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Sub-bituminous Coals: An Overview

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Contents


YOU THINK.
YOU CAN WORK
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RAND
MERCHANT
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Traditional values. Innovative ideas.


360°
thinking.

Dedicated to the memory of my mother
Amelia Jones
In the year of the centenary of her birth.

Preface

The book covers sub-bituminous coal utilisation at this point in time, a decade and a half into the 21st Century. Coals of all ranks are experiencing 'unpopularity' because of carbon dioxide emissions. That issue is given its due place in the book, which after an introduction to the origin and nature of sub-bituminous coals gives an account of several scenes of power generation from them. Other aspects covered include gasification, briquetting and liquefaction. It is intended that a reader of the book will achieve both scientific knowledge of all of these topics and an awareness of their role in world energy supply. Perhaps he or she will be bold enough to attempt to glimpse into the future and to predict the degree to which sub-bituminous coals will contribute to world energy needs in the mid 21st Century at which time, it is hoped, carbon dioxide emissions will clearly be on a path towards the 2100 Kyoto targets.

Clifford Jones.
Churchill, Victoria.

1 Background on the nature of sub-bituminous coals

1.1 Introduction

Such coals are in between lignites (brown coal) and bituminous coals in the coalification series, numerous accounts of which are in the literature including one by the present author [1]. Degree of development along the coalification series is the most important factor in determining the nature of a coal as it is this which fixes its rank. Accordingly geological age will be the first feature of sub-bituminous coals to be discussed.

1.2 Geological age

Table 1.2 gives geological ages of a number of sub-bituminous coals from diverse sources, and discussion follows. The terms given in the literature sources drawn on are in inverted commas, with explanatory details following. Precise definitions of the various geological time spans differ between sources.

Source of the coal and reference	**Details**
Colombia [2]. *See also Table 1.3.*	'Late Cretaceous to Cenozoic'. Late Cretaceous: 100.5–66.0 Ma [3]. Cenozoic: Less mature than that [4].
Callide Basin, central Queensland [6].	'Late Triassic': 201 to 237 Ma[1] [7].
Walloon, Queensland [6].	'Mid Jurassic': 161.2 to 175.6 Ma [9].
Huntly, New Zealand [11].	'Eocene': 34 to 56 Ma therefore within the Cenozoic Era [12].
Healy Creek formation, Alaska [13].	'Tertiary': within the Cenozoic Era encompassing Eocene [14].
Indonesia [17].	'Eogene', within the Cenozoic Era overlapping with Tertiary [14].
Collie Basin, Western Australia [18].	'Later Permian': Permian Period from 251–299 Ma [19].
Edmonton, Alberta [21].	'Upper [late] Cretaceous' – see row 1.
Meghalaya, India [22].	Eocene.
Çan-Etili Basin, Turkey [23].	'Miocene': 5.3 to 20.30 Ma [24].
The Pyrenees [25].	'Cretaceous-Tertiary': ≈ 65 Ma [26].
Mukah Balingian, Eastern Malaysia [27].	'Neogene': within Cretaceous [14].
Nigeria [30].	'Later Cretaceous'.
Fushun Basin, N.E. China [31].	'Eocene'.
Bourgas, eastern Bulgaria [32].	'Eocene'.
Meghalaya, north east India [33].	'Eocene'.
South central Venezuela [34].	'Miocene'.

Surat Basin, southern Queensland and northern New South Wales [35].	'Jurassic'.
Sarawak, Malaysia [36].	'Tertiary'.
Oaklands, NSW [37].	'Permian'.
North East Uzbekistan [38].	'Jurassic'.
Hat Creek, British Columbia [39].	'Upper Eocene to mid-Oligocene'.

The Colombian coals in the first row of the table are from the Amagá formation, which in recent years has had an indifferent safety record [5]. Callide coal is mined at an open cut by Anglo American. The power plant there uses supercritical steam (see Chapter 2). In the mid 20th Century Callide coal was used to a small degree in steam locomotives, comprising 3% of the coal used by the Queensland Railways at that time [8]. The same source records that some Collie coal was held in Victoria, southern Australia, for contingencies when the brown coal production there was insufficient for the huge electricity generation role which it played.

Walloon coals have been considered for coal seam gas production. It was once believed that Jurassic coals were too immature to be abundant methane producers, and this has been challenged with Walloon as an example [10]. Coal from Huntly (following row) is also being examined as a source of methane. Huntly is in the Waikato coal fields, more fully discussed in Chapter 2. The coal from the Healy formation (next row) is used in power generation [15]. In Plate 1.1 below the coal reserve and the power plant (bottom right) at Healy are shown in co-existence with wind turbines indicated with an arrow.

Plate 1.1 Healy, Alaska. Image taken from [16].

Collie coal (row 7) is also used to make electricity [20]. Coals of ranks other than sub-bituminous are produced in Alberta (next row), where there are nine coal mines in all. The rank of a coal is evaluated by standards, notably ASTM D388 – 12 'Standard Classification of Coals by Rank'. A coal can be at a state of maturity such that assignment of a single rank is impossible and the Turkish coal in the next row of the table is a case in point, being described in reference [23] as being 'in a transition' between lignite and sub-bituminous. The deposit at Mukah Balingian in Malaysia (final row) exists in a quantity of 550 million tonnes and has been noted for its potential to provide energy for that region of the world [28]. It is a fairly elementary calculation to show that that amount could raise 1000 TW-hour of electricity, seven to eight times the current annual electricity production for the whole of Malaysia [29]. Across a range of nine samples from Nigeria (next row) the proportion of vitrinite varied from 63 to 80%. Vitrinite reflectances at ≈ 0.5 to 0.6% were consistent with the sub-bituminous classification. The Chinese sub-bituminous coal in the next row co-exists with oil shale, which is extracted. The Bulgarian coal is up to 97% in the vitrinite group of macerals and are high in sulphur, up to almost 12%. The deposit in India in the following row contains sub-bituminous and high-volatile bituminous as does the Miocene deposit in Venezuela. The coal deposit crossing the NSW/Queensland border in the following row also contains high-volatile bituminous as well as sub-bituminous. The range in rank is evident from the range of vitrinite reflectances, from 0.45 to 0.71%. The deposit in Sarawak in the next row contains lignite and sub-bituminous coal with vitrinite reflectances in the range 0.26%–0.39%.

The most striking point emerging from the table is the huge range of ages of the sub-bituminous coals, from tens of millions to hundreds of millions of years. This reflects a terminological difficulty when coal rank is seen as a measure of coal age, which it is not. That is because advance along the coalification series requires factors additional to time [40]. These factors relate to conditions of coalification including depth and temperature. Heat flux received by a deposit will not be constant or steady over the coalification time. Both its duration and the maximum temperature experienced by the deposit are factors determining the ultimate rank.

1.3 Petrographic composition

Each of the coals having made an appearance in Table 1.1 will be discussed in terms of petrography. A further study of that from the Amagá formation in Colombia uses huminite rather than vitrinite in its maceral classification [41]. This is more common for lignites than for sub-bituminous coals. Coal from the Callide Basin in Australia had a preponderance of intertinite, and a vitrinite reflectance of 0.53. That from Walloon is 75% vitrinite with a similarly low reflectance indicative of sub-bituminous rank. Coals from the Huntly field in New Zealand have vitrinite reflectances in the range 0.34 to 0.53% [42]. They are also rich in vitrinite and fit the description 'bright coal', a term which applies to coals 80% or higher in vitrinite and displaying bands of vitrain [43], which Huntly coal does. The sub-bituminous coal formation from the Healy formation in Alaska is lenticular, suggesting ingress into an inorganic formation of water bearing plant debris. On this hypothesis it is also therefore allochthonous. Sub-bituminous coals from Indonesia had vitrinite reflectances up to 0.42%. By way of comparison, an anthracite from Papua in the same study had a vitrinite reflectance of 4.94%.

Continuing with coals from Table 1.1, the sub-bituminous coal from Collie in WA has macerals from the vitrinite and inertinite groups as its major petrographic constituents, with little liptinite [44]. One seam within the central Alberta sub-bituminous coal reserve contains epigenetic pyrite [45], that is pyrite not initially a mineral external to the coal but formed within the coalifying mass by ingress of water containing iron as a solute. The coal from Meghalaya in India displays marked lithotypes (banded structure) and is very high in vitrinite. The Turkish coal has vitrinite reflectances in the range 0.38 to 0.54%. The fact that it is Miocene is consistent with its transitional state as noted: many lignites are Miocene. The Uzbekistan sub-bituminous coal referred to has a vitrinite reflectance of 0.5%. With reference to the coal from BC in the following row, Oligocene is also within the Cenozoic Era. The deposit contains lignite (of huminite reflectance 0.38) and sub-bituminous coal (of huminite reflectance 0.5). The pay of this deposit ranges from 350 m to 550 m in thickness, making it one of the major sub-bituminous reserves of the world.

1.4 Moisture content

Many lignites in the bed-moist state are over 50% moisture by weight. It is stated in [46], where a Canadian sub-bituminous coal was of particular interest, that sub-bituminous coals as mined are often as low as 1 to 6% in moisture. To that is added the fact that some cleaning procedures raise this by as much as 25%. The Powder River Basin in Wyoming is the most important sub-bituminous coal deposit in the world, and therefore has major coverage later in this book. Powder River coal is used on a large scale for electricity generation, and moisture of course involves reduction of calorific value on a simple weight basis. Wyodak is one area within Powder River, and a Wyodak coal is reported as having 29.2% moisture as received in a programme of work into trace element emissions from combustion [47].

From the above it is clear that there can be major amounts of water in sub-bituminous coals and that this is an issue in utilisation. Consequently drying is often required and there are investigations into news means of drying. The major benefit to be expected from drying is expressed by calorific values of 19.3 to 28.0 MJ kg^{-1} for a US sub-bituminous coal in respectively wet and dry states [48].

Reference [46] is concerned with microwave drying of coal from Highvale, Alberta (see Table 1.4 *et seq.*). Conditions were up to 800 W of power at a frequency of 2.45 GHz. The coal was tested in pelletised form and heating rates were 3°C per minute up to a ceiling of 650°C. The plot showing the rate of microwave drying of 30 g of the Highvale coal vis-à-vis conventional drying is striking, displaying total drying under microwave application in time of the order of 200s. Conventional drying can never be total except in the hypothetical limit where it is done under conditions of zero humidity; the moisture in the coal will always equilibrate with that of the atmosphere, giving a non-zero result. The curve in [46] for conventional drying declines to about 10% moisture after time of the order of two hours. This is for convective conditions of drying. In terms of thermodynamics the situation is not simple. Water in macropores in the coal might be treated as if it were simply in a container and sustained convention with dry air expected to remove it. In reality as well as the coal in the smaller (meso- and micro-) pores there is some imbibed in the cross-linked structure of the coal. This the microwaves can remove but not, except under much more vigorous conditions than would be normal, convective drying.

1.5 Calorific values

This topic has been anticipated above in the values given for a US sub-bituminous coal and comments thereon. The mean value across 277 samples of the calorific value of Powder River coal is given in [49] as 8220 BTU per lb ≡ 19.2 MJ kg^{-1}. The mean ash content was 6.4%, making the calorific value on an ash-free basis 20.5 MJ kg^{-1}. A value of 18.22 MJ kg^{-1} has been reported for Collie coal [50] and the same source gives the same value for the recently discovered sub-bituminous coal at Talisker, also in Western Australia.

1.6 Other properties

The **Hardgrove index**, a measure of grindability, has been reported for Collie coals from four seams [51], and for blends of coals from the different seams. Values in the range 48 to 57 were reported for air dried coals. Values were a few percent lower for oven dried coals. (The higher the Hardgrove index the greater the grindability.) Sometimes a value of 50 is seen as that above which grinding will not be the rate-determining step in supply of coal in pulverised form to a furnace [52]. Table 1.3 below gives Hardgrove Indices for a selection of sub-bituminous coals.

Table 1.3 below gives details of some other Hardgrove indices for sub-bituminous coals.

Source of the coal and reference	**Hardgrove index**
La Loma, Colombia [53].	46
Collie, Western Australia [54]. *Power generation from Collie coal is discussed in Chapter 2.*	47–58 Blends of different coals from Collie conformed well to calculated weighted averages of the Hardgrove Index.
Kalimantan, Indonesia [55].	18–21
Alaska [56].	Typically 32.

Table 1.3. Hardgrove indices of selected sub-bituminous coals.

In the work in the first row of the table, the Hardgrove index of the coal was compared with those of biomass pellets seen as substitutes for carbon mitigation purposes. These (which included Miscanthus) gave values in the range 14–29. In the work on Collie coals, experiments were conducted whereby different times were allowed for air drying of raw samples before testing for grindability. There was some randomness of behaviour, and for five different coals from Collie across a moisture content range of 17 to 22% the Hardgrove Indices, on a very scattered plot, varied in the range 46–59. It is noted for the Kalimantan coal [55] that the Hardgrove Index range signifies resistance to grinding. The value given as a typical one for Alaskan sub-bituminous coals is also on the low side.

A Wyodak sub-bituminous coal is reported as having a BET surface area of 50 m^{2}g^{-1} [57]. These and other properties of sub-bituminous coals will be examined for particular examples at later stages of the book.

1.7 Sapropelic coals equivalent to sub-bituminous in rank

A sapropelic coal, in contrast to a humic coal, originates not from peat but from sapropel. Sapropel is formed from freshwater life on a time scale of thousands of years. Like humic coals, sapropelic coals advance along a coalification sequence, and examples of sapropelic brown coals are many. There are also sapropelic sub-bituminous coals called ‘black cannel coal’ [58] or as ‘black subcannel coal’ [59].

An example of occurrence of black subcannel coal, the sapropelic analogue of sub-bituminous coal, is the Colob coal field in Utah [56] where, subcannel coal co-exists with sub-bituminous coal. The bed of black subcannel coal is in a bed of thickness 1.7 m, beneath a sub-bituminous coal layer about half that thickness.

1.8 Application of Hilt’s Law

Hilt’s Law states [60]:

In a vertical sequence at one locality in a coal field the rank of the coal rises with greater depth and the effect is clearly related to the thermal gradient [56]. Returning to the coal deposit at Hat Creek which, as noted, is one of the major sub-bituminous coal reserves of the world, the lignite is on top of the sub-bituminous. For it to have been the other way round would not only have been in contravention of Hilt’s Law but also counterintuitive in the extreme. Nevertheless contraventions are not unknown, for example in Great Britain where decrease in rank with depth has frequently been reported at certain sites within coal fields [61]. A clue can be found by considering the heterogeneity of a deposition in which layers of vegetation undergoing coalification are interspersed with minerals, and the variation in such quantities as thermal conductivities and specific heats which are relevant to the action of the thermal gradient. Hilt’s Law can be tested more precisely by examining vitrinite reflectance as a function of depth within a coal seam.

1.9 Minerals and inorganics

Table 1.4 below, which anticipates some of the major sub-bituminous coal deposits featuring later in the book, gives details of ash-forming constituents for several sub-bituminous coals.

Location of the coal and reference	**Details**
Powder River Basin [62].	A generalised value of the ash content of PRB coals is given in section 3.2 as 6.6%. In [62] elements in the actinide series (e.g. thorium) and in the lanthanide series (e.g. cerium) are identified in PRB coal ash. *See also row 7.*
Wara, South Kalimantan, Indonesia [63].	15.4% ash dry basis.
Highvale, Alberta [64].	16.85% dry basis.
Collie, Western Australia [65].	5.7% as received basis.
An Indonesian sub-bituminous coal [66].	3%
Talcher coal field, India [67].	41–42%
Wyodak (part of PRB) [68]	5.5% as received basis.

Table 1.4. Ash-forming constituents.

