Projecting the Full Pollutant Cycle from Coal Utilization to 2200: Understanding the Global Environmental Implications

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Major Theme: Limits to Growth

Abstract

The mining and consumption of coal has long been a primary factor in global energy supply. Australia, Canada and the United States of America (USA) are four crucial coal exporters and consumers worldwide. Their historical coal production trends, future coal production trends, mining methods, coal quality trends are critical in determining the capacity and feasibility of global continuous coal use toward 2050 and beyond to 2200. As a finite and exhaustible resource, coal has a logistical 'peak' regarding its limited reserves and increasing demand. In order to predict the magnitude and timeframe of the 'Peak' of these four countries, Hubbertarian peak models are developed with a range of available coal production data to establish future coal production forecasts. Pollutant emissions such as sulfur dioxide and particulates associated with coal mining and use in electricity generation are important environmental constraints, although they often receive less attention than greenhouse emissions. Given the availability of pollutant release data from Canada, Australia and the USA, we assess the pollutant intensities associated with coal mining and electricity generation, and combine this with Hubbert peak models to project potential future pollution loads from coal mining and use. Overall, this paper uses historical data to project the future production of coal in Australia, Canada and the USA and combines this pollution intensity to assess the environmental implications of continued coal use. The paper therefore addresses two central themes of sustainability – that of resource depletion and pollution loads, both of which require careful scrutiny in the face of climate change, public health and related issues.

1 Introduction

Coal is a primary form of fossil fuels and it remains dominant in global energy supply (WCI, 2010). In 2007 coal contributed 135.23 billion GJ of energy, which accounts for 34% of global energy demand (IEA, 2009). For the foreseeable short-term future, coal will remain an important source of energy in meeting increasing global demand. However, as with any exhaustible natural resource, exponentially increasing coal use is inevitably accelerating the depletion of economical coal reserves. Furthermore, coal mining and consumption can cause significant environmental impacts, including water pollution, waste generation and especially greenhouse gas emissions. From an environmental sustainability perspective, it is critical to predict and evaluate future coal production trends combined with pollutant emissions.

This paper compiles and presents the available data on coal mining, with a particular emphasis on historical coal production trends, available resources, average coal quality (or rank), long term projections of coal production to 2200 and associated pollution loads such as sulfur dioxide, particulates and nitrous oxides. This is then discussed within a sustainability context of addressing issues such as resource depletion and pollution loads.

2 Methodology and Data Sources

The various aspects of sustainability investigated are assessed through the compilation of detailed data sets on coal mining, coal resources, coal quality and pollutant releases.

2.1 Data Sources

The primary sources are historical government series/periodicals, industry sources and statutory environmental reporting sources (such as pollutant release inventories), specifically:

Australia

- Mining, resources and quality – 1829-2008 (Mudd, 2009; ABARE, 2010; GA, var.)
- Pollutant releases – 1999-2009 (NPI, 2010; Martin, 2010)

Canada

- Mining, resources and quality – 1886-1956 (NRC, var.-a), 1957-2008 (NRC, var.-b, 2010)
- Pollutant releases – 1999-2009 (EC, 2010)

United States of America (USA)

- Mining, resources and quality – 1890-1975 (BoM, var.), 1976-2008 (DoE, 2009; EIA, var.)
- Pollutant releases – 1999-2005 (EPA, 2010)

2.2 Hubbert's 'Peak Oil' Model

The rise and fall in petroleum production was first modelled by Hubbert (1956). A basic assumption of this approach is that the cumulative production of an exhaustible resource can be represented by a logistic growth/decay curve over time (Gaussian curves also work) (Cavallo, 2004). The logistic growth is given by:

$$Q(t) = \frac{Q_{\max}}{(1 + a \ \exp bt)},$$

where Q_{max} is the ultimate recoverable resource and *a*, *b* are constants. In this report, Q_{max} equals the cumulative coal production by time *t* plus the remaining recoverable resource. Several social and economical assumptions of the model include: (i) affordable prices for consumers and good profitability for owner of the resource; (ii) stable markets both in political and market rules; (iii) continuous increasing consumption; (iv) perception of limitless resources by producers and consumers: availability of imports; and (v) extraction costs, profit levels and technology development are kept in reasonable magnitude.

2.3 Projecting Pollution Potential

The future modelling of pollution loads from coal mining are completed by linking pollutant metrics with annual production. That is, by taking 'kg pollutant/t coal' and t coal/year you derive kg pollutant/year. This is a simplified approach, which has the inherent assumptions and issues of Hubbert-style models, but nonetheless provides a starting point to consider the potential future pollutant loads associated with the coal industry. Ideally, linking pollutant metrics to future scenarios of environmental regulations and technology options for coal would be preferred, however, this would require considerable data collection and extensive analysis to ascertain the current situation and prospects to inform such scenarios. As such, this simplified approach was adopted as a pilot study to lay the foundation for future work.

