Fuel for the Future

Fuel for the Future:

Processed High Quality Coals for Low-and Zero-emissions Power

By

George Domazetis

Cambridge
Scholars
Publishing

Fuel for the Future:
Processed High Quality Coals for Low- and Zero-emissions Power

By George Domazetis

This book first published 2019

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-5275-3683-1
ISBN (13): 978-1-5275-3683-8

Dedicated to Thalia

TABLE OF CONTENTS

PREFACE

The greatest global challenge today is perhaps the impact of increasing levels of Greenhouse gases (GHGs) in the atmosphere and the consequences that flow from this, viz. increasing temperatures, melting ice and glaciers, higher sea levels, and climate change. The primary contributor to the GHG levels is the widespread use of fossil fuels for power generation, transport, agriculture, industry, and domestic sectors. The problems are exacerbated by various factors, such as large scale deforesting, low efficiency in fossil fuel usage, the increasing demand for transport and power generation.

It is important to foster a balanced debate on this important problem. The drive to reduce poverty and improve living conditions worldwide also calls for urgent action. An important factor in improving living conditions for developing countries is secure and affordable power. Low cost and abundant fuels have been crucial to the growth of developed economies, and it is reasonable to offer the same advantages to the economies of developing nations. It also needs to be stated that a secure and affordable power supply is necessary for all economies. The drive to lower the cost of renewable sources of power is also an important contributor to lower emissions.

The world is faced with a dilemma. If fossil fuels are used at an increasing rate the problems from higher levels of GHG will become greater, and both developed and developing nations will suffer, with the poorer countries experiencing the greatest difficulties. It is highly unlikely, however, that the world would shut down all coal-fuelled power generation, or cease using fossil fuels, as the consequences of this would be traumatic.

It is obvious that many initiatives and innovations are required to address these difficulties, including political, economic and technological ideas. Some of these include reducing the carbon footprint in our daily lives, utilising renewable power generation where it is economically competitive, increasing the efficiency of fossil fuels electricity generation with the goal of zero-emissions plants, enlarging carbon sinks such as forests, and developing power distribution systems that better enable communities to meet the variable demand for power. The nature of the problem requires a worldwide effort that ultimately is about the human spirit and the belief that we can share the challenges together, and together achieve our collective goal. Such a collective effort would ensure energy security, provide access for all nations to reliable and affordable energy, and enable economic growth, while protecting the planet for future generations.

The ultimate goal is to take advantage of plentiful and relatively cheap fossil fuel to generate electricity with zero emissions, without an unacceptable increase in the price paid for power. This goal is technically feasible – however, even if coal-fuelled power generation with zero-emissions is developed and implemented, this in itself will only slow down the increasing levels of GHGs. Other sectors need to reduce emissions significantly to avoid the consequences of increasing global temperatures. For example, transportation may undergo a transition to electricity-driven vehicles, and this would be boosted by the availability of a low emission and affordable electricity supply.

This volume discusses the research and development of low rank coals, carried out within the context of addressing the environmental impact of these coals when used to generate electricity. Low rank coals make up about half of the world's coal deposits and are widely used due to their low cost. Currently these operate with the highest carbon emission intensity. Research that can take advantage of the low cost of low rank coal, and achieve low or zero emissions, has the potential to provide affordable electricity, thereby achieving the twin goal of secure, affordable power with a reduction in emissions. The concept is to chemically process these coals into high quality fuel, with high efficiencies in processing and power generation. The research discussed in this volume deals predominately with low rank coals, and how high quality fuel may be produced with the properties required for maximum performance of new power generating plants, and coal gasification. The process does not discharge any pollutants to the environment, and new coal power plants would be designed for low emissions, with the ultimate goal of converting these into zero-emissions plants. This concept would include the capture and utilisation of carbon dioxide as a feedstock to manufacture valuable materials.

It is hoped that ultimately this coal treatment process will be developed commercially and thus make a significant contribution to the overall effort at combating the problem(s) arising from the increasing concentration of GHGs in the atmosphere.