Other elements found in the PRB coal ash included uranium and plutonium (actinides), and Europium and Ytterbium (lanthanides). The Wara mine is only 5 km from the Tutupan mine, also yielding coal for power generation, where the coal is bituminous in rank. The Highvale coal has the additional advantage of being only moderate in sulphur. It was mentioned previously in this chapter that Collie coal is used to make electricity. It is burnt as pulverised fuel and the flyash is used in the manufacture of concrete. The work described in [66] (next row) originates in Italy, and the coal was obtained from an ENEL[2] power plant which uses sub-bituminous coal imported from Indonesia. The work in [67] is focused on the highly classical procedures for reducing the ash content of a coal by flotation. In summary, if sufficiently broken up a coal will behave in an aqueous medium of pre-calculated specific gravity in such a way that coals very high in minerals sink, coals low in minerals float and there are 'middlings'. It is claimed in [67] that coal of 26.6% ash can be obtained at 66.5% yield from the coal initially over 40% ash. Wyodak (following row) is part of PRB, and it is encouraging to note that the value given for the ash content of the Wyodak coal is comfortably within the range of ash contents for PRB coals generally given in row 1.

Coal from the ENEL plant was the basis of a study involving co-firing with biomass for carbon mitigation purposes [69]. The biomass chosen was cellulosic ethanol residue (CER), which is what remains when lignocellulosics are broken down into sugars for fermentation. Small samples of blends of this and the Indonesian coal used at ENEL were heat in a thermal analysis unit under a flowing air atmosphere. The temperature corresponding to the maximum weight loss, called the combustion index, did not as might have been expected intuitively increase linearly with the proportion of biomass in the blend. Up to about 20% CER this temperature is fairly steady at about 100°C rising to around 500°C at 100% CER. The ignition temperature is defined as the temperature at which, after moisture loss, the rate mass loss reaches 1% per minute and was 300°C for the coal only dropping monotonically to about 250°C for the CER only. The burnout temperature is defined as that at which, on the declining part of a DTG curve, the mass loss rate returns to 1% per minute. This was about 540°C for the Indonesian coal only, dropping monotonically to a little above 400°C for the CER only. Activation energies were determined numerically from the thermal analysis traces at various degrees of extent of conversion to combustion products (α). They showed a marked decrease with α across the range 0.2 to 0.8, with an average 44.9 kJ mol^{-1} for the coal and 76.6 kJ mol1 for the CER. Up to 20% CER – the highest proportion used – the value is dominated by that for the coal being respectively 44.3, 46.0, 48.6 and 41.1 kJ mol^{-1} 5%, 10%, 15% and 20% CER. These data are seen as providing input to co-firing in a boiler furnace, very common in meeting carbon dioxide reduction targets. The ultimate is of course biomass only, as has happened at the huge Drax power station in England which uses bituminous coal. The CER if just dumped would, as well as being a spontaneous heating hazard, over a time of the order of years decompose, with methane in the products. This is of course a more powerful greenhouse gas than carbon dioxide. There is major 'cellulosic ethanol' production in Italy (its destination being petroleum blends) so this resource would be plentiful and cheap as a fuel for power generation.

1.10 Concluding remarks

This chapter can hopefully be drawn on when such things as power generation from sub-bituminous coals and gasification of them are discussed in the subsequent chapters. We finish the chapter with mention of the term 'semi-bituminous coal' The term was coined in relation to Pennsylvania coals in 1877 [70] as part of a classification based on the ratio of fixed carbon to volatile matter, called the 'fuel ratio'. On this basis a bituminous coal has a fuel ratio of up to 5, a semi-bituminous coal a fuel ratio of 5 to 8, a semi-anthracite a fuel ratio of 8 to 12 and an anthracite a fuel ratio of 8 to 100 [71]. Clearly a semi-bituminous coal is a low-volatile bituminous in today's terminology and is in no way synonymous with sub-bituminous, which has a boundary with high-volatile bituminous. The term was widely used in Britain well into the 20th Century (e.g. [72]) with the same meaning.

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2 Utilisation in power generation

2.1 Introduction

With coals of all rank, power generation is the most important outlet for utilisation. This chapter will therefore cover some major scenes of power generation from sub-bituminous coals on a geographical basis.

2.2 Australia

2.2.1 Callide

Callide coal was introduced in the previous chapter. There are three units: Callide A (120 MW, commencing operations 1965), Callide B (700 MW) and Callide C (810 MW) [1]. The total capacity then is 1630 MW. Only unit C uses supercritical steam at this time. Plate 2.1 shows Callide power station.

Plate 2.1. Callide power station, Queensland. Image taken from: http://www.travelling-australia.info/MainGraphics2004/P045050068Bz-750.jpg

Oxyfuel combustion is under development at Callide [2]. In Oxyfuel combustion burning is in oxygen, making the carbon dioxide more concentrated than in flue gases from air-fuel processes and therefore easier to sequestrate. Callide is in the Bowen Basin, where it is known that some sapropelic materials (see section 1.7) exists [3].

It was noted in the previous chapter that Callide coal was once considered as a standby fuel for electricity generation in Victoria, where locally mined soft brown coal is used. It would have been a suitable substitute for brown coal briquettes for use in start-up, having a calorific value and a hardness comparable to those. The distance from Callide to Melbourne is about 1200 miles yet Callide coal rather than NSW bituminous coal was considered as a contingency fuel. The latter would have been too different from briquetted Victorian brown coal to be used in the power plants of Victoria, and here is an interesting example of the importance of coal rank. A sub-bituminous coal was suitable as a substitute for a lignite under certain circumstances and subject to certain conditions, but not a bituminous coal. The daily newspaper 'The Morning Bulletin' reported in November 1949 that when Callide coal was first evaluated for use in power generation its price had to be compared on a heat basis with that of imported coal.

2.2.2 Collie

This also was described in the previous chapter. The power station there commenced service in 1999, and its nameplate capacity is 340 MW. There is activity into geosequestration of carbon dioxide from Collie and from four other power stations in Western Australia in the South West Hub CCS scheme [4, 5]. The other power stations are Kwinana (420MW from coal, oil and natural gas [6]), Wagerup (380 MW from gas and petroleum distillate [7]), Mandurah (1.4 MW from waste fuels [8]) and Pinjarra (285 MW from natural gas [9]).

Carbon dioxide for sequestration at South West Hub will be in the supercritical state and will enter a saline sandstone aquifer. The critical constants for carbon dioxide are 31.1°C and 73.8 bar (7.38 MPa) [10]. Now the pressure converts to a value in metres of water of:

$$7.38 \times 10^{6}\ \mathrm{Pa}\ (=\mathrm{N\ m^{-2}})/(9.81\ \mathrm{m\ s^{-2}} \times 1000\ \mathrm{kg\ m^{-3}}) = 752\ \mathrm{m}$$

and this is the basis of the rule-of-thumb that aquifer sequestration of carbon dioxide requires depths of 800 m or greater. At the South West Hub trials have been at a depth of 2945 m. The pressure at the base of a column of water of this height would be 29 MPa (290 bar). The phase diagram for carbon dioxide is reproduced in an appendix to this chapter, and from it it is clear that this pressure would maintain supercriticality. Further comments are in the appendix.

2.3 Alberta

The Wabamun power plant in Edmonton has ceased production after 54 years of service [11] and decommissioning is under way. Wabamum coal, which supplied the now defunct facility, is early Paleocene [12], of the order of 55 million Ma, a division of the Tertiary period (see Table 1.1). The coal is rich in huminite and displays lithotypes.

The Genesee power station south west of Edmonton is supplied with sub-bituminous coal from a mine of the same name [13]. Its capacity is 1200 MW from three equivalent steam turbines. The coal as supplied has a calorific value of 17.2 MJ kg^{-1}. The Keephills power plant in Alberta also uses sub-bituminous coal, from the Highvale mine [14]. Across three units it has a nameplate capacity of 1250 MW. Coal from Highvale also goes to the Sundance power station [15]. Having developed in stages since it came into operation in 2009, Sundance now has a capacity of 165 MW[3].

2.4 Indonesia

At the Paiton power station complex in East Java a unit ('Paiton III') came into operation in 2012 which uses sub-bituminous coal from Kalimantan[4] and has supercritical steam [16]. Its capacity is 815 MW. Paiton III uses 400 tons (363 tonnes) of coal per hour [17], a figure which is examined in the shaded area below.

Using a value of 18 MJ kg^{-1} for the calorific value (see section 1.5) and, having regard to the use of supercritical steam, an efficiency of 0.43, the expected rate of power production is:

$$\{[363 \times 10^{3}\ \mathrm{kg\ hour^{-1}}/(3600\ \mathrm{s\ hour^{-1}})] \times 18 \times 10^{6}\ \mathrm{J\ kg^{-1}} \times 0.43 \times 10^{-6}\}\ \mathrm{MW} = 780\ \mathrm{MW}.$$

This is 4% below the nameplate capacity, so the figures hang together.

Paiton III is the first power plant in Indonesia to use supercritical steam.

Also in Kalimantan is the Adaro coal mine, the product of which is sub-bituminous [18]. Production in 2013 was 52.3 million tonnes. Plate 2.2 below shows Adaro coal.

Plate 2.2. Coal from the Adaro mine in Indonesia. Image taken from: http://www.adaro.com/wp-content/uploads/2013/07/cleaner-coal-main.jpg

An agreement was recently made [19] whereby Adaro coal is supplied to an electricity producer in Kalimantan[5] in a quantity sufficient for generation at 200 MW. Adaro coal has the benefit of being low in sulphur. It is also low in nitrogen, an advantage since NO_x emissions from coal-fired plants do have to be controlled. At the temperature of coal combustion, fuel NO_x – that from the fuel's own nitrogen content – is expected to dominate to the exclusion of thermal NO_x which arises, of course, from nitrogen in the air supporting the combustion. Temperatures for thermal NO_x are higher than those expected from combustion of a coal, especially a lower rank coal. Thermal NO_x is more of a problem with natural gas combustion or fuel oil combustion.

Adaro sub-bituminous coal has been imported into Israel, and a study there [20] investigated its firing in a boiler furnace originally designed for bituminous coal. Performance advantages of the sub-bituminous coal over the bituminous previously used were perceived, including lower NO_x, SO_2 and ash. These of course reflect the properties of the particular sub-bituminous and bituminous coals being compared, and the obvious general trend expected from such a substitution was observed: lowering of heat output, therefore of steam and of electricity produced. Often at a power station only some of the complement of pulverisers (see section 1.6) installed will be in use at any one time, and withdrawal from service of one of them for maintenance or repair will not cause disruption to supply. The experience in Israel was that all of the pulverisers had to be used to sustain the thermal output, a further disadvantage arising from the substitution.

2.5 New Zealand

Decommissioned in 1991, the Meremere power station used sub-bituminous coal from the Waikato coal fields. Samples of coal from there have been characterised [21] and vary in appearance from bright to dull. Some samples are banded whilst others are not.

Three other quantities were determined for this coal: the axial and diametric point loads and in anisotropic index. Having units MPa, point loads are frequently determined for minerals. Their determination [22] involves application of a load, and the load sufficient to cause breakage is recorded. If the diametric value is required a sample of length-to-diameter ratio > 1.0 is used. If the axial value is required a sample of length-to-diameter ratio in the range 0.3 to 1.0 is used. In either case the load in units of force is divided by the square of the distance between the clamping points on the tester device which transmit the force to the sample, to give a quantity having units MPa. Waikato sub-bituminous coal by this means gave an axial value of 1.05 MPa and a diametric value of 0.49 MPa. This was compared in [21] with values for materials from the same deposit mainly inorganic in composition. For example, sandstones from the deposit gave axial values in the range 0.79 to 1.27 MPa and diametric values in the range 0.30 to 0.85 MPa. The anisotropic index is simply the axial value divided by the diametric, calculable for the coal as 2.1, the value which is given in [21].

Clearly this point load is a measure of compressive strength and broadly identifiable with it. Close comparisons might require knowledge of conditions and conventions in determinations, which is why standards such as ASTM C349 – 14 are used [23]. Even so one is probably justified in comparing the point load values for the New Zealand sub-bituminous coal with the compressive strength of a Chinese anthracite reported in [24]. This has a compressive strength, depending on the direction of the applied force, in the range 22 to 50 MPa, one and a half orders of magnitude higher than the point load of the New Zealand sub-bituminous coal. (See also Table 9.1 for details of the Buller field in New Zealand.)

2.6 Spain

The sub-bituminous coal of Teruel is used in electricity generation at the power plant of the same name, where it is blended with bituminous coal [25]. The capacity of the power station across several units is 1075 MW. Teruel coal, which is Early Cretaceous, has the disadvantage of being high in sulphur: six samples from different parts of the Teruel mining zone when examined [26] had sulphur contents in the range 6.0 to 14.9% [25]. Vitrinite reflectances were in the range 0.53 to 0.76%. Coals at the high end of the sulphur content range are avoided in utilisation and there is flue gas desulphurisation at Teruel power station. The high sulphur is due to there having been gypsum ($CaSO_4$) in the deposit. In general, sulphates can be reduced to sulphur in lower oxidation states including H_2S in the coalification milieu. This in turn can react with the organic material originating from the vegetation to form organic sulphur structures analogous to thiols. If iron is present amongst the inorganics pyrite (FeS_2) can be formed from sulphur having initially been in sulphate form.

Imported Indonesian sub-bituminous coal is used at a power plant in northern Spain [27]. The coal is low in ash at 2.7% and has a carbon content on a dry basis of 76%.

2.7 South west USA

The Cholla power plant in Arizona uses sub-bituminous coal from the McKinley mine in New Mexico, as well as some bituminous coal [28]. Its installed capacity is 995 MW across four non-equivalent units [29]. Sub-bituminous coal is also used at the following power plants in Arizona and New Mexico: Apache AZ (506 MW from a mix of sub-bituminous coal and natural gas), Coronado AZ (810 MW), Four Corners AZ (2040 MW), San Juan NM (1808 MW) and Springerville AZ (1750 MW). The largest then is Four Corners, which obtains its coal from the Navajo Mine. That part of Arizona is called Black Mesa, and it was noted over a century ago that the coal there is Cretaceous [30].

The San Juan power plant receives coal from a mine of the same name, of which it uses 6 million tons (5.4 million tonnes) per year [31]. Parts of the San Juan reserve contain coal having ascended in rank to bituminous [32]. Springervale obtains its coal from North Antelope Rochelle Mine, which is within the Powder River Basin (PRB). PRB coal is the subject of a later chapter. Coronado obtains coal partly from PRB and partly from McKinley [33]. The Apache power plant burns partly PRB coal and partly coal from Lee Ranch in New Mexico, both sub-bituminous [34]. Annual production at Lee Ranch is 5358749 short tons (4.86 million tonnes), and it is operated by Peabody. Navajo power station, also in Arizona, uses not sub-bituminous coal but bituminous, sourced at the local Kayenta mine [35].

2.8 Other regions using sub-bituminous coals in power plants.

These are given in Table 2.1 below, which is followed by comments.

Place.	Details.
Taiwan	Taichung power plant at 5.5 GW (ten 550 MW units) capacity. Both sub-bituminous and bituminous coal. Sub-bituminous coal is bought from Indonesia [36].
Chelyabinsk province of Russia.	Troitskaya power station: 2059 MW using sub-bituminous coal [37].
Malaysia	Janamanjungs Stesen Janakuasa Sultan Azlan Shah power plant: 2250 MW using imported sub-bituminous coal from Kalimantan [38].
Thailand	A 660 MW facility using imported sub-bituminous and bituminous coal [39].
Hong Kong.	Castle Peak power plant: 4180 MW. Fuel includes sub-bituminous coal imported from Indonesia [40].
South Korea.	Samcheok power plant: a circulating fluidised bed (CFB) facility to co-fire sub-bituminous coal with biomass. Coal imported from Indonesia [41].
India.	Power station at Orissa with two 2110 MW units using sub-bituminous coal [43].
Pakistan.	Sub-bituminous coal at Balochistan. Utilisation in electricity production hoped for: power generation in the region currently inadequate [44].
Chile.	370 MW from the Santa Maria power plant [45]. A second 350 MW unit planned.
Malaysia.	Bituminous and sub-bituminous coals used at the Tanjang Bin power plant (2244 MW) [46]
New South Wales.	Eraring power station (2880 MW), using sub-bituminous coal from the nearby Myuna mine [47].
Denmark.	Trials with an Indonesian sub-bituminous coal at a 600 MW unit [48].
Argentina.	Sub-bituminous coal used at the 240MW Rio Turbio power plant as the sole fuel [49].
Brazil.	Sub-bituminous and bituminous coal from the Rio Grande do Sul and Santa Catarina coal fields used at several power plants in the south of the country [50].
The Philippines	Sub-bituminous coal from Semirara Island, the Philippines, mined [51] for power generation at levels of up to hundreds of MW. Coals from the Island vary in vitrinite reflectance from 0.36 to 0.46%, and in ash content from <5% to > 30%.
Japan.	5 to 6 million tonnes imports of sub-bituminous coal in 2012 [52]. Some from Adaro (see section 2.4).