3 Results: Coal Production and Projections

3.1 Australia

Black coal is major product of Australian coal industry. New South Wales and Queensland are two primary states which provide 98 per cent of total black coal production in Australia (ABARE, 2010). Brown coal mining only occurs in Victoria and is all consumed by domestic electricity generation (Mudd, 2009; GA, var.).

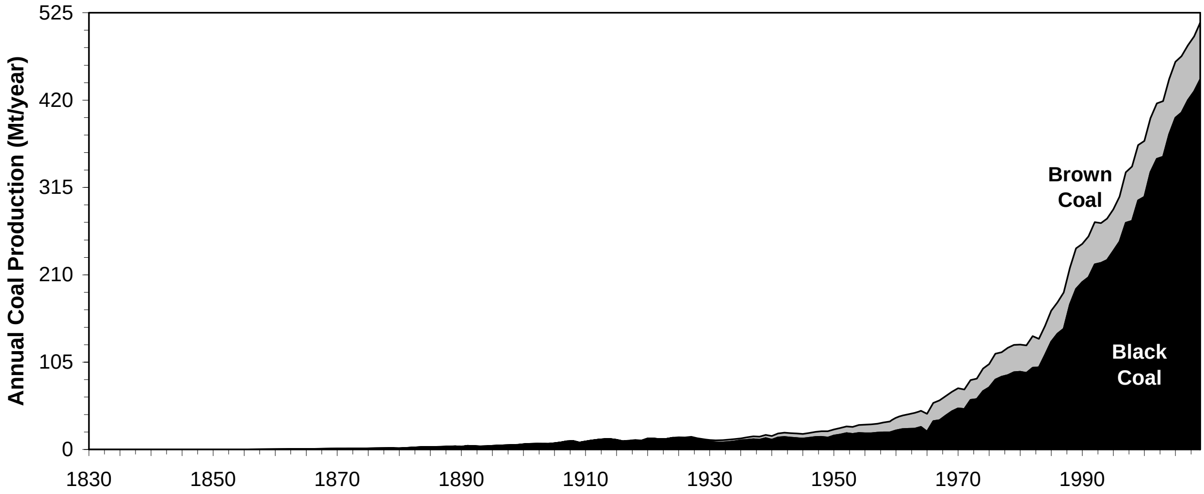

Figure 1: Annual Australian coal production by main coal type (1830 to 2008)

As illustrated in figure 1, black coal dominates national coal production. In the 1970s, the rapid increase in international demand for high quality coal has significantly stimulated Australian black coal production. By 2008, the annual production of black coal is 430.5 million tonnes (Mt) which accounts 86.7 per cent of Australian total coal production. There has been a 43 –fold growth since 1908. Brown coal production also has a continuous increasing trend since 1888. There has been an approximate three times increase from 23.34 Mt in 1968 to 66 Mt in 2008.

As shown in figure 2, Australian coal production is projected to peak at ~950 Mt/year in 2052, based on total coal, or peaking in 2040 at ~730 Mt/year based on separate modelling of black and brown coal production. Peak coal production is therefore projected to occur by mid-century, and enters effectively a terminal decline. The correlation coefficients for all models are high, ranging from 98.3 to 99.3%, for either brown or black coal, total coal, or annual versus cumulative production models.

In comparing the separate projections for black, brown or total coal, it is clear that brown coal will last longer, primarily due its lower extraction rate at present. This means, however, that coal quality will gradually decline as black coal peaks and wanes and brown coal begins to dominate coal production. By 2009, cumulative black and brown coal production in Australia was 11.58 and 2.26 Gt, respectively, with remaining economic resources reported as 43.8 and 37.1 Gt, respectively (GA, var.). Although it is commonly claimed that Australia has ‘centuries’ of coal resources remaining, it is clear that this is not the case and that peak coal will occur within the next few decades if existing production trends continue, but perhaps more importantly that coal quality will decline considerably as brown coal eventually dominates.

