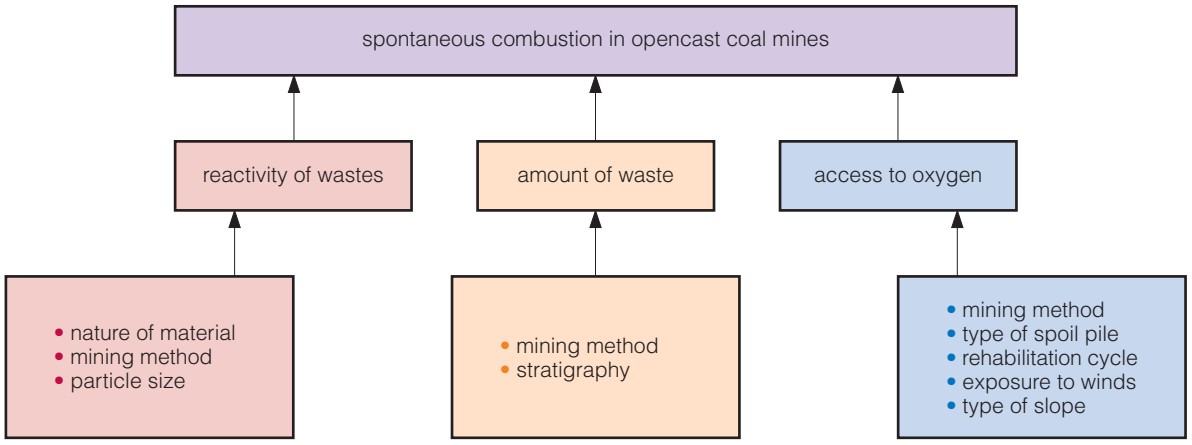

Figure 3 Schematic representation on the most important factors determining the likelihood of spontaneous combustion at an open cut coal mine site (Carras and Leventhal, 2001)

temperature increases:

110°C CO, carbon monoxide, released
170°C H_2, hydrogen gas, released
240°C C_2H_4, methane, released
300°C C_2H_6, ethane, released

Combustion will occur anywhere between 110°C and 170°C and flames will appear around 200°C (Stracher and Taylor, 2004). Many detectors are therefore based on either temperature and or the appearance of at least one of these gases.

According to Cliff (2005), although methane is combustible, it is not in itself the cause of spontaneous combustion. Carbon molecules within the coal itself, especially those with oxygen attached, are more reactive. Low rank coals contain more of the oxygenated species than high rank coals and hence have a higher inherent reactivity. However, coal rank is not always a sign of propensity to combust – there are many other factors involved. Although it is generally known that lower rank coals are more prone to spontaneous combustion than higher rank coals, there does not seem to be an official ranking system. The 'self-heating rate', tested under laboratory conditions, is based on adiabatic oxidation but does not necessarily reflect the other factors that affect spontaneous combustion. Beamish and Beamish (2011) note that the current self-heating rate system categorises the majority of coals being mined worldwide as 'high propensity' and therefore suggests that a more appropriate system is needed. Further, according to Beamish and Beamish (2011), the current systems used only provide an indication of the coal reactivity to oxidation and, in order to be effective in practice, sampling programmes should be tailored to suit each mine project – to identify site specific factors such as anomalous sulphur deposits. However, it is not the release of these gases from the coal which concerns us in this report, but rather the gases released during combustion.

There are two main types of emission factor for spontaneous combustion – those based on measurement data and those based on empirical methods (such as emission factors and known volume of coal combusted). Both are discussed in the sections to follow. Empirical estimates may be the simplest approach but these are rarely seen in the literature. Conversely, there are hundreds of scientific papers published on how to monitor emissions from active spontaneous coal combustion fires. However, these papers do acknowledge that monitoring emissions from this source is a challenge. van Dijk and others (2011) go as far as to say that, with respect to attempting to directly measure the total gas emitted from spontaneous combustion sources, *'this is virtually impossible, and could only be attempted in a few well controlled sites (because coal fires are very dynamic and irregular by nature).'*

2.2 Sampling emissions

The pollutants monitored and the way in which they are sampled varies with the type of project. Spontaneous combustion is measured/quantified for a number of reasons:

- safety – for prediction of potential accidents during storage and transfer of coal;
- for management purposes – to evaluate the fires in order to determine whether extinguishment is possible or whether containment is more appropriate;
- for local environmental issues – to determine which pollutants are being released to the local communities
- for inventories – to provide data on regional, national and global emissions of pollutants such as CO_2 and mercury.

This report is concerned with the latter scenario. In the first three cases, the data are generally gathered for a single fire or a single area whereas the fourth case requires the gathering of data from many locations. However, data from single locations can be accumulated and combined to provide data for a larger area or can be used to provide emission factors which can be extrapolated to other

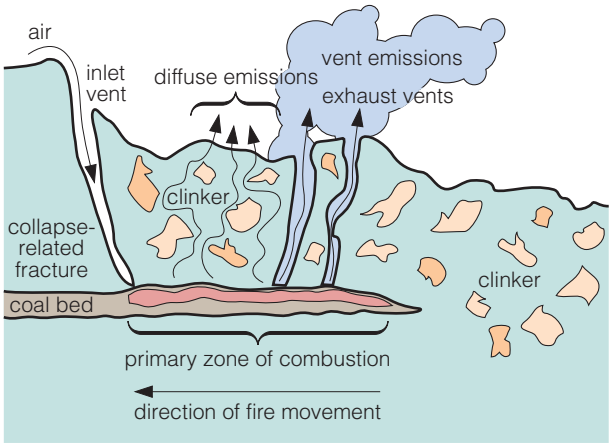

Figure 4 Conceptual model of a coal fire including depictions of diffuse and vent emissions (Engle and others, 2010)

larger areas. This report concentrates on quantifying emissions from spontaneous combustion at both the local, national and global scales. The monitoring/detection systems used for measuring emissions from combustion in all the situations listed above are similar and based on the same principles. However, the way the data are collected and how they are used can differ significantly. The following sections summarise the different approaches used for sampling emissions at single locations versus larger areas. After that, the chapter looks at the methods used to measure the different pollutants and the related parameters required to quantify emissions.

One of the major challenges for emission monitoring from coal fires is determining the sample location. In most instances, emissions do not arise from one point source at coal fires, rather there are two main routes (O'Keefe and others, 2011):

- advective transport through vents and other surface openings;
- upward diffusion and possibly advection through soils and overburden.

The flow of vent and diffuse emissions are shown in Figure 4.

Therefore, unlike stack emissions, emissions from spontaneous combustion are often diffuse and numerous, and, in some cases, cover significant areas. And so, although the same measurement principles can be used, the way they are applied to the sampling site must be modified accordingly. Perhaps more importantly, sampling locations at spontaneous combustion sites are often selected by default as they are the only sites approachable, accessible or safe to be near, bearing in mind that many of these sites are dangerous and conditions are challenging (heat, flames, smoke and so on).

2.2.1 Sampling at single locations (vents)

Emissions from what can be regarded as small point sources such as vents or fissures can be monitored by a number of means:

- grab sampling;
- optical techniques and remote monitoring

Grab sampling, using special glass, plastic or stainless steel canisters (depending on the target capture species) can be performed at the site and the sample sent to the laboratory for analysis. Grab sampling is often used for measuring species such as VOC (volatile organic compounds). Optical systems, which apply beams across the plume or across a sample of the plume, can be used over vents and fissures.

In addition to the gases themselves, the flow rate from the vent will also need to be determined in order to calculate a total emission rate (*see* Section 2.3.1). The calculation is then (O'Keefe and others, 2011):

Emission rate = concentration x velocity of gas at vent x cross-sectional area of vent

If the vent is wide, then samples and measurements may be taken at several points evenly distributed over the area to produce an overall average emission value.

Cook and Lloyd (2012) included sampling at points on a mine fire where there was visible smoke. However, they noted that these locations were sporadic across the surface. They also noted that the emission 'values are subject to large errors and are probably only within an order of magnitude at best'. Cook and Lloyd (2012) carried out most of their monitoring with diffuse sampling units (*see below*). The air released from vents and fissures above strong underground fires can be as high as several hundred °C and so care must be taken when sampling.

2.2.2 Emissions through piles and overburden/diffuse emissions

Not all the emissions from an underground or covered fire will be released through vents and fissures. For larger fires, covered by overburden or other material, it is common for gases to permeate up through the rock, topsoil and overburden over a wide area above the seam. These diffuse emissions can be significantly more difficult to measure. Since it is impossible to measure all the emissions across a wide and often ill-defined land area, sampling areas and points must be selected to give a representation of the average emissions across the site and then these values will be used to prepare an overall estimate for the whole site.

Engle and others (2012b) note that there are two types of chambers used to monitor gas fluxes:

- accumulation chambers – where the chamber sits firmly over the soil surface and the rate of gas accumulation is monitored as a result of the release from the soil which eventually reaches a steady-state. The rate of concentration over time is measured;
- dynamic chambers – where the emissions are fed directly to analysers to give real-time emission rate data.

Dynamic chambers are most popular in spontaneous combustion studies. Dynamic closed chambers are best for gases that can be measured quickly as they are collected in a closed chamber in a short period of time before any interference from the build-up of water vapour can occur. Dynamic open chambers are more suitable for longer sampling times (>1 minute) but are sensitive to flow rate and chamber turnover rate and so the size of the chamber may have to be determined on a site-specific basis to suit the gas emission conditions.

Figure 5 shows an example of a dynamic open collection chamber used to collect emissions from the surface of coal spoils. The chamber feeds directly to analysers for target gases such as CO_2 and CH_4. Chambers of this size can collect suitable samples within a matter of minutes, giving a rapid turnover time (Carras and others, 2009).

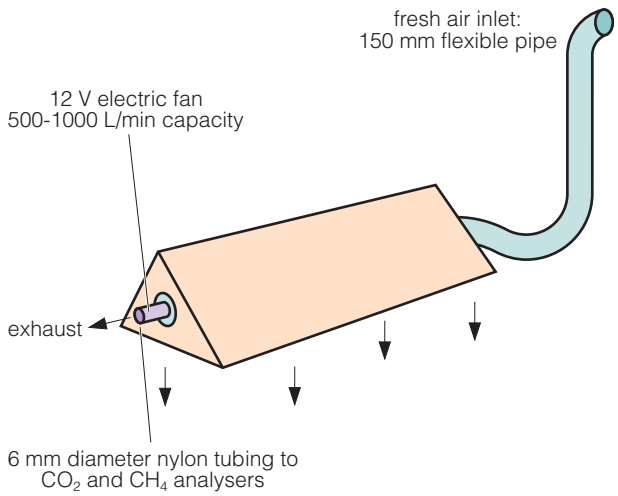

Figure 5 Schematic diagram of the large chamber used to measure gas from spoil piles and other surfaces (Carras and others, 2009)

Cook and Lloyd (2012) report on the measurement of emissions from waste coal piles in South Africa. They compared a number of collection chambers, some with rigid sides and some with more flexible sides, of various sizes and shapes from 0.3 m^2 to 9 m^2. The leakage from each system was compared by measuring the leakage rate of a known tracer gas applied inside the container over a period of time. The systems were checked on different surfaces and under different wind conditions. The best system was shown to be a unit created from half of a 220 litre plastic drum, 0.91 m high by 0.54 m in diameter. The unit could collect a volume of 0.115 m^3 over an area of 0.491 m^2. The

Table 1 Fluxes and emissions from target areas (Cook and Lloyd, 2012)

Type of area	Flux, kg/m²/y					Area	Emission, t/y			
	CO_2	SOx	NOx	NH_4	CH_4		CO_2	SOx	NOx	NH4
Levelled soil and interburden	0.24	3.8–2	1.5–3	5.9–4	0	45	108	17.3	0.7	0.3
	0.06	3.4–2	1.9–3	1.2–4	0	235	141	78.8	4.5	2.8
	71.95	5.4–2	4.4–3	5.0–4	0	881	633,915	476	38.5	4.4
	2.81	9.7–3	–1.0–3	5.1–4	0	952	26,766	92.1	–9.5	4.9
	–2.57	4.7–2	2.3–3	–2.6–4	0	1	0	0.5	0	0
	–0.23	–7.7–4	2.8–3	not determined	0	1,475	0	–11.4	40.6	0.1
Rehabilitated and covered	0.04	3.58–2	2.8–3	6.2–4	0	17	7	6.5	0.2	0.1
	0.28	1.0–1	3.4–3	5.4–4	0	17.3	49	18.0	0.6	0.1
	0.31	–3.8–2	1.5–3	–2.0–4	0	60	188	28.2	1.4	–0.2
	1.34	6.1–2	7.0–4	not determined	0	105	1,407	64.1	0.7	not determined
Rehabilitated and grassed	0.07	5.6–2	3.12	4.5–4	0	10	7	5.6	3.1	0.0
	0.31	4.1–2	2.9–3	4.6–4	0	103.5	324	41.9	3.0	0.5
	–0.22	1.3–3	5.8–4	1.1–5	0	3,252	0	41.3	19.0	0.4
	0.22	4.3–4	7.3–4	1.1–4	0	650	1,408	2.8	4.8	0.7
	0.38	1.8–4	1.4–2	–3.2–4	0	62	234	0.1	8.7	–0.2
	0.22	–3.9–2	1.7–2	–2.9–4	0	34	74	–13.1	5.7	–0.1
	–4.9	6.8–2	6.6–4	not determined	0	105	0	71.8	0.7	0.0
Burnt and partially covered	58.75	2.2–2	2.8–2	–8–5	0.55	62	36,428	13.8	17.4	–0.1
	2.08	2.6–2	9.9–3	4.5–4	0	34	706	8.8	3.4	0.2
	0.75	2.8–2	4.1–2	1.8–4	0	1	7	0.3	0.4	0
	10.06	2.5–2	–9–3	1.1–4	0	1	101	0.2	–0.1	0.0
	0.2	7.1–2	7.8–3	6.2–5	0	60	120	42.5	4.7	0.0
	320.9	2.3–2	7.2–3	3.7–4	0	61	195,728	13.9	4.4	0.2
Fresh and smoking * area in which smoke was observed	67.5	–1.3–3	2.1–4	1.1–4	0	(21,934*)	(21,934)	(–0.4)	(0.1)	(0.0)
	44.52	–1.6–3	7.2–3	3.7–4	0	(48.8)*	(21,726)	(0.8)	(0.5)	(0.0)
	7,393	–4.8–3	7.2–3	3.7–4	0.0075	(0.1)*	(6,653)	(0.0)	(0.0)	(0.0)
	7,292	2.8–1	7.2–3	3.7–4	1.20	(0.6)*	(43,021)	(1.7)	(0.4)	(0.1)
	780	2.0	7.2–3	3.7–4	0	(0.01)*	(78)	(0.2)	(0.0)	(0.0)

collection system was connected, via plastic tubing, to a sampling system and gas was withdrawn at a rate of 2.40 L/min. There were four sampling ports into each collection unit, for sampling different pollutants. Samples for NOx, SOx and ammonia were collected in impinger trains (*see below*) and the solutions analysed appropriately. The results of the emission fluxes in each area are shown in Table 1. The emission rates were then multiplied by the area of each site, in hectares, to give total emissions in tonnes per year. This approach is discussed further in Chapter 3. The sites in the table include abandoned and rehabilitated coal mines that were not on fire as well as a burnt and partially covered site and a fresh and smoking site. From the results it is clear to see that the emission rates from rehabilitated and covered sites are significantly lower than those from freshly burning sites, as would be expected. There was considerable variability at some sites. Negative emission rates resulted when the emissions sampled were lower than the background concentrations of the target gases. At large sites where there are already elevated background concentrations, this can be an issue. The values in parenthesis were considered to be prone to error, as discussed earlier, as they were sampled over smoking vents.

The range of CO_2 emission fluxes across the burnt site (0.2–320.9 kg/m^2/y) and the fresh and smoking site (44.52–7,393 kg/m^2/y) indicate just how variable emissions can be across individual sites. Some of the negative CO_2 measurements were reported to be due to photosynthesis occurring in plants in the sample area during measurement. However, Cook and Lloyd (2012) state that most of the dumps appeared relatively homogeneous and were chosen at random and so 'there is no reason to suspect gross homogeneity'. The standard deviation was put at ±20% to account for lack of representativeness. Cook and Lloyd (2012) also stressed the effectively lowered emissions from mining sites which had been properly remediated and covered. Methane was only detected from the burning coal site.

Engle and others (2010) at the US Geological Study (USGS) measured the CO_2 flux from the Mulga gob fire in northern Alabama, USA. The CO_2 passing through the soil from the fire in the area below was collected in an accumulation chamber (3 litre capacity). The CO_2 in the chamber was then withdrawn and passed to an NDIR (non-dispersive infrared, *see* Section 2.3) monitoring system to give concentration measurements in real-time. The soil flux of CO_2 was then calculated as follows:

$$F = \rho V/A \times \delta C/\delta t$$

Where:

ρ = gas density
V = flux system volume
A = footprint of the flux chamber
$\delta C/\delta t$ = rate of accumulation of CO_2

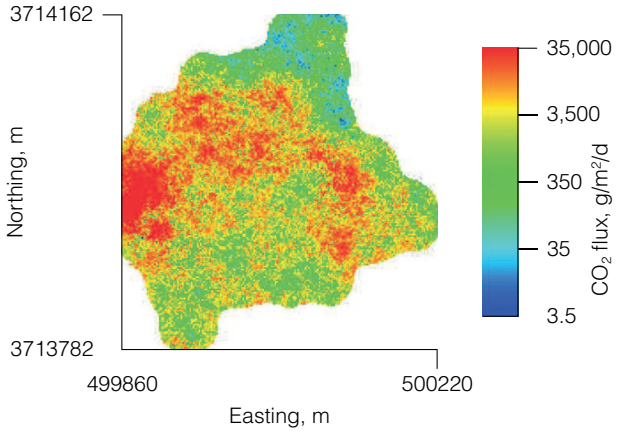

Figure 6 **CO_2 flux map** (Engle and others, 2012b)

In order to get a valid representation of emissions over the area of the fire, 24 collection points were selected across the relevant site. This included sites of obvious fire activity and near vents, as well as control points for background points at a distance from the fire. Surface temperature and GPS (global positioning system) location were also logged.