Table 2.1. Examples of electricity generation from sub-bituminous coal.

The Taichung Power Plant (first row) is the largest coal-fired power plant in the world. The Troitskaya power station, which is close to the border between Russia and Kazakhstan, uses supercritical steam as does the Malaysian facility in the next row. In Thailand (following row) import from Indonesia of sub-bituminous coal for power generation is expected to increase, and new power plants are to be sited near the sea for ease of transfer of coal. By row five of the table, the trend whereby Asian countries import sub-bituminous coals from Indonesia is becoming very clear. Such countries have organised themselves into the Asian Sub-bituminous Coal Users' Group, and this met in Bangkok in October 2015[7]. It was first set up by CLP Power Hong Kong, who operate Castle Peak. Similarly the South Korean entry in the following row features imported Indonesian coal. The Łagisza Power Plant in Poland has a circulating fluidised bed similar to the one at Samcheok [42]. It uses bituminous coal, although in the costing this was compared with Indonesian sub-bituminous coal. The Indonesian coal was assigned a calorific value of 20.6 MJ kg^{-1} in the study, and the bituminous a value of 25.2 MJ kg^{-1}. The power plant at Odissa uses coal from the Talcher field, where there is bituminous coal as well as sub-bituminous[8]. The Santa Maria power plant in Chile came into service only in 2012, and local sub-bituminous coal has been compared for performance with bituminous. The Tanjang power station in the following row burns either bituminous coal or bituminous blended with up to 30% of sub-bituminous.

Eraring (next row) is exceptional amongst the coal-fired power plants of NSW in that it uses sub-bituminous coal, not bituminous. Myuna is in the Sydney basin, where most of the coal **is** bituminous. Some coal from the Rio Turbo mine (row 13) is used at the San Nicolas power plant in Buenos Aires. San Nicolas also uses fuel oil and natural gas. Rio Turbio is a new facility.

Japan uses coals – sub-bituminous and other ranks – in power stations. One would not imagine total reliance on coal as Japan is very heavily capitalised with oil refineries, residual material from which will provide for some power generation. An example of a power station in Japan using sub-bituminous coal is the Hitachinaka Thermal Power Station, belonging to the Tokyo Electric Power Company [53]. It comprises two units, as shown in the plate on the following page. Unit 2 only uses sub-bituminous coal in a 50% blend with bituminous, unit 1 a 30% blend. Expansion of the power station from one unit to two was a contingency measure after the 2011 earthquake. It is pointed out in [53] that 50% is a very high proportion of sub-bituminous coal in a blend with bituminous for power generation: 25% sub-bituminous is in general more common in such blends [54].

Both units at Hitachinaka produce 1000 MW of electricity, with 2870 tonne per hour of steam in turbine entry, and steam in the condition 250 bar and 600°C. From [55] the specific enthalpy of steam in this state can be found as 3493.5 kJ kg^{-1}. In the limit where on turbine exit the the fluid is liquid water at 30°C its enthalpy is 314 kJ kg^{-1}. These figures are examined below.

Plate 2.3 Hitachinaka Thermal Power Station, Japan. Image taken from [53].

The heat in per second is then:

$$(2870 \times 10^{3}/3600)\ \text{kg s}^{-1} \times (3493.5 - 125.7)\ \text{kJ kg}^{-1} \times 10^{-3} \times \text{MJ kJ}^{-1} = 2684\ \text{MJ}.$$

The efficiency is then:

$$(1000/2684) \times 100\% = 37\%$$

The above is reasonable though on the low side for steam in such condition, and the potential source of error is the assumption of the fluid condition on turbine exit. This point will be examined. Imagine that the fluid on exit is not liquid water not at 30°C but at 60°C. The specific enthalpy of the exit fluid is then, from steam tables:

$$(2870 \times 10^{3}/3600)\ \text{kg s}^{-1} \times (3493.5 - 251.2)\ \text{kJ kg}^{-1} \times 10^{-3} \times \text{MJ kJ}^{-1} = 2584\ \text{MJ}$$

and the efficiency becomes 39%. Also to be considered are turbine details, including whether there is re-heating.

It has been noted [56] that Japan has recently bought less Australian bituminous coal and more Indonesian sub-bituminous.

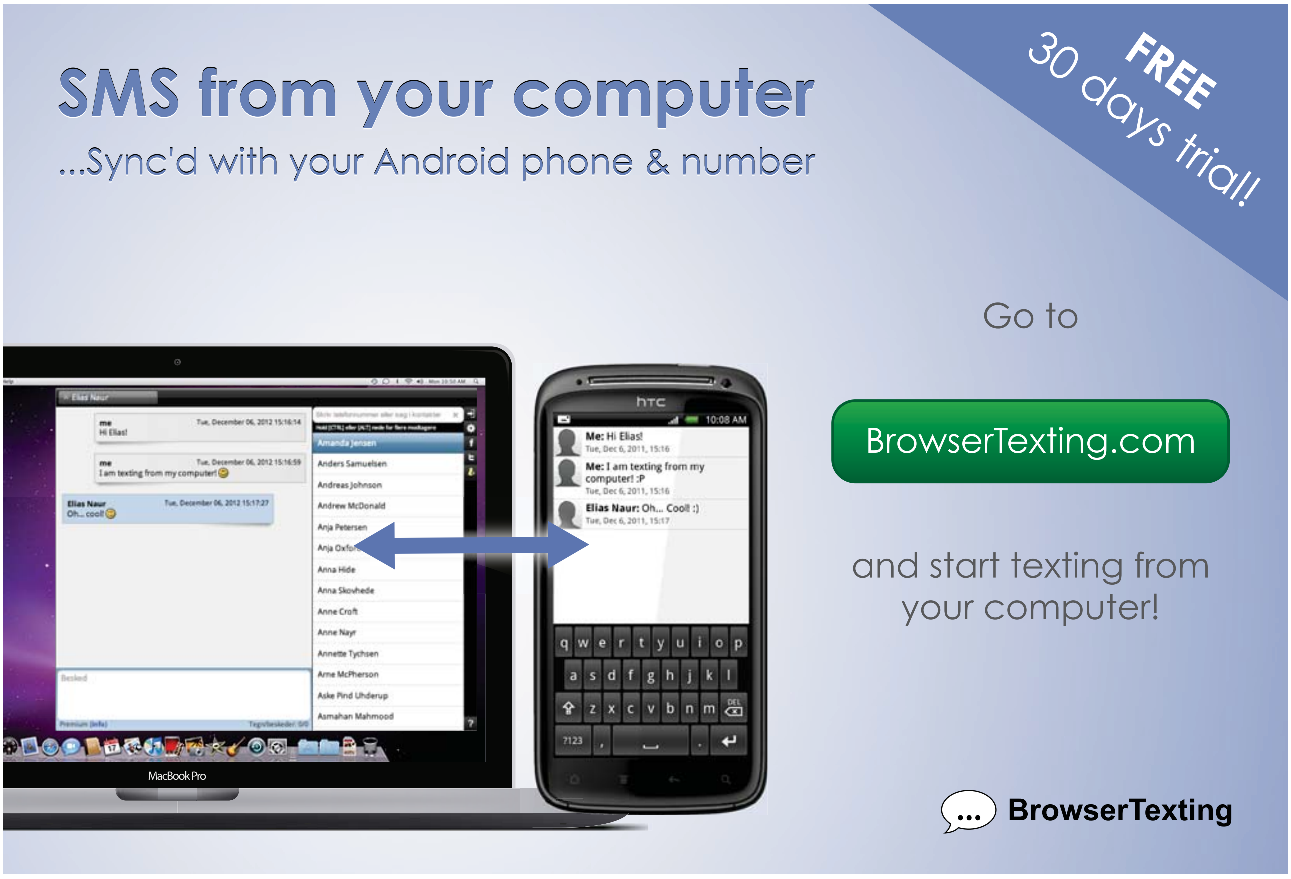
2.9 Flyash (a.k.a. Pulverised fuel ash)

In electricity generation using coal as pulverised fuel it is intended that the ash will be conveyed as particles of micron size or smaller with the flue gas for removal by electrostatic precipitation. If the ash shows a propensity to fusion this might not be so, the ash instead consolidating and depositing on surfaces. A high ash fusion temperature is therefore as plus for a coal intended for this application and the ash fusion temperature can be resolved into softening temperature (a self-explanatory term) and hemisphere temperature (the temperature at which the surface tension of the molten ash causes it to have a hemispherical shape). Ash fusion temperatures for a New Zealand sub-bituminous coal have been reported. In oxidising atmospheres and without any pre-treatment of the ash, the softening temperatures and hemisphere temperatures were in the range respectively 1150 to 1280°C and 1170 to 1300°C.

Ash fusion temperature information for a number of other sub-bituminous coals is given in Table 2.2 below.

Origin of the sub-bituminous coal and reference.	Ash fusion temperature/°C.
India [57].	1380 to 1430 (Hemispherical).
Bulgaria (two distinct sub-bituminous coals) [58].	1420 and 1535 (Hemispherical).
Jacob's Ranch[9], Wyoming [59].	1210.

Table 2.2. Ash fusion temperatures.



2.10 Further comments

The contribution made by sub-bituminous coals to the electricity supply of the world is major. Powder River coal is so dominant in this that it is treated in a separate chapter, which follows.

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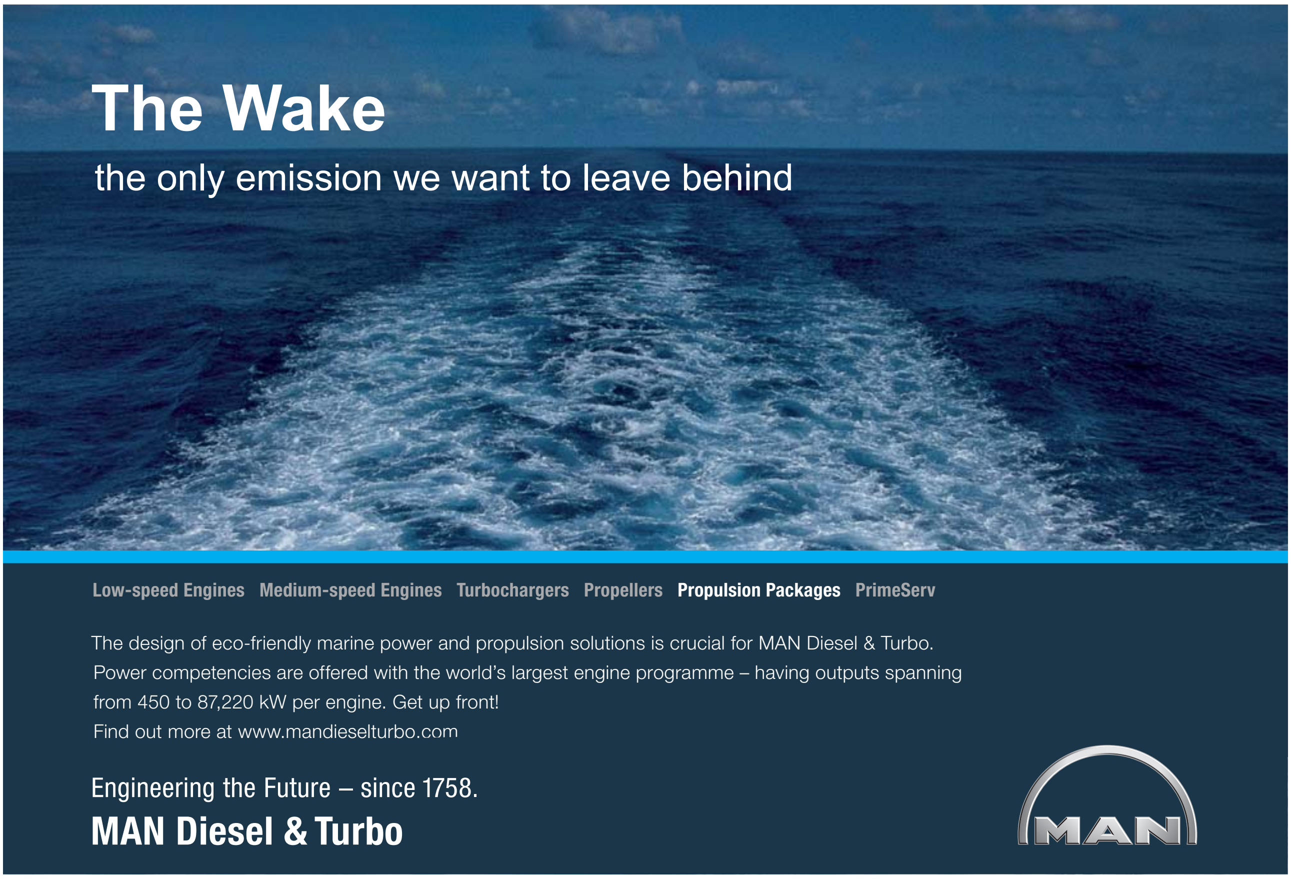
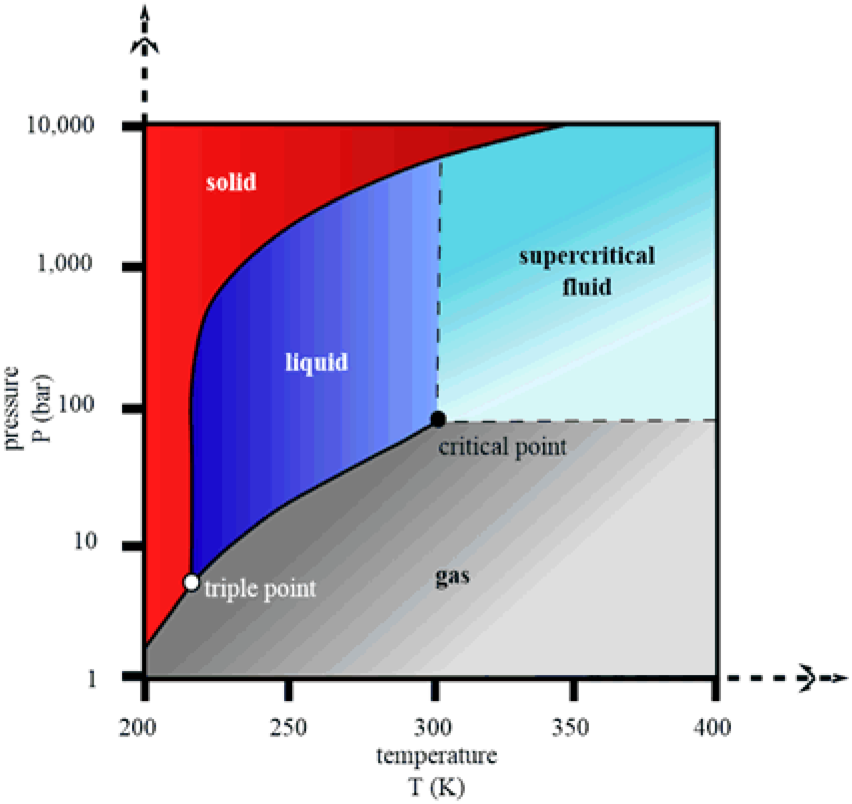


2.12 Appendix to Chapter 2

Phase diagram for carbon dioxide, showing the supercritical region.