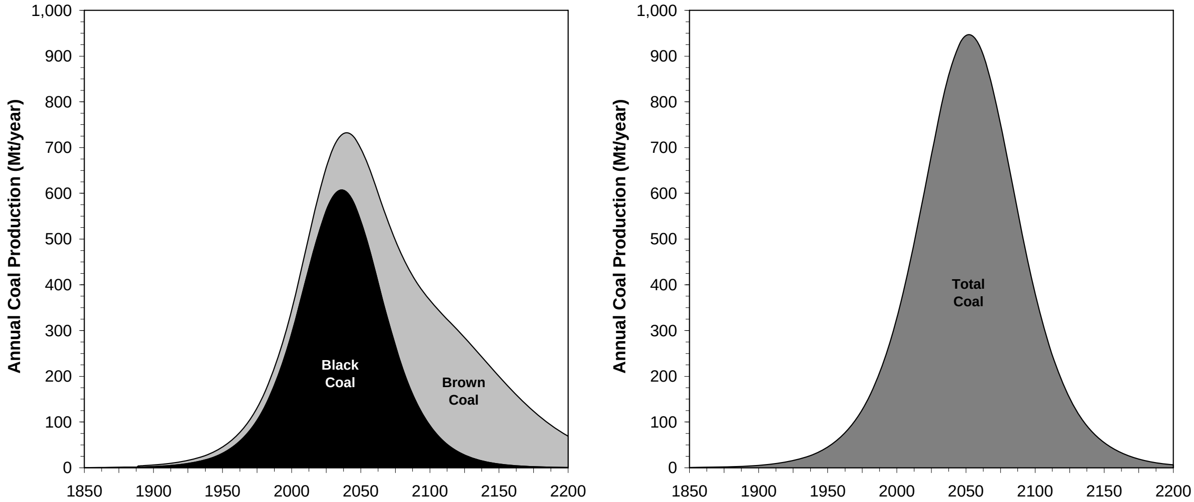

Figure 2: Projected Australian coal production to 2200: black and brown separately modelled (left); total coal model (right)

3.2 Canada

Canada mines bituminous and sub-bituminous coal and lignite, with recent production history shown in Figure 3. Canadian coal production experienced strong growth in the 1970s but has stagnated since the 1980s. Before the 1960s, bituminous coal accounted for over 80% of Canadian production. However, the mix of coal has changed dramatically. By 2006, annual production of sub-bituminous coal and lignite was 36.5 Mt, or 56.5% of annual production.

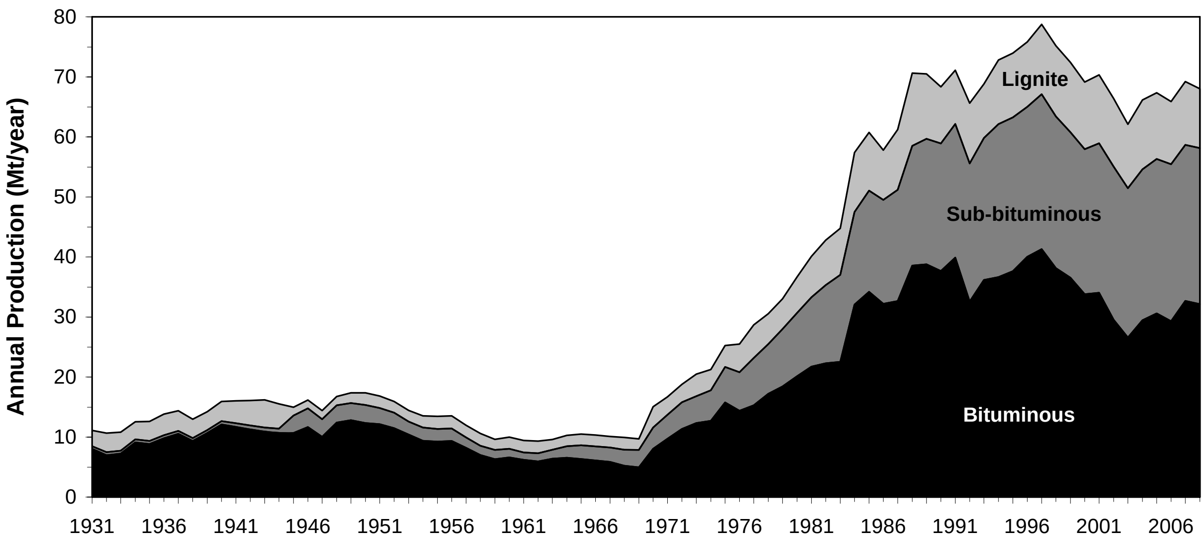

Figure 3: Annual Canadian coal production by coal rank from 1931 to 2008

The forecasts of Canadian coal production toward 2200 are shown in Figure 4. The total coal model peaks with maximum annual production of 96.0 Mt coal in 2028. The bituminous coal model achieves maximum production of 46.4 Mt in 2033, while the sub-bituminous coal model has already reached its peak of 27.6 Mt in 2009. The model projects lignite to have the longest production period before reaching its peak of 26.5 Mt in 2050. Like Australia, Canadian coal will face a permanent decline in coal quality after 2040s due to the rising dominance of lignite over bituminous and sub bituminous coal. The correlation coefficients for all models are very high, ranging from 86.7 to 99.7%, for either brown, bituminous or sub-bituminous coals, total coal, or annual versus cumulative production models.