The research discussed in this volume is the result of fruitful collaboration between Clean Coal Technology Pty Ltd and La Trobe University in Australia. It is with considerable pleasure that I highlight the contributions made by staff and post-graduate students at the University, particularly Professors B. D. James (deceased) and J. Liesegang, whose support and input proved invaluable to the success of the project. Contributions by staff in the Departments of Chemistry, Physics, and Earth

Sciences, particularly Mr J. G. H. Metz, Dr R. Glaisher (deceased), Dr P. J. Pigram, and Dr I. Potter, are gratefully acknowledged. I am grateful to Professor J. Hill for his interest and involvement. The work by M. Raoarum and P. Barrila provided an especially useful contribution to the project. Facilities and welcome support were provided by the Victorian Partnership for Advanced Computing Facility, Melbourne, and the Australian Partnership for Advanced Computing National Facility (currently the National Computational Infrastructure), Australian National University, Canberra.

ABBREVIATIONS

Acid washed
aw
As received
ar
Atomic absorption spectroscopy
AAS
Binding energy
BE
Carbon capture and storage
CCS
Carbon-13 nuclear magnetic resonance cross-polarisation with magic angle spinning ^{13}C NMR CP/MAS
Chemical oxygen demand
COD
Circulating fluidised bed combustion
CFBC
Clean Coal Technology Pty Ltd/La Trobe University
CCT/LTU
Combined heat and power
CHP
Commonwealth Scientific and Research Organisation
CSIRO
Computational fluid dynamics
CFD
Computer-controlled scanning electron microscopy
CCSEM
Cost of electricity
COE
Density functional theory
DFT
Di-methyl ether
DME
Direct coal-fuelled turbine combined cycles
DCFTCC

Direct coal-fuelled turbine
DCFT
Distributed activation energy model
DAEM
Dry ash free basis
daf
Dry basis
db
Electron paramagnetic resonance
EPR
Externally-fired combined cycles
EFCC
Fischer-Tropsch
F/T
Force field
FF
Fourier-transform infra-red spectroscopy
FTIR
Gas chromatography/Mass spectrometry
GC/MS
Global Warming Potential index
GWP
Greenhouse gases
GHGS
Heat of formation
ΔH_f
Higher heating value
HHV
Inductively coupled plasma atomic emission spectroscopy
ICP-AES
Integrated gasification combined cycles
IGCC
Internal rate of return
IRR
International Energy Agency
IEA
Kelvin (degrees)
K
Laser-induced breakdown spectroscopy
LIBS

Life cycle assessment
LCA
Lower heating value
LHV
Megajoules per kilogram
MJ/kg
Megawatt hour
MWh
Megawatts
MW
Milligrams per litre
mg/L
Milligrams
mg
Million metric tons
MMT
Molecular dynamics
MD
Molecular mechanics
MM
Multiple high-resolution transmission electron microscope
HRTEM
Net present value
NPV
Nitrogen oxides
NOx
Normal temperature and pressure
NTP
Operating and maintenance cost
O&M
Parts per million
ppm
Pressurised fluidised bed combustion
PFBC
Proton exchange membrane electrolysers
PEM
Pulverised coal
PC
Reverse osmosis
RO

Scanning electron microscopy and energy dispersive x-ray analysis
SEM-EDX
Semi-empirical quantum mechanics
SE-QM
Single point self-consistent field
1scf
Solid oxide electrolysis cell
SOE
Substitute natural gas
SNG
Sulphur oxides
SOx
Supercritical
SC
Thermal gravimetric and differential thermal analysis
TG/DTA
Time of flight – secondary ion mass spectrometry
TOF-SIMS
Total dissolved solids
TDS
Total organic carbon
TOC
Turn over frequency
TOF
Ultra-supercritical
USC
United States Environment Protection Agency
US EPA
Water gas shift
WGS
X-ray absorption near edge structure
XANES
X-ray diffraction
XRD
X-ray fluorescence
XRF
X-ray photoelectron spectroscopy
XPS

CHAPTER ONE

COAL-FUELLED POWER GENERATION AND THE NEED FOR CLEAN TECHNOLOGIES

It is understood that the unrestricted use of fossil fuels may lead to levels of greenhouse gases (GHGs) that would result in the "overheating" of the globe and cataclysmic climate change. The general perception is that the increase in GHGs emissions, especially from fossil-fuelled plants, must be reduced to low or zero-levels. Some insist that coal-fuelled power generation and coal mining operations should cease.