The data were then treated to estimate the temperature and CO_2 distribution across the entire sites and the results were then mapped using sequential Gaussian co-simulation to give a map of heat and CO_2 emissions, as shown in Figure 6. This makes it possible to

create an estimate of total CO_2 emissions across the whole site. The total CO_2 emissions for the 8.7 ha area studied were estimated at 210–378 t/d (2400–4400 g/m^2/d). For comparison, a 500 MWe coal-fired power plant emits around 10,000 t/d CO_2.

Engle and others (2010) acknowledge that there are potential errors and unknowns with using this type of system, which include:

- data are collected at one time, in this instance during a single day of sampling, and therefore cannot represent temporal variations in emissions;
- the methods used require expertise in both monitoring methods and mathematical data treatment methods;
- more sampling points, more evenly spread would give better data;
- no measurement technique is without error;
- only flux emissions were measured – vent emissions would need to be measured separately.

2.2.3 Ambient monitoring and remote sensing

Since the emissions from spontaneous combustion are carried by prevailing winds, it is possible to measure the increased background concentrations of pollutants as a result of coal fires in areas nearby. Carras and others (2005) measured fluxes of GHG emissions in Sydney, Melbourne and Brisbane, Australia. However, to obtain a suitable sample, several traverses of the plume had to be made at various heights above the ground which required the use of aircraft. Aircraft monitoring with infrared (IR, *see* Section 2.3) heat signatures from boreholes at coal mine fires were carried out as early as the 1960s, if not before (Greene and others, 1969). Engle and others (2011, 2012b) used an IR camera on the Cessna plane above several coal combustion sites in the Powder River Basin. The aircraft was maintained at a fixed height (2900 m) above sea level. Ambient monitoring using vehicles driven into areas downwind of mines has also been applied (Carras and others, 2009).

Ambient monitoring can also be combined with atmospheric modelling and back-calculations to estimate the emissions from individual sources. However, this approach can be complex and time consuming, especially in areas where there are numerous sources of pollution. Carras and others (2005) therefore suggest that any such ambient monitoring studies should select sampling sites carefully:

- sufficiently close to the site of spontaneous combustion to enable a large measurable signal;
- chosen on the basis of meteorology to best capture the CO_2 signal;
- chosen to minimise the influence of other sources.

Monitoring methods are available which can be used to determine emissions or flux concentrations from considerable distances away from the actual site of release. This is known as remote monitoring or remote sensing. Perhaps the most remote monitoring possible is with the use of monitoring systems housed on commercial satellites orbiting the Earth. Satellites such as Landsat 5 TM, 7ETM+, the US-Japanese ASTER, German BIRD and US MODIS are often used to provide thermal maps for coal fire studies, especially in China. The Advanced Very High Resolution Radiometer (AVHRR) is a space-borne sensor run by the National Oceanic and Atmospheric Administration (NOAA) from satellites which measures the thermal radiation emitted by the planet, around 11 and 12 μm, respectively Kuenzer and others, 2007c).

Some satellite data are only accurate to 120 m spacial resolution which is limited in its accuracy for small or deeper fires. By combining the results from different radiation band sets (dual band method), more accurate data can be obtained. Much of the published data from the 1990s and early 2000s are based on satellite data which have undergone significant processing and interactive analysis to provide more information on small fire areas. Understanding thermal data is a challenge, as the reading from coal fires must be distinguished from readings from vegetation, and from solar reflectance during daylight hours (Kuenzer and others, 2007c).

The relationship between heat maps produced by thermal data obtained from satellites and approximation to CO_2 emissions is discussed more in Section 2.5.2.

2.3 Target pollutants

The sections below briefly summarise the available methods for quantifying emissions of the pollutants most commonly associated with spontaneous combustion. Whilst CO_2 and CO emissions will be directly related to the carbon content of the coal, the emissions of other species such as trace elements will depend on the volatility of the element, the chemistry of the coal, the temperature of the burn and other physical factors such as fracturing of the overburden (Engle and others, 2012b).

There are standard methods for measuring pollutants, as defined by the International Standards Organisation (ISO) and CEN (Comité Européen de Normalisation). Countries may have their own additional standards for those pollutants not covered by ISO or CEN standards. However, these standards all apply to prescribed sources, such as coal-fired power station stacks or waste incinerators. There are standards for detecting emissions for the purpose of avoiding spontaneous combustion, as mentioned earlier. Emission detection requirements are often also defined in coal company and mining operational guidelines (Beamish and others, 2012). There are standard methods for determining the propensity of coal to oxidise. There are also standardised methods for using equipment such as remote IR monitors for measuring fugitive emissions. However, there are no standardised methods for quantifying total emissions from spontaneous combustion. In the absence of this guidance, those who wish to monitor emissions from spontaneous combustion must either use basic standard methods, such as those listed in Table 2 or simply use the methods available to them. Sampling and analysis of emissions from coal combustion via the plant stack has been covered in several previous IEA CCC reports (Sloss, 1998; 2009).

2.3.1 CO_2, CO

Commercial monitors are available which can detect a number of gases simultaneously and many of these systems are portable enough to be taken out to coal fire sites. CO_2 and CO are commonly monitored in situ with NDIR (non-dispersive infrared spectroscopy) or DOAS (differential optical absorption spectroscopy) systems. Or the gas can be extracted and analysed by NDIR or FTIR (Fourier transform infrared spectroscopy). CO_2 can be monitored directly using commercial UV (ultraviolet) and IR monitors which can be adjusted to select a wavelength which is most suitable to detect the target gas whilst ignoring signals from interfering gases such as water vapour. For example, Gangopadhyay and others (2005) report on the ways in which remote sensing bands can be selected to suit specific studies. According to Ide and Orr (2011), methods for measuring CO_2 emissions based on surface observations and measurements are far less well established than methods based on remote sensing. O'Keefe and others (2010) report on monitoring emissions from several coal fires in the USA and found that CO_2 emissions appeared to be more stable than emissions of CO and Hg, which were affected more by local conditions.

Both CO and CO_2 are colourless and odourless gases. CO monitors are often used as the primary means of detecting or predicting spontaneous combustion. CO concentrations rise as the coal oxidises and an alarm can be set at a temperature which will indicate concentrations of concern. A simple internet search will bring up a host of companies that provide CO monitors in all sizes and types, from domestic units up to those for industrial use. Larger systems will have self-checking and auto-calibration built in and the alarm can be set to suit the location and requirements.

Table 2 Standard methods for monitoring pollutants from point sources (Curtis, 2013)

Compound/Method	Standard Number	Description
Alternate reference method procedure	DD CEN/TS 14793:2005	Intralaboratory validation procedure for an alternative method compared to a reference method
Calibration of CEMS	BS EN 14181:2004	Quality assurance of an AMS
Carbon Monoxide (CO)	BS EN 15058:2006	Determination of the mass concentration of carbon monoxide (CO). Reference method: non-dispersive infrared spectrometry
Flow automatic	BS ISO 14164:1999	Determination of the volume flowrate of gas streams in ducts. Automated method
Flow (manual method)	BS EN ISO16911-1:2013	Manual and automatic determination of velocity and volumetric flow in ducts. Part 1: Manual reference method
Flow (automated method)	BS EN ISO16911-2:2013	Determination of velocity and volumetric flow in ducts. Part 2: Automated measuring systems
Hydrogen chloride	BS EN 1911:2010	Manual method of determination of HCl
Hydrogen chloride	PD CEN/TS 16429:2013	Sampling and determination of hydrogen chloride content in ducts and stacks – Infrared analytical technique
Hydrogen fluoride	BS ISO 15713:2006	Sampling and determination of gaseous fluoride content
Mercury	BS EN 13211:2001	Manual method of determination of the concentration of total mercury
Mercury calibration	BS EN 14884:2005	Determination of total mercury: automated measuring systems
Metals	BS EN 14385:2004	Determination of the total emission of As, Cd, Cr, Co, Cu, Mn, Ni, Pb, Sb, Tl and V
Nitrogen oxide (NOx)	BS EN 14792:2005	Determination of mass concentration of nitrogen oxides (NOx). Reference method: Chemiluminescence
Oxygen	BS EN 14789:2005	Determination of volume concentration of oxygen (O_2). Reference method. Paramagnetism
PAH analysis	BS ISO 11338-2:2003	Determination of gas and particle-phase polycyclic aromatic hydrocarbons. Sample preparation, clean-up and determination
PAH sampling	BS ISO 11338-1:2003	Determination of gas and particle-phase polycyclic aromatic hydrocarbons. Sampling

Table 2 Standard methods for monitoring pollutants from point sources (Curtis, 2013)

Compound/Method	Standard Number	Description
Particulate	BS ISO 12141:2002	Determination of mass concentration of particulate matter (dust) at low concentrations. Manual gravimetric method
Particulate / Dust	BS EN 13284-1:2002	Determination of low range mass concentration of dust. Manual gravimetric method
Particulate high range	BS ISO 9096:2003	Manual determination of mass concentration of particulate matter
Particulate $PM_{10}/PM_{2.5}$	BS EN ISO23210:2009	Stationary source emissions. Determination of $PM_{10}/PM_{2.5}$ mass concentration in flue gas. Measurement at low concentrations by use of impactors.
Particulate PM_{10}/PM2.5 for high concentrations	BS ISO 13271:2012	Determination of $PM_{10}/PM_{2.5}$ mass concentration in flue gas. Measurement at higher concentrations by use of virtual impactors
Particulate $PM_{10}/PM_{2.5}$	BS ISO 25597:2013	Test method for determining $PM_{2.5}$ and PM_{10} mass in stack gases using cyclone samplers and sample dilution
Sulphur dioxide (SO_2)	BS EN 14791:2005	Determination of mass concentration of sulphur dioxide. Reference method
TOC high range	BS EN 13526:2002	Determination of the mass concentration of total gaseous organic carbon in flue gases from solvent using processes. Continuous flame ionisation detector method
TVOC	BS EN 12619:2013	Determination of the mass concentration of total gaseous organic carbon at low concentrations in flue gases. Continuous flame ionisation detector method
TVOC by NDIR for non-combustion sources	BS ISO 13199:2012	Determination of total volatile organic compounds (TVOC) in waste gases from non-combustion processes. Non-dispersive infrared method equipped with catalytic converter
VOC speciation	BS EN 13649:2002	Determination of the mass concentration of individual gaseous organic compounds. Activated carbon and solvent desorption method

2.3.2 SOx, NOx and particulates

SOx can be measured with wet chemical methods – by adsorbing the gas through a series of solutions in impinger bottles to allow the SOx to dissolve. The concentration in solution can then be analysed by titrimetry and the concentration in the sample gas calculated based on the known volume sampled.

NOx can be absorbed into solution through a sampling impinger train and then analysed via ion chromatography or chemiluminescence.

Depending on the size and type of particulates being studied, the methods used range from optical methods (light-scattering, absorption or reflectance) to filters, gravimetric analysis (weight) and impactors.

2.3.3 CH_4 and VOC

In most combustion systems, CH_4 would be completed converted to CO_2 during the combustion process. However, as we know, coal fires are often a mixture of regions of combustion and regions of oxidation and so some characterisation studies include data on CH_4 emissions. CH_4 can be measured directly with flame ionisation detection (FID).

Volatile organic compounds (VOC) are often captured with grab sampling techniques into stainless steel canisters which can be shipped to a laboratory for analysis. Gas chromatography (GC) is ideal for identifying and quantifying carbon-containing species such as aliphatic (methane up to decane) and aromatic (benzene, toluene, ethylbenzene and xylene) compounds. In some cases, the concentrations of some carcinogenic species can exceed limits prescribed as being potentially damaging to human health (O'Keefe and others, 2011). Some hydrocarbons can be studied by GC followed by FID and/or thermal conductivity detectors.

Engle and others (2012a) used GC/MS (gas chromatography/mass spectrometry) to identify VOC emissions from three coal fires in the Powder River Basin, USA. The emissions were shown to be very variable with one site, Welch Ranch, having benzene emission concentrations up to 3.8 ppmv, indicating incomplete combustion of the coal. Benzene concentrations at other fires in the region were lower at below 0.007 ppmv. Around 28 aliphatic compounds were detected (CH_4 up to C_9H_{20}) varying in concentrations from as low as below the detection limit to around the ppm level. Aromatic compounds such as benzene and o-xylene were also detected in the ppb to ppm range.

2.3.4 Trace elements, including mercury

Mercury and mercury monitoring has been covered in numerous IEA CCC reports (Sloss, 2012). Mercury is commonly monitored using techniques such as DOAS (vapour only) and CVAAS (cold vapour atomic absorption spectroscopy) or CVAFS (cold vapour atomic fluorescence spectroscopy).

Hower and others (2009) measured mercury release from two vents at the Tiptop coal mine fire in Kentucky, USA. The mercury was measured using a simple sensor based on a thin gold film which, in the presence of mercury vapour, undergoes an increase in electrical resistance proportional to the mass of mercury in the sample. The sensor indicated concentrations of 390 and 580 µg/m^3 at the two vents during a sampling project in May 2009. However, in January of the same year, the mercury content at one vent was below the detection limit (<9 µg/m^3) and above the detection limit (>2100 µg/m^3) at the other. The latter result was suspected to be as a result of the vent temperature exceeding the temperature limit for reliable measurement with this system. However, further studies detected mercury concentrations exceeding 500 ppm, around five times the USA eight-hour exposure limit, in the immediate vicinity of the vent.

In the estimate of mercury emissions from China, produced by Streets and others (2005) the emission factor for mercury emissions from spontaneous combustion from coal was 0.02–0.43 g/t and this was obtained based on the average Hg content of Chinese coals and an 83% emission rate. This was in a similar range to emission factors for mercury emission from coal combustion in utilities. Total emissions of mercury from spontaneous combustion of coal globally could amount to around 50 t/y, equivalent to the total US emissions of Hg from coal combustion in power plants in recent years (Kolker and others, 2009).

Other trace elements such as heavy metals are commonly monitored using DOAS, AAS (atomic absorption spectrometry) or AFS (atomic fluorescence spectrometry). Kuenzer and others (2007b) note that food crops in coal fire areas, such as those in China, have elevated concentrations of Cu, F, Pb, Zn and Cd. Pone and others (2007) studied emissions from coal fires in the Witbank and Sasolburg coalfields in South Africa. Arsenic and related organic compounds were detected, with

thallium arsenate ($TlAsO_4$) being one of the dominant forms of arsenic at lower temperatures. However, during spontaneous combustion, at temperatures above 600°C, the majority of arsenic would be in the AsO and As_2O_3 gas phases.

2.3.5 Other species

Other pollutants such as halides and ammonia can be monitored with standard systems such as FTIR, DOAS and NDIR but are not often considered as important as the other pollutants from spontaneous combustion and so are rarely mentioned. NH_3 (ammonia) can be measured by dissolving in impinger solution followed by UV spectroscopy.

2.3.6 Solids

Coal-fire gas minerals (CFGM) are found deposited around sites where combustion has taken place and can be used to determine sites where spontaneous combustion has occurred in the past. CFGMs can also be measured as they are released from actively burning piles and fumaroles (vents and fissures) by scraping them from the top layer of soil or rock which can be stored and sent to a laboratory for detailed analysis. Pone and others (2007) report on the use of X-ray diffraction (XRD), scanning electron microscopy (SEM) with energy dispersive X-ray spectrometry (EDX) for analysing CFGM samples from various sites in the Witbank coalfield in South Africa. Further mineral analysis was achieved with gas chromatography (GC), electron capture detection (ECD), mass spectrometry (MS), and FID. A wide range of aliphatic and halogenated hydrocarbons were identified and quantified. The study of these species helps to give a better understanding of the reactions that occur during spontaneous combustion as well as providing an indication of potential harmful contamination. Compounds such as ammonium chloride (salammoniac, NH_4Cl) were measured, which are also associated with volcanic sources.

Engle and others (2012a) used XRD and organic analysis as well as diffractometers to study the minerals and tar deposits on the mouth of coal fire vents at three spontaneous combustion sites in the Powder River Basin, MO and WY, USA – Welch Ranch, Ankney and Hotchkiss. Tar samples and hydrocarbon deposits were measured with GC/MS. Gypsum and sulphur deposits were identified along with Tschermagite quartz and Cristobalite quartz. Riihimaki and others (2009) used zircon samples (ZrSiO4) and ‘zircon He dating’ based on thermochometric and radiogenic analysis, to study the history of spontaneous coal fire occurrences from pre-glacial periods in the USA.

2.4 Other emission monitoring parameters

In addition to monitoring concentrations of pollutants, measurement studies must also include other parameters such as volume or flow rate, temperature, and so on, to allow the calculation to be made to create an overall emission rate under standard conditions. This is one way of creating an emission factor for a source such as spontaneous combustion based on measured data.

2.4.1 Volume/flow rate

Methods used for the quantification of emissions must take into account the total volume of gas emitted. This means that, in addition to the data on pollutants being released, data on the total gas release rate must also be obtained. In many cases, these data will be obtained from a small sample area and extrapolated to give a total value for a significantly larger area.