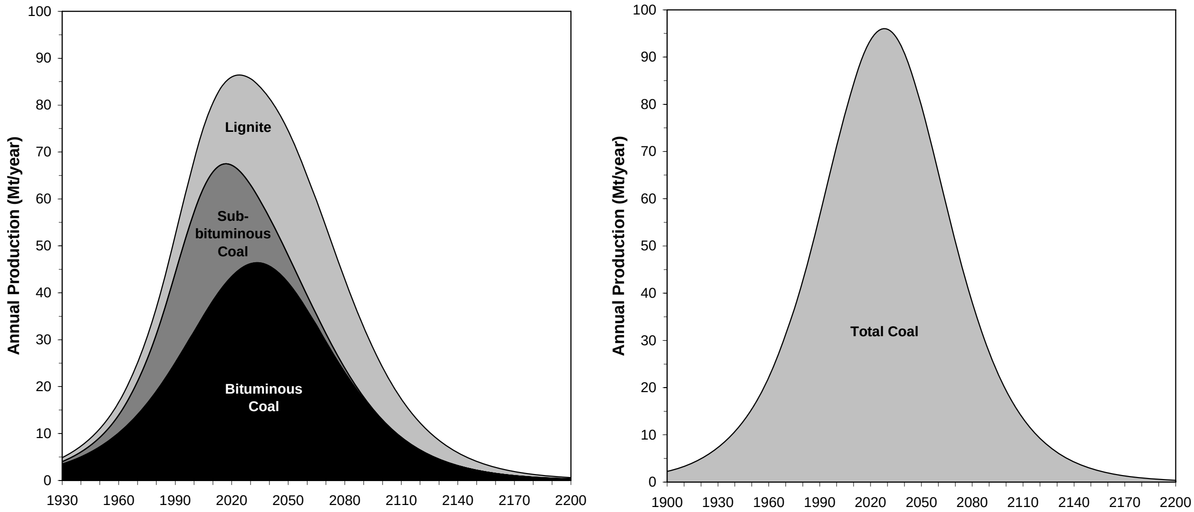

Figure 4: Projected Canadian coal production to 2200: all coal ranks modelled separately (left); total coal model (right)

3.3 *United States of America (USA)*

According to Figure 7, there has been a substantial increasing trend of most ranks of coal production in the United States since 1960s, although anthracite has been virtually exhausted. Before 1968, the annual production records of coal in U.S. are dominated by high ranking coal of anthracite and bituminous coal. Sub-bituminous coal and lignite were considered as undesirable sub-products or wastes associated with high ranking coal mining. Since 1970s annual production of anthracite in U.S. has been consistently declining from 39.95 Mt in 1950 to 1.54 Mt in 2008. Annual production of bituminous coal also declined from a peak of 682.9 Mt in 1990 to 507.5 Mt in 2008. Like Australia and Canada, the mix of coal production has been shifted from high quality coals to lower quality coals (ie. increasingly lignite).