There is also the view that emphasises the benefits and security derived from cheap and secure energy to expand and modernise economies. Developing countries, in particular, observe that developed nations have obtained the benefits of a secure and plentiful supply of energy, and demand they also derive such benefits for their economies.

Fossil fuels, and particularly coal, have become a source of controversy and political agitation.

Developed and developing economies are all dependant on an affordable and secure source of power. Electricity generation is a basic requirement for daily activities, clean water, and the disposal of sewage, which are critical in improving health and maintaining good living standards; it also contributes to lessening poverty and improving the well-being of countless human beings. This, however, may clash with the environmental hazards associated with fossil fuels' pollution, which may result in poor health as well as long term climate change. The climate change due to the rising concentrations of GHGs in the atmosphere poses long term hazards to all nations.

In view of these problems, we may ask, "What is the future of coal-fuelled power generation?"

Historically, electricity has been generated using coal, gas, diesel, nuclear, hydro and, recently solar, wind, and to a lesser extent bio-fuels. Fossil fuels are burnt and the heat is used to create steam that drives turbines connected to generators. Gas-fuelled turbine power plants burn gas, and the hot gases are expanded through turbines which are connected to power generators. Coal-fuelled power generation has undergone significant improvements in efficiency, and with the additional advances in the management of power transmission and distribution, as well as economies of scale, coal became the dominant fuel for power generation worldwide.

Coal power generation is projected to remain the major source of electricity for the foreseeable future. The International Energy Agency (IEA) reports that coal fuels about 40% of the world's power generation, but there is a greater proportion of coal-fuelled power in many countries. The IEA also shows that improvements in power generation efficiency would be a significant step towards a reduction in CO_2 emissions from coal (Burnard and Bhattacharya, 2011). Projections of energy production in the USA show coal consumption decreased from 2017 onward, mostly replaced by gas, while data for China and India show these countries rely heavily on coal-fuelled power generation. The proportion of electricity generation using coal is large for many nations, even though effort is being expended in lowering emissions; e.g. the proportions of power generation using coal reported for the period from 2007 to 2011 are 79% for China, 49% for the USA, and 92% for Poland. Coal power generation in India accounts for 73% of electricity production, and although this proportion may decrease, reports indicate overall coal-fired capacity may increase substantially by 2040, despite considerable increases in wind and solar power. China is expected to produce 50% of its total power with coal, which is still projected to be the major fuel for power generation in 2050. The IEA Coal Information Overview provides details of coal use in regions around the world.*

Coal varies in rank (heating content), in composition, and in the amounts of pollutants such as sulphur and ash. Consequently, a variety of electricity generation technologies have been developed (and continue to be developed) in response to the particular coal properties. Historically, the majority of pulverised coal power plants are subcritical, and operate at lower efficiency levels (30% for low rank coal, 38% for black coal). New plants are being developed in an effort to reduce and eliminate CO_2 emissions. For example, oxy-combustion has been developed as an advanced technology to include capturing CO_2. Coals with high sulphur content can be used in fluid-bed combustion plants that retain sulphur with the ash, and sulphur oxides from pulverised coal power plants may be removed by cleaning flue gases. Pulverised coal combustion is the major technology for power generation; as the term implies, coal is crushed into a powder and fed to a coal burner with air. Coal gasification is a technology used to produce synthesis gas (mainly CO and H_2), and this can be used as fuel for power generation with gas turbines, or to provide synthetic household gas, or to

* For more information, see http://www.iea.org/topics/coal/.

produce liquid hydrocarbons, such as sulphur-free diesel. An overview of developments for clean energy is provided by Johnsson (2007), and a discussion of advances in modelling of coal combustion and gasification at the Sandia Laboratories is given by Hecht and Shaddix (2015).

Historically, progress in power generation has occurred through improvements in efficiency and economies of scale, which have ensured a secure and affordable power supply to underpin economic activity and improve living standards. The prolonged period of burning fossil fuels, however, has resulted in degradation of the environment, and air pollution, which can lead to poor health to populations, and now poses global changes to the climate, leading to more severe weather events and rising sea levels.