For vents and fissures, the flow rate of gases can be determined with a pitot tube, in the same manner

Table 3a Vent locations, areas, pitot-tube flow rate and supporting information, gas concentrations, soil and vent temperatures, gas emission rates, annual gas emissions, and gas flux, Old Smokey coal mine, May (O'Keefe and others, 2011)

Vent #	1	2	3	5	6	7	8	9	10	11	12	13	14
Emissions over 5-min intervals													
Vent area, m^2	0.1411	0.2976	0.0015	0.402	0.2712	0.0782	0.04	0.1662	0.0198	0.1088	0.1232	0.531	0.201
Pitot flow rate													
Flow rate, m/s	1.22	9.26	2.07	5.30	2.88	2.00	0.98	1.26	1.44	1.20	0.70	3.32	1.68
Std dev velocity	0.42	0.46	0.07	0.21	0.51	0.28	0.44	0.14	0.16	0.24	0.23	0.25	0.18
Temperature, °C	28.1	33.0	30.8	33.9	36.4	66.1	53.4	50.8	49.7	36.9	32.7	75.4	58.1
Relative humidity, %	56.8	27.1	25.3	28.4	39.9	41.6	29.0	31.4	33.2	26.6	27.2	35.8	43.8
ρ, kg/m^3	1.08	1.09	1.10	1.09	1.07	0.95	1.02	1.01	1.01	1.07	1.09	0.91	0.98
Barometric pressure, kPa	96.33	96.33	96.33	96.33	96.32	96.29	96.26	96.25	96.24	96.24	96.26	96.27	96.29
Gas concentrations													
CO_2% vol	1.81	1.31	0.03	0.20	1.18	0.60	0.24	0.28	0.30	0.42	0.24	0.50	0.73
CO ppm	1122.4	992.6	32	166.4	952.4	688.6	370.8	333.4	394.2	546.2	358.2	773.6	900.6
CH_4% vol	0.13	0.14	0.00	0.00	0.11	0.10	0.04	0.00	0.00	0.11	0.00	0.13	0.14
H_2S ppm	4.8	8.1	0.6	1.4	7.8	4.9	3.2	3.7	3.6	3.7	3.3	4.8	4.6
Soil temperature, °C	n.a.	67.6	27.8	27.6	66.0	57.1	53.6	37.1	39.8	39.9	43.9	56.7	53.4
Vent temperature, °C	66.3	75.4	36.0	22.4	54.0	74.6	65.2	31.8	40.3	45.9	38.1	86.3	54.4

Table 3a Vent locations, areas, pitot-tube flow rate and supporting information, gas concentrations, soil and vent temperatures, gas emission rates, annual gas emissions, and gas flux, Old Smokey coal mine, May (O'Keefe and others, 2011)

Vent #	1	2	3	5	6	7	8	9	10	11	12	13	14
Emission rates													
CO_2 emission rates, mg/s	1300 ±430	17,000 ±850	0.41 ±0.013	2100 ±81	4800 ±840	890 ±130	71 ±32	430 ±48	61 ±6.7	290 ±56	96 ±31	9500 ±730	2000 ±220
CO emission rates, mg/s	50 ±17	820 ±41	0.028 ±0.0009	110 ±4.3	250 ±43	65 ±9.2	7.1 ±3.2	32 ±3.6	5.1 ±0.56	24 ±4.7	9.2 ±3	940 ±72	160 ±17
CH_4 emission rates, mg/s	33 ±11	660 ±33	0±0	0±0	160 ±29	55 ±7.8	4.8 ±2.2	0±0	0±0	27 ±5.2	0±0	870 ±67	140 ±15
H_2S emission rates, mg/s	0.26 ±0.09	8.2 ±0.4	0.00063 ±0.00002	1.2 ±0.045	2.5 ±0.43	0.56 ±0.079	0.075 ±0.034	0.43 ±0.048	0.057± 0.0063	0.2 ±0.039	0.1 ±0.033	7 ±0.54	1 ±0.11
CO_2 emissions, t/y	40 ±14	540 ±27	0.013 ±0.00042	65 ±2.6	150 ±27	28 ±4	2.3 ±1	14 ±1.5	1.9 ±0.21	9.1 ±1.8	3 ±0.98	300 ±23	64 ±6.8
CO emissions, t/y	1.6 ±0.54	26 ±1.3	0.00088 ±0.000029	3.5 ±0.14	7.8 ±1.4	2 ±0.29	0.22 ±0.1	1 ±0.11	0.16 ±0.018	0.76 ± 0.15	0.29 ±0.094	30 ±2.3	5.1 ±0.54
CH_4 emissions, t/y	1 ±0.36	21 ±1	0±0	0±0	5.2 ±0.91	1.7 ±0.25	0.15 ±0.068	0±0	0±0	0.84 ± 0.17	0±0	28 ± 2.1	4.4 ±0.47
H_2S emissions, t/y	0.0082 ±0.0028	0.26 ±0.013	0.00002 ±0.00000064	0.036 ±0.0014	0.078 ±0.014	0.018 ±0.0025	0.0024 ±0.0011	0.014 ±0.0015	0.0018 ±0.0002	0.0063 ±0.0012	0.0032 ±0.001	0.22 ±0.017	0.032 ±0.0034
Flux rates													
CO_2 flux, mg/s/m^2	9200	57,000	270	5200	18,000	11,000	1800	2600	3100	2700	780	18,000	10,000
CO flux, mg/s/m^2	41	89	0.014	21	87	33	7.2	25	3.5	20	13	280	95
CH_4 flux, mg/s/m^2	78	1400	0	0	320	190	11	0	0	110	0	3400	780
H_2S flux, mg/s/m^2	0.0093	0.25	0.00002	0.035	0.069	0.0085	0.0014	0.0085	0.0011	0.0054	0.0031	0.093	0.017

Table 3b Vent locations, areas, pitot-tube flow rate and supporting information, gas concentrations, soil and vent temperatures, gas emission rates, annual gas emissions, and gas flux, Old Smokey coal mine, July (O'Keefe and others, 2011)

Emissions over 5-min intervals								
Vent #	1	2	3	5	6	7	8	13
Vent area, m^2	0.1411	0.2976	0.0015	0.402	0.2712	0.0782	0.04	0.531
Pitot flow rate								
Flow rate, m/s	3.96	0.66	1.32	1.14	0.98	1.38	0.42	1.28
Std dev velocity	0.41	0.08	0.19	0.18	0.19	0.22	0.29	0.34
Temperature, °C	40.4	27.7	27.5	27.5	30.3	58.2	29.9	40.9
Relative humidity, %	84.2	65.6	63.4	68.6	61.4	73.6	60.4	67.2
ρ, kg/m^3	1.04	1.10	1.11	1.11	1.10	0.95	1.11	1.07
Barometric pressure, kPa	96.76	96.77	96.76	96.80	96.80	96.78	96.76	96.81
Gas concentrations								
CO_2% vol	3.61	1.18	0.02	0.00	0.25	0.72	0.47	1.28
CO ppm	814.8	739	39	27	132	785.6	448.6	1405.4
CH_4% vol	0.11	0.27	0.00	0.00	0.00	0.09	0.00	0.17
H_2S ppm	3.4	3.0	0.3	0.0	0.4	3.8	3.9	10.8
Soil temperature, °C	41.3	28.1	26.1	27.1	29.1	39.8	41.1	37.9
Vent temperature, °C	70.0	36.8	22.1	28.9	28.0	58.3	45.3	80.0

Table 3b Vent locations, areas, pitot-tube flow rate and supporting information, gas concentrations, soil and vent temperatures, gas emission rates, annual gas emissions, and gas flux, Old Smokey coal mine, July (O'Keefe and others, 2011)

Emissions over 5-min intervals								
Emission rates								
CO_2 emission rates, mg/s	12,000 ±1200	920 ±110	0.17 ±0.025	0±0	290 ±57	650 ±100	34 ±23	5100 ±1300
CO emission rates, mg/s	170 ±17	37 ±4.4	0.019 ±0.0028	3.1 ±0.49	9.7 ±1.9	45 ±7	2 ±1.4	360 ±94
CH_4 emission rates, mg/s	130 ±14	77 ±9.3	0±0	0±0	0±0	29 ±4.6	0±0	240 ±63
H_2S emission rates, mg/s	0.86 ±0.088	0.18 ±0.022	0.00021 ±0.00003	0±0	0.032 ±0.0064	0.26 ±0.041	0.021 ±0.015	3.3 ±0.88
CO_2 emissions, t/y	370 ±38	29 ±3.5	0.0054 ±0.00079	0±0	9 ±1.8	21 ±3.2	1.1 ±0.74	160 ±42
CO emissions, t/y	5.3 ±0.54	1.2 ±0.14	0.00061 ±0.000089	0.098 ±0.016	0.31 ±0.06	1.4 ±0.22	0.065 ±0.045	11 ± 3
CH_4 emissions, t/y	4.2 ±0.43	2.4 ±0.29	0±0	0±0	0±0	0.93 ±0.15	0±0	7.6 ±2
H_2S emissions, t/y	0.027 ±0.0028	0.0057 ±0.00069	0.0000065 ±0.00000095	0±0	0.001 ±0.0002	0.0083 ±0.0013	0.00068 ±0.00047	0.1 ±0.028
Flux rates								
CO_2 flux, mg/s/m^2	85,000	3100	110	0	1100	8300	850	9600
CO flux, mg/s/m^2	43	56	0.014	2.7	9.9	33	4.8	280
CH_4 flux, mg/s/m^2	320	970	0	0	0	130	0	710
H_2S flux, mg/s/m^2	0.021	0.0065	0.0000076	0	0.0011	0.0045	0.0007	0.081

as would be used for stack monitoring. Engle and others (2011) used a pitot to monitor flow rates from fissures at the Welch Ranch coal fire in the Powder River Basin, WY, USA. Flow rates ranged from 0.84 to 3.66 m/s.

At the same time, measurements for temperature, density, pressure and relative humidity will be recorded with standard instruments so that the emissions can all be calculated and reported at standard temperature and pressure. Tables 3a and 3b show an excellent example of the amount of data that can be collected to give an overview of emissions from a single coal fire site (Old Smokey coal fire, KY, USA; O'Keefe and others, 2011). From information such as this, the researchers can get an idea of total emissions over time. Consecutive studies can give an indication of whether the fire is moving, expanding or declining. In this case, it would appear that vents 3 and 5 appear to be declining towards total inactive status.

2.4.2 Heat/thermal radiation

Thermal monitors based on thermocouples can be located at certain sites throughout a seam or coal stockpile. More accurate data can be obtained from IR (infra-red) scanners. IR scanners can give a detailed image of the heat profile within a stockpile. The measurement of heat in coal seams is a good indication of either the possibility that spontaneous combustion is likely or that it is already under way. The report by Nalbandian (2010) gives an excellent summary of various monitoring and prediction systems for spontaneous combustion based on IR and heat sensor networks within coal piles.

Direct temperature measurements can be taken at the site but this can be a safety concern due to extreme temperatures at some sites. Figure 7 shows Glenn Stracher using a Pasco Physics Thermocouple Probe to measure the temperature of coal-fire gas exhaled between blocks of sandstone in a spoils pile at the Kleinkopje Colliery in the Witbank coalfield, South Africa. The probe was inserted several cm between the blocks of sandstone. When heat energy melted the plastic probe handle and the wire insulation attached to it, the Pasco Physics Explorer Data Logger recorded a temperature of 330°C and the temperature was increasing rapidly. The probe had to be removed to avoid completely destroying the handle and the insulation on the wire. Note the Magellan GPS unit on Stracher's belt and the white-coloured minerals letovicite and mascagnite nucleated on the sandstone; in association with the gas.

Figure 7 Direct heat measurement at site of spontaneous combustion (Photo courtesy of Harold Annegarn and Glenn Stracher)

Satellite remote sensing based on thermal IR (TIR) is reported to be a simple and cost-effective tool for detecting, mapping and monitoring coal fire areas. Spacial resolution ranging from 60 to 120 m can detect hot spots associated with individual coal fires. In the future, this resolution may improve to 10–20 m (Kolker and others, 2009). The image processing calculations and models are beyond the scope of this report. Sources of uncertainty in TIR imagery include surface emissivity, atmospheric absorption and emission occurring between the TIR sensor and the surface topography of the sensor's field of vision, and distortion of the heat-source area resulting from non-co-planarity between the flight pattern of the instrument and the ground (Engle and others, 2011).

There appears to be an almost empirical relationship between the temperature of a coal stockpile and the emissions and this can be used to allow thermal imaging to be used to help in emission estimation – that is, temperature can be used as a proxy for spontaneous combustion and GHG emissions. IR can also be used more remotely to categorise fires on a much larger and wider scale. IR data can be collected by remote sensors, including sensors located on aircraft and satellites. These data can then be used to estimate GHG emissions. Although this approach is likely to be subject to significant uncertainty, it is still a viable approach to be used in inventory estimation (Carras and others, 2005).

Engle and others (2011) collected sample data over a defined area at the coal fire site using the type of gas sampling methods described in Section 2.3.2 *above*. The fluxes were found to vary from <0.4 to 14,800 g/m^2/d CO_2. These data were correlated with temperature measurements taken at ground level (10 cm soil depth) in the study area. The temperatures ranged from 9.6°C to 48.0°C. These ground level data were the compared with data from the TIR. The TIR was able to provide a thermal map of the fire area. Although the measured soil temperatures corresponded with those measured by TIR, the TIR data generally suggested lower surface temperatures. This disagreement was assumed to be as a result of the scaling of data by the TIR. CO_2 emissions from the area were calculated based on empirical data (coal carbon content and total coal burn, discussed in more detail in Section 2.5). The GHG emissions were then distributed across the modelled thermal landscape. The results from the measured CO_2 flux and thermal readings at ground level were then compared with the data obtained and derived using the TIR. The variation in CO_2 emissions correlated well with the temperature variations indicated by the TIR system, and a heat colour image map was prepared, as shown in Figure 8. Despite being derived from different approaches, the aerial and ground-based CO_2 emission estimates roughly agree within a factor of two.

The areal method was assumed to give consistently lower estimates for several reasons:

- no data on heat of vaporisation at vents;
- unmeasured CO_2 data from non-coal sources (such as soil);
- residual effects from atmospheric interference.

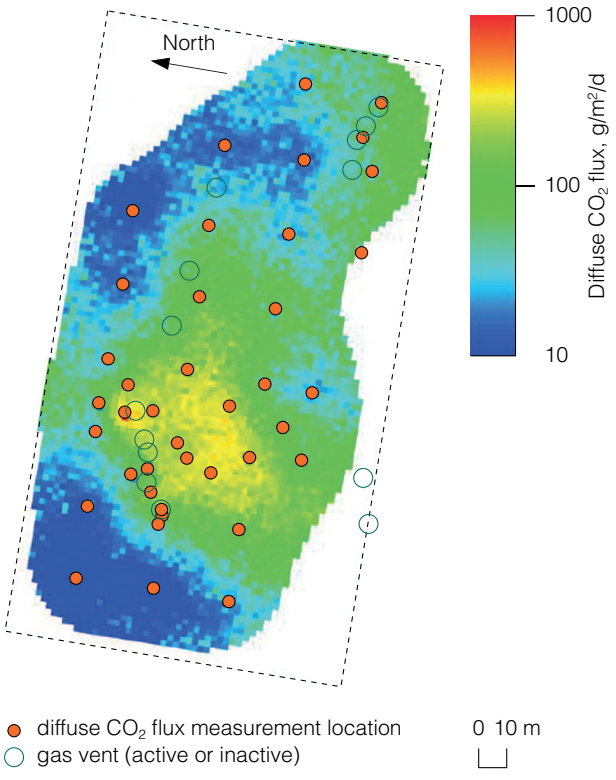

Figure 8 Heat colour image showing mean diffuse CO_2 flux (Engle and others, 2011)

Further work could significantly improve the applicability of remote TIR data to coal fires and this approach would be particularly suitable for use in remote locations.

Kuenzer and others (2008a) report on the use of MODIS thermal band data for coal fire detection. Whilst the data were useful for the detection of coal fire zones and hot spots, the data were not suitable for quantitative coal fire analysis on fire outline, temperature or classification into surface or subsurface. Thermal data are much more useful at night, when interference from the sun, such as ground heating, is minimised. Radiant temperatures on background surfaces such as sand dunes can vary by 28°C between sunrise and sunset. The sides of coal slopes facing away from the sun, may have a temperature 20°C lower than those facing into the sun in the middle of the day. These temperatures must be considered when determining which thermal anomalies are actually due to coal fires. Zhang and Kuenzer (2007) note that the thermal anomalies around cracks were less

affected by background temperature changes and that these showed up most clearly on the thermal imaging. The majority of coal fires detected by this approach are therefore those with numerous fissures and vents. Anomalies due to underground fires could only be detected at nighttime when the background temperature did not mask the readings. For more information on the use of thermal satellite data for coal fire detection and quantification, the interested reader is referred to the excellent papers by Kuenzer and others (2007a,b,c,d,e; 2008a,b,c).

Mathematical models must be used to take into account the temperature profiles and the depth of underground fires (Kolker and others, 2009). The heat signal is proportional to the intensity of the fire – for surface fires. However, for deeper fires, the heat is dissipated through the overburden. Heat signals will be higher where the overburden is thin or where the fire breaks through fissures or vents to the surface. This has to be taken into account when analysing remote data based on thermal profiles – models must be able to determine whether a heat signal is a strong underground fire or a weak surface fire, both of which may give relatively weak heat signals. Wessling and others (2008) have produced a numerical modelling system to analyse thermal surface anomalies induced by underground fires. The model assumes that the overlying material is homogenous, which may not always be the case. The model shows that the heat of the fire moves upwards and heats the overlying material and so only a fraction of this heat actually reaches the surface, depending on the depth of the fire. And so, unless the depth of the fire is known and can be taken into account, thermal images will underestimate emissions from underground fires. The effect of fissures, cracks and vents, which can appear very rapidly, are difficult to account for in such models.