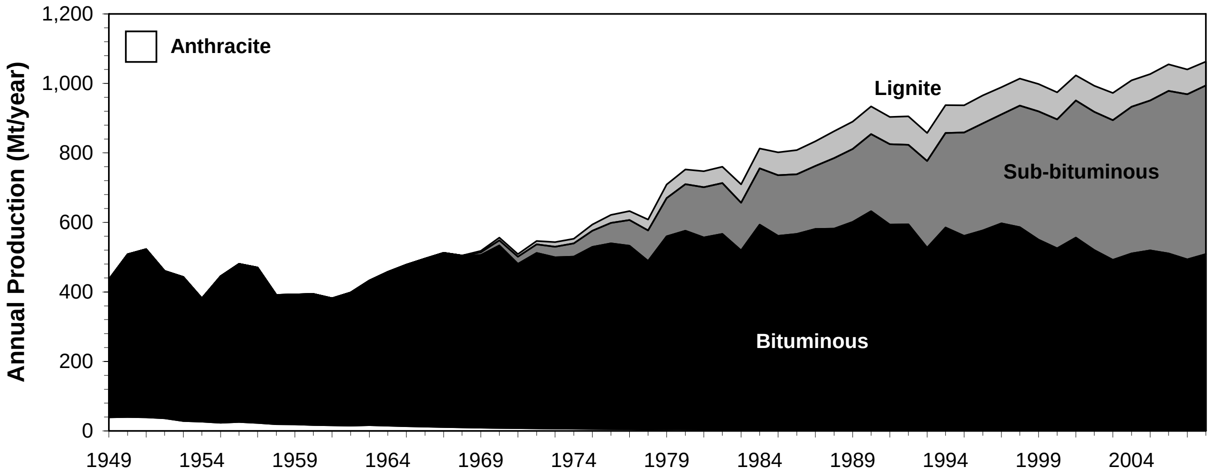

Figure 5: Annual USA coal production by coal rank from 1949 to 2008

In Figure 6, the total model of annual production coal peaks at 1,414 Mt in 2067. The peak models for bituminous and sub-bituminous coal project annual production peaks of 848.5 and 1,482 Mt in 2026 and 2046, respectively, while lignite is projected to peak at 312.6 Mt in 2069. High rank coals, which include anthracite and bituminous coal, are depleting much faster than sub-bituminous and lignite production. The correlation coefficients for all models are very high, ranging from 88.4 to 99.5%, for either brown, bituminous or sub-bituminous coals, total coal, or annual versus cumulative production models.

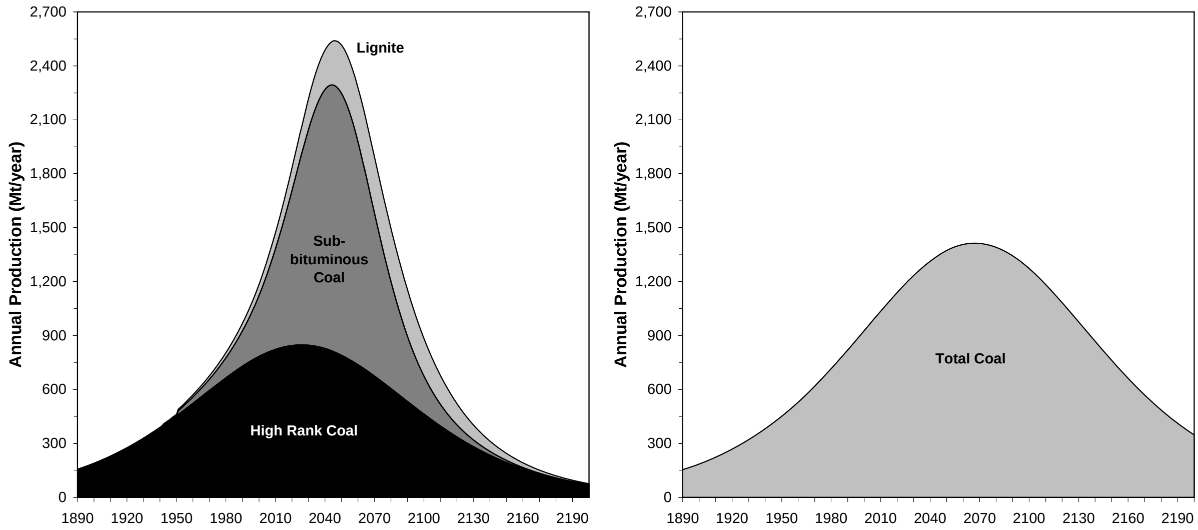

Figure 6: Projected USA coal production to 2200: all coal ranks modelled separately (left); total coal model (right)

3.4 Coal Quality Trends

The unit heat content of coal (GJ/t) is a crucial indicator in demonstrating coal quality. Given the ongoing rise in lignite production, and projected declines high quality coals, the effective average heat content of coal will continue to decline in Australia, Canada and the USA. Based on typical values (eg. ABARE, 2010; EIA, 2008), Australian coal's average heat content has decreased from ~29 GJ/t in the early 1900s to ~25 GJ/t by 2008. Similarly, the average heat content of Canadian coal has reduced from ~25 GJ/t in 1949 to 22.3 GJ/t in 2008, while for USA coals the heat content declined from ~29 GJ/t in the 1950s to 23.5 GJ/t in 2008. A forecast of coal heat content is shown in Figure 7.