Additionally to the content of section 2.2.2 of the main text the following should be noted. The boundary for the supercritical state is almost vertical, indicating that the temperature must be maintained at or above the critical temperature of 31.1°C for the carbon dioxide to remain in the supercritical region of the phase diagram. This is provided for by the natural thermal gradient of the earth's crust, which in addressing this issue specifically is given in the work cited below as 25°C per 1000 m depth. The 2950 m depth of the well at South West Hub would on this basis provide for a temperature 74°C above the surface temperature, or an actual temperature of 74°C for outside conditions at freezing. That would ensure maintenance of supercritical conditions.

The above figure for the temperature gradient within the earth is perfectly general. The source drawn on was chosen because it is an application to supercritical carbon dioxide.

The model for aquifer pressure invoked here – treating it as a column of water of height equivalent to the aquifer depth – requires good *hydraulic connectivity* between the surface water and the aquifer [1].

The term ultra supercritical does not have a precise meaning in thermodynamics: it simply means 'very highly supecritical'. Nevertheless the term is used in power genetration and use of ultra-supercritical steam requires construction materials capable of withstanding the conditions. Ultra-supercritical plants are by now fiarly common with lignite-fired power generation, less so with sub-bituminous. An example of a sub-bituminous power plant using ultra supecritical steam is one in south east USA [2].

In Chapter 9 sub-bituminous coal in Vietnam is discussed. Mitsubishi Research Institute in a pdf document accessible online present figures for proposed ultra-supercritical power generation with this and aim at 44.5% efficiency with steam at 24.5 MPa (245 bar) at 600°C. A reader can easily ascertain that that is outside the co-ordinates of the phase diagram above, justifying 'ultra'!

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3 Powder River Basin coals

3.1 Introduction

The Powder River Basin (PRB) crosses the state border between Wyoming and Montana. Plate 3.1. below shows the location of PRB and also shows the destinations on the domestic market of coal produced there.

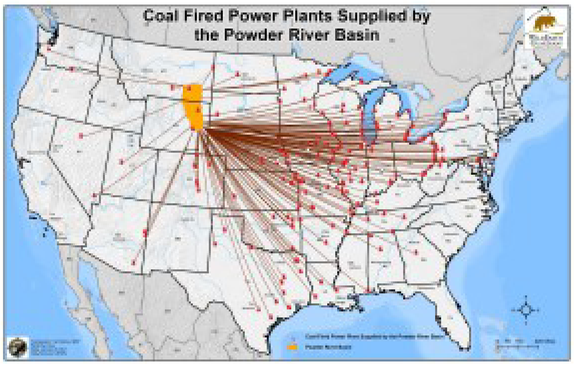


Plate 3.1. Map showing PRB and sales destinations of coal therefrom. Image taken from [1].

PRB occupies an area of over 61000 square kilometres [1]. Production in 2012 was 462 million short tons (419 million tonnes) of sub-bituminous coal [2]. The coal, which is low in sulphur, accounts for 40% of the total coal production of the US.

3.2 Characteristics of PRB coal

The coal is sub-bituminous as noted[10]. The calorific value of PRB sub-bituminous coal is given in [3] as 8683 BTU $lb^{-1} \equiv 20.3$ MJ kg^{-1}. Its analysis figures on a dry basis are moisture 23.8%, ash[11] 6.6% and sulphur 0.4%. Not only is the sulphur low, but the inorganic content is high in calcium oxides and this enables such sulphur oxides as are formed in combustion to be trapped in the ash. A Hardrove Index for PRB coal of 60 has been reported [4].

3.3 Mines at PRB

There are sixteen such, and they include the Calabo mine near Gillette in Campbell County WY, which is operated by Peabody [5]. Production there in 2013 was 9 million short tons (8.2 million tonnes). A study of variation of vitrinite reflectances of PRB coals [6] has revealed values in the range 0.32% to 0.64% for those in the Gillette coal field. There are also the Rawehide and North Antelope mines fairly close to Gillette, both operated by Peabody.

The Absaloka Mine is across the border to the north, in Powder River County MT, as are the the Spring Creek and Decker mines. As the border is approached and crossed, vitrinite refelectances of the coal drop to a fairly uniform value of ≈ 0.38%. The indication is that coal from this part of the basin is of lower rank than that from close to Gillette, although it is all sub-bituminous. Other mines at PRB include Belle Ayr, Black Thunder and Buckskin (all WY).

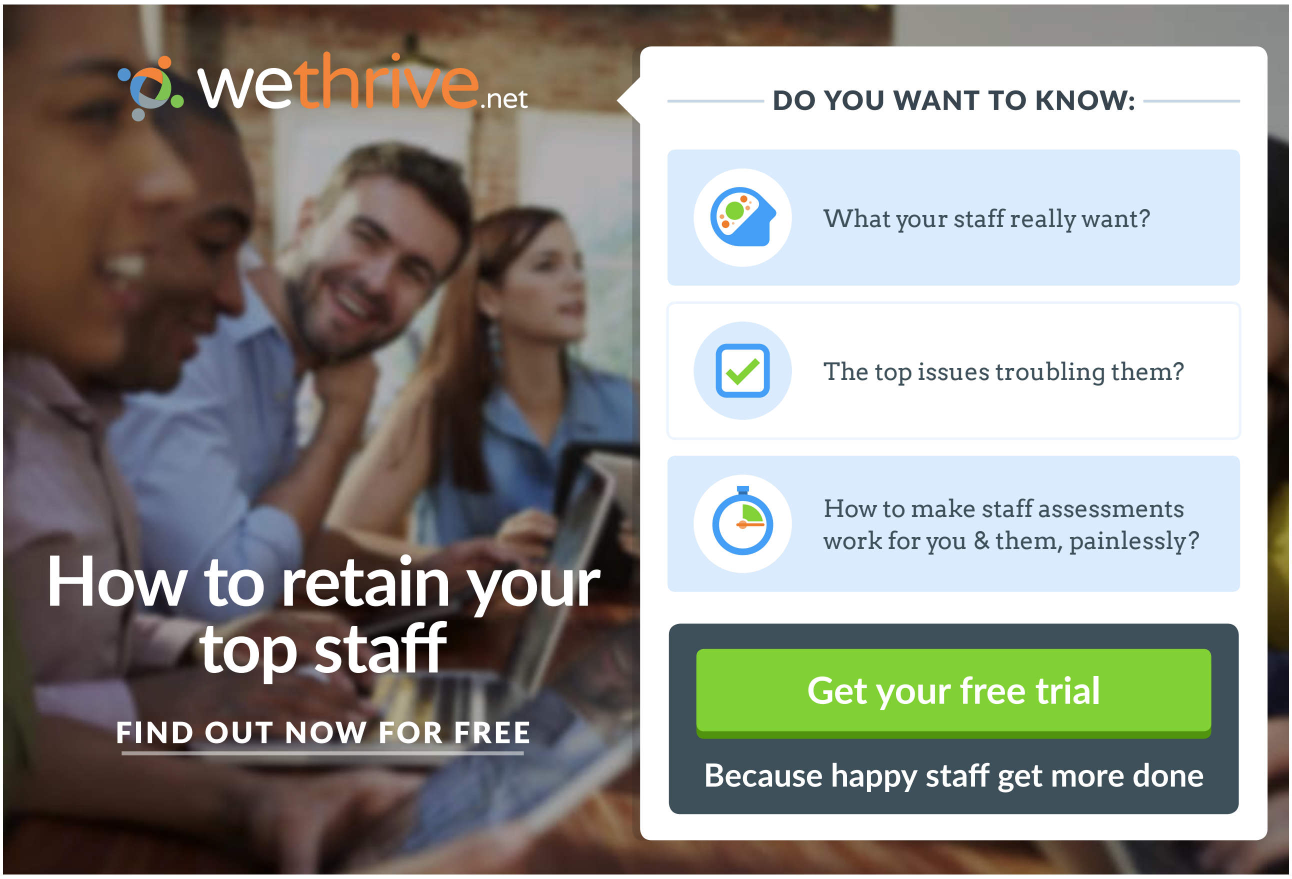
3.4 Power plants using PRB coal

These are listed by state in Table 3.1 below, which is followed by comments. This list is believed to be close to complete.

State	Names of the power plants capacities
WY[12]	Laramie River [7]: 1710 MW from three units all using PRB coal. Dry Fork [8]: 385 MW from one unit using PRB coal.
ND	Stanton [9]: 190 MW. Operated by Great River Energy.
MI	Eckert [10]: 351 MW from PRB coal. Erickson [11]: 155 MW from PRB coal. Monroe [12]: 3300 MW from PRB coal. Presque Isle [13]: 431 MW from PRB coal. St. Clair [14]: 1547 MW from PRB coal.
MO	Sikeston [15]: 235 MW from PRB coal.
WA	Centralia [16]: Local coal supplemented by PRB coal. Three units, two using coal and one natural gas. Total capacity 1340 MW.
LA	Big Cajun II [18]: PRB coal from the North Antelope Rochelle mine in particular. 1700 MW.
MD	Charles P. Crane [19]: 400 MW between two units from PRB coal.
AR	Flint Creek [20]: 528 MW from PRB coal. Independence [21]: 850 MW from PRB coal. White Bluff [22]: 1480 MW with PRB coal as the primary fuel.
MN	Allen S. King [23]: 560 MW from a blend of 90% PRB coal and 10% petroleum coke as the fossil fuel component, and some wood to provide for carbon mitigation. Sherburne County [24]: 2222 MW across three units from PRB coal.
IN	Rockport [25]: 2620 MW between two units with PRB coal as the primary fuel.
NE	North Omaha [26]: 5 × 625 MW units using PRB coal.
WI	Pleasant Prairie [27]: 1233 MW from PRB coal. Edgewater [28]: 770 MW from PRB coal.
CO	Arapahoe [29]: 56 MW from PRB coal. Pawnee [29]: 552 MW from PRB coal. Comanche Station [29]: 660 MW from PRB coal.
GA	Robert W. Scherer [30]: 4 × 880 MW from PRB coal.
IL	Newton [31,32]: 1151 MW between two equivalent units from PRB coal.
AL	James H. Miller [33]: 2822 MW from PRB coal.

KS	‘Jeffrey Energy Center’ [34]: 2155 MW from PRB coal. ‘Lawrence Energy Center’ [34]: 530 MW from PRB coal.
TX	Fayette [35]: 1690 MW with PRB coal as the primary fuel. Harrington [36]: 1018 MW with PRB coal as the primary fuel. J. Robert Welsh [37]: 1584 MW from three equivalent units using PRB coal. Tolk [38]: 1080 MW from PRB coal. W.A. Parish [39]: Four units using natural gas and four using PRB coal. Limestone [40]: 1614 MW from PRB coal and Texan coal. Big Brown [41]: 1150 MW from PRB coal and Texas lignite. Monticello [42]: 1880 MW from PRB coal and Texas lignite. Martin Lake [43]: 2250 MW from PRB coal and Texas lignite.
Ontario, Canada.	Nanticoke [44]: 4512 MW partly from PRB coal. Thunder Bay [45]: 326 MW from Canadian lignite and PRB coal.
Manitoba, Canada.	Brandon [46]: 333 MW from PRB coal and natural gas.
West Yorks., England.	Drax: trials at blending PRB coal with local bituminous coal.

Table 3.1 Power plants using PRB coal.



The Laramie River and Dry Fork power stations are both operated by Basin Electric Power Co-operative. The Stanton station in ND has sometimes used PRB coal and sometimes North Dakota lignite. This is the only recipient in North Dakota of PRB coal, so at any particular time there might be nil purchase of PRB coal in North Dakota notwithstanding its fairly close geographical location. The Eckert power station (following row) near Lansing, Michigan has been in service since the 1950s and is seen as an aging facility. The Monroe power plant, also in Michigan, has had major modernisation to reduce emissions. PRB coal for the Presque Isle facility is conveyed by ship via Lake Superior. Consumption of PRB coal at Sikeston in Missouri is 1 million short tons per year. The interested reader can easily perform a calculation like that in section 2.4 to show how this is consistent with the nameplate capacity of 235 MW.

The 'local coal' referred to in the entry for Washington State is from the Centralia mine and is also sub-bituminous [17]. The Big Cajun II plant in Louisiana (next row) one of the units is to be converted to natural gas, a readily available commodity in that state. Conversely, both units at Charles P.Crane (next row) were originally fired with fuel oil. The power plants under the entry for Arkansas in the next row have a combined capacity of 2.9 GW, representing major capitalisation. Note that petroleum coke is used in a blend with PRB at the Allen S. King plant in Minnesota. This of course is obtained from refineries, and in Lousiana it is co-fired with lignite in power generation. At Rockport Indiana, following row, supercritical steam is used. The North Omaha plant in Nebraska originally used bituminous coal. Sometimes when there is a change from a higher rank coal to a lower one the nameplatae capacity of a power plant is reduced ('derating'), but at North Omaha the transition took place without such a penalty. The three power plants in the entry for Colorado use PRB coal solely. There are other coal-fired plants in the state which use coal mined in Colorado. The Robert W. Scherer power plant in Georgia receives coal from PRB by railroad. With reference to the Newton power plant in Illinois, dissatisfaction has been expressed that it does not support the local coal industry by using Illinois coal [32]. A move to this would involve installation of flue gas desulphurisation (FGD), not required when low-sulphur PRB coal is used. The Lawrence Energy Center in Kansas did not initally use PRB coal, but was modified to do so. The very heavy utilisation of PRB coal in Texas is clear from the following row. From the next two rows it is evident that major amounts of PRB coal have found their way across the border with Canada.

3.5 Exports

We saw in the previous chapter how many Asian countries import sub-bituminous coal from Indonesia. In 2012, 3.213 million tons of PRB coal were exported repesenting 10% of the total coal exports of the USA [47]. A major proportion went to China. The low sulphur is the motive for purchase by China, which of course has abundant coal of its own though the production infrastructure is well sub-standard. Exports of PRB coal from the west side of the US via the Pacific Ocean have been precluded by the absence of facilities there for loading the coal on to ships [48].

3.6 Pricing

Factors influencing most strongly the price of a particular coal are calorific value and sulphur content. On US markets these are expressed respectively as BTU per lb and on sulphur dioxide production in lb per lb of coal burnt. Having regard to the fact that the molar mass of sulphur dioxide is twice that of elemental sulphur, this is twice the sulphur content of the coal. Below are June 2015 prices for US coals including PRB taken from [49]. The first number in each entry is the calorific value in BTU lb^{-1} and the second the lb sulphur dioxide produce per lb coal burnt. Because the molar mass of sulphur dioxide is exactly twice that of elemental sulphur, this figure is twice the sulphur content of the coal on a fractional basis.

That PRB coal is very cheap is clear from the comparison. Its low price in some degree is due to its restriction to thermal use: being sub-bituminous it is not suitable for use as a coking coal. This also reduces potential export markets. It was pointed out in the previous section how PRB coal in huge quantities is transported major distances within the US, for example to Texas. This is made possible by the low purchase price.

Central Appalachia[13]: 12500 BTU lb^{-1}. 1.2 lb SO2 lb^{-1} coal burnt.	Northern Appalachia[14] 13000 BTU lb^{-1}. <3.0 lb SO2 lb^{-1} coal burnt.	Illinois Basin: 11800 BTU lb^{-1}. 5lb SO2 lb^{-1} coal burnt.	Uinta Basin[15]: 11700 BTU lb^{-1} 0.8 lb SO2 lb^{-1} coal burnt.	PRB: 8800 BTU lb^{-1}. 0.8 lb SO2 lb^{-1} coal burnt.
$52.75 per short ton.	$58.75 per short ton.	$40.45 per short ton.	$39.20 per short ton.	$11.55 per short ton.

3.7 The Powder River Basin Coal Users' Group

The remit of this is to provide 'the safe, efficient and economic use of PRB coals…' [50]. It was first formed in 2000. It recognises meritorious activity by organisations using PRB coal by making awards. For example, the Harrington power plant (fifth row from the bottom of Table 3.1) received such an award in 2013. The citation mentioned *inter alia* the economic use of water at the plant.