2.4.3 Time period

Sampling periods used in the testing discussed in this report are often in terms of minutes, often less than ten minutes, and so the results are simply snap-shots of the emissions. However, many of the studies reviewed in this report comment on the variability of emissions from coal fires over time. O'Keefe and others (2010) state that some of this variation occurs in timescales too short to be observed during sampling events while others would require weeks, months or years to adequately characterise. The authors then go on to say the *'annual emission estimates reported herein are at best within an order of magnitude.'* Some of the variability in emissions is due to 'breathing cycles' which vary from seconds to minutes, and also coal fire dynamics which vary with the coal and rock within the combustion zone. This would include the suppression of fire by waste rock or the propagation of the fire by burning support pillars. Over and above the variability over time, there was also variability between vents. For example, at one site in the USA the CO_2 flux varied from 1600 mg/s/m^2 to over 88,000 mg/s/m^2 – that means the variability between vents in this one location was over two orders of magnitude.

Hower and others (2011) used long-term sampling, over three weeks, to get an idea of the temporal variation in emissions at the Ruth Mullins coal fire in Perry County, KY, USA. Samples were collected at one minute intervals and so gave a detailed picture of just how variable emissions can be. The 'breathing cycles' of the fire could be distinguished as CO concentrations were generally 400–450 ppm but dropped as low as 100 ppmv and increased to as much as 800 ppm. These excursions usually lasted for several hours before the concentration would return to 400–450 ppm.

Dlamini (2007) monitored concentrations of CO_2, SO_2, NOx and H_2S at a site of spontaneous combustion at a coal mine in Witbank, South Africa, using continuous ambient gas analysers. The data were correlated with weather conditions over extended periods of time. The results indicated that concentrations of the different gases varied throughout the day, with changes in weather conditions, chemical reactions and source strength. The variations in pollutant concentrations during the day for a sample day in winter 2004 are shown in Figure 9. For species such as NO_2, the variation was only slight, but for SO_2, the concentration varied between 5 ppb and >140 ppb. Not surprisingly, wind rose analysis of the data indicated a strong correlation between concentrations of pollutant and wind

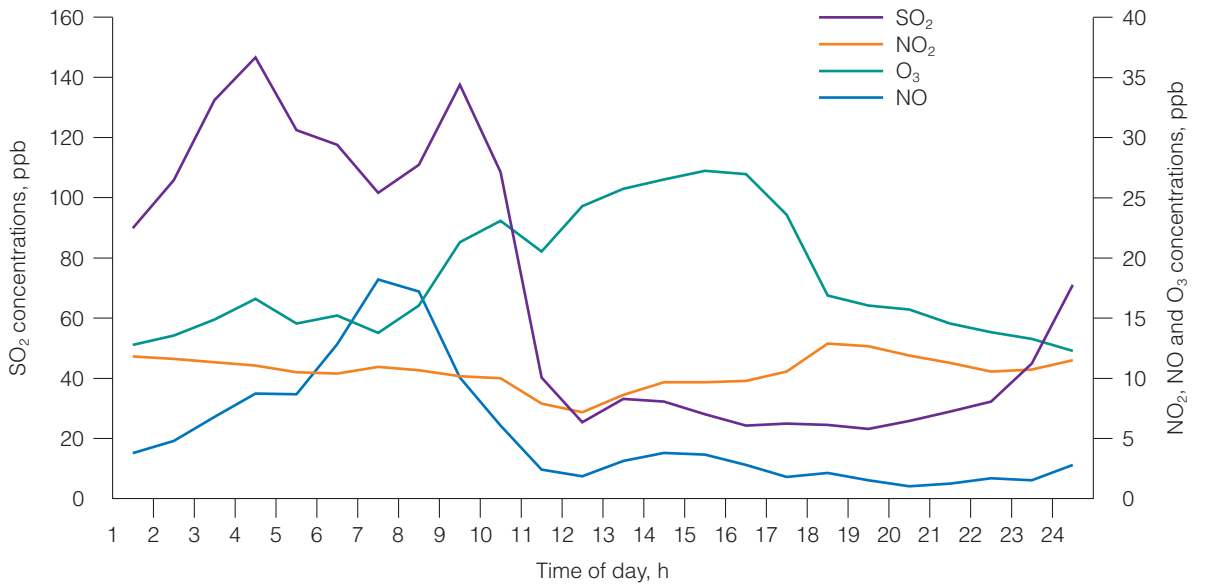

Figure 9 Diurnal pattern of SO_2, NO, NO_2 and O_3 observed in winter 2004 (Dlamini, 2007)

direction. Average concentrations were shown to vary significantly from season to season. SO_2 concentrations were higher in winter (67 ppb) than in summer (11 ppb) whereas NO_2 concentrations were higher in summer (43 ppb) than winter (11 ppb). In some areas, at certain times, the South African air quality daily standard limit for SO_2 (50 ppb) was exceeded. These variations in local concentrations of pollutants are largely as a result of the variation in ambient and weather conditions. This approach to pollution monitoring would not be able to show any variation in actual emission rates with any accuracy.

2.5 Empirical estimates and emission factors

Although emission factors for all relevant pollutants, including trace elements such as mercury, could be based on empirical estimates, the vast majority of examples found in the literature were for greenhouse gases (GHG; for the purposes of this report, this includes CO_2 and CH_4 only).

Perhaps the simplest way of estimating potential GHG emissions from spontaneous combustion would be to assume that all the carbon in the coal is combusted and to multiply this by the amount of coal consumed. Ide and Orr (2011) considered the most empirical of approaches based on the stoichiometry of coal combustion assuming the average formula of coal as $CH_{0.867}N_{0.018}O_{0.096}S_{0.003}$, based on coal from the Colorado region. This gives an approximate formula of $CH_{0.9}$. The chemistry of combustion can then be summarised as:

$$2\ CH_{0.9} + 2.45\ (O_2 + 3.76\ N_2) \rightarrow 2\ CO_2 + 0.9\ H_2O + 9.212\ N_2$$

However, in reality, the kinetics of coal combustion are never this complete or simple and the rate of the reaction will be variable.

Engle and others (2011) estimated GHG emissions from the Welch Ranch fire in the Powder River Basin, WY, USA. The assumptions and calculations used were as follows:

- the average heating value of PRB (Powder River Basin) subbituminous coals was 21–22 MJ/kg and a consumption rate of 1.8–2.1 t/d coal was assumed;
- the average carbon content of the coal was estimated at 54%.

Combining these data gives a release of around 0.97–1.1 t/d of carbon.

The calculations were then used to predict individual and overall GHG emissions. The flow-weighted molar ratio of GHG at the vent exhaust were estimated to be 225:2:1 as CO_2:CH_4:CO. Giving total emissions of 3.5–4.1 t/d CO_2 and 11–13 kg/d CH_4 (CO is not a GHG and therefore not included in the calculation). Converting the CH_4 values to CO_2-e (CO_2 equivalent value) gives an additional 0.24–0.28 t/d of CO_2e emissions (around 3% of the total). This is a very simple approach and does rely on knowledge of the coal type and coal volume consumed whilst relying on empirical assumptions on complete and efficient combustion of the coal involved. Anglo American in South Africa use a similar approach of multiplying the estimated total loss of coal production affected by spontaneous combustion by the CO_2 emission factor for the coal to obtain total emissions of GHG from their coal stock (McIntyre, 2013).

Although emission factors can be based on simple coal characteristics, as discussed above, more site-specific emission factors can be created from monitoring data. All the sampling processes discussed earlier in this chapter will produce emission estimates in terms of g/d, g/m^3, g/m^3/d and so on, depending on the format of the study. These emission rates offer a feasible approach to estimating emissions for inventories which are more site-specific than the empirical calculations but not as time consuming and costly as a programme monitoring every single area affected by coal fires.

Ide and Orr (2011) carried out an excellent study comparing methods to estimate and measure CO_2 emissions from the North Coal fire in the San Juan Basin, USA. One of the major conclusions was that, of the 4066 t CO_2/y being released from one area of the fire, a 'significant proportion' (almost 70%) was actually from the combustion of CH_4 flowing into the combustion zone from unburnt coal. This means that, for deep mines, simply estimating the volume of coal used is not enough to produce the total estimate for CO_2 emissions.

Carras and others (2005, 2009) have worked with CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia) and ACARP (Australian Coal Industry Research Programme) to establish methods for estimating GHG emissions from spontaneous combustion in Australia. This work has led to the establishment of emission factors for several broad categories of coal fire site, based on the extent of spontaneous combustion present:

- Category 1 – intense spontaneous combustion characterised by smoke and steam, major cracks, surface discolouration and obvious signs of venting;
- Category 2 – spontaneous combustion with less well pronounced signs, small cracks, surface discolouration and occasional wisps of smoke and steam;
- Category 3 – no sign of spontaneous combustion.

This approach was proven to be applicable due to the relationship between GHG emissions and the temperature of the site. Since temperature is easier to monitor than GHG emissions, and can even be monitored remotely (*see* Section 2.4), this approach may be suitable for locations where sampling is more difficult due to accessibility or safety concerns.

Table 4 Emission fluxes from coal mine sites in Australia (Carras and others, 2009)

Site	GHG flux
Sites with obvious combustion and gas venting	33–936 mg/m^2/s CO_2 0–15.6 mg/m^2/s CH_4 33–1116 mg/m^2/s CO_2-e
Sites with combustion but no venting	0–17.5 mg/m^2/s CO_2 0–3 mg/m^2/s CH_4 0–20.4 mg/m^2/s CO_2-e
Sites where there is no visible combustion	0–2.4 mg/m^2/s CO_2 0 mg/m^2/s CH_4 0–2.4 mg/m^2/s CO_2-e

Carras and others (2009) concentrated on the measurement of GHG from the two main coal producing regions in Australia – the Hunter Valley and North Ryde, NSW, and the Bowen Basin, Queensland. The coal produced is bituminous with total carbon contents between 80% and 90% (daf, dry ash free). Measurements were made at sites showing clear signs of combustion as well as in areas where combustion was weak. The results can

be summarised as shown in Table 4. It is clear that there is a significant difference between the sites with emissions from active and venting sites being orders of magnitude greater than those from less active sites. Based on this, Carras and others (2009) were able to produce average GHG estimates for the different regions in Australia:

North Ryde 0.12 mg/m^2/s CO_2-e
Hunter Valley 0.15 mg/m^2/s CO_2-e
Bowen Basin 0.08 mg/m^2/s CO_2-e

In this way, estimates for total emissions from these different regions can be prepared based on region-specific emission factors. Tables 5 and 6 shows even more detailed estimates for GHG

Table 5 CO_2-e emission rates for the Hunter Valley and Bowen Basin spoil according to type of spontaneous combustion (Carras and others, 2009)

Type of surface	Emission rate, kg/y/m^2
Active spontaneous combustion with marked surface signs	
large cracks with obvious signs of gas venting	Arithmetic mean 8200 Geometric mean 5012 41 samples
smoke and steam	
hot gases	
surface discolouration	
Active spontaneous combustion with less obvious surface signs	
surface discolouration	Arithmetic mean 94.6 Geometric mean 38 40 samples
no large cracks	
little smoke or steam	
Bare spoil, rehabilitated spoil with no spontaneous combustion	Arithmetic mean 12.6 Geometric mean 7 32 samples

Table 6 CO_2-e emission rates for the Hunter Valley and Bowen Basin reject and tailings according to type of spontaneous combustion (Carras and others, 2009)

Type of surface	Emission rate, kg/y/m^2
Active spontaneous combustion with marked surface signs	
large cracks with obvious signs of gas venting	Arithmetic mean 3200 Geometric mean 2642 9 samples
smoke and steam	
hot gases	
surface discolouration	
Active spontaneous combustion with less obvious surface signs	
surface discolouration	Arithmetic mean 101 Geometric mean 58 15 samples
no large cracks	
little smoke or steam	
Bare spoil, rehabilitated spoil with no spontaneous combustion	Arithmetic mean 28 Geometric mean 6 47 samples

emissions from the Hunter Valley and Bowen Basins based on the level of activity occurring within the spoil and within the rejects and tailings and based on a kg/y basis. These values could be used as emission factors for future GHG emission inventories where the values for the emission rate are multiplied with the known volume of coal involved in each year. Although the emission fluxes are quite low, Carras and others (2009) show that emissions at a rate of 0.1 mg/m^2/s CO_2-e equates to 3.2 kg/m^2/y which means an additional 3 kt CO_2 per year from every km of affected land.

Engle and others (2012b) produced similar analysis for emissions of CO_2 from different sites in the USA and has compared these with data from other studies, such as that of Carras and others. The results are shown in Table 7. It is suggested that these flux estimates could serve as a first step towards providing a range of possible values for coal-fire CO_2 emissions for national and international inventories. However, Engle and others (2012a) emphasis the potential for error that may arise from temporal variability – the variation in fire intensity and emissions over times, often changing dramatically in very short periods (less than 48 h).

Mercury emissions from three coal fire sites in the Powder River Basin were measured by Engle and others (2012). Emissions from vents at the Hotchkiss fire ranged from 16 to 118 ng/m^3, from 15 to 836 ng/m^3 at the Welch Ranch fire and from 84 to 12,100 ng/m^3 at the Ankney fire. This large variation will be as a result of the different mercury contents of the coal seams as well as as a result of the different burn intensities and burn chemistry at the different sites. As has been discussed in other IEA CCC reports (Sloss, 2012), mercury behaviour from coal combustion can be variable, even in relatively stable combustion systems.

2.6 Comments

There are no known national or international methods prescribed for quantifying emissions from spontaneous combustion of coal and therefore general monitoring standards can be used and adapted to suit the purpose. However since emissions from coal fires are sporadic, not evenly distributed and often underground, obtaining a representative sample is a significant challenge. And so studies on emissions from spontaneous combustion often involve mapping of the site in order to obtain a representative distribution of sampling sites across the entire affected area. This can involve a significant amount of effort and, in areas where fires are strong and ongoing, or the site is remote, a significant physical challenge. Further, sampling projects have shown that emissions can also vary over time, through the natural progression of the fire and also as a result of fire 'breathing cycles'.

Simpler approaches for obtaining pollutant emission rates from spontaneous combustion include remote sensing, such as the use of satellite data on the heat output of a geographical area to predict areas of combustion and probable related emission rates. However, this approach requires a significant amount of modelling and data manipulation to take into account all the variables which may affect the transfer of the heat signal from a remote ground to location to a sensor located on a satellite in space.

Perhaps the simplest approach to estimating emissions from spontaneous coal combustion is the empirical approach, where the chemical characteristics of the coal, such as the carbon content, are used to estimate the formation of CO_2. This approach requires numerous assumptions, such as the complete combustion of the coal. However, it is a quick and simple approach and, for studies where site analysis is not possible due to location or safety constraints, may be the only option.

The methods discussed in this Chapter concentrated on measuring emissions to produce emission rates or emission factors for the coal site. In order to create an inventory from these data, activity data are also need. These are discussed in Chapter 3.

Table 7 Summary and comparison of total CO_2 fluxes for coal fires in the USA and Australia (Engle and others, 2012a)

Fire	Area, ha	Total CO_2 flux, $mg/m^2/s$	Estimate type	Coal rank	Source
Mine fires					
Hotchkiss, WY, USA	4.7	0.90–1.1	Diffuse only	Subbituminous	Engle and others, 2012b
Welch Ranch, WY, USA	1.7	1.9–6.0	Airborne and ground-based	Subbituminous	Engle and others, 2011
Outcrop fires					
Ankney, WY, USA	0.58	25–780	Airborne, rate of fire advance	Subbituminous	Engle and others, 2012b
North Colorado, USA	5.3	0.28–0.51	Subsidence rate, chimney modelling and ground based	High volatile bituminous	Ide and Orr, 2011
Gob fire					
Mulga, Alabama	9.1	27–48	Diffuse only	Low volatile bituminous	Engle and others, 2011
Other					
Combusting coal mine spoil with active gas venting	–	260–290*	Diffuse only	Bituminous	Carras and others, 2009
Combusting coal mine spoil with no signs of venting	–	3.0–4.1*	Diffuse only	Bituminous	Carras and others, 2009
Coal mine spoil with no signs of combustion	–	0.4–0.6*	Diffuse only	Bituminous	Carras and others, 2009

* CO_2-e, including adjustment for CH_4 emissions

3 Activity data for inventories

The methods discussed in Chapter 2 give a snapshot of emissions – that is, short-term data on the total amount from any vent or over an area of combustion. However, for these data to be useful in an inventory, they must be converted to an emission factor and multiplied by an activity value to give total emissions.

Total emissions = emission factor x activity data

Emission factors may be in terms of mg or ppm per volume of emitted gas (m^3), per area of soil (m^2 or ha^2) and may even have a time factor ($ppm/m^2/day$). This means that the correct activity data must be applied to complete the inventory. For estimating emissions from a large coal dump, this would involve multiplying the emission factor prepared for the coal (based on monitoring at a selected site or group of sites) by the total coal burnt. For an underground fire, this would mean multiplying the emission factor over the sampled area, by the total area assumed to be on fire. For spontaneous combustion, obtaining the activity data can be as much of a challenge as obtaining the emission rate or emission factor. Estimating the quantities of coal involved in fires in stockpiles or in abandoned mines is not simple. If we then move up a level and consider the amount of data required to estimate total emissions from a country where there are numerous stockpiles and underground fires, then we can understand why these inventories are rare and the data are often considered as an educated guess at best.