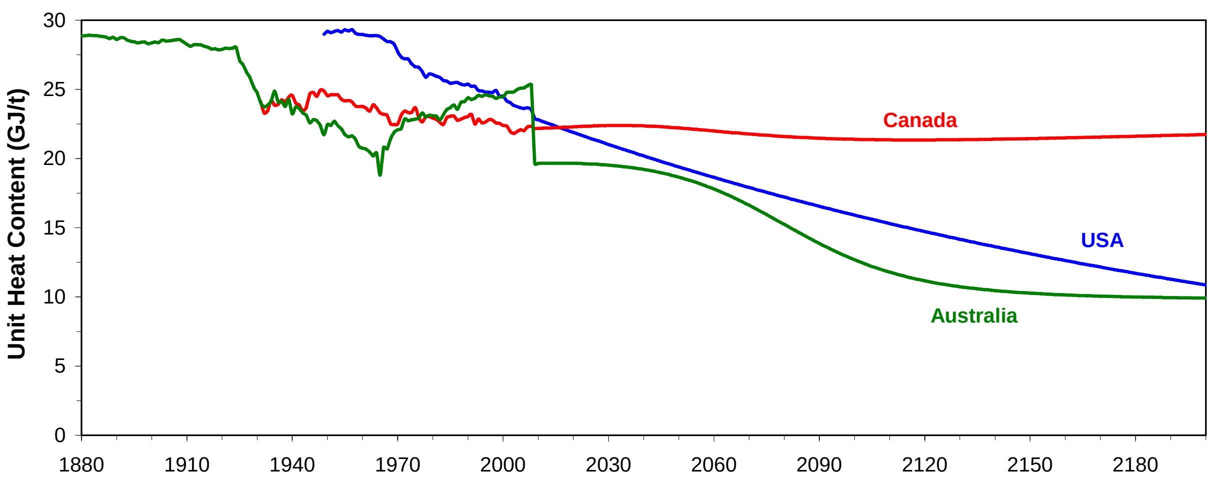

Figure 7: Coal quality trends forecast toward 2200

4 Pollutant Releases and Emissions Intensity

4.1 Summary Data

The principal air pollutants associated with coal mining and electricity generation are carbon monoxide (CO), particulate matter with diameter less than 10 μm ('PM10'), oxides of nitrogen (or 'NO_x'), sulfur dioxide (SO_2) and volatile organic compounds (VOCs). In Australia, Canada and the USA, annual emissions are reported through statutory government programs, namely the National Pollutant Inventory (NPI), National Pollutant Release

Inventory (NPRI) and Toxic Release Inventory (TRI), respectively (see Martin & Mudd, 2010). Pollution release data was compiled and assessed for these countries (no data is publicly available for China), and summarised in Tables 1 and 2.

Table 1: Pollutant loads associated with coal mining (kg pollutant/t coal)

		QLD	NSW	SA	WA	Canada	U.S.A.
Total No. Mines		5	4	1	2	Average#	Average#
Data Points		50	40	10	20	10	2,392
Coal Type		Bit / SB	Bit / SB	SB	Bit / SB	Bit / SB / L	Bit / SB / L
Avg Prod (Mt/yr)		17.99	34.54	3.43	6.38	69.36	1,026
PM10	min	1.186	0.201	0.090	0.304	-	-
	avg	1.657	0.472	0.159	0.369	0.155	0.017
	max	2.642	0.710	0.277	0.451	-	-
SO_2	min	0.0002	0.002	0.001	0.001	-	-
	avg	0.006	0.005	0.004	0.006	0.048	0.0011
	max	0.011	0.009	0.007	0.009	-	-
NO_x	min	0.197	0.066	0.106	0.075	-	-
	avg	0.326	0.122	0.123	0.163	0.026	0.0018
	max	0.620	0.182	0.138	0.535	-	-
CO	min	0.140	0.037	0.057	0.035	-	-
	avg	0.207	0.083	0.074	0.053	-	0.003
	max	0.368	0.112	0.082	0.062	-	-
VOC	min	0.046	0.020	0.010	0.008	-	-
	avg	0.054	0.021	0.012	0.010	0.016	0.0014
	max	0.092	0.022	0.016	0.012	-	-

Notes: Bit – bituminous coal; SB – sub-bituminous coal; L – lignite. #Based on national pollutant load totals for the coal sector divided by total coal production (individual site data not available; one year's data only).

Table 2: Pollutant loads associated with coal electricity generation (kg pollutant/ GWh)

		QLD	NSW	SA	WA	VIC	Canada
Total No. Power Plants		2	4	2	1	3	National Average#
Data Points		10	32	18	4	6	10
Coal Type		Bit / SB	Bit / SB	SB	Bit / SB	L	Bit / SB / L
Electricity (GWh/yr)		16,354	47,595	5,200	3,216	27,156	411,731
PM10	min	0.236	0.032	0.094	0.200	0.155	-
	avg	0.456	0.048	0.171	2.980	0.168	0.026
	max	0.901	0.057	0.209	5.916	0.181	-
SO_2	min	2.2390	3.489	1.471	7.834	1.768	-
	avg	2.552	3.770	1.676	9.159	1.826	1.141
	max	2.792	4.034	1.967	10.804	1.885	-
NO_x	min	2.954	2.050	2.104	1.921	1.658	-
	avg	3.673	2.361	2.423	3.544	1.659	0.435
	max	4.458	2.591	2.996	6.174	1.660	-
CO	min	0.086	0.061	0.070	0.162	0.363	-
	avg	0.103	0.064	0.082	0.190	0.482	0.045
	max	0.130	0.066	0.082	0.224	0.601	-
VOC	min	0.010	0.011	0.012	0.013	0.010	-
	avg	0.012	0.011	0.016	0.015	0.010	0.0014
	max	0.015	0.013	0.023	0.018	0.011	-