3.8 Calculated estimates of amounts

A rule sometimes used is that a sub-bituminous coal deposit contains 1770 tons[16] per acre-foot [51]. One acre foot of coal is that occupying the space enclosed by one acre of surface and one foot depth. The acre-foot is clearly a unit of volume and is equal to 1233 m^3. These figures are applied to PRB in the shaded area below.

The figure of 1770 tons per acre-foot converts to 1.44 tons per cubic metre.

The area of the PRB was given earlier in the chapter as 61000 square kilometres. The total amount of coal in PRB, by no means all of which could be extracted by present-day mining methods, has been estimated by the USGS as 1.16 trillion tons [52]. A single coal seam representing the entire basin would have a thickness:

$$1.6 \times 10^{12} \text{ tons}/(1.44 \text{ tons m}^{-3} \times 61000 \times 10^{6} \text{ m}^{2})$$

$$= 18 \text{ m (60 ft.)}$$

Coal seam thicknesses of this value and higher – 'up to 100 ft' is reported for part of southern PRB [53] occur and the calculation has delivered only a semi-quantitative result.

3.9 Ash fusion temperatures

This topic was introduced in section 2.9, where its significance was explained. A value of 2160°F (1182°C) has been reported for a coal from the Spring Creek mine in the PRB [54]. Jacob's Ranch, which features in the table of ash fusion temperatures in Chapter 2, is also in PRB.

3.10 Conversion to liquid fuels[17]

There is limited research activity into the conversion of PRB coals to liquids including a recent investigation involving Wyodak coal [55]. Catalysts were iron II carbonate and sodium carbonate singly and together, and pyrolysis/gasification of the coals in an atmosphere of nitrogen or of nitrogen and water. Gasification was at 800°C and was partial, there being char as a side product as well as low molecular weight hydrocarbon gases. Tars – possibly the most important class of product in work directed at liquefaction –varied in aliphatic:aromatic ratio with different catalysts. This was seen as one of the important findings of the work: it means that catalyst composition can be varied to give tars, the precursor to synthetic oils, a particular desired aliphatic:aromatic carbon ratio influencing such factors as the API Gravity and the viscosity.

Obviously oil made from coal is not carbon neutral, and one might legitimately wonder what is the incentive to make oil from PRB coal. Quite simply it is the superior combustion hygiene of most oil burners over coal ones, at least over a transitional period whilst coal burning is reviewed and redeveloped in the light of events and requirements over the last fifteen or so years. The huge expanse of terrain comprising PRB does in fact contain some conventional crude oil which has been drilled for and raised. There is a return to the matter of conversion to liquids in Chapter 11.

3.11 Further remarks

This chapter has dealt with the enormous contribution made by PRB coal to the electricity demand of North America. Other aspects such as gasification of PRB coal will be dealt with in subsequent chapters alongside coverage of such topics for sub-bituminous coals from other sources. In spite of the huge amount of lignite used in power generation in the USA, the proportion of lignite to sub-bituminous coal mined in 2010 was 0.11. The Powder River resource has clearly strongly affected this proportion. Production of liquid fuels from PRB coals is discussed in a later chapter.

3.12 Possible carbon sequestration at PRB

There is major CBM production at PRB. In a quiescent coal field conditions of methane retention in the pores are close to equilibrium, but not during CBM production and especially not towards the end of a CBM recovery operation. If carbon dioxide is at this stage injected into the coal bed, being denser than methane (by a factor of 44/16 = 2.75) it displaces further methane in a fashion analogous to enhanced oil recovery. As a very significant bonus the carbon dioxide itself becomes adsorbed on to the coal, so carbon dioxide sequestration and improved CBM recovery become a combined operation [56]. This is not yet a reality at PRB but has been investigated with Wyodak coal [57] and estimates have been made of the degree of CCS which could accompany CBM production at Wyodak. In evaluating such operations a simple fact of thermodynamics is relevant and has to be carefully considered: if a CO_2 molecule is to replace a CH_4 one at a particular adsorption site it is not a simple exchange, as heats of adsorption of the two gases will be different. A related calculation follows as an appendix to the chapter. Safety issues at PRB are discussed in Chapter 11.

3.13 Chemical and petrographic features of selected PRB coals

Certain PRB coals are studied along these lines in [58] and important findings are as follows. Coal from the Wyodak-Anderson bed is believed to have originated from dome-shaped peat depositions ('raised peat'), where the coalification process was initiated by conversion of the humic acids. ('Peat domes' are commonly observed in the landscape of countries including England.) There is volcanic ash present at Wyodak-Anderson; constituents enabling the ash to be so classfied include quartz and zircon, and higher than usual amounts of the elements phosphorous, niobium, strontium, barium and zirconium. Additional to Wyodak-Anderson is the Anderson-Dietz coal bed some kilometres further west, and coal samples from here were in the main low in ash. Two particular macerals in the vitrinite group – detrogelinite and corpohuminite – were found the be prevalent at Anderson-Dietz. The former is a gellified maceral, having lost its woody nature through an intermediate colloidal existence. The Anderson-Dietz bed had been the subject of an earlier study [59] in which macerals in all three groups – huminite (a.k.a. vitrinite), liptinite and intertinite – were identified. Huminite is the most abundant group at Anderson-Dietz (>85%). A moderately plentiful representative of the huminite group is sporinite (up to 6%). Often in coal analysis generally the proportions of organic and inorganic ('pyritic') sulphur are of interest in utilisation, and this point is examined for Anerson-Dietz in [59]. For 33 samples examined the pyritic sulphur was lower than the organic, up to about 1 and 2% of the dry coal weight respectively. Interstingly, pyritic plotted against organic gave an impressive positive correlation with coefficient 0.87.

3.14 Minor inorganic constituents

The following have been detected at trace element level in ash from PRB coal [60]: Cerium, Europium, Holmium, Lanthanum, Lutetium, Praseodymium, Promethium, Samarium, Terbium, Ytterbium, Actinium, Thorium, Uranium, Plutonium, Berkelium, Californium [60]. Several of these would not even have been known to the devlopers and early operators of PRB, for example Berkelium (discovered 1949) and Californium (discovered 1950). The fact that these are 'synthetic' elements observed only as a result of nuclear reactions has been raised as a point of criticism [61] as has the fact that the total known amount of Promethium in the earth's crust is of the order of half a kilogram.

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3.16 Possible carbon sequestration at Wyodak

The study in [57] releates to a 4.8 km × 4.8 km area (about 9 square miles) of Wyodak-Anderson and carries the recommendation that there be one injector per square mile, so nine injectors. The datum is given that one such injector could enable 0.658 million tons of CO_2 to be injected in 20 years. (The 20 year reference time is probably based on payback time considerations.)

Converting to an annual basis and equating tons to tonnes for the purposes of an approximate calculation such as this, about 300000 tonnes per year of carbon dioxide could be injected through the nine injectors collectively. Wyodak coal is about 50% carbon on an as-fired basis [1], so this amount of carbon dioxide would be produced by the utilisation of:

$$300000 \times (12/44) \times 2 \text{ tonnes of the coal} \approx 150000 \text{ tonnes}$$

of the coal. In supercritical plant this would raise around 10^{15}J of electricity annually or ≈ 0.25 billion kWh. This is over a minuscule area of terrain and would offset the carbon dioxide from 30 MW of round-the-clock poduction with Wyodak coal.

Reference

[1] https://www.ecn.nl/phyllis2/Biomass/View/2203

4 Briquettes

4.1 Introduction

The compression of coal into pieces of regular shape – briquetting – sometimes requires a binder, sometimes not. Lignites, of lower rank than sub-bituminous coals, have over the years since the late 19th Century been used in this way, although there is a notable slump in the lignite briquettes market at this time. Briquettes production for sub-bituminous coals will be reviewed in this chapter.

4.2 Examples

These are given in Table 4.1 below, which is followed by comments.

Origin of the coal and reference.	Details.
Powder River Basin [1].	Available with or without blended biomass. Calorific value up to 25.2 MJ kg^{-1}.
Tono, Washington State [3].	Briquette production from slacks.
South Australia [4].	Application of the patented BCB Process – Binderless Coal Briquetting – on a trial basis.
Collie, Western Australia.	See comments on the main text.
Kalimantan, Indonesia [7].	Briquetting factory at Tabang.
Waikato, NZ [9].	Slacks tested for briquetting. Results without a binder disappointing.
Mongolia [11].	Briquetting of sub-bituminous coal from the Nuurst deposit.

Table 4.1. Briquettes from sub-bituminous coal.

The reason for incorporating biomass into a coal briquettes is of course that that component is carbon-neutral. It was noted in Chapter 3 that PRB coal is transported long distances by rail, and if the coal is moist part of the transportation cost goes to transporting the water! This point is made very strongly in [2] where, with PRB as an example, subsitution of briquettes with their lower water content is advocated. Of course there would be further issues to be addressed including the grindability of the briquettes in comparison with that of the unprocessed coal. The next entry in the table introduces an important point: that 'slacks' or 'fines' created in coal handling can be made into briquettes. Not only are fines and slacks without treatment unacceptable to purchasers of coal, they also exacerbate spontaneous heating hazards. For them to be made use of in this way is therefore very beneficial. In the work described in [3] an asphalt binder was used.

In the BCB process in the following row, applied *inter alia* to a sub-bituminous coal from South Australia, the briquettes are initially produced at a little below the equilibrium moisture content. They are then stockpiled, and uptake of moisture to the equilibrium level takes place and is a factor in consolidating the briquettes' structure. Plate 5.1 shows the BCB pilot plant.

Plate 4.1. BCB Process – Binderless Coal Briquetting – pilot plant.
Image taken from: http://www.csiro.au/news/newsletters/SIROSCOPE/2009/March09/images/binderless2.jpg

There is a long history to the matter of briquettes from Collie coal (following row). As long ago as 1909 there was discussion of the manufacture of briquettes from Collie coal in the press [5], when successes at coal briquetting by that time in Germany and in New Zealand were invoked in favour of entry by Western Australia into the business. In 1915–16 Investigations into the briquetting of Collie coal took place, not only locally but in England [6]. In England coal tar pitch and petroleum residue were being used to make a binder. These were not so readily available in Western Australia but even so a binder was developed, and briquettes having good stability – resistance to disintegration – when stockpiled were made. Railway use was the incentive for development and an interesting points was made in the WA Parliament in support of such use: the briquettes had a lower tendency to eject hot particles via the chimney than did the bituminous coals which they were intended to replace, and this was seen as being a major advantage when a train was passing through a rural area in dry weather.

At Tabang [8] in east Kalimantan there were plans to produce produce binderless briquettes from sub-bituminous coal in a binderless way by the BCB method previously referred to. Plate 4.2 shows the briquetting plant at Tabang.

Plate 4.2. Briquetting plant at Tabang. Image taken from:
https://www.thiess.com/projects/tabang-coal-processing-project/detail

The plant was ready to enter service in 2009. There were proposals for PRB coal also to be received at the Tabang plant [8].

The investigation of Waikato coals in the next row dates back 90 years. The existence of slacks across the gamut of New Zealand coals was perceived as a problem, and effort was expended at making these into briquettes. In the particular case of the sub-bituminous coal from Waikato briquetting trials using an applied pressure of 30 tons per square inch (≡ 400 MPa). The product was too mechanically weak for commercialisation. Here again railway use was envisaged. Waikato coal alone had a strong tendency to emit hot particles in locomotive use, and it was found that a 50:50 blend of Waikato coal with a bituminous coal eliminated this.

Considerably more recently [10] tests have been made in the co-briquetting of sub-bituminous coal from Waikato with peat. Blends of peat-20% coal and peat-40% coal were examined across a range of moisture contents. An important property of any fuel briquette is the compressive strength, units MPa. This was reduced by the incorporation of coal. For example, at 8% moisture the peat only had a compressive strength of 1.5 MPa, the peat-20% coal a value of 0.85 MPa and the peat-40% coal a value of 0.4 MPa. However, the effect was less marked at higher moisture contents and at 28% moisture all three had compressive strengths in the nieghbourhood of 0.3 to 0.6 MPa.

The intended use of the briquettes from Nuurst sub-bituminous coal in the following row is electricity generation. Some of the coal in this deposit has crossed the classification boundary between sub-bituminous to high-volatile bituminous [12], although that identified for the briquetting enterprise referred to will be entirely sub-bituminous.

4.3 Further remarks

That coals of sub-bituminous rank can be briquetted to make a general-purpose solid fuel is clear. That being said, the second decade of the 21st Century is not an auspicious time for coal briquettes, and the most promise for development and expansion is held by coal briquettes also containing some biomass.

4.4 References

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[6] 'The West Australian', 27th January 1943.
[7] http://www.afr.com/business/mining/coal/fedwhite-energy-to-ramp-up-indonesian-plant-20110530-ictzq
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5 Carbonisation and gasification

5.1 Examples of carbonisation

These are in Table 5.1 below.

Source of the coal and reference.	Details.
PRB [1].	The ENCOL project, carried out in WY: 'Liquids-from-Coal' (LFC) demonstration plant to process 1000 ton per day (0.907 tonne per day) of PRB coal from the Rochelle mine. Production of solid, useable as a fuel or as a metallurgical reductant, and a liquid composed of tars which could be the basis of a liquid fuel.
Sosnica mine, Poland [2].	Laboratory scale carbonisation at 500, 600 and 700°C. Chemical activation with KOH and ammoxidation at 350°C.
Puertollano, Spain [3].	Chars obtained by carbonisation of sub-bitumunous coal at temperatures up to 900°C activated with carbon dioxide. Surface areas up to ≈ 1700 $m^2 g^{-1}$.
Alberta [4].	Coke residues from combustion (unburnt carbon) of sub-bituminous coal studied. Unchanged fusinite evident.
Indonesia [5].	See comments in the main text.
Peru [6].	8.8 million tonnes of sub-bituminous coal produced at the Goyllarisquizaa Mine over the period 1903–71, all of it for carbonisation. Resumption of activity in 1978.
Shenfu, China [7].	Sub-bituminous coal treated with saturated steam at 1 bar before carbonisation at 950°C according to standard 'crucible tests'. Improvements over the untreated coal in terms of caking propensity, mechanical strength of the carbonised solid and its reactivity towards metal ores.
Iran [8].	Sub-bituminous coal in co-existence with bituminous.

The product of primary interest in the ENCOL project was the liquid, which was compared with the specifications of a No. 6 fuel oil, frequently used as a boiler fuel. It stood up well in all respects, being lower in sulphur and in kinematic viscosity. It was recommended that its saleability would be enhanced by its fractionation into four products: cresols, two further distillates with distinct boiling ranges and heavy residue. Each would require further processing. The solid residue, analogous to petroleum coke, from the ENCOL process was seen as being suitable for electricity generation and has the advantage over unprocessed coal that it is less productive of dust. In its grindability it compared well with that of a Central Appalachian bituminous coal.

Moving on to the next row, 'ammoxidation' simultaneously oxidises the coal and adds nitrogen to it. In the work described in the second row of the table, remarkably high BET[18] areas of the product carbons – up to 2700 m^2g^{-1} – were reported. Those from the Spanish coal were similarly high, although these values of the surface area were obtainable only with a high degree of activation with carbon dioxide entailing loss of a major proportion of the initial carbon solid. With the Alberta coal in the following row, the most intersting feature was the retention of the macerals. It is less surprising that the maceral having shown the greatest resistance to change was fusinite, an interinite maceral. There was also noted that there had been little fluid behaviour, which is intuitively consistent with the low rank.

In the work in the following row, primary interest was on the fate of halogens in the coal on pyrolysis. Pyrolysis at temperatures up to 600°C led to production of HCl. Some of the HCl so formed reacts with metals in the char and with active sites in the carbon structure and is retained as inorganic and organic chlorine respectively and this can be released as HCl on pyrolysis at higher temperatures. The preparation of metallurgical reductants from coal of any rank other than bituminous has long been a challenge and results such as those reported for the Shenfu coal in the next row are encouraging. The Iranian sub-sbituminous coal (following row) will form a good, hard product on carbonising.

Obviously in all of these applications there will have been a product gas, and carbonisation where gas is the primary product is called partial gasification. The chapter now moves on to gasification.