The following sections discuss the methods used to obtain the activity data used for emission inventories for spontaneous combustion.

3.1 Coal stock-piles and shipments

Emissions from spontaneous combustion are hard to quantify due to the diffuse/large area of the source and the variability of the combustion conditions over time. As discussed in Section 2.2, it is possible to use an empirical approach to estimate CO_2 emissions. However, any estimate of emissions from spontaneous combustion for a regional inventory would need to include:
(1) emission factors for all relevant pollutant species from different coal/fire types;
(2) data on the amount of coal combusted over time (total volume of coal)

For (1), it would be possible to create a table or file of emission factors considered to be most relevant for different coal fire types. This could include options such as stockpile fire of low sulphur bituminous coal, or underground subbituminous coal. Where possible, users could substitute site-specific emission factors calculated from actual measurements, as was shown in Tables 2, 3 and 4. For (2), each region would need to have an accurate log of all fires under way and the amount of coal being consumed by each.

For stockpiles and shipments, the estimation of coal lost to spontaneous combustion can normally be achieved by a qualified visual assessment – for example, half of a 20 t stockpile on fire means the loss of 10 t of coal. Normally this estimate would be made by an on-site engineer with first-hand knowledge of the situation. The estimation of coal involved in a coal fire can also be achieved using IR analysis of stock-piles, as discussed in Chapter 2 – IR imaging cameras can give an excellent visual representation of how much of a coal heap or stockpile is combusting at any one time.

3.2 Mines – surface and underground

Estimating the activity data – the amount of coal consumed – is considerably harder for mines than for coal stockpiles. As mentioned above, for the most part, coal producers will know how much coal is in a stockpile or shipment and should be able to make visual estimate of what fraction of this coal has been consumed. The situation is different from coal mines since it is not possible to see just how much coal has been consumed. Mining experts may be able to make an educated guess based on knowledge of the thickness of the seam and the rate of advance of the fire.

Most coal beds are horizontal and any fire will spread along the outcrop where it has made contact with the air or whatever has initiated the combustion. With time, the fire will burn deeper into the hillside and the overlying rocks and soil will progressively subside into the burnt-out void. This collapse can cause a new source of air to enter and fuel the fire further. Some fires are intense enough to cause the continuation of the burn deep below the surface – two to three times the thickness of the coal bed. The fire may smoulder for long periods or may erupt into a 'roaring inferno that melts rock'. The fire may continue until all the coal is used up, until the air runs out or is cut off or until the fire burns down to a water table in the coal (Heffern and Coates, 2004).

Estimating how much coal is combusting underground at any one time is therefore a challenge and can be approached in a number of ways.

3.2.1 Area

Chapter 2 discussed sampling chambers for monitoring the flux of gases being released at the surface of mines. These chambers generally cover only small areas (1 m^2 or less). Although several sample points are selected to represent the site, the only way of getting data for the full site area is to multiply – this is known as scaling. Scaling can be achieved based on the mean, geometric mean, or median of all the flux measurements from the study area. However, since fires are rarely equally spread out across a site, this averaging approach may not always be suitable. Engle and others (2012b) note that there are geostatistical methods available to spatially weight data to suit a site. Engle and others (2012b) have done a considerable amount of work using this approach and the interested reader is recommended to study the work of these authors for more details. An example of an emission flux map is shown in Figure 10. These data are from the Ruth Mullins coal fire in Perry County, KY, USA. The fire is located on a densely vegetated hill slope over a middle Pennsylvanian bituminous coal mine which has been closed since the 1960s: 49 flux measurements were made at 37 sampling points across the site. Significant statistical and mathematical modelling was required to produce this map from the data collated and, as a result, there is some uncertainty associated with the estimates. However, the data are impressive and the results will be extremely useful in terms of improving the understanding of emissions from such sites and developing monitoring techniques.

As discussed in Section 2.5.2, the heat profile across a site can give an indication of where the fire is most intense and, as a result, where emissions may be highest. By combining this heat mapping with emission data, a site-specific emission map can be generated. Bhattacharya and others (1991) used a multispectral scanner under an aircraft to complete an aerial survey of the Jharia coalfield in India. The airborne survey was complemented by a ground based thermal IR survey. Combining the airborne and ground level data with an aerial map of the area produced a map showing areas of spontaneous combustion divided into three categories:

- surface or near surface fires;
- underground fires;
- burning dumps including fire prone areas.

Interpretation of the mapped data along with underground mine plans meant that fire zones as deep as 70 m could be detected. This approach may provide information for remote areas – where airborne

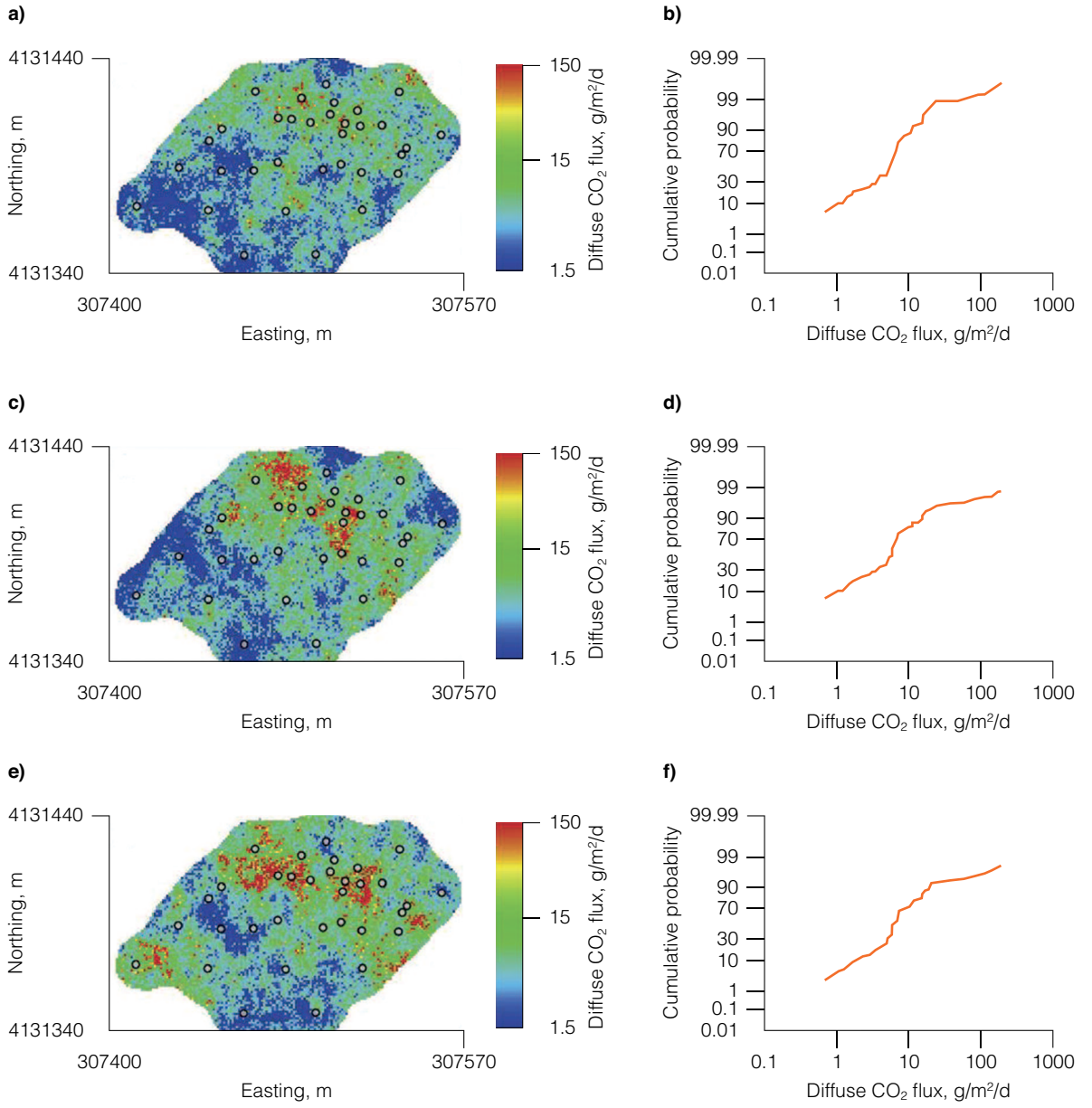

Figure 10 Three sequential Gaussian realisations of CO_2 flux and their cumulative probability distributions (Engle and others, 2012b)

studies combined with knowledge of the coal seams could give a best guess of the amount of coal involved in combustion.

The study by Ide and Orr (2011) is an example of the combination of emission data and area measurement in estimating emission inventories for a single coal mine area – the North Coal Fire in the San Juan basin, USA. The emission rate was based on measurements of exhaust gas velocity from a fissure in combination with measurement of VOC gas fluxes from non-fractured regions using a flux chamber accumulator. From the fissures, the exhaust rate was measured at 1.66 m/s, based on the size of the fissure and the exhaust gas density and temperature, the mass flow of the exhaust was estimated at 8,125 t/y giving a proportional CO_2 flow rate of 2112 t/y, since CO_2 was around 26% of the exhaust gas. Results from the sampling chamber used in a grid over a sample area, multiplied by the total area of the site gave an additional 1,954 t CO_2 from the site (over and above that from the vents/fissures). Ide and Orr (2011) estimated, based on isotope analysis, that around 13.2% of the exhaust stream

Table 8 Estimates of CO_2 emission rates, coal consumption rates and air requirement rates in different methodologies (Ide and Orr, 2011)

Method/rate	CO_2, total t/y	CO_2 from coal, t/y	Coal consumption, t/y
Surface subsidence	–	849	249
VOC	2112	279	113
Flux chamber	1616	213	87
VOC+flux chamber	4066	537	218
Chimney+flux chamber	3570	471	191

(538 t) was produced from the coal and, calculating backwards by stoichiometry, estimated that the coal was burning at a rate of 218 t/y. Ide and Orr then went on to estimate emissions based on modelling of the combustion zone as a convection chimney analogue, assuming the combustion takes place through one single chimney and ignores other fissures or upward flow through the soil or overburden.

The paper by Ide and Orr (2011) summarises some very different and sometimes complex approaches to estimating CO_2 emissions from an underground coal fire and the interested reader is recommended to obtain the original document for more detail. The results of the different methods mentioned above are summarised in Table 8. The total CO_2 emission values include the native San Juan Basin gases whereas the coal CO_2 refers only to the CO_2 resulting from the coal combustion. Isotope analysis indicated that only 13.2% of the CO_2 in the exhaust comes from the coal and the remainder comes from native San Juan Basin CO_2 and the oxidised CH_4. Values obtained from the VOC method (flux from the vents/fissures) and those estimated from the chimney model are similar. The data in Table 8 refer only to the study area and not the entire area of the North Coal, San Juan Basin fire. The study concluded that at least 4066 t CO_2/y are released from this region of the fire with a significant fraction of this CO_2 arising from the combustion of CH_4 flowing into the combustion zone from the unburnt coal.

A coal fire area in Wuda, Inner Mongolia, was studied by Yan and others (2006) using data from the ASTER in the visible and IR region. Combining the spectral data with the ASTER data gave a map that is divided into pixels, as defined by the resolution of the system. Mathematical manipulation of the pixels and object-orientated image analyses were both used to produce an activity map of the region. The object-orientated analysis was shown to be more suitable, providing more accurate definition of regions such as coal, coal dust, sand, grassland and so on.

According to Stracher and Taylor (2004), the Beijing Remote Sensing Corporation (BRSC) has produced optical and thermal imaging from surface and subsurface detectors at several sites in China which provides valuable information for determining whether fires can be dealt with.

The International Institute for Geo-Information Science and Earth Observation (ITC), based in the Netherlands with German partners, worked within China to map and predict coal fires with the following general objectives:

- to detect, map and monitor coal fires on a regional scale and model individual coal fires on a local scale;
- to estimate a baseline scenario for the amount of CO_2 emitted from the coal fires at regional and local scales – assuming no fire fighting activities are undertaken in the near future;
- to calculate the decrease in the greenhouse gas emission should the coal fires be put out successfully;
- to assess the environmental impact in the coal mining and coal fire areas;
- to develop and implement a dedicated coal fire Geographic Information System (GIS) in China,

which would meet with the user requirements, chiefly the requirements of the local fire fighting team. Such a GIS would be able to generate among others, fire risk and hazard maps, fire fighting priority maps;

- to propose steps necessary to prevent the development of new coal fires.

The programme ran two projects in Ningxia and Xinjiang to map out the current fires in the regions. Out of these projects came two useful GIS programmes:

CoalMan — A PC-based monitoring and management information system developed for the Fire Fighting Team of the Ningxia Autonomous Region in China. CoalMan comprises a database of original data, as show in Figure 11, based on maps, satellite images, infrared images and aerial photographs. The system is designed to be user friendly so that it can be used by fire-fighting staff and less trained users. The system provides an image of potential sites of current coal fires with information on size and depth of the fire as well as the amount of coal burnt. A time analysis function allows the user to determine where new fires have appeared and where existing fires have been dealt with successfully.

CFMIS — One of the objectives of the Xinjiang project was to develop a GIS based Coal Fire Monitoring Information System (CFMIS) – a database of coal fires in the region. A screen capture from the system can be seen in Figure 12 and more information can be found on the website http://www.itc.nl/~coalfire/activities/overview.html.

Kuenzer and others (2012) have carried out in situ mapping of the coal fires in the Wuda region of China. The detailed mapping included gridding of the area, noting bedrock surface temperatures, crack temperatures and vent temperatures using a handheld IR system and capturing these data on a mobile GIS device. Results of the study, which looked at historical evidence of fires, concluded that the underground fires in the region have been moving eastwards over the last ten years. The number of fires has also dropped from 18 in 2004 for 6 in 2012, with the intention that these remaining fires will be extinguished by the end of 2013. Kuenzer and others (2012) intend to return after this period to monitor, using an airborne thermal scanner, whether these fires remain extinguished or flare up again.

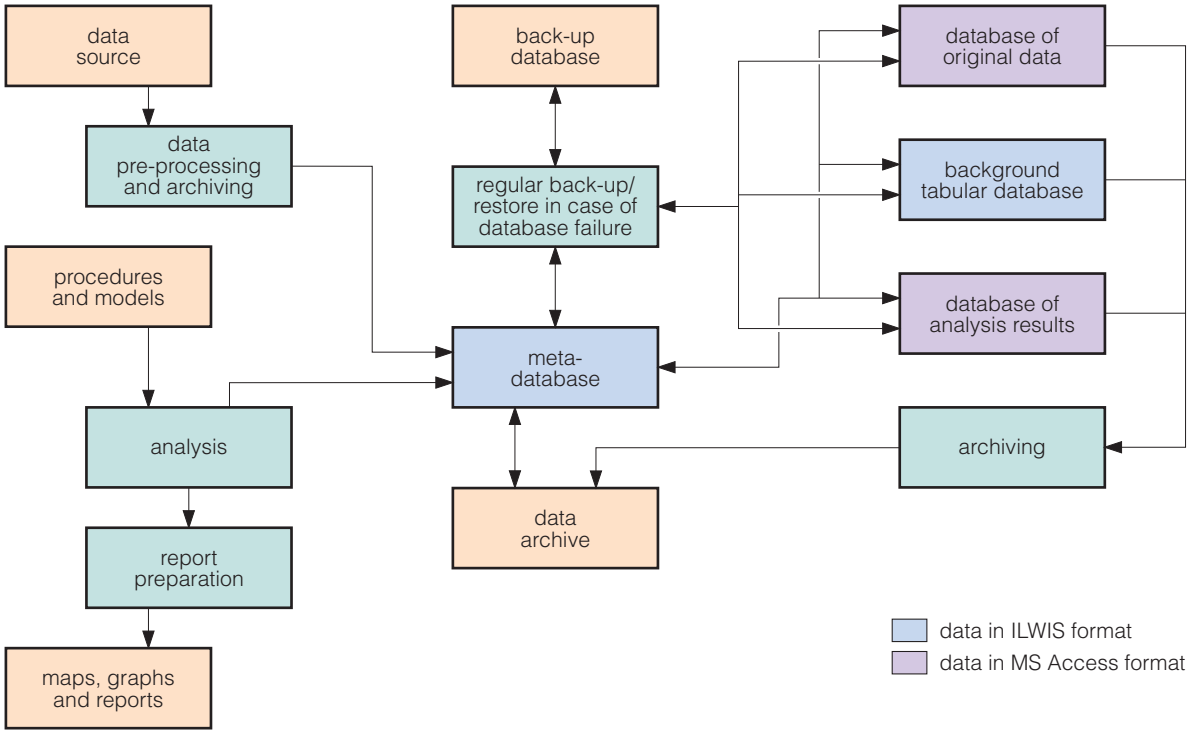

Figure 11 Data flow in the database of CoalMan (ITC, 2013)