Coal's molecular matrix is composed mostly of carbon and hydrogen, with variable amounts of oxygen, nitrogen, and sulphur, with water- and ash-forming components; when pulverised coal is mixed with air in a coal flame, the combustion with oxygen produces carbon dioxide, water, pollutants such as sulphur and nitrogen oxides, and ash particulates. The environmental and health problems posed by the fossil-fuelled power generation sector (and also from the transport sector) have been discussed for decades and various programs have been implemented to reduce pollutants (such as removing sulphur and nitrogen oxide emissions) and to find measures that may ultimately remove the emission of all pollutants to the atmosphere. Because the problem is global, and because power generation is essential to nations and their economies, a large number of measures have been examined and continue to be discussed for changes to future power generation; these measures include new ways to use fossil fuels, increased use of solar and wind power, developing electric cars, increases in the efficiencies by the user of electricity (thereby lowering the demand), and advances in the management of electricity transmission grids to use a mix of power sources that would ensure lower emission intensities are maintained. The ultimate goal of these programs is the transition towards low- to zero-emissions power, by using a judicious combination of power generation from fossil, nuclear, bio-fuel, solar, wind and hydro sources. Of particular interest is the concept of zero-emissions fossil fuel power generation that includes the capture of CO_2 for use as a feedstock for the synthesis of valuable products, thereby offsetting the costs for the capture of CO_2. This strategy requires long term planning, and a radical change in the management of electricity transmission grids, but offers the promise of secure and affordable power for the foreseeable future, with a mitigation of CO_2 emissions. This is an exciting concept that, if successfully implemented on a commercial sale, would be a major factor to solving the problems of climate change attributed to using coal as a fuel. A secure and affordable supply of electricity, with low emissions, would enhance economic activity and prosperity in regions with significant coal resources.

The economic and policy dimensions of global climate change have been discussed in the Stern Review (2006), which concluded, "The benefits of strong, early action considerably outweigh the costs" and estimated the annual worldwide costs of stabilising CO_2 to 500-550ppm at about 1% of the global GDP by 2050. The review identified four ways to achieve the desired reduction in emissions:

1. Reducing demand for emissions-intensive goods and services.
2. Increased efficiency, which can save money and reduce emissions.
3. Action on non-energy emissions, such as avoiding deforestation.
4. Switching to lower-carbon technologies for power, heat, and transport.

These general recommendations have been accepted by most governments and industries. There is universal agreement on the need to increase the efficiency of coal-fuelled power generation. The efficiency of fossil-fuelled plants is that proportion of the heat content of the fuel that produces electricity; power plants produce steam in boilers, and the steam drives turbine generators. Increasing the temperature of the steam increases the efficiency of power generation. Subcritical power plants operate at temperatures up to 374°C and pressures of 3,208 pounds per square inch (psi). Supercritical power plants (SC) operate at up to 566°C, and ultra-supercritical power plants (USC) may operate at up to 760°C and pressure levels of 5,000 psi. The environmental impact of fossil-fuelled plants is assessed by the emissions' intensity, reported as the kilograms of CO_2 per megawatts of electricity sent to the grid; higher efficiencies result in lower emission intensities.

The combination of higher efficiency in power generation and the relatively lower costs of coal provides a secure power supply, and can lead to lower emissions while slowing the increase in the cost of electricity to the end-user. The Stern Review highlights measures that may be taken nationally and internationally to limit the amount of CO_2 emitted to the atmosphere – these include placing a price on CO_2, the development of low-carbon and high efficiency technologies, and dealing with barriers to changing behaviour.

Due to the looming problems resulting from inefficient plants and the overuse of fossil fuels, major Clean Coal Technology Research, Development and Demonstration Programs (CCT RD&D) have been undertaken to examine a number of initiatives to minimise, and ultimately negate, the environmental problems posed by the increasing use of fossil fuel, while maintaining the security and affordability of low cost coal-fuelled power generation. These programs have provided incremental improvements in efficiencies, but have not instigated the global radical changes that would result in the required reduction in emissions from fossil-fuelled power generation. While progress has occurred in the development of the implementation of higher efficiencies from SC and USC pulverised coal-fired technologies, lower efficiency sub-critical plants continue to be used for power generation. Generally, an SC plant operates at about 45% efficiency, and a USC plant may operate at ≥45% based on the lower heating value (LHV) of bituminous coals. Future developments in alloys may lead to a USC efficiency of 50% (LHV). Progress in circulating fluidised bed combustion (CFBC) plants utilising low-rank fuels would also result in lower emissions of SO_X and particulates.