Notes: Bit – bituminous coal; SB – sub-bituminous coal; L – lignite. #Based on national pollutant load totals divided by total electricity generation (individual site data not available).

4.2 Projecting Pollution Loads

As noted by Martin (2010), in major coal mining provinces there is evidence to show that pollution burdens are increasing – such as the Hunter Valley in Australia. Given the unit pollutant release metrics in Table 1 and their trends over time, these are combined with the peak models for total coal to project total pollutant burdens associated with coal mining. Further work is required in future to project coal-fired electricity production and associated emissions. Only Australia is presented, given that the results are similar due to the use of the peak coal production models, plus the fact that Canada and the USA only have one year of data (though with many points), with pollution burdens shown in Figure 8.

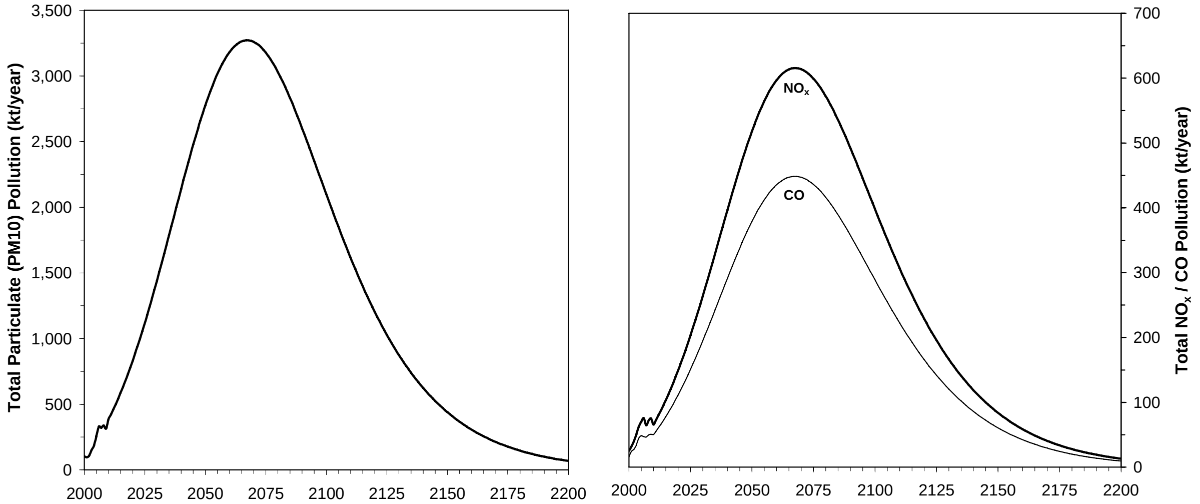

Figure 8: Projected pollution burdens associated with Australian coal mining

5 Discussion

The data and modelling presented herein raises a number of issues – from the extent of coal production to its associated pollution during mining and combustion for electricity, as well as the various reporting systems used by mining companies and government.

In the development of Hubbert-style curves for peak coal production in the USA, Canada and Australia, all models show a peak around the middle of this century, reminiscent of the famous "Limits to Growth" study – regardless of whether individual ranks or total coal was used. Although there are subtle to moderate differences, the models clearly show that, on the basis of finite economic coal resources, coal cannot continue to be relied upon indefinitely. It is also important to consider these projections in the light of the greenhouse gas emissions scenarios used for global climate change models, as they suggest that there may not be as much readily mineable coal as assumed in climate change modelling (see Mohr, 2010).

The unit pollutant metrics was shown to vary widely, both for individual sites (ie. compare minimums and maximums in Tables 1 and 2) as well as between regions and countries. For example, unit SO_2 emissions in coal mining ranged from 0.0011 kg SO_2/t coal in the USA, averaging 0.006 kg SO_2/t coal in Australia to 0.048 kg SO_2/t coal in Canada. In electricity generation, unit SO_2 emissions ranged from 1.14 to 9.16 kg SO_2/GWh. Similarly, unit PM10 emissions ranged from 0.017 to 1.657 kg PM10/t coal or 0.026 to 2.98 kg/GWh. There are various factors which could explain this apparent volatility in unit pollutant metrics. Firstly, this variability is undoubtedly related to impurities in the coal (eg. high/low sulfur coals), though the coal rank does not automatically correlate to impurities (ie. lignite can be low in sulfur or bituminous coal can be high in sulfur).