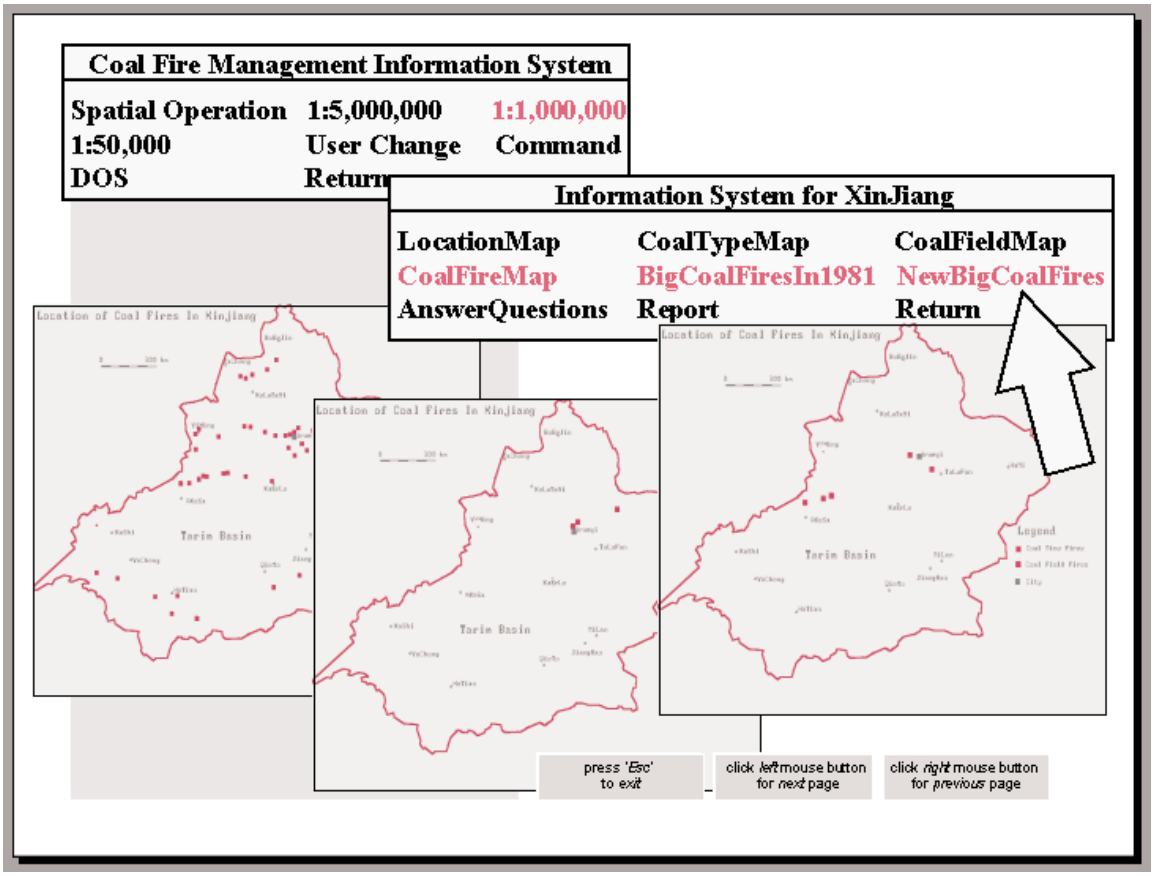

Figure 12 Screen capture from CFMIS (ITC, 2013)

van Dijk and others (2011) emphasise the challenges that exist in remote sensing which hamper the derivation of quantitative estimates, with the main challenges being as follows:

- surface observation of an underground phenomenon;
- in situ 'ground truth' mapping does not represent real ground truth because severely affected areas are inapproachable;
- dependency of coal fire heat emission on numerous parameters;
- very dynamic changes of parameters – cracks and collapse occurring in a matter of seconds;
- human influence, especially coal fire mitigation measures – covering fires and excavating fires;
- temporal variation of coal fire related heat emission;
- scarceness of additional data in coal fire areas (amongst others for false alarm removal in remotely sensed data);
- number of thermal satellite sensors very limited;
- limited spacial resolution of thermal sensors due to low energy position in electromagnetic spectrum;
- insufficient linkage between geological/geophysical and remote sensing scientists. Small thermal remote sensing community and even smaller coal fire remote sensing community.

Although this mapping area is available, for the moment, the literature focuses on development of the methodology and comparison of remote data with ground level data at specific sites. Or else the data are used to provide maps of where fires are occurring in a real time basis. However, no studies have been found where country-wide maps, based on remote data, have been combined with emission rates or emission factors to produce a country-wide inventory of emissions. The CoalMan system mentioned above is not designed as an emission estimate tool but rather as a fire fighting tool – for it to be used for the former, significantly more refinement would be required and it would appear that this is not currently the aim of the project

3.2.2 Depth/volume/heat content of coal

Perhaps the simplest approach to determining the depth or volume of coal involved in an underground fire is to use mining data – many mines have plans of the coal seams to determine which are most valuable and most accessible. The estimation of coal volume in the underground seam requires numerical modelling. Estimating consumption due to combustion requires the assumption that the coal fire is a point source at a certain depth, that the overlying material is of uniform physical property and that the heat conduction to the surface is based on linear flow, all of which are far from reality (Prakash and Vekerdy, 2004).

Prakash and Vekerdy (2004) also used the CoalMan system (*see* Section 3.2.1) to study fires in North China. The model conduction and convection of heat are included in the depth estimation analyses. However, more research is needed to refine these estimates. The system can assign ranges of estimated fire depth with intervals of 10 m. As Prakash and Vekerdy (2004) point out, in some parts of the world where many inter-layered coal seems occur, such crude estimates would be meaningless for targeting fire fighting operations or for estimating coal volumes. As mentioned earlier, the CoalMan system is not designed as an emission estimate tool.

In the absence of mine-specific data, other approaches are needed to estimate the amount of coal involved in an underground fire. Topography is one possible approach. Coal loss due to underground fires can affect the surface topography in different ways (Kuenzer and Stracher, 2012):

- sinkholes – the collapse of surface bedrock into a hollow space underground;
- trenches – usually due to the connection of several sinkholes in a row;
- depressions – smaller drops in surface height due to volume deficit beneath;
- partial-surface subsidence – when part of a larger bedrock surface collapses;
- large-surface subsidence – the complete collapse of bedrock above burnt coal seams;
- slides – gravity forced movement downwards and outwards as support material is removed.

Ide and Orr (2011) describe the use of cameras and surface contour mapping, combined with modelling and specialist knowledge, to estimate the volume of coal used from the subsidence which has occurred over a coal fire. This assumes that the surface deforms exactly by the volume of coal consumed and that this subsidence is uniform. In practice, subsidence may occur only periodically and abruptly and this approach is likely to underestimate the amount of coal consumed. However, the volume of coal lost can be estimated in this way, taking the ash content into account. Ide and Orr (2011) used this approach to obtain activity data and then multiplied this by the stoichometrical CO_2 production rate discussed in Section 2.5 to produce a total estimate of CO_2 emissions from an area of the Durango mine fire in Colorado, USA. The surface volume change was estimated at 1400 kg/m^3, corresponding to 279 t of coal per year. Based on the stoichiometry from Section 2.2 (3.04 tCO_2 per t of coal), this gives a CO_2 emission rate of 849 t/y.

Prakash and others (2001) used Landsat thermal data in combination with radar data, topographical maps, elevation models and field data to determine areas of subsidence in the Dafeng mining area in northeast China. Correlating changes in elevation between the current radar readings with the historical topographic maps showed regions where the land had been lowered significantly. However, some of these changes were due to mining activities rather than spontaneous combustion and so knowledge of the area was necessary to categorise each area appropriately. Prakash and others (2001) seemed to be suggesting that this approach would be suitable for routine monitoring of coal mining areas for safety rather than as a means of estimating the volume of coal loss.

van Dijk and others (2011) estimated CO_2 emissions from several coal fires in China based on the estimated volume of coal consumed but also on the amount of energy released by the combustion. They suggest that, if the amount of heat energy released by a fire is known, then it is possible to derive the amount of subsurface coal that is burning. This approach requires a good understanding of the heat transfer for subsurface coal fires to the surface. The surface heat profile of deeper fires are more

affected by the conduction properties of the overburden. Having said that, however, van Dijk and others note that the mining engineers, fire-fighters and coal mining administration staff who live and work in the area are the people who can best determine how much coal is burning in a fire. They go on to warn that caution is required against over estimation of the burning volume where financial support for fire extinction is provided by the government or other subsidy mechanism.

3.2.3 Geographical data

It is virtually impossible to keep an up-to-date record of all fires known to be burning out of control across China never mind across the whole of the world. However, there is a world coal-fire map available from Elsevier which attempts to keep a watching brief on known fires, as shown here: http://www.elsevierdirect.com/brochures/coalpeatfires/onlinwemap.html.

Although it may not be appropriate to use such a map to prepare an inventory, the map does give a useful indication of the large number of fires ongoing around the world at any time and the scale of the problem and could be the basis of an inventory map, if additional confirmation and data were provided.

As outlined in Chapter 2, emissions from even single coal fires can vary over time and across the affected area. For countries such as China and India, an inventory of all fires under way at any time is a significant challenge. It is therefore very likely that any figures produced for a regional or national inventory are, in many cases, rough estimates with very large amounts of uncertainty. van Dijk and others (2011) note that, even if quantification of the emissions of one local area would be possible, it is still difficult to extrapolate these results to a whole country. However, that is not to say that such estimates should not be attempted. Rather that there should be work towards a standardised approach to obtaining such estimates so that comparison between sites or regions would be based on shared assumptions and identical methodologies.

As concluded by van Dijk and others (2011) studies quantifying emissions from single sites will vary from those looking at regional data, and much more so for those looking at national or international values. Individual sites can be analysed using site-specific data. For regional studies, the results from individual sites can be added together and extrapolations made on the assumption that similar sites give similar results. For national data, the estimates can only be seen as an upper limit of potential emissions. The production of national and international estimates has the following outlook (van Dijk and others, 2011):

- it is not possible to use earth observation data for direct detection of CO_2 from point sources. Spatial resolution is currently inadequate and this is unlikely to improve in the near future;
- routine detection of thermal anomalies in fire areas is possible with satellites and this could be applied globally given support for sensor availability and processing capacity;
- a link between thermal anomaly data and amount of coal burn to produce CO_2 emission data depends on further development of thermal models and their coupling to remote sensing data.

And so there is a significant amount of further research and development required in this field before a knowledge of the geographical location of coal fires can actually be used in regional, national or international emission inventories.

3.2.4 Time period

As mentioned in Chapter 2, coal fires do not tend to burn in a uniform manner over time. Since some fires burn for years, emission inventories must be based on the amount of emissions for each year (or relevant time period) individually. This requires knowledge of how much coal is available to burn and how much has burnt during the target period. Not only that, but the intensity of combustion, and the

associated emissions, will vary over time. New fires may burn faster than older fires, giving a higher emission rate (*see also* Table 3).

Cook and Lloyd (2012) compared emissions from several coal fires in South Africa. They noticed that at a site where the fire was almost burnt out, the emissions of CO_2 were 58 kg/m^2/y and CH_4 emissions were 0.55 kg/m^2/y. However, at two sites where the fire was more intense the CO_2 emissions were over 7000 kg/m^2/y. The emission rate for CH_4 varied significantly between the two burning sites, 0.0075 kg/m_2/y at one and 1.2 kg/m^2/y at the other. At the first site, rehabilitation of the coal stockpile was already under way and so the emissions were being brought under control whereas at the second site, the coal was raw and freshly mined.

van Dijk and others (2011) note that fires burn at different intensities, some with temperatures as high as 1200°C, while others smoulder. Fire progression rates have been observed to range from less than 10 m/y up to 100 m/y. And so the estimation of the spread of a coal fire must take this into account if a valid estimate of total coal burn over, say a year, is required. This is yet another area where qualified local engineers are most likely to provide a best guess of how much coal will be lost over the study period.

3.3 Comments

Producing an overall emission estimate for inventory production requires the multiplication of an emission rate or emission factor, as discussed in Chapter 2, by an activity value – that is, a measure of how much coal has been lost/combusted. For small sources such as individual coal stockpile and shipments, this is relatively easy as it can be based on knowledge of the original stockpile size and an educated guess, based on visual interpretation, weight or even IR data. For larger sites such as coal mines, estimating coal loss is more of a challenge and will require either site-specific knowledge of the coal seam sizes and dimensions or secondary derivation through heat production (IR and remote sensing) or changes in site topography. All of these approaches are based, to some extent, or extrapolation or best guesses. Although there are maps of coal fires taking place nationally and internationally, these are currently not regarded as detailed enough to be used as activity data for inventory production.

And so inventory production for national and international inventories are currently undertaken very rarely and by a number of varied methods, from remote sensing, to empirical extrapolations. Chapter 4 looks at examples of how inventories are currently being prepared around the world.

4 International and national issues and approaches

With respect to international guidelines and standards, there do not appear to be any official or legally defined or recommended approaches for estimating or quantifying emissions from spontaneous combustion. As mentioned in Chapter 2, CEN and ISO have standards for the general measurement of different pollutants, but none includes guidelines on how to measure these pollutants at coal fire sites.

Producing a standardised approach would be desirable but not without its challenges. The following sections discuss the situation in selected countries which have significant issues with spontaneous combustion. Some countries appear to be edging towards the desire for a standardised approach while others are not.

According to O'Keefe and others (2010) despite the lack of monitoring or reporting requirements for spontaneous combustion, '*by applying simple calculations, general estimates of the potential impact of coal fires on emission inventories can be explored*.'

In 2007 Kuenzer and others (2007a) stated that '*to date, the question of coal fire related GHG (greenhouse gas) quantification on a local, regional, and country-wide or even global scale is still unanswered*.' And O'Keefe and others (2010) agree that '*despite their potential for environmental impacts, coal fires are not accurately quantified in terms of national or global emissions, and only a handful of field studies quantify emissions*.' O'Keefe and others (2010) note that, due to a lack of data, national and global emission inventories do not include inputs from coal fires. This includes the US EPA GHG inventory which does not list spontaneous combustion as a potential source category. They go on to suggest that although CO_2 emissions from coal fires are significant, they are low compared to emissions from coal-fired power plants. According to Kolker and others (2009) emissions such as Hg and CO_2 from spontaneous combustion of coal can contribute to issues such as climate change '*but data on these emissions are not sufficient for uncontrolled coal fires to be taken into account as a source category in current climate model projections*.'

van Dijk and others (2011) emphasise that the quantification of emissions from spontaneous combustion has to be performed differently for local, regional and country-wide studies. Local estimates can be based on detailed in situ measurements and site-specific mapping data and models. Regional studies require the grouping of data from individual sites and extrapolating these based on the assumptions of homogeneity between similar sites. For country-wide studies the estimate can only be seen as an upper limit value.

4.1 International standards and practices

For sources such as coal-fired power plants, the methods used for reporting emissions to inventories are specified by either ISO, CEN or with national standards. However, because, as yet, emissions from spontaneous combustion do not have to be reported to any official inventories, no standards have been defined. This means that researchers can use any methodology they have available. This, in turn, means that results from different studies may not be directly comparable.

At the moment, the requirements for inclusion of spontaneous combustion in emission inventories are few and far between. Under the Intergovernmental Panel on Climate Change (IPCC) guidelines for fugitive emissions, emissions from mining, processing, storage and transportation of coal there are four major stages listed for GHG emissions (IPCC, 2006):

- mining emissions – gases such as methane released during mining;
- post-mining emissions – gases released during storage and transport;
- low temperature oxidation – this is the prelude to potential spontaneous combustion. However,

the IPCC states that '*the rate of formation of CO_2 by the process is low*';
- uncontrolled combustion – spontaneous combustion.

The IPCC acknowledges the latter as a source but goes on to state that *'uncontrolled combustion only due to coal exploitation activities is considered here*.' That is to say that any incidences of spontaneous coal combustion which arise due to natural issues (such as lightning, earth movement or forest fires in remote locations) would NOT be included in a country's GHG inventory. Further, abandoned mines are recognised within the chapter but *'methods do not yet exist for abandoned or decommissioned surface mines*.'

According to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, CO_2 emissions from 'uncontrolled combustion' in coal should be reported in the sub-category 1.B.1.b. – 'Uncontrolled Combustion, and Burning Coal Dumps', as outlined here: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

In Section 4.1, Volume 2 of the 2006 IPCC Guidelines, there are some descriptions on uncontrolled combustion due to coal exploitation, but no clear methods to estimate emissions are provided. Only general guidance is provided on page 4.30, which reads:

'*While emissions from this source may be significant for an individual coal mine, it is unclear as to how significant these emissions may be for an individual country. In some countries where such fires are widespread, the emissions may be very significant. There are no clear methods available at present to systematically measure or precisely estimate the activity data, though where countries have data on amounts of coal burned, the CO_2 should be estimated on the basis of the carbon content of the coal and reported in the relevant subcategory of 1.B.1.b.*'

Default values of carbon content of coal can be found in Chapter 1, Volume 2 of the 2006 IPCC Guidelines (Fukuda, 2013). Emission factors for GHG in the post-mining sector, including fugitive emissions as well as spontaneous combustion, are estimated to have an uncertainty value of a factor of 3 or smaller (using a Tier 1 approach – using global emission factors and data) or ±50% (using a Tier 2 approach – using more basin-specific data on coal types and volumes) (IPCC, 2006).

With respect to activity data, Section 4.1 of the IPCC guidelines suggest the use of data on raw coal production for estimating emissions of GHG from all of the emission stages listed above. For mines where coal washing/cleaning is used, there is the option to use data on saleable coal, if this is available (IPCC, 2006).