While modern electricity production and distribution systems are increasingly reliant on a mix of power generation from coal, nuclear, hydro, and gas, the largest relative increase in power generation has been from solar and wind. The cost of renewables has continued to decrease and, as a result, these increasingly supply a higher proportion of power to communities. Grids are managed to cope with the intermittent nature of renewables. The IEA reports that renewable sources made up almost two-thirds of new net electricity capacity, amounting to about 165 gigawatts (GW), with 74 GW in China. Indeed, for the first time, additions of solar PV power outpaced the growth of other sources, including that of coal-fuelled power generation. Conventional low efficiency coal-fuelled plants are an undesirable option for future power generation (Katzer, 2017).

There is a diverse range of coal types, with variable properties, and thus coals of differing quality are available for power generation. Low quality coals would not be desirable as fuel for future cleaner power generation technologies. Low rank coals are problematic as fuels for subcritical plants, and these problems would increase if these coals are used to fuel future high efficiency plants. Technologies have been sought to improve the quality of coals; the motivation to process low rank coals into high quality fuel is their low cost per unit heat of the mined coal. This relatively low cost must be maintained with any high efficiency plant, and this may be realised by developing a concept that integrates the coal treatment process with the power generating plant, to achieve high thermal and power efficiencies. This concept is similar to operational combined heat and power plants. The coal treatment process is integrated with a power station to refine raw coal into high quality fuel designed for maximum performance of the high efficiency power plant. The major features of the high quality processed coal are low to virtually zero ash, low sulphur and chloride content, high heating value, and the ability to use catalysts to enhance reactions between coal and steam for gasification.

The ultimate clean future for the coal project is zero-carbon emissions, by collecting CO_2 for use as a raw material for the production of valuable materials, such as methanol, or di-methyl ether (DME). The overall trajectory towards a zero-emissions commercially viable coal-fuelled power generation is common to all major CCT Programs.

The specific purpose of this volume is to discuss the research that is central to understanding the properties of low rank coals that render them as poor quality fuels, and from this outline the methodology required to process these for future use as high quality fuels in low- to zero-emissions concept(s). This research deals with low rank coals and the efforts undertaken to process these into high quality fuels; this is a portion of the much wider worldwide programs towards the development of low carbon emissions fossil-fuelled power generation systems. This volume discusses coal-fuelled power generation using high quality fuels obtained by processing low cost, low rank coals, and a strategy towards zero-emissions power. The discussion also draws on innovation achieved in the larger worldwide CCT Programs, such as low-NOx burners, higher efficiency plants, oxy-combustion, and the production of hydrogen.

A detailed treatment of all coal types and their use is beyond the scope of this volume; research on coal utilisation has been carried out over many decades, and a great amount of literature has been published on coal properties, coal combustion slagging and ash fouling, with additional literature dealing with clean coal programs. As a result, it is impractical to include all of the scientific literature dealing with all coals, and instead the information that has been selected mostly deals with low rank coals. As the treatment methodologies to produce low ash coal are primarily chemical, the major focus has been on understanding the chemistry required to render low rank coals into high quality fuels for future coal combustion and gasification.

Clean Coal Programs

Major programs have been undertaken worldwide to develop lower emission coal-fuelled power generation, with the twin goals to reduce, and eventually eliminate, environmental problems derived from using coal, and to provide secure and affordable power generation in the foreseeable future. Examples of these programs include the US Department of Energy Clean Coal Technology Program (DOE CCT), the Japanese Clean Coal Project

(JCOAL) and the European Commission Research & Innovation on Energy (EU). The DOE, JCOAL and EU programs are discussed briefly here to illustrate the nature of the worldwide effort. China has also made significant progress in implementing high efficiency power plants and renewable power.