5.2 Introduction to gasification

This chapter will be organised in such a way the the sub-bituminous coals having featured in earlier chapters will be considered in turn for gasification, starting with Collie coal.

5.3 Example: Collie, Western Australia

5.3.1 General-purpose fuel gas

As long ago as 1949, when manufactured fuel gas was much more prevalent than it was later to become as natural gas started to replace it, Collie coal was evaluated for gasification [9]. At that time Western Australia used imported coal from Newcastle NSW coal to make gas for reticulation to homes and businesses. The coal would have had to be brought ≈ 2500 miles by road or rail, so the incentive to use local coal was strong.

The fact that gasification of Collie coal is still on the agenda is evidenced by a very recent published study appertaining to it [10]. Three different atmospheres were used: CO_2 only, 15% H_2O balance argon and 15% H_2O balance CO_2. Temperatures were 800–900°C. Interest was chiefly water and carbon dioxide as gasification agents and their reactivities. The atmosphere promoting most rapid conversion of solid to gas was that containing both water and carbon dioxide, whilst carbon dioxide only was, in these terms, the weakest. The gasification rate with 15% H_2O balance CO_2 was not equal to the sum of the rates with 15% H_2O balance argon and CO_2 only, and it was concluded from this that the reactions:

$$C + CO_2 \rightarrow 2CO$$

and

$$C + H_2O \rightarrow CO + H_2$$

are kinetically interdependent when both gasifying agents are present. Another route to gasification is of course pyrolysis, and Collie coal was examined for pyrolysis under several experimental arrangements including fixed bed, fluidised bed and drop tube in [11]. Experiments were performed with and without added steam. Temperatures were in the range 600 to 1200°C. The most important finding was that the considerable moisture content of the coal as mined – about 20% of the weight – undergoes reaction with the coal carbon during pyrolysis and affects the properties of the carbon residue. Where it is intended to beneficiate the coal by carbonising it, this is an important issue.

5.3.2 Urea via synthesis gas

There has recently been an investigation into the manufacture of urea from Colli coal via synthesis gas [12]. This involves the production of a hydrogen/carbon dioxide mixture from reaction of the coal with steam, removal of the carbon dioxide and reaction with nitrogen to form ammonia. This can be reacted with carbon dioxide to form urea, and all of this is well known. At the commencement of the project it was envisaged that the annual conversion would be of 2.6 Mtonne per year of Collie coal, and a mass balance on this is attempted below.

Collie coal is ≈ 70% carbon by weight [13]. The initial reaction:
$C + H_2O \rightarrow CO + H_2$
will in the reaction of 2.6 Mtonne coal involve:
$0.7 \times 2.6 \times 10^9/0.012$ mol of carbon = 1.52×10^{11} mol.
This is unaffected by the shift reaction which converts CO to CO_2 for removal.
1 mol $H_2 \rightarrow 2/3$ mol NH_3
and
1 mol $NH_3 \rightarrow 0.5$ mol urea, N_2H_4CO (molar mass 0.06 kg)
So amount of urea from 1.52×10^{11} mol carbon is one third of this quantity or
5.1×10^{10} mol or **3 Mtonne**.

5.3.3 Producer gas

Producer gas is made by passing air into coal, coke or wood. It dates from the 19th Century but is not obsolete in the 21st. Because of the low calorific value it is not usually feasible to reticulate producer gas: it has to be manufactured where it is required. Over a century ago the matter of producer gas manufacture from Collie coal was a live issue [14]. Its proposed application was as fuel for engines.

5.3.4 Further remarks

There is activity neither in coal seam gas nor in underground gasification at Collie at the present time.

5.4 Powder River

Table 5.2 below summarises selected activity in PRB coal activity. Comments follow the table.

Reference.	**Details.**
[15]	Coal gasified with water in a nitrogen carrier gas in a laboratory-scale, fixed bed vessel. Temperatures up to 900°C. Sodium carbonate catalyst. A significant dependence of the total conversion to gas on the amount of catalyst.
[16]	PRB coal gasified in carbon dioxide. Principal reaction: $C + CO_2 \rightarrow 2CO$ $FeCO_3$ catalyst.
[17]	Slurry with water as a form of PRB for gasification.
[18]	Mercury content of PRB coals given and evluated for release in gasification.
[19]	Kellogg, Brown and Root (KBR) Transport Gasifier a.k.a. TRIG™. Fuel gas for power generation from coal gasification in air/steam or in oxygen/steam. Development and testing with PRB coals.

Table 5.2. Gasification of PRB coal.

In the work described in the first row there was tar in the products, signifying of course incomplete conversion of coal carbon to carbon monoxide. This is common in industrial scale gasifiers of lower rank coals. In the work described in the second row the iron II carbonate is redued to elemental iron in the first, pyrolytic stages of the gasification and this is converted to iron oxides by the admitted carbon dioxide. The iron oxides shuttle oxygen by the reactions:

$$C + Fe_3O_4 \rightarrow 3FeO + CO$$

and

$$C + FeO \rightarrow CO + Fe$$

A slurry (row 3) is a suitable medium for combustion or gasification, as pointed out in [18], where it is also reported that the maximum loading for slurry stability and ease of pumping is 42.5% coal, balance water. Surfactants can be used in amounts of the order of 1% to improve slurry stability. In [17] it is noted that PRB coals show mercury releases of 3.9 mg per million BTU of heat from the coal when burnt. Using a value of 20 MJ kg^{-1} for the calorific value, this converts to 0.08 p.p.m. of mercury by weight in the coal. TRIG™ uses a fluidised bed gasifier, and the method once established used PRB coals over a period in excess of a decade. It is recorded [20] that conversions of the organic coal substance of 98% or better were achieved. A reader is asked to note that the three journal articles cited in the table are all post 2010, which signifies recent and current interest in the gasification of PRB coal.

5.5 India, Bangladesh and Pakistan

Calculations in a financial paradigm to evaluate possible underground gasification of a sub-bituminous coal in India have been reported [21] in a very recent contribution to the literature. The 'bottom line' is the cost of operating integrated gasification and electricity production at 100 MW from the gasification product. The calculated result was $US1.73 per GJ of heat in the gas, and $US28.18 per MW-hour of electricity generated from it. These figures can be further analysed.

1 GJ is, to within a few percent, equal to 1 million BTU. The Henry Hub price for natural gas – a widely applied benchmark – in the first half of 2015 ranged from $US2.61 to $US2.99 per million BTU, so the price of the manufactured gas originating in India is favourable according to this comparison. The current price of electricity in India is 8 US cents per kW-hour or $US80 per MW-hour, so here again the calculated results for integrated underground gasification and power generation are promising. Interestingly, the authors of [21] make a comparison with the cost of electricity supply from underground gasification with air of PRB coal with air and generation from the product gas at 200 MW. This is given as $US12 per MW-hour.

Tabulations of coal reserves of the world e.g. [22] state that recoverable reserves of sub-bituminous coal in India are nil. This is not because it is non-existent but because it is too deep for mining to be feasible in the circumstances. Part of the importance of underground gasification is that it enables coals inaccessible by mining to be utilised.

Prospects for power generation via underground gasification is considered in less precise terms for sub-bituminous coal from Bangladesh, where there is significant sub-bituminous coal, in [23]. Land subsidence always has to be thought of wherever underground coal gasification is proposed. It is less likely to be a difficulty where the gasification site, in effect a 'reactor', is deep [24]. Subsidence is high on the agenda of issues to be addressed before integrated underground gasification of sub-bituminous coal and electricity production becomes a reality in Bangladesh.

There is sub-bituminous coal in Pakistan at Balochistan as noted in an earlier chapter, but no activity in underground gasification. There is active interest in underground gasification of the lignite deposit at Thar [25].

In Alberta, Canada, Mannville coal, sub-bituminous in rank, has been evaluated in economic terms for underground gasification [26] to produce hydrogen as a fuel gas for the local tar sands industry. Gasification produces H_2 and CO, the latter convertible to CO_2 by a shift reaction and removable. An important aspect of the study being reviewed is possible capture and sequestration of the carbon dioxide, and the cost of the hydrogen depends on whether or not this takes place. The final conclusion was that without CCS the hydrogen would cost $1.78 per kg to produce, and with it $2.11 to $2.70 per kg, at the 2013 value of the dollar.

5.6 Hydrogasification

A sub-bituminous coal from Wangjiata, China was examined for hydrogasification in work described in [27]. In the presence of a metallic catalyst, samples of the coal were heated to 750°C and reacted in nitrogen at 10 bar pressure. In the absence of a catalyst the residual char yield was about 50%; it was lowered by about half with a catalyst of which several were tried, a better return of liquid and gaseous product. The gases included propane, propene, ethane and ethene. The liquids were largely aromatics including benzene, toluene, xylene (BTX) as well as some oxygenates including phenol and cresols.

5.7 Co-gasification with biomass

In a recently reported study [28] an Indonesian sub-bituminous coal was co-pyrolysed with straw and with wood, and the char obtained from the co-pyrolysis gasified with steam. The reactivity to steam gasification of either char from co-pyrolysis – that from the coal with straw and that from the coal with wood – was higher than that from the coal alone. The coal during pyrolysis is believed to have received radicals and hydrogen atoms formed in biomass pyrolysis, and this has influenced both its reactivity towards pyrolysis and the gasification reactivity of the solid residue. The biomass was also higher in potassium than the coal, and as potassium is known to have a catalytic effect in char gasification that would have influenced to gasification rate. The potassium was probably devolatilised from the biomass and deposited on the char.

5.8 Coalbed methane (CBM)

5.8.1 PRB

There are thousands of CBM wells in the PRB, and an annual production of billions of cubic metres of gas. CBM was discovered there in 1957, and production from two wells in the part of the basin called the Wyodak-Anderson coal zone began in 1981 [29]. Between then and 1989 when those wells were abandoned, there was major production. In the same year production began at a different part of the basin, that in Campbell County and drilling and production expanded. Plate 5.1 below shows a gas well in Campbell County, an image taken as recently as the winter of 2015.

Current CBM production at PRB is of the order of 25 million cubic metres per day. Most of it enters the interstate pipeline network and is used in distant locations including the West Coast. A fraction of it is retained for Wyoming, where it is reticulated to users.

Plate 5.1 Gas well at Campbell County, PRB. Image taken from: http://www.wyohistory.org/essays/coalbed-methane-boom-bust-and-hard-lessons

5.8.2 Other sources of CBM occurring with sub-bituminous coal

These are given in Table 5.3 below.

Location and reference.	**Details.**
Huntly, NZ [30].	An estimated 2 to 4 m^3 of gas per tonne of coal.
Bangladesh [31].	6.76 to 12.68 m^3 of gas per short ton of coal
Surat Basin, Australia (see Table 1.2) [31].	1 to 14m^3 of gas per short ton.
Santa Terezinha coal field, Brazil [32].	1 m^3 per tonne.
Upper Silesian coal basin, Poland [33].	12 to 14 m^3 per tonne.
Fruitland formation, NM and CO [34].	Sub-bituminous and bituminous coals in co-existence. Abundant natural gas. See also the comments in the main text.
Donets Basin, the Ukraine [35].	Range in rank from sub-bitumunous to anthracite. Respective vitrinite reflectances up to 0.6% and up to 3.5%.
New South Wales [36].	Oaklands coal, similar methane potention to PRB.
Southern Perth Basin, Western Australia [37].	14 billion m^3 of methane present.
Philippines [38].	Major CBM in the Semirara sub-bituminous coal reserve.

South Australia [39].	Exploration activity at the Southern Cooper Basin, the Perdika Basin and the Polda Basin, all sub-bituminous.
Karoo Basin, South Africa [40].	Basin largely sub-bituminous. Methane present.
Ordos Basin, China [41].	Coal sub-bituminous to high-volatile bituminous. 0.11–6.26 m^3 methane per tonne of coal.
Kushiro coal field, Japan [42].	Sub-bituminous coal. The last coal mine in Japan to be closed. Before closure producing 2.5 million m3 of methane annually.

As a point of semantics, it should be noted that CBM is often and not incorrectly termed natural gas, indistinguishably from that arising in conventional gas fields or from tight gas fields. The sub-bitumunous coal at Huntly in the first row has made several previous appearances in this book. Reference [31] gives for comparison a value for PRB of up to 2.67 m^3 of gas per short ton. The Brazilian coal field in the next row extends to below the sea, and it is estimated that the offshore part of the field (which also contains high-volatile bituminous coal) has a methane content of 56 billion cubic metres. The Upper Silesian coal basin contains sub-bituminous as well as higher rank coal, and vitrinite reflectances range from 0.84 to 1.5%.

Reference [34] digresses into sapropelic coals and notes that gas from these contains more C_{2+} hydrocarbons than gas from humic coals. This moves the discussion on to an important point. With conventional natural gas there is often condensate, and this might well be of greater monetary value than the gas which bears it. It sells for a price about equivalent to that of crude oil on a barrel basis and requires less refining as there is no heavy residue. The view is often taken that CBM does not contain condensate and this is largely true. However even with CBM from humic coals there can be some higher hydrocarbons, more therefore from sapropelic coals, and whether these constitute 'condensate' is a fruitful line of enquiry for future production. At the Ukranian coal reserve in the next row an averaged value of the methane content was found to be 14.7 m^3 per tonne. This is a high value, and is well exceeded in parts of the Donets Basin. Plate 5.2 shows a mine at Donets.

The Perth Basin (following row) takes in the sub-bituminous coal at Collie, which has featured previously in this book. The coal from the Philippines in the next row is Miocene. The assertion is made in [37] that it is equivalent to PRB coals in methane content.

Plate 5.2. Mine in the Donets Basin. Image taken from:
http://www.encyclopediaofukraine.com/pic%5CA%5CR%5CArtemivsk%20(Luhansk%20oblast)%20mine.jpg

At the Polda Basin in the following row, a petrographic similarity to Walloon coal (Table 1.2) has been noted. Coal at the Ordos Basin in China is low in vitrinite and remarkably high – up to 85.6% – in macerals of the inertinite group.

5.9 Concluding remarks

A point made earlier in the chapter will be reiterated: many of the references drawn on are recent, indicating current interest and activity. Developments can be expected.

5.10 References

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6 Sub-bituminous coal in isolated settings and in unworked deposits

6.1 Introduction

Sometimes coal of any rank is a geological feature of an otherwise inorganic formation, almost an intrusion, and being in small quantities is not seen as being a reserve for mining. Sometimes the geographical location of a site of coal precludes mining, there being in any case no market for it or means of transporting it. One tends to look in the geology literature rather than the fuel technology literature for examples of such, some of which follow.

6.2 Examples

These are in the table 6.1 below, which is followed by comments.

Location and reference.	**Details.**
Emma Fiord Formation, Canadian Arctic Archipelago [1].	Sub-bituminous coal in co-existence with sapropelic material (see section 1.7).
Western Black Sea, offshore and onshore (Turkey) [3].	Sub-bituminous coal, vitrinite reflectance 0.45 to 1.70%.
Offshore Vietnam [4][19].	Sub-bituminous coal, vitrinite reflectance 0.30 to 0.60%. Cenozoic.
Fushun Basin, NE China [5].	20 to 200 m of sub-bituminous coal beneath 50 to 300 m of oil shale. Oil shale production at the scene. Eocene.
Pannonian Basin, Slovenia [6].	Sub-bituminous coal, vitrinite reflectance 0.35 to 0.45%. Also bituminous coal.
'South Portuguese Zone' [7].	Sub-bituminous coal, vitrinite reflectance ≈ 1.1%.
Prince Charles Mountains, Antarctica [8].	Coals varying in rank from sub-bituminous to high-volatile bituminous.
Buller field, NZ [9]	Proposed for power generation.
Bornholm, Baltic Sea[20] [10].	Sub-bituminous coal to the exclusion of higher ranks.
Tanzania [11].	Sub-bituminous and bituminous coal at the Mchuchuma mine.
Greenland [13].	Low-sulphur sub-bituminous coal at Disko Island and at Narsarsuaq (a.k.a. Naggusuaq).
Cagayan Basin, The Philippines [13].	Sub-bituminous coal not yet utilised. Believed to be suitable for electricity generation.
Karakoram, the Himalayas [15].	Coal sub-bituminous to bituminous in rank.
Dathwegyauk coal mine, Burma [16].	An estimated 33.9 million tonnes of sub-bituminous coal.