Carras and others (2009) report that the most recent guidelines produced by the IPCC for national inventories states that '*uncontrolled combustion in waste piles is a feature for some surface mines. However, these emissions, where they occur, are extremely difficult to quantify and it is infeasible to include a methodology*.' Carras and others (2005) reiterates that spontaneous combustion as a source of GHG emissions '*has been excluded from greenhouse gas inventories as it is considered that there is no acceptable method for estimating emissions*.' That is to say – most countries simply do not bother to estimate emissions from this source. However, some countries have chosen to do so. For example, Table 9 shows how the Norwegian Government reported emissions from spontaneous combustion of coal in the Norwegian inventory for 2012 (Sandmo, 2012). Since Norway has very little to report in the way of emissions from this source, the methodology used is clear to follow – an emission factor for the general combustion of coal (2.52 t CO_2/t coal combusted) was multiplied by an estimate of the total quantity of coal consumed/combusted. The final value must have been low as it did not appear in the final overall inventory for Norway. Whilst this approach may be applicable to regions such as Norway, where the number of coal fires can be easily quantified and an estimate prepared, the same approach would be far more challenging for countries such as China and India where there are a significant number of fires under way, many in remote locations.

Table 9	CO_2 emissions from the spontaneous combustion of coal as reported in the Norwegian Emission Inventory 2012 (Sandmo, 2012)
3.3.3	**Fugitive emissions from uncontrolled combustion and burning coal dumps**
	3.3.3.1. Description In 2005, a fire broke out in one of the Norwegian coal mines at Spitsbergen, causing minor emissions.
	3.3.3.2. Method Emissions have been calculated by multiplication of the quantity of coal combusted by standard emission factors for combustion of coal.
	3.3.3.3. Activity data The company operating the mine has provided an estimate on the quantity of coal combusted in the fire.
	3.3.3.4. Emission factors Emission factors for direct-fired furnaces, as given in Appendix B, have been used in the calculations.
	3.3.3.5. Uncertainties The uncertainty in the activity data, that is the quantity of coal combusted, is unknown. However, as the emissions are small, the uncertainty is insignificant.
	3.3.3.6. Completeness The only fire in a Norwegian coal mine since 1990 is included. Emissions from a smouldering fire in a Russian mine, which is supposed to have lasted for several years, are not included in the emission inventory, due to lack of data. The same applies to another fire in 2008. These emissions are, however, probably insignificant.

The UNFCCC (United Nations Framework Convention on Climate Change) Clean Development Mechanism (CDM) facilitates the production of bi-lateral projects to reduce GHG from various sources. As yet, there have been no projects dealing with emissions from spontaneous combustion (http://cdm.unfccc.int/).

van Dijk and others (2011) warn of the possible overestimation of international and national GHG emissions from spontaneous coal combustion, especially when considering reduction strategies and potential CDM projects. A tight system of auditing including baseline assessment and quantification would be difficult to establish given the erratic and dynamic nature of coal fires. A baseline defines how much coal is burning in a coal fire in a certain amount of time. These data would be used to calculate emission certificate policies in the case of CDM contracting for the extinction of a specific fire area.

Extensive studies have been carried out in the Wuda mining area by Kuenzer and others (2012) with the aim of a GHG release baseline for individual fires. In turn, this aimed at establishing a baseline for carbon credit trade under the CDM. However, the studies concluded that '*coal fires are a too complex system and underlie too many fluctuations for long term baseline definition . . . Therefore the definition of a baseline and the integration of coal fire extinguishing activities into Kyoto or post Kyoto based treaties could not be reached*.'

4.2 National approaches and issues

As mentioned in Section 4.1, although the IPCC recognises spontaneous combustion as a source of GHG emissions, it suggests that there are no suitable methodologies available for estimating these emissions and, as a result, this source is excluded from many national inventories. However, some countries have chosen to look more closely at possible approaches to evaluating emissions from this sector.

Table 10 Greenhouse has emissions from black coal mining in 1995-96 (Day and Riley, 2004)

GHG emission source	Open-cut		Underground	
	$ktCO_2$-e	uncertainty	$ktCO_2$-e	uncertainty
Energy consumption	4,700	10%	1,290	10%
Fugitive emissions	6,700	factor of 2	12,600	25%
Waste coal oxidation	1,870	large	low	?
Land use	1	±300	0	±10
Embodied energy	70	30%	40	30%
	13,340		13,930	

The following sections discuss, where possible, the methods used to prepare inventories for emissions from spontaneous combustion in different countries. Data on known spontaneous combustion issues and activities are also included to give an idea of how relevant and important this issue is in each region discussed.

4.2.1 Australia

The Australian National Greenhouse Accounts guide on emission factors includes details of how to estimate emissions from working and abandoned mines but does not seem to include any details on emissions from spontaneous combustion (AG DCCEE, 2012). The Australian Carbon Tax does not include emissions from the spontaneous combustion of coal because of the variability of this source and the uncertainties in their estimation (Nelson, 2013).

In the 2004 report from the CCSD (Cooperative Research Centre for Coal in Sustainable Development), Day and Riley (2004) cited GHG emission data from black coal mining in Australia for 1995-96, as shown in Table 10). The data suggested that around 14% of the total CO_2-e (GHG emissions expressed as equivalent CO_2) emissions from open-cut mining arose from 'waste coal oxidation', which was assumed to include combustion. The uncertainty for this estimate was graded as 'large'. Emissions from waste coal oxidation in underground mining were estimated to be 'low'.

4.2.2 Asia

China is a leader in both coal production and coal use and many coal fires continue to burn out of control across the country. Coal fires have occurred for years in China, with the earliest being dated as during the Pleistocene age. References to spontaneous combustion have been recorded as early as 1000 AD and even the travel documents of Marco Polo refer to 'burning mountains along the silk road'. The main area of concern at the moment is the coal mining belt which runs for 5000 km from east to west along the northern half of the country. Over 50 coal fields in this area are affected by fires (Kuenzer and Stracher, 2012).

According to Kuenzer and others (2012), the fires in China are usually triggered by human interference and are not started by forest fires or lightning. In the Xinjiang province, underground coal in the Liu Huanghou coalfield has been burning for between 20 and 40 years. The fires are thought to have started by accident in small illegal mine shafts dug by local farmers. The nearby city, Urumqi, is one of the most polluted cities in the world as a direct result of particulates and fumes from these fires. It has been estimated that it will cost more than $10 million and take four years to put out these fires (Stracher and Taylor, 2004). There is a single coal fire in Wuda, China, which consumes around

Table 11 Estimation of coal fire induced gaseous emissions in China in comparison with human induced emissions in Germany (Kuenzer and others, 2011)

Gaseous emission	Coal fires in China, kt/y	Total German emissions, kt/y*
CO_2	16,380	858,111
CO	490	4,952
SO_2	150	831
CH_4	2,380	3,271
CO_2-e	54,740	75,233

* total emissions from Germany, including industry, households and traffic

200,000 t of coal per year, equivalent to around 0.60 Mt/CO_2 (Ide and Orr, 2011). The paper by Kuenzer and others (2012) notes that extensive research and work in the Wuda area has meant the reduction of coal fires from 18 in 2004 to 6 in 2012, with this remainder to be extinguished by the end of 2013. Airborne thermal analysis will be repeated after this time to monitor whether the fires remain extinguished or flare up again.

It has been estimated that Chinese coal fires account for as much as 2–3% of the total global emissions of CO_2 from fossil fuel combustion. The economic loss from the burning coal may be 125–250 $million/y (Stracher and Taylor, 2004). More recent estimates from Kuenzer and Stracher (2012) put the total loss of coal in China from spontaneous combustion at 20 Mt/y – equivalent to Germany's annual hard coal production. The results are summarised in Table 11. The emissions from coal fires were based on an empirical calculation, assuming that 14 Mt of coal are burnt per year at an emission rate of 1.17 t CO_2/t coal and 0.17 t CH_4/t coal, and a global warming potential of CH_4 of 23 times that of CO_2. The emissions of CO_2 are much lower for Chinese coal fires. However, the total CO_2-e for Chinese fires is comparable with that for German emissions because of the higher global warming potential of CH_4. Emissions of SO_2 from the Chinese fires is also relatively high, largely because these emissions are not controlled by technologies such as flue gas desulphurisation.

Kuenzer and Stracher (2012) quote the often cited inference that 200 Mt/y of coal is lost, ten times as much as is actually combusted since the adjacent coal becomes inaccessible. However, van Dijk and others (2011) note that the 100–200 Mt/y value has been quoted so much in the literature that it is almost accepted as fact whereas the calculation and assumptions used to attain this number have never been fully explained. They go on to suggest that, based on the actual number of fires in China, the total is likely to be nearer 0.14–14 Mt/y of coal loss and a resulting 0.25% contribution to global CO_2 emissions. Whilst this number is small, it may still be significant in terms of being a possible target for reduction.

van Dijk and others (2011) give an excellent example of GHG emission inventory production for China. The estimate was based on the IPCC method for GHG, using a default Tier 1 CO_2 emission factor reflecting the full carbon content of the coal and including the fraction of carbon which may be released as CH_4 (0.3% of the CO_2 value). Data on the coal fires in the main region for coal fires in China (Ningxia, Inner Mongolia, and Xinjiang) are summarised in Tables 12 and 13 respectively. Because sampling at all the sites was not possible and because such sampling was unlikely to be truly representative of the actual emission values, the estimates were prepared based on empirical data – that is, on the estimated volume of coal combusted and the coal composition. The amount of coal combusted was estimated based on an approximated 3D model using geological maps, mining information, borehole information and spatial details. The emission estimates were then based on:

- carbon content specific to coal type (based on laboratory measurements);
- real burning volume (not necessarily the entire seam);
- depth component (if the seam is dipping, it will not burn below a certain depth);
- degree of combustion;
- permeability of the overlying rock;
- any additional information available.

Table 12 Coal fire statistics from the Ningxia province, China (van Dijk and others, 2011)

Coalfield	Coal Fire Name	Burning area, 10,000 m^2	Burning depth, m	Thickness of seam, m	Quality of coal	Carbon content, %	Status
Rujigou	Beikalagou	6.425	150	10	anthracite	95	burning
	Nanshan	4.975	100	20	anthracite	95	burning
	Honglianbei	1.15	60	21.5	anthracite	95	burning
	Hongwanxing	3.175		29	anthracite	95	burning
	Shanger	6.85	90	14.4	anthracite	95	burning
	Gudao	1.444		4.3	anthracite	95	burning
	Beiyi	5,275	95	12	anthracite	95	burning
	Naner	2.53	67	23	anthracite	95	burning
	Longlinchu			25	anthracite	95	firespot
	Nasixing			25	anthracite	95	firespot
	Hongwan		210	25	anthracite	95	burning
	Kengmuchang			25	anthracite	95	burning
	Hongliang		370	29.4	anthracite	95	burning
	Nansi		120	20	anthracite	95	burning
	TOTAL	38.447	60-370				
Redaolin	Huifeng	3.7	68	6			burning
	Xishan	5.227	79	6			burning
	Dayushugou	6.025	69	6			burning
	TOTAL	14.952	68-79				
Maliantan Shitanjing	Maliantan			8	coking coal/ fat coal	75	firespot
	Yikuan	3.1	54	6.4	coking coal/ fat coal	75	burning
	Shankuan	7.3	110	6.4	coking coal/ fat coal	75	burning
	Lijiagou	3.2	113	7	coking coal/ fat coal	75	burning
	Erkuan		163	6.4	coking coal/ fat coal	75	extin-guished
	TOTAL	13.6	54-163				
Hulusitai	Wulan	0.5		10.2	coking coal	75	burning
Xianshan	Shanxiahejian		87	5.24	coking coal	75	extin-guished
TOTAL	67.499	54-370	Total lost coal: 15 Mt				

Table 12 Coal fire statistics from the Ningxia province, China (van Dijk and others, 2011)

Coalfield	Coal Fire Name	Burning area, 10,000 m^2	Burning depth, m	Thickness of seam, m	Quality of coal	Carbon content, %	Status
Rujigou (extinguished)	Dalingwan	8.837	120	15.8	anthracite	95	extinguished
	Yingbo	6.889	395	25	anthracite	95	extinguished
	Shuixian	0.406	180	25	anthracite	95	extinguished
	Xigou	15.325	350	20.4	anthracite	95	extinguished
	Shangyi	1.15	78	4.5	anthracite	95	extinguished
	Dashidou	25.304	250	17,5	anthracite	95	extinguished
	Heitouzhai	7.734	150	20	anthracite	95	extinguished
	Xingshen	0	160	25	anthracite	95	extinguished
	Honglianxi	0	60	25	anthracite	95	extinguished
	Hongliandong	0	75	25	anthracite	95	extinguished
	Nanyi	0.832	53	8	anthracite	95	extinguished
	Beishan	2.125	140	21	anthracite	95	extinguished
TOTAL		68.602	53-395	Total lost coal: 35 Mt			
TOTAL OF ALL FIRES	**136.1**			**Total lost coal: 50 Mt**			

The resulting GHG emission estimate must then be calculated as a quantity per day, month or year.

Since quantifying the emissions on a fire-by-fire basis was not feasible, the fires were grouped by similarities such as coal type, stage of fire and, where possible, degree of combustion (ventilation conditions, surface fracturing and subsidence). van Dijk and others (2011) commented that remote IR data could have been used for the estimation of coal burn rate but stressed that these may lead to an underestimation. The empirical data provided in Tables 12 and 13 are preferred for extrapolation.

For Ningxia, the total coal burn per year was estimated at 2 Mt/y. The carbon content of the coal was 95% thus 1 tonne of coal burn releases 3.5 t CO_2. So 2 Mt of coal burn, as well as 0.3% of CH_4 release, taking the global warming potential of CH_4 into account (21 x CO_2), gives:

$$2 \text{ Mt} \times 3.5 + 2 \text{ Mt} \times (0.3\% \times 3.5 \times 21) = 7.441 \text{ Mt } CO_2\text{-e}$$

Table 13 Coal fire statistics in Xinjiang province, China (van Dijk and others, 2011)

Coal Fire Name	Burning area, 10,000 m^2	Burning depth, m	Thick-ness of seam, m	Quality of coal	Carbon content, %	Status	Lost coal, Mt	Lost coal, Mt/y
Tiechangou	1.2	120	10	long flame	65	burning	216	10
Lamamiao	1	100	6	long flame	65	burning	784	10
Beiyanghe				long flame	65	burning	10	
Hefen	3	100	4	long flame	65	burning	216	10
Kulongtiebuke				long flame	65	burning	10	
Hingshan	0.9	50	28	un-sticky	71	burning	20,800	10
Qitaibeishan	3.53	28	28	un-sticky	71	extinguished	6,000	
Laojiumiao	0.05	50	14	un-sticky	71	burning	130	10
Balikongguan tanyo				un-sticky	71	burning	10	
Sikeshu	2.72	175	23	gas coal	80	burning	5,474	10
Bayingou	11.76	200	27	gas coal	80	burning	3,998	10
Shihezinan-shan				weak-sticky	74	burning	15	
Qingshuihe-quoergou				long flame	65	burning	15	
Toutunhue	14.35	100	8	un-sticky	71	burning	33,736	50
Xishan	1.03	100	20	long flame	65	burning	3,350	10
Tiechanggou	0.47	125		gas coal	80	extinguished	4,825	
Dahuanshan	27.46	175	30	gas and fat	82	extinguished	49,022	
Shuixigou	0.5	125	25	gas coal	80	burning	556	10
Dabancheng	0.5	100	13	gas coal	80	burning	169	10
Nanshan	18	250	27	gas coal	80	burning	31,302	10
Shandaoling	0.7	25	14	un-sticky	71	extinguished	100	
Nandahu	0.12	50	53	long flame	65	extinguished	130	
Qiquanhu	0.6	100	8.5	long flame	65	burning	10	
Ke-er Jian	1.02	100	15	long flame	65	burning	1,139	50
Erweiergou	1.2	50	18	gas and fat	82	extinguished	4,680	
Huorongdong	0.4	75	23	gas/ long flame	70	burning	10	
Nileke	0.38	60	8	gas coal	80	burning	232	10
Aremale	0.5	60	23	gas/ long flame	70	extinguished	1,196	10
Zhaosu	0.28	75	23	long flame	65	extinguished		
Hamangou	0.39	55	17	long flame	65	burning	38	10

Table 13 Coal fire statistics in Xinjiang province, China (van Dijk and others, 2011)

Coal Fire Name	Burning area, 10,000 m^2	Burning depth, m	Thick-ness of seam, m	Quality of coal	Carbon content, %	Status	Lost coal, Mt	Lost coal, Mt/y
Yangxia	1	200	30	gas/ weak sticky	67	burning	624	15
Aer Ezeibulayan	9.4	225	28	gas/fat coal	82	burning	18,880	10
Tielieke	0.2	55	8	lean	86	burning	150	30
Kalasu	10	150	16	gas/ weak sticky	67	burning	9.987	
Qiaokuang	0.7	100	8	lean	86	burning	2,000	20
Kuangchenzi	2	125	8	fat	86	burning	1,976	10
Bayiling	0.3	100	6	lean	86	burning	568	30
TOTAL	**115.66**	**Lost coal: 202,278 Mt; Lost coal per year: 435 Mt**						

The same calculation was carried out for the Wuda region for 2002 and 2009 (during which time the number of fires was estimated to have increased by a factor of 5). The carbon content of the Wuda coals was much lower at 65%, giving a CO_2 emission factor of 2.2 t/t coal. The calculations were as follows:

$$0.2 \text{ Mt} \times 2.2 + 0.2 \text{ Mt} \times (0.3 \times 2.2 \times 21) = 0.470 \text{ Mt } CO_2\text{-e} \quad (2002)$$
$$1 \text{ Mt} \times 2.2 + 1 \text{ Mt} \times (0.3 \times 2.2 \times 21) = 2.350 \text{ Mt } CO_2\text{-e} \quad (2009)$$

Interestingly, this empirical estimate agreed reasonably well with data based on gas emission estimates which put emissions from the region in 2005 at around 0.09–0.360 Mt CO_2-e, based on coal combustion at 0.07–0.270 Mt/y. Estimates from remote sensing data in the same region had put the coal combustion in the region at only 0.051 Mt/y, which, according to van Dijk and others, confirms that thermal data may underestimate coal fires by not picking up on smaller or deeper fires.