The comprehensive DOE CCT Program seeks to improve current power generation plants, and to develop new technologies that would meet energy requirements economically while addressing environmental impacts. A general review of the USA's activities and the funding of technologies by Longwell et al. (1995) gives an assessment of the future goals of the DOE's coal research, development, demonstration and commercialisation programs extending to 2040. During this period, coal is projected to continue to fuel electric power generation, along with a growing use of gas. The DOE coal program addresses mainly power generation technologies, with an emphasis on environmental concerns and clean fuels; the review also addresses the barriers to higher efficiency in both power generation and fuel production, ways to reduce CO_2 emissions, control of air pollutants, and the discharge of solid wastes. This assessment also noted increases in efficiency would require extensive R&D to overcome a number of barriers. The highest efficiencies are obtained with gas turbine combined-cycle systems, and for these the production of a hot gas stream of sufficient purity is required, which is the major challenge to developing commercial plants. Critical components required for these advanced power generation plants include the continuous removal of slag from combustion chambers, high temperature filters for Pressure Fluidised-bed Combustion (PFBC) systems, a high temperature air/furnace heat exchanger for indirect fixed systems, a hot gas clean-up system for PFBC and for Integrated Gasification Combined-Cycle (IGCC) systems, and turbine blades that would operate at high temperatures and can cope with trace impurities that may escape the high temperature gas clean-up system. Fuel cells are also capable of clean operation and high efficiency, but their high cost is a major problem. Solutions to these challenging problems require a continued program of advanced research and component development. The large array of technologies considered will also require detailed systems studies and the development of realistic commercialisation strategies.

The DOE "Program Update of 2000" report discusses 38 projects, which included ways to control and lower emissions of sulphur dioxide (SO_2), nitrogen oxides (NOx), mercury and particulate matter for existing plants. The program includes developments in Fluidised-bed Combustion (FBC), IGCC, and Advanced Combustion/Heat Engines. Innovations are created to improve efficiencies and environmental performance for electricity generation and the production of synthesis gas. A significant component of the DOE Program includes coal upgrading projects, such as the ENCOAL® Mild Gasification Project, the Advanced Coal Conversion Process, and methanol production at a commercial-scale demonstration plant with the Liquid Phase Methanol (LPMEOH™) Process (this produced 80,000 gallons/day of methanol for Eastman Chemical Company). Considerable reductions have been achieved in SOx and NOx emissions from US coal-fuelled power plants to meet regulations imposed by the Clean Air Act (DOE, 2001). The DOE CCT trajectory includes the development of new higher efficiency power plants, thereby decreasing the emission intensity (kgCO_2/MWh), and would meet the increasing demand for electricity. The Program culminates in the Vision 21 Plan; a wide range of power generation options are considered, including fuel cells and turbines fuelled with natural gas and coal – this anticipates a range of facilities that will be able to convert fossil fuels in a cost effective manner into electricity, process heat, fuels, and/or chemicals, with low CO_2 emissions (National Research Council, 2003).

Carbon dioxide capture for use in enhanced oil recovery has been pursued through joint industry- and DOE- funded arrangements. Currently, the expanded Petra Nova operational plant captures emissions from a 240 MWe generation facility situated at Houston, with a demonstrated ≥90% carbon capture rate. This facility is reported to capture ≥5,000 tons of CO_2 per day, used for enhanced oil recovery, which is expected to boost the production of oil by an additional 14,500 barrels per day. This offsets the costs of CO_2 capture, and for this particular example, predictions of enhanced oil recovery for the site are 60 million barrels of oil (at the price of oil, this represents a total revenue of $2-$3 billion). This is an example of a commercial CO_2 capture program. Currently, however, simple carbon capture and storage encounters energy penalties and costs; ultimately cost effective technologies with zero-emissions may be achieved by capturing CO_2 for use as a feedstock to produce valuable products such as liquids and plastics. The costs of CO_2 capture would be offset by returns from valuable products. The long term goal for zero-emissions has been accepted by major organisations; the central feature for this is the cost effective production of hydrogen, to be used in reactions with CO_2 to provide high value products.