Ecuador [17].	See comments in the main text.
Uruguay [18].	Several scenes of sub-bituminous coal evaluated from drilling or from surface samples ('outcrop').
Peru [17,18].	See comments in the main text.
Bogovina Basin, Serbia [19].	Sub-bituminous coal believed to be Lower Miocene. Huminite, liptinite and inertinite up to 81.4%, 16.1% and 13.5% respectively. Huminite reflectance 0.41 to 0.42%.
Lafia and Enugu deposits, Nigeria [21].	Respectively 77.6 and 63.1% vitrinite. Enugu of vitrinite reflectance 0.54 to 0.63%, and significantly higher in volatiles than Lafia [23].
East and west of the Lambert Glacier, Antarctica [24].	Coal of vitrinite reflectance 0.6 to 1%, seen as encompassing sub-bituminous and bituminous.
Saudi Arabia [25].	See comments in the main text.
Pakistan/Afghanistan border [26].	Coal sub-bituminous to bituminous in rank.
Reshit, northern Pakistan [26].	The scene of mining on a small scale. Coal sub-bituminous in rank.

Dominant macerals in the coal from the Canadian Arctic (row 1) include alginite, exudatinite and sporinite, all in the liptinite group [2]. The coal at the Western Black Sea is fairly incidental, the commercial interest being in hydrocarbons; this is consistent with the comments in the previous section. The same is true of the coal offshore Vietnam, which co-exists with lignite. This is consistent with the lower vitrinite reflectance, which indicates that the sub-bituminous coal is closer to the boundary with lignite than to the boundary with bituminous. The Fushun Basin (following row) is a major producer of shale. At the Pannonian Basin (following row) there is oil at depths between 300 m and 1500 m. The coal at the Antarctic location co-exists with silicified[21] peat. At Buller sub-bituminous coal and bituminous co-exist: the vitrinte reflectance range is 0.5 to 1.5. Clearly the literature cited in the table up to and including the ninth row is focused either on hydrocarbon prospects or on the geology without any regard for sub-bituminous coals *per se*.

Plate 6.1. Scene from the Mchuchuma mine in Tanzania. Image taken from: http://www.theeastafrican.co.ke/image/view/-/1102578/medRes/235072/-/maxw/600/-/12df6s1/-/mine.jpg

At Mchuchuma (row 10) a coal-fired power station is planned [12]. A 600 MW output using subcritical steam is projected, full operation being hoped for in 2019. A scene from the Mchuchuma mine forms Plate 9.1 below. The coal at Disko Island (next row) has been reported [14] as having a vitrinite reflectance of 0.48%, consistently with its sub-bituminous rank. The coal from the Himalayas in the row 13 conforms in the highest degree conceivable to the term 'isolated settings' in the chapter title. Large parts of the region containing the deposit are uncharted. The mine in Burma in the next row is also in a fairly remote spot, close to the Burma-India border. The region is however served with transport including a railway. Ecuador does not currently produce coal of any rank. There has been exploration and exploratory drilling at places including the Rio Malacatos field (sub-bituminous), the Azoques-Biblian mine (lignite to sub-bituminous) and the Cuenca El Derrumbo field (lignite to sub-bituminous) [17]. Possible utilisation needs more work on such matters as ash content. The sub-bituminous coal (next row) in Uruguay is Permian. Classification of these as sub-bituminous might be broadened to sub-bituminous/lignite or to sub-bituminous/bituminous on further exploration.

Turning to Peru, sub-bituminous coal from the Goyllarisquizaa Mine, used in carbonisation, was discussed previously. There are other scenes of sub-bituminous coal in Peru which have not been worked and are not likely to be without much further preparatory work; these belong in this chapter. These are Cretaceous or Jurrassic and include the coal in the Huancavelica region of the country, once a scene of mining of mining mercury ore and now a centre of hydroelectricity. The only thermal power plant in Peru uses fuel oil.

The deposit in Serbia has been included in this chapter on the grounds that it has not been significantly worked in the 21st Century (although prior to that there was major exploitation). The current coal production of Nigeria (following row) is almost negligible [20] in spite of there being well characterised deposits of coals across the ranks taking in sub-bituminous. That Nigeria is not aquiescing in this state of affairs is evidenced by recent work on the combustion of Lafia coal in a fluidised bed [22] on an intermediate scale using coal admittance rates to the bed of up to 0.3 kg s^{-1} giving heat release rates up to $\approx$ 10 MW. The work is focused on eventual electricity production from the coal in a fluidised bed, so there is some emphasis on NO_x production in particular possible use of oxyfuel to eliminate thermal NO_x. The second of the Antarctican coals in the table (following row) occurs as layers within a formation of dolerite. The information on Saudi Arabia in the next row appertains to the Jauf formation which contains major oil fields. Co-existence of a layer (not fragments) of a sub-bituminous coal with sand and plant remains was observed in core logging at Jauf [25]. The coal at the Pakistan/Afghanistan border (very difficult to access) was found as stated in the table to be in the sub-bituminous to bituminous range to the exclusion both of lignite and of anthracite. The small scale mining of sub-bituminous coal at Reshit (following row) began after the discovery of coal there in 1996, and awareness of the obvious benefit of a coal deposit to such an isolated community. At a Himalayan location, it is possibly the highest altitude scene of coal mining in the world.

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7 Conversion to liquid fuels

7.1 Introduction

Work on sub-bituminous coals from a number of deposits is discussed below. Such work on PRB coals was discussed in section 3.8.

7.2 Exploratory work on liquefaction of sub-bituminous coals

The information is given in the table below, which is followed by comments.

Origin of the coal and reference.	**Details.**
Tanito Harum, Indonesia [1].	Reaction with carbon monoxide and water at 365°C and at 400°C with an alkaline catalyst. Conversion to liquid of up to 69%.
Shenfu, China [3].	Liquefaction of 1 g samples by hydrogen at 5 MPa, 400°C with a solvent and a catalyst originating at BASF. Solvents included crude methyl naphthalene oil, and polar additives were used. Asphaltenes, presasphaltenes and gas in the products.
Shenhua, China. Co-liquefation with sawdust [4].	1 g samples of coal/sawdust blends. Use of tetralin and H2 at 5 MPa with an iron sulphide catalyst in a thermal analysis unit at 400oC. Conversions with coal/sawdust blends up to 91.7% for equal masses of the two in the blend down to 60.1% for 5:1 coal/sawdust composition.
Belle Ayr PRB[22] [5].	Treatment with hydrogen at > 15 MPa with a solvent at 440–450°C. Reactor residence times up to 45 minutes. Pyrite catalyst. C1–C4 gas and liquids in the diesel boiling range dominant in the products.
Wyoming [6].	Nickel/molybdenum and cobalt/molybdenum catalysts. Hydrogen gas (6 MPa) without a solvent at 400°C. See comments in the main text.
Xinglong, China [7].	Solvent-induced swelling with THF or pyridine prior to liquefaction at up to 450°C.
Deitz, Montana [8].	2.5 g samples of the coal. Use of hydrogen gas (6.9 MPa) with tetrahydroquinoline (THQ) and naphthalene. Sulphided ammonium molybdate (SAM) catalyst, also a catalyst (termed STM) made by reacting SAM with THQ. Temperatures up to 425°C. Products classified into oils (O), asphaltene (A) and gas. A high O:A ratio favourable for product utilisation. Comments continued in the main text.
Wyodak, PRB [9].	H2 (7.5 MPa) at 418°C. Solvents including THQ, pyridine and tetralin. Suite of four Wyodak coals.
Belle Ayr [10].	H2 at up to 15.5 MPa plus a hydrogen donor solvent. Pyrite catalyst. Products including C1→4 gas and liquid in the distillate boiling range. Per g of coal reacted there 0.048 g of liquid product.

Table 7.1. Work on the liquefaction of sub-bituminous coals.

The Tanito Harum coal was studied alongside a number of lignites, and it is noted that compared with the liquefaction product from those that from Tanito Harum was high in asphaltenes. A little over simply perhaps, one might reason that fuel from Tanito Harum could contribute to the 7000 barrels per day of bunker fuel which Indonesia's shipping or persons around the multiple islands of that nation requires [2]. (The number is of course much larger if oil and LNG tanker movements are factored in.) The coal from Shenfu (next row) also featured in Table 5.1. Preashpaltenes are so named because of their appearance in advance of asphaltenes in the common sequence of solvent extraction, and are often more polar than asphaltenes. Both have molar masses of the order of 1000 g mol^{-1}. Moving on to the next row, the liquefied products are oils, asphaltenes and preasphaltenes. Proportions do not differ markedly across the range of intitial blend compositions. Obviously the motive for co-liquefaction with sawdust is an end product which is in part carbon-neutral.

In the work in the next row of the table, comparisons are made with the behaviour of a bituminous coal subjected to the same experimental conditions. The inherently higher reactivity of sub-bituminous coals as compared to bituminous is invoked and the interesting point made that this necessitates more rapid suppy of hydrogen for liquefaction of sub-bituminous, otherwise broken bonds in the coal will combine with each other instead of with hydrogen. The result of this will be insoluble organic matter (IOM) which is not a desired product.

In the work in the following row the Wyoming coal was examined alongside two others of different rank and the liquefaction products divided into two classes: asphaltenes and 'OGW' (oil, gas and water). The work is focused on catalyst performance, and for the Wyoming coal total conversion was better with a Ni/Mo catalyst than with a Co/Mo catalyst. Moving on to the next row of the table, liquefaction was with tetralin and hydrogen (4 MPa) or with tetralin only, in which case an equivalent pressure was provided by admittance of nitrogen. The trend of results is interesting. With the untreated (not solvent-swollen) coal conversion is higher under hydrogen than under nitrogen. The reverse is true – though not to a very marked degree – with coal swollen either by pyridine or by THF, and total yield of liquid higher with the swollen coals.

In the work in the following row of the table light aromatics were dominant in the liquid products. The composition of the catalyst had a strong effect on the distribution of product between liquid and gaseous, the former always being lower than the latter and favoured by higher loadings of calcium in the catalyst. The gases included C_3 hydrocarbons which can of course be made into LPG and there was also ethane, a very saleable substance. Moving to the next row we note that Deitz is in fact part of PRB. The best O:A ratio, a value of 1.25, was obtained with naphthalene only and no catalyst at 425°C, but the total conversion was only 25.4%. The highest total conversion of 86.5% was achieved with two-stage heating – initially 350°C raised to 425°C – with SAM and THQ. This gave an O:A ratio of just under 0.5. The gas yield was 5.1% of the coal weight, and the dominant constituent was carbon dioxide with some carbon monoxide, hydrogen sulphide and hydrocarbons. The two-stage heat process did seem to provide for good results, for example an O:A ratio of 1.19 with THQ and no catalyst , the total conversion being 39.5%. This work consisted then of holding in balance single- or two-stage heating with two catalysts and presence or absence of THQ additional to naphthalene. Sometimes THQ itself was absent but the catalyst made from it present. Under two-stage heating conditions thisgave a total conversion of 79.4% and an O:A yield of 0.41. The reason for the requirement of a good O:A yield is of course that asphaltenes are on high molar mass – in excess of 1000 g per mol as noted above – and this is characteristic of residuals in crude oil refinining, whereas coal-derived counterparts of distillates are more saleable. Even so a product with a high proportion of asphaltenes could be used in two common ways: as shipping fuel or in a power plant set up to use heavy fuel oil. Such might of course be the desired end product of the liquefaction.

Moving on to the next row, with pyridine as solvent conversions were up to >80% and comparable conversions were observed with toluene and with THQ. One of the Wyodak coals was subjected before the liquefaction tests to pretreatment, drying or solvent (THQ) immersion. Conversion in a toluene solvent was enhanced by either sort of treatment. Other things being equal, THF pre-treatment raised the conversion from 76% to 84%. Prior drying of the coal under nitrogen also had a strong liquefaction promoting effect. The papers in rows four and nine of the table were seen by the authors as being complementary. This leads to the point that at the time the work was done in the mid 'eighties oil prices had undergone a steep surge [12] so that interest into making oil from coal was strong and attracted funding.

For the coal in the work in [11] the 'empirical formula' can be calculated from proximate analysis data as $C_{5\cdot 74}H_5O_{1.07}$[23] ($\equiv CH_{0.87}O_{0.19}$). Oxygen loss is by devolaltilisation and retention in the solid products. The effect of the liquefaction is conversion, to the degree of 4.8%, to hydrocarbons in the neighbourhood of C_{12}. The molar mass corresponding to the empirical formula is 91 g mol^{-1} whilst that of the hydrocarbons from it is of the order of 120 g mol^{-1}. The gain is therefore about 30 g mol1, the resultant of oxygen loss and hydrogen acquisition. The solvent does not have a conceptually simple 'shuttling' role but donates. The catalyst possibly 'shuttles' hydrogen.

7.3 Further remarks

A point already touched on is that the viability of coal-to-oil schemes are very dependent on crude oil prices and very vulnerable when they drop. Coal-to-oil schemes have tended to meet contingencies, for example in South Africa during sanctions and in Germany during WWII (bituminous coal and lignites rexpectively). One has to remember also that over supply of crude oil is avoided. There is the additional factor of non carbon neutrality of anything made from coal, and the competition with such things as biodiesels and ethano; fuels which are carbon neutral.

7.4 References

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8 Safety issues with sub-bituminous coals

8.1 Case studies

Table 8.1 below gives details of fatal accidents involving sub-bituminous coals. The coal was sometimes in co-existence with bituminous.

Location, year and reference.	Details.
Kaitangata, New Zealand 1879 [1].	34 deaths, no survivors. Carbon monoxide explosion believed to have been the cause.
Frontier mine, Wyoming 1923 [2].	99 deaths. 'Pockets of gas' most likely methane the cause.
Hanna, Wyoming, 1908, one of a succession of serious accidents there [3].	59 deaths. Some of the bodies from an earlier (1903) accident at Hanna never recovered. The 1908 accident caused by explosive gas.
Amaga Colombia (see section 1.2) [5].	12 fatalities from flooding at a mine in 2014.
West Ridge mine, Utah [7]	1 fatality by crushing at a piece of plant. September 2014.

Although Sir Humphry Davy had given the world his safety lamp long before the Kaitangata accident in 1879, a naked candle was in use at the mine. The consequences were very grave. The Frontier mine in Wyoming (next row) had been in use for about 25 years by the time of the explosion, and its products were directed to railroad use. There were many 'pockets of gas' and these could (ought) to have been burnt off in a controlled way for the safety of the miners. There were established means for doing this long before 1923. Coal from Hanna was exclusively for railroad use. The accident record of coal mining in Wyoming in the late 19th and early 20th Centuries is dismal, and a reader will find examples additional to the above in [4], in which it is recorded that coal mining began in Wyoming in 1868. Plate 10.1 below shows a miner preparing for duty at Hanna mine. The considerable propensity of Amaga coal (next row) to spontaneous heating has been noted [6].

Plate 8.1 Miner starting a shift at Hanna mine, Wyoming. Note that he is carrying a food container in his right hand and mining implements over his left shoulder. Image taken from: http://www.wyohistory.org/essays/thunder-under-house-one-family-and-hanna-mine-disasters

The West Ridge mine in Utah (next row) produces 10000 US tons of raw coal per day and methane release [7] is 1454019 cubic feet per day (≈41000 cubic metres per day or 25 tonnes per day). A *totally arbitrary* calculation not intended to relate in any way to West Ridge follows in the shaded area below.

The methane production rate converts to 1000 cubic feet per minute. To keep the methane at below 1.25% by volume – one quarter of the lower flammability limit of methane – 80000 cubic feet per minute of air will be required. We simply note that this is a sensible order of magnitude and that a reader will find comparable figures in online sources for such ventilation rates e.g. [8].