Secondly, the extent of pollution control is clearly critical in pollutant loads. In the lignite power stations of the Latrobe Valley, Australia, air pollution control technology such as electrostatic precipitators and wet scrubbers are used to capture sulfur dioxide and particulates from power station exhaust fumes. Finally, there appear to be substantive issues of difference between the data for the various pollutant release inventory systems. That is, the methodology used to monitor and/or estimate pollutant loads in the USA, Canada and Australia do not appear to be consistent. All of these countries have modern environmental regulations, as well as the project configurations largely being similar (mines and power stations) and it could be expected that unit pollutant metrics should therefore reflect this.

Another major issue is the total pollution burden released by the ongoing expansion of the coal industry. Since the rise of environmental regulation in the USA in the 1970s (and similarly in Canada and Australia), there is sound evidence to show that pollution control technology has helped to reduce emissions and impacts while still facilitating an expansion of the coal industry, as shown in Figure 9.

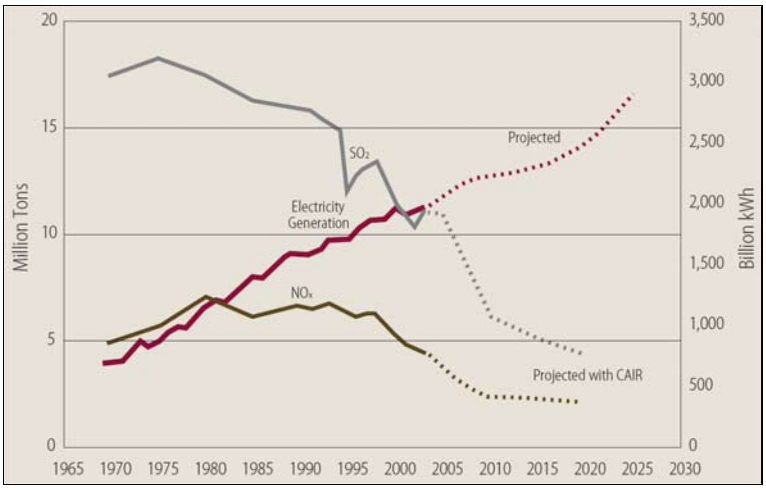

Figure 9: Historical and projected pollution burdens associated with electricity, USA (MIT, 2007)

Although this demonstrates the positive effect that pollution control technology can have on reducing pollution burdens to the environment, the ultimate question is whether such technology is capable of coping with an ever-expanding coal industry, especially coal-fired electricity. That is, as shown by the pollutant loads for Australia, it can be expected that such loads will increase commensurate with production, and that it will take a substantive and sustained effort to amelioriate these loads. In some major coal regions regions of Australia, like the Hunter Valley, the cumulative impacts from growing pollution burdens is fermenting a growing grassroots community campaign for improved monitoring and environmental and public health outcomes (see Higginbotham *et al.*, 2010).

For greenhouse gas emissions, coal quality is critical since lower rank coals have less unit heat content and require more to be used for the same power output (hence higher unit CO_2 metrics). At present, it would seem most likely that any version of allegedly 'clean coal' technology would require more energy to operate and lead to a faster resource depletion rate (although clean coal is clearly a technological utopia which can never be attained).

For other important air pollutants (PM10, SO_2, NO_x, etc), it is not simply coal quality which is important for pollutant metrics and loads but primarily pollution control technology.

6 Conclusion

This paper has compiled a range of data on coal mining and associated pollution loads, focussing on Australia, Canada and the USA. Despite confident assurances from the coal industry that we have 'centuries left', the reality is that coal production and use is most likely to peak by the middle of this century and begin an inevitable decline. Given the scale of coal use in these countries, this represents a critical issue to address in the long term. As shown by the compiled pollutant release metrics, there is often a wide range of unit metrics for coal mines and power stations. Whether this is the result of different systems and estimation methodologies or a true reflection on the variability of the real industrial world is hard to discern at present (this is a ripe area for future research). It is clear from that the pollutant metrics and modelling that it is just as critical to understand the growth in coal mining alongside issues such as pollution burdens, since this correlates to potential problems such as public health and environmental impacts. From an environmental sustainability perspective, it is critical to predict and evaluate future coal production trends combined with pollutant emissions.

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