Empirical estimates, using the same technique as above, put emissions from the whole province of Inner Mongolia at 8.2 Mt CO_2-e. And for the Xinjiang province the total was 39 Mt CO_2-e/y, based on a coal burn of 13.5 Mt/y and a coal carbon content of 75%.

van Dijk and others (2011) stress that an exact quantification of coal fires on a country-wide scale for China is not possible with the limited data currently available. However, extrapolation will give an idea of the upper limit. There are around 50 coal fire areas known in China with Wuda being one of the most severe – so the total emissions for China will certainly be less than 50 times that from the Wuda province. In fact, the three areas discussed above have by far the greatest concentration of fires between them. The other areas have considerably fewer fires and are likely to comprise more than 1 Mt coal loss per year combined. So the total amount of coal burnt in Xinjiang, Ningxia and Inner Mongolia and other provinces is likely to be no greater than the total of the three provinces studied (13.5 + 2 + 3.5 Mt) plus the combined 1 Mt from other provinces combined giving a total burn of 20 Mt. Assuming a conservative 2.7 t CO_2/t (averaging coal rank), and using the same calculations as above, this gives:

$$20 \text{ Mt} \times 2.7 + 20 \text{ Mt} \times (0.3\% \times 2.7 \text{ x. } 21) = 57.5 \text{ Mt } CO_2\text{-e}$$

van Dijk and others (2011) stress that this is likely to be an over estimate since this assumed 100% efficiency of coal burn, assumes the upper rate of CH_4 release and is based on the maximum coal loss in each province. Based on a global CO_2 emission estimate of 28 Gt/y for 2008, the contribution from Chinese coal fires is 0.22%.

The majority of mines in **India** (~90%) are operated by subsidiaries of Coal India Ltd and so are operated by a central nationalised company. The Jharia coalfield (JCF) has one of the largest coal mine fire complexes in the world. The first fire broke out in 1916 and by the 1960s there were numerous fires with flames reaching 20 feet. To date around 70 fires are still burning at the JCF with over 37 Mt of coal having been lost to fires and 1453 Mt remain in the combustion area. It is thought that the fires started as a result of bad practice prior to nationalisation of the coal mines in the 1970s and also due to illegal distillation of alcohol in abandoned mine sites. Funds have been provided by the Ministry of Coal to relocate the population who are affected by these fires. Various techniques such as surface sealing and trenching have been tried to stop the fires but subsidence and inaccessibility in some areas means that many of the fires continue and cannot be controlled (Stracher and Taylor, 2004).

Based on the same empirical assumptions as used for China (*see above*) van Dijk and others (2011) proposed that total coal loss to spontaneous combustion in India is likely to be around 100 Mt CO_2-e, around twice that from China.

Indonesia has had significant problems due to deforestation and land clearance as a result of both intentional and accidental fires. The threat of the spread of spontaneous coal combustion to surrounding forests and agriculture is therefore considered significant. Forest fires in 1997 and 1998 ignited hundreds of coal fires at outcrops (Ide and Orr, 2011). The US Department of State and Office of Surface Mining have worked with the Indonesian Ministry of Energy and Mineral Resources to provide training and technical assistance on managing coal fires. The Ministry now has an official decree on coal fire management and has committed a portion of the Coal Royalty Fund to support coal fire suppression activities. An inventory of coal fires was established in East Kalimantan and, by 2003, 164 coal fires were listed, although the inventory was 'far from complete'. Based on extrapolation of the average number of fires within certain areas, the actual number of fires in East Kalimantan could be between 760 and 3000. The current staffing rate within the Indonesian Ministry of Energy and Mineral Resources for dealing with these fires is only enough to deal with ten fires per year and so, unless further action is taken, this will remain a problem in Indonesia for the significant future (Whitehouse and Mulyana, 2004).

4.2.3 Europe

Poland has national standards relating to spontaneous combustion:

- PN-G-04039:1998 Hard Coal – The sampling for testing of self ignition of coal;
- PN-G-04558:1993 Hard coal – The determination of the index of self ignition;
- PN-G-07010:1994 Hard coal and hard coal briquettes – Stockpiling (involving practices for the counteraction of self ignition).

These standards involve monitoring gas release to determine the likelihood of spontaneous combustion for safety reasons. They do not relate to the quantification of gases for inventory calculation and it would appear that the quantification of gases from this source is currently not a priority in Poland (Pyka, 2013). However, new research on emissions from coal waste dumps in the upper and lower Silesian Coal Basins has recently been published which may indicate some new interest in this area (Fabianska and others, 2013).

Stracher (2013) suggests that there is work being carried out to evaluate emissions from coal stockpiles in countries such as Portugal and that there are problems associated with emissions from

peat fires and well as oil shale fires and data from these will be published in the near future.

A fire broke out earlier this year at the Daw Mill Colliery, **UK**, owned by UK Coal Mine Holdings Ltd, in Warwickshire and 92 workers were successfully evacuated. Despite attempts to control the fire, the mine had to be evacuated with the seam still alight. During the build-up to the start of the fire, the CO concentrations rose from a standard 7 ppm to over 10,000 ppm within four hours (Wishart, 2013). The fire, which was still burning in May 2013, is estimated to have cost UK coal £100 million in lost equipment and £160 million in lost coal (Sunday Times, 2013).

4.2.4 South Africa

Spontaneous combustion has been reported at several closed workings at the Witbank collieries following reopening. Spontaneous combustion was first recorded in the Sasolburg coalfield in 1985 as old workings were reopened. Despite treatment by cladding, dozing and sand dumping, some areas continue to burn (Pone and others, 2007). In 1986 Coal Mining Research Council funding was approved for research on fires in shallow mines

Anglo American estimate emissions from spontaneous combustion by estimating the total loss of coal production affected and multiplying by the CO_2 estimated to be emitted due to combustion. Although these emissions are estimated they are not publicly reported due to the uncertainties and errors within the calculation (McIntyre, 2013).

Cook and Lloyd (2012) have prepared an estimate of GHG emissions from surface and abandoned mines in South Africa. It is reported that 'guestimates' for these emissions amounted to over 1 Mt CO_2/y which is significant in the context of total emissions from South Africa. The original estimates for emissions from the South African Government to the IPCC were recalculated based on a review of the methodology.

Using gas sampling units (*see* Section 2.2.2), Cook and Lloyd (2012) compared emissions from several sites at closed mines and sites of previous spontaneous combustion. Based on the average emissions from these sites, total emissions from surface mines and abandoned mines in South Africa were estimated at around 1.950 Mt/y $CO_2 \pm 0.35$. Of this, 0.220 Mt/y (around 11%) is attributable to areas with visible smoke or fire.

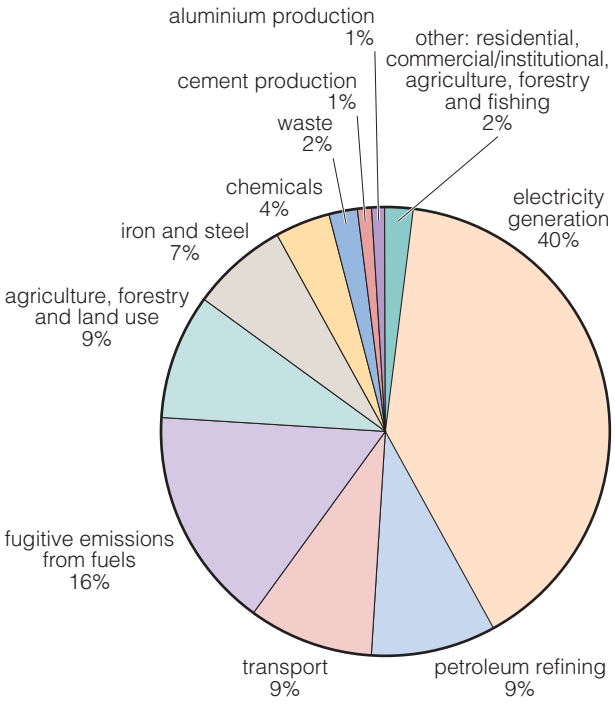

Figure 13 Breakdown of South Africa's GHG emissions by sector (NT RSA, 2013)

The South African government is proposing a carbon tax to be introduced in 2015. It is possible that emissions from spontaneous combustion could be included in this under 'fugitive emissions from coal mining'. In the most recent national inventory, emissions from this sector are 16% of all GHG emissions in the country, as shown in Figure 13. This includes emissions of methane from coal mining, which contributes the majority of these emissions. The actual values for GHG emissions from the mining sector in South Africa in 2000 showed CO_2 emissions at 24.33 Mt and CH_4 emissions at 40,336.25 Mt with a total CO_2-e of 40,391 Mt. Although

Table 14 Emissions from spontaneous combustion at the Witbank and Sasolburg coalfields in South Africa, ppm (Pone and others, 2007)

Compound	Witbank	Sasolburg
Methane	1793	11,710
CO	641	27,500
CO_2	31,925	89,612
Cysteinesulphonic acid	6.3	6.1
Carbon bisulphide	0.4	2.2

some methane may be coming from oxidation or inefficient sites of spontaneous combustion, the majority of the CO_2 emissions can be assumed to be from spontaneous combustion and the majority of CH_4 from mining. However, since carbon taxes put a monetary value on these emissions, unless the emissions from spontaneous combustion were proven to be insignificant, emissions from this sector would also need to be quantified and reduced. Further, spontaneous combustion is a waste of fuel and a safety risk and so could be a sensible target for reducing GHG emissions in a beneficial manner. Either way, some more detailed evaluation on emissions from spontaneous combustion from South African coal mines will be required as the carbon tax comes into play (NT RSA, 2013).

Newer, but as yet unpublished, data has been submitted to IPCC based on South African emission factors rather than Australian emission factors (as used for the 2000 estimate quoted above). In the new inventory the value for fugitive methane emissions from mining has been reduced to 2.25 Mt/y (Witi, 2013). If this value still contributes the majority of GHG emissions from the mining sector, as implied above, then the total emission estimate, including the value for emissions from spontaneous combustion, may be reduced significantly as a result.

Monitoring of emissions from fires at the Witbank and Sasolburg coalfields at ground level indicated that these were found to be at toxic concentrations, as shown in Table 14.

4.2.5 USA

Coal fires have been recorded in Pennsylvania since 1869 when an underground fire killed 110 men but self-extinguished after a year. According to official state data, there were around 140 underground coal mine fires and 58 burning refuse piles in Pennsylvania in 2004 (Stracher and Taylor, 2004). The Centralia mine in Pennsylvania has burnt twice since 1962 and originally started when rubbish was burnt at an abandoned strip mine to reduce a rodent infestation. Congress ensured that $42 million was used to relocate the 1100 residents of the area who were affected by toxic gases and polluted streams, in addition to cracked highways and other effects. The fire may burn for a further 100 years and further relocation of the local population may be required. Similarly a poorly planned fire at the Percy mine in Youngstown, PA, led to a fire which has been burning for over 30 years and $30–40 million will need to be invested to either extinguish the fire or relocate residents (Stracher and Taylor, 2004). This same fire has been mentioned in several subsequent publications which would suggest that the problem remains.

According to Ide and Orr (2011), natural coal bed fires do not fall under the category of abandoned mined land and are therefore often not monitored by the Department of the Interior. However, Kuenzer and Stracher (2012) note that the Federal Office of Surface Mining manages a database that contained 150 known fires in the year 1999 but it is unclear if this is kept up to date. Individual states such as Colorado may create their own reports on the status of coal fires. Of the 1736 abandoned mines in Colorado, 36 are currently burning and 50 are considered dormant.

O'Keefe and others (2010) note that regional and global estimates of CO_2 from coal fires are not common and so carried out some of the first published in situ measurements of CO_2, CO and Hg from gas vents at the Truman Shepherd and Ruth Mullins Fires in Floyd County, KY and Perry County, KY respectively. Extrapolating from Chinese data and using theses national statistics, O'Keefe and others

(2010), estimated the mass of coal lost to spontaneous combustion in the USA in 2007 was around 5.8 Mt/y – 120 Mt/y. Assuming 65% w/w carbon content and a combustion ratio of 2.38 t of CO_2 produced per 1 t of coal combusted gives an estimate of 14 Mt/y – 290 Mt/y of CO_2 from this source, although O'Keefe and others (2010) suggest that this would be an over-estimate. This is relatively small compared with the 2400 Mt/y CO_2 which was estimated to arise from coal combustion for energy generation in the USA in 2006. Similarly emissions of Hg from spontaneous coal combustion could amount to only 0.58–11.5 t/y compared with the 59 t/y arising from coal-fired utilities in the country. These emissions from spontaneous combustion may be small but they are certainly not negligible and could be significant on a more local basis.

4.3 Comments

The IPCC recognises spontaneous combustion as a potential source of GHG emissions and, although it provides basic guidance on how estimates could be prepared, these data are not specifically required in national inventories. As a result, few national and international GHG inventories even mention spontaneous combustion. That is not to say that some data are not available – extensive studies have been carried out at numerous sites in the USA, China and India. However, these studies have not been combined to give an official estimate of GHG emissions from the spontaneous combustion sector in any of these countries.

Australia has excluded spontaneous combustion from inclusion in the carbon tax system because of the uncertainties in the emission estimates. At the moment, South Africa includes spontaneous combustion along with mining emissions under a 'fugitive mining emissions' category for carbon tax but it is unclear to what extent this will actually apply to spontaneous combustion.

5 Conclusions

Coal fires are accidental and random and therefore not occurring in such a way that can be predicted or controlled in the long term. Unlike coal use in the power sector, where controlling emissions from a source is a permanent achievement, reducing emissions from one coal fire will only control emissions from that fire – several more may arise elsewhere at the same location or nearby. And so, although emissions from spontaneous combustion may be a concern in some areas, they are commonly dealt with on a case-by-case basis, primarily for safety and stock maintenance concerns, and are not often seen as a potential target for GHG reduction. However, the question of the significance of these emissions with respect to national and international GHG budgets is still of interest.

There are two distinct approaches to estimating emissions from spontaneous combustion:

- empirical data – based on an emission factor for the coal and a known amount of coal consumed;
- measurement data – based on site-specific monitoring to produce more accurate emission factors/rates and activity data.

The empirical approach may give a 'worst case scenario' approach by assuming the complete release of the pollutants concerned from the maximum amount of coal consumed. The measurement approach may give more accurate, site-specific, estimates but requires a significant amount of time and expertise to collect and process emission and consumption data. However, a combination of both approaches could give the most suitable data for emission inventories. Site-specific measurement data can be used to produce site-specific emission factors. These emission factors may be used to estimate emissions from similar types of fires (strength of burn, coal type and so on) elsewhere. Whereas emission factors for GHG emissions from coal combustion in power production will be based on the coal type and the combustion system, emission factors for spontaneous combustion are far more variable. Emissions are affected by factors such as the rank of coal, the intensity of the fire, the amount of coal consumed, any overburden, ambient conditions and the flow of air to the affected area.

Estimating emissions from small sources such as individual fires and stockpiles can be performed on a stockpile-by-stockpile/site-by-site basis, although variables such as those discussed above, are still an issue. In some cases, assuming the worst case scenario – such as complete combustion of the known volume of coal in a stockpile, will give the maximum amount of GHG emissions possible. Estimating emissions on a regional, national or international basis requires a vast amount of data. In many cases, the fires are in locations that are either not easily accessible or are too dangerous to approach. Some are in remote regions where very little is known about the amount of coal involved. For estimates at this level, emission factors have to be combined with a best guess as to how much coal is involved over any prescribed period of time. Coal fire maps pinpoint known fires around the world. However, these do not have sufficient accuracy to be used in any global emission calculation.

By far the most studies on spontaneous combustion are concerned with emissions of CO_2. CH_4 emissions tend to be smaller but, because of the higher global warming potential of CH_4, some studies take these latter emissions into account. In some cases at deep mines, the contribution of CH_4 to emissions may be significant as CH_4 is drawn from surrounding seams.

Although studies have been carried out looking at emissions of organic compounds and trace elements, especially mercury, from spontaneous combustion, for the most part these studies are academic. They indicate that, at some sites, the air in the vicinity of spontaneous coal combustion can be severely hazardous to human health. They also indicate that emissions of pollutants such as mercury should be studied more carefully as they may be significant contributors to local emission concentrations of these species. However, in most cases, the total emissions of these pollutants are still not considered of sufficient significance to be regularly included in national or global emission inventories.

The IPCC have deemed emissions of GHG from spontaneous combustion too difficult to quantify with enough accuracy to make the data useful and do not require this source to be included in national inventories. The Australian government have also deemed emissions from spontaneous combustion to be too difficult and too insignificant to estimate and do not include it under the national carbon tax. A group working towards obtaining baseline data for the potential inclusion of this source in the CDM also determined that the methodologies were not yet appropriate for producing data with sufficient accuracy. The only country which appears to be considering the emissions from this sector with any serious concern is South Africa where, for the moment, they are included within fugitive emissions under the proposed carbon tax to commence in 2015.

It would appear that, for the moment, estimates of international or national emissions from this source will, for the most part, be seen as best guesses. However, considerable work towards establishing measurement methodologies based at ground level as well as remote sensing methods, combined with growing amounts of data on the areas known to be prone to this issue, means that, in future, estimates will become more and more accurate. Standard methodologies, based on site-specific emission values combined with geographical data from satellite sensors, are likely to improve estimates from global spontaneous combustion sources significantly in the coming years.

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