In Australian mining practice evacuation is required if the methane level reaches or exceeds 2% [9]. At 1.25%, the value used in the calculation, trip of electrical devices is required.

8.2 Safety at PRB

A report is extant which summarises the safety record of coal production at PRB over the quarter-century 1980–2005 [10], and records an average annual death rate over that time span of 5 per year. Over the same period the average for the total of the USA in power-related coal winning was 33 per year. A finger is pointed clearly at dust explosions as the origin of many of these deaths, and accordingly studies of dust explosions. In experimental testing the severity of a dust explosion in air is expressible in terms of two quantities: the maximum pressure P_{max} and the maximum rate of pressure rise (dP/dt)max. In [11] the latter is given for a PRB coal as being:

$(dP/dt)_{max}$ of 500 bar s^{-1} at a dust concentration of 750 g m^{-3}, maximum pressure 8 bar.

8.3 Spontaneous heating

A recent discourse [12] is concerned with spontaneous heating of a sub-bituminous coal from Indonesia. Not for the first time, oygen consumption rate (OCR) was used as an indicator of spontaneous heating activity. At the commencement of an experimental trial this was just under 20 mg O_2 mg^{-1} coal day^{-1} at 70°C, the corresponding values at 50°C and 30°C being 5 and 1 in the same units. As sites in the coal become occupied with oxygen molecules the rate of uptake declines, to almost zero for the higher temperatures. It is widely known that water plays a significant role in spontaneous heating of coal of any rank, largely because water vapour can enter pores within a coal and become adsorbed, releasing the 'heat of wetting' which acclerates the primary effect which is oxidation. Hysteresis in an adsorption-desorption cycle is common and was indeed displayed by the Indonesian sub-bituminous coal. At 40°C and 100% humidity, the coal adsorbed water at up to 20% of the coal weight, declining to about 6% at 50% humidity. This lab-scale work was followed by an investigation involving two 'test piles' intially at ambient temparature, one of 4 m height the other of 15m: obviously other things being equal the higher pile will self-heat more powerfully. The profile through each pile was approximately an isosceles triangle. Temperature measurement was carried out at points within the piles over a one-month period, and for the higher pile an internal temperature of up to > 70°C was observed after a month, and this was still rising when testing ceased. For the shorter pile The maximum internal temperature attanied was a little below 60°C ands declined towards the end of the measurement period. Quite clearly, the shorter pile was thermally sub-critical at that ambient temperature and the taller pile super-critical. Laboratory simulation of these effects at oven temperatures with small (> 1 kg) samples would have been a helpful extension of the work in [12] which, as stated, has been chosen for coverage herein partly on account of its being very recent. That there is current interest in the issue of spontaneous heating of sub-bituminous coal is clear. As a general point one expects them to be more susceptible to self-heating than bituminous coal or anthracite and less susceptible than lignite. This trend can be correlated directly with volatile matter content.

8.4 References

[1] http://www.nzhistory.net.nz/kaitangata-mining-disaster

[2] http://fronterminedisaster.blogspot.com.au/p/disaster-community.html

[3] http://www.hannabasinmuseum.com/hanna-1908-explosion-of-mine-number-one.html

[4] Papa P.W. 'It Happened in Wyoming' Rowman and Littlefield (2013).

[5] http://www.trust.org/item/20141031211728-2r8z2/

[6] http://archives.datapages.com/data/tsop/tsop_2010/tsop-abstracts-and-program-v27-2010-34.htm

[7] http://www.msha.gov/fatals/coal/2014/final-reports/final-c14-11.asp

[8] http://www.msha.gov/REGS/FEDREG/FINAL/1996FINL/5453(4).htm

[9] Ventilation of Underground Mines Draft Code of Practice Safe Work Australia (2011).

[10] 'Coal-fired power plants: Additional hazards require additional solutions' F.E. Moran Special Hazard Systems, Northbrok IL n.d.

[11] Amyotte P.R., Basu A., Khan F.I. 'Reduction of dust explosions hazard by fuel substitution in power plants' Transactions of the Institution of Chemical Engineers Part B **81** 457–462 (2003).

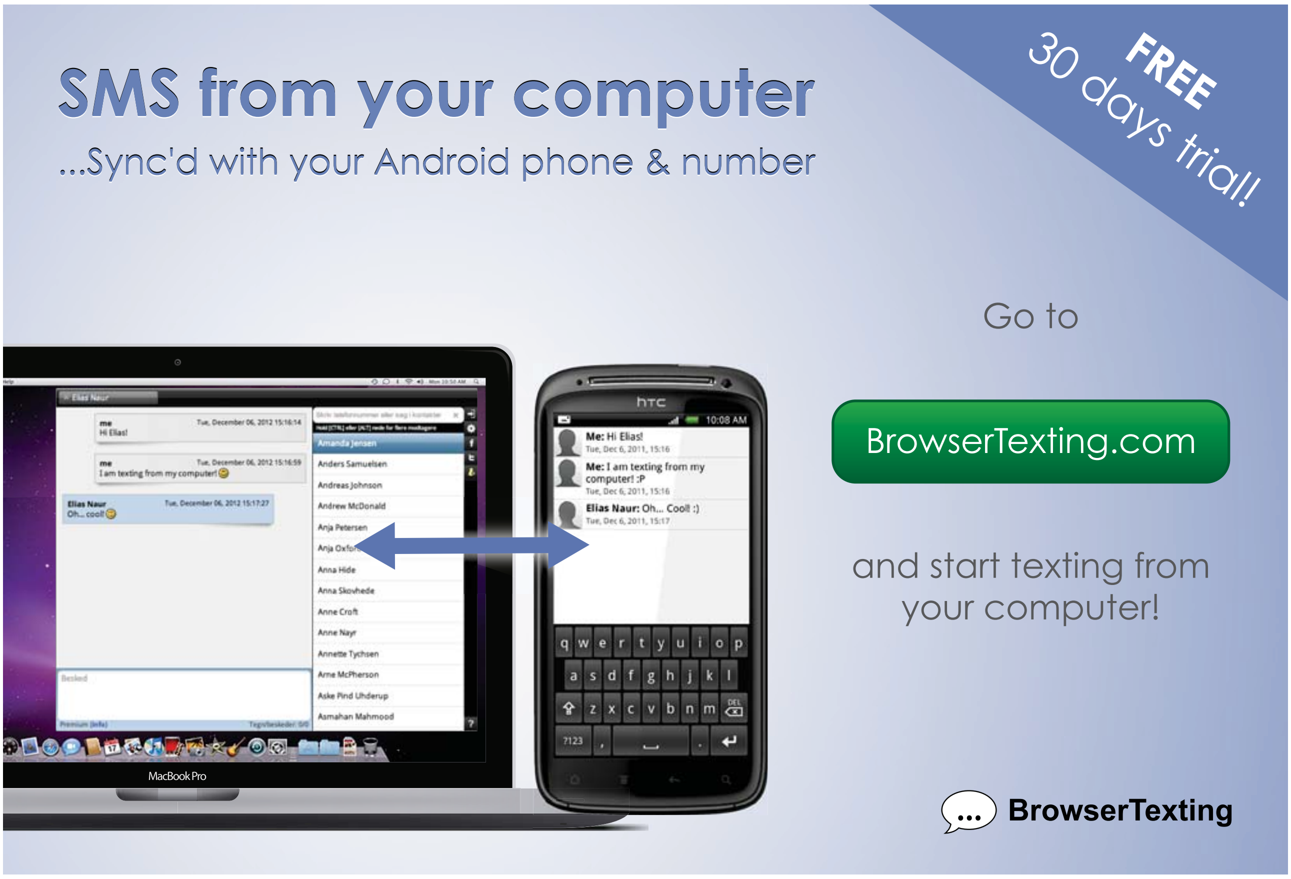
[12] Pak H., Tada T., Kikuchi N., Shigesa T., Higuchi T., Yamamoto S. 'Evaluation of Spontaneous Combustion in Stockpile of Sub-bituminous Coal' Kobelco Technology Review **33** 21–27 (2015).

9 Pricing of sub-bituminous coals

9.1 Examples of current or recent prices

Table 9.1 below gives some information relevant to this.

Location.	**Details.**
PRB (see also section 3.6).	At the time of going to press of the order of $US10 per US ton the index price for PRB coal having a calorific value of 8800 BTU lb^{-1} (20.5 MJ kg^{-1}) and a sulphur content of 0.8%.
Collie (see also section 2.2.2).	Late 2014, circa $A40 per tonne [1].
Indonesia	July 2013, $61.95 per tonne [2]. February 2014, $60.10 per tonne [3]. May 2014, $57.75 per tonne [4]. June 2015, $43.90 per tonne [5].
Contract awarded by Taiwan to US and Indonesian suppliers jointly (see also Table 2.1).	October 2012, $95 CIF[24] [6].
Tenders for supply to South Korea for power generation.	October 2012, $71–73 per tonne NAR basis, 25 MJ kg^{-1} [6].
US average 2013.	$14.86 per US ton [8].



Reference [1] states that Collie coal was at that time poised for a price increase of about $A7 per tonne. The price for the Indonesian coal is that given by IHS McCloskey[25], who assign prices to coals from many countries; these are adjusted twice a week. IHS McCloskey prices are for a particular calorific value on a Net as Received (NAR)[26] basis, in the case of the prices in the table 4900 kcal kg^{-1} (20.6 MJ kg^{-1}). Reference [2] gives the benchmark calorific value for bituminous coals as a *minimum* of 18 MJ kg^{-1} and of anthracite a minimum of 21.0 MJ kg^{-1}. The low minimum for bituminous is probably due to the need to bring high-ash bituminous coals within the scope of the pricing. That is implicit in the term 'as received' and subsequent cleaning is of course possible. The June 2015 price is said [4] to be indicative of adverse circumstances ('tough times') for sub-bituminous coal production in Indonesia. The interesting point is made in [5] that exports of Kalimantan coals are affected by the water levels at two local rivers. The Korean temder in row 5 was for bituminous as well as sub-bituminous: for the former the price was $82 NAR basis, same calorific value. The calorific value is perhaps an impossibly high one for sub-bituminous. This makes the value a pivot point for scaling: in practice a lower calorific value coal will be accepted and the price adjusted accordingly. This is very simple [7]. One formula is:

$$P_{cs} = P_b \times CV_{cs}/CV_b$$

where P refers to price and CV to calorific value, the subscripts 'cs' and 'b' referring respectively to price paid and the benchmark price. The advantage of the above, especially where an 'as received' basis applies, is that two factors strongly affecting the CV – the moisture and ash contents – do not and need not appear explicitly in the formula. We transfer the benchmark price of $72 per tonne for calorific value 25 MJ kg^{-1} from the particular to the general and postulate that sub-bituminous coal of 18 MJ kg^{-1} is in fact supplied. The price paid will be:

$$(18/25) \times \$72 \text{ per tonne} = \$52 \text{ per tonne.}$$

Moving on to the next row of the table, the value has to be compared with $60.61 per US ton for bituminous, $19.96 per US ton for lignite and $87.82 per US ton for anthracite. This leads to the point that the prices expressed on a heat basis can show different trends. The price on a heat basis is usually per million BTU (MBTU). Converting to SI units gives:

$$10^6\text{BTU} = 10^6 \times 252 \text{ cal BTU}^{-1} \times 4.2 \text{ J cal}^{-1} = 1.06 \text{ GJ.}$$

We assign values of 25, 20, 18 and 12 MJ kg^{-1} to the calorific values of anthracite, bituminous coal, sub-bituminous coal and lignite respectively on an as-received basis. The price of 1 million BTU (1 GJ) from the sub-bituminous coal, having regard to the fact that 1 US ton = 907 kg, will be:

$$14.86 \text{ \$ ton}^{-1} \times (1/907) \text{ ton kg}^{-1} \times 10^9 \text{ J}/18 \times 10^6 \text{ J kg}^{-1}) = \$0.91.$$

The costs for one million BTU from the bituminous coal, the anthracite and the lignite are respectively \$3.34, \$3.87 and \$1.84. In weight terms the order of costs was:

anthracite > bituminous > lignite > sub-bituminous

and this trend is repeated when the calculation is done on a per unit heat basis. PRB coals are used to such a huge extent that it is reasonable to compare the price per million BTU with that for natural gas in the same units. (In marketing, only gaseous fuels are traded on a heat basis to the exclusion of weight basis). The benchmark natural gas price which applies in the US is the Henry Hub price, which on the day on which in November 2015 averaged \$2.09 per million BTU, so PRB coal represents a highly viable fuel in these comparative terms. The above order of costs on a heat basis could be annotated:

$$\begin{array}{c}\text{natural gas}\\ \downarrow \\ \text{anthracite} > \text{bituminous} > \text{lignite} > \text{sub-bituminous}\end{array}$$

A reader will have noted from earlier parts of this chapter that the averaged value for the US exceeds that for PRB. PRB is the largest, but there are other deposits of sub-bituminous coal in the USA. Such coals occur in the Illinois basin, which takes in parts of Illinois, Kentucky and Indiana where bituminous domonates but, as stated, sub-bituminous is to be found. There is also significant sub-bituminous coal in Utah. (See also section 2.7.) One reason PRB coal is cheap is that mining is at open pits. It has been pointed out [9] that this cost benefit is being diminished by the need to dig deeper and to install conveyors to utilisation sites.

9.2 Further remarks

'Carbon costs' obviously have to be factored into the use of sub-bituminous coals in power generation. Relevant factors are the possibility of sequestration and the cost and tradability of carbon credits.

9.3 References

[1] https://au.news.yahoo.com/thewest/regional/south-west/a/25260822/wa-to-pay-more-for-collie-coal/
[2] IHS McCloskey Coal Report July 2013.
[3] IHS McCloskey Coal Report February 2014.
[4] IHS McCloskey Coal Report May 2014.
[5] IHS McCloskey Coal Report June 2015.
[6] IHS McCloskey Coal Report October 2012.
[7] Thomas L.C. 'Coal Geology' John Wiley (2002).
[8] http://www.eia.gov/Energyexplained/index.cfm?page=coal_prices
[9] http://www.wyofile.com/rising-cost-of-powder-river-basin-mining-adds-to-coal-crunch/

Endnotes

1. Mega annum.
2. Ente nazionale per l’energia elettrica
3. See also Table 1.3.
4. Which features in Table 1.3 on account of its low Hardgrove Index.
5. See also Table 1.3.
6. The southernmost coal (only) fired power plant in the world.
7. See also section 3.7.
8. See also Table 1.4.
9. See section 3.7.
10. Bituminous coal is not totally absent from PRB and can be found in the northern and eastern parts. It is to be expected that in such an expansive deposit there would be sufficient variation in maturity to cross a boundary in rank. See also the comments in vitrinite reflectance in section 3.3.
11. See also Table 1.4. Such details are also continued in section 3.10.
12. Letter denoting for the states of the US are those in ISO 3166-2.
13. Eastern US including Kentucky, Tennessee, Virginia, and West Virginia.
14. Includes parts of Pennsylvania, West Virginia, Ohio, Kentucky, and Maryland
15. Colorado and Utah.
16. 1 ton = 0.907 tonne.
17. See also the coverage of the ENCOL project in Chapter 5.
18. Brunauer, Emmett and Teller.
19. See also Appendix to Chapter 2.
20. Part of Denmark.
21. Impregnated with silica.
22. See also section 3.3.
23. Reference [13] gives a generalised formula of $C_{13}7H_{97}O_9$ ($CH_{0.71}O_{0.07}$) for such coals.
24. Cost, Insurance and Freight.
25. A ‘research firm’ formed in 2007 by merger of IHS (US) with McCloskey (UK). The original remit of McCloskey was to provide energy related information to the Financial Times. That of IHS was wider and included commodities other than coal.
26. Sometimes values are on a GAR – Gross as Received – basis. The difference is of course that in the gross value the product water condensation has been allowed for. The gross is always higher than the net. Reference [3] gives 21 MJ kg^{-1} as the GAR for the specified value for a sub-bituminous coal for which supply tenders were being sought.