The DOE has sought ways to improve the performance, and reduce the capital costs, of coal gasification. This includes work on advanced gasifiers configured with supporting systems that incorporate innovative technologies. The intent is to utilise highly efficient new reactors for smaller scale applications and superior products, with the use of low cost, low rank coals, and thereby expand opportunities for gasification systems with lower feedstock costs. A significant development is that of gasifiers for higher hydrogen content in synthesis gas (syngas) production. Research has been conducted on advanced water-gas shift processes and catalysts to reduce the cost of high-hydrogen syngas production. The production of hydrogen, and higher quality syngas, are important ingredients in developing technologies with lower CO_2 emissions. Chemical looping is also being researched, in which oxygen is used through an oxidation-reduction cycling of an oxygen carrier, which is a single metal oxide, such as copper, nickel, or iron, or a metal oxide supported on a high-surface-area substrate, such as alumina or silica (Aston et al., 2013). The DOE funded a pilot scale operation and testing of syngas chemical looping for H_2, and Alstom carried out research on chemical looping for high-hydrogen syngas for power generation and/or liquid fuel production.[*] The production of syngas with a higher H_2 content may also be achieved by developing catalysts for the gasification of coal with steam, and the relevant chemistry is discussed in Chapter Seven of this volume.

The DOE reports the following activities during 2018:

> R&D is focused on developing and demonstrating advanced power generation and carbon capture, utilization and storage technologies for existing facilities and new fossil-fuelled power plants by increasing overall system efficiencies and reducing capital costs. In the near-term, advanced technologies that increase the power generation efficiency for new plants, and technologies to capture carbon dioxide (CO_2) from new and existing industrial and power-producing plants are being developed. In the longer term, the goal is to increase energy plant efficiencies and reduce both the energy and capital costs of CO_2 capture and storage from new, advanced coal plants and existing plants. These activities will help allow coal to remain a strategic fuel for the nation while enhancing environmental protection.[†]

The DOE also seeks to facilitate partnerships with industry, and academic researchers, in the areas of solid oxide fuel cells, stress and geomechanical impacts in the subsurface related to CO_2 storage, pre-combustion carbon capture, and advances in fossil power system operation and economic performance.[‡]

---

[*] For more information, see https://www.netl.doe.gov/research/coal/energy-systems.
[†] For more information, see https://im-mining.com/2018/11/13/advancing-coal-power-plants-future.
[‡] For more information, see https://www.energy.gov/fe/science-innovation/office-clean-coal-and-carbon-management.

Japan imports its energy, and the goal of the Japanese effort is to ensure a secure and sustainable supply of coal; to this end, Japan relies on access to reserves of coal such as are found in the USA, Europe, China, Indonesia, India and Australia. The JCOAL Program undertakes activities to identify and characterise overseas coal resources, and provide assessments of the technological capabilities required by Japanese coal importers and users. Japan has a greater focus on developing plants of increasing efficiency (and a resulting lower coal use), such as SC and USC plants, as part of their power generation mix (JCOAL, 2007). The overall strategy of the Japanese CCT Program has been technical innovation in the use of coal to fuel their power generating industry. This extensive and wide ranging program places considerable emphasis on the future use of various forms of coal gasification technologies, such as IGCC and integrated coal gasification with fuel cell combined cycles. Additional effort has gone into coal-derived synthesis gas conversion into liquid fuel or chemical raw materials, such as methanol and DME, as an alternative to diesel, and gas to liquid hydrocarbons for diesel production. The ultimate goal of the JCOAL is also zero CO_2 emissions coal-fuelled plants.

The European Commission has allocated the largest portion of its funding to collaborative research and innovation, which includes renewable sources and improving the efficiency of electricity use in homes and offices in cities. The EU effort on CCT has been mainly on carbon capture and storage from high efficiency coal-fuelled plants. The EU Commission added the “Energy Technologies and Innovation” in 2013 to respond to new challenges and to consolidate research and innovation across Europe. The activities included the “Horizon 2020 Energy Challenge” which focuses on "Energy Efficiency", "Competitive Low-Carbon Energy" and "Smart Cities and Communities", and covers the full innovation cycle – from proof-of-concept to applied research, pre-commercial demonstration and market uptake. [*] The International Energy Agency (IEA) reported on EU achievements in the development of clean coal power generation technologies by improving the performance of pulverised coal-fired power plants, including reducing slagging and fouling of boilers, and improved environmental outcomes. The effort also included co-combustion and fluidised bed applications, the development and introduction of advanced power generation systems, and methods for CO_2 control (Minchener and McMullan, 2007). The IEA assessed the ongoing progress in coal-fuelled power generation and made a number of recommendations, including introducing policies that would reduce constructions of new subcritical

[*] For more information, see https://ec.europa.eu/info/publications/interim-evaluation-horizon-2020_en.

coal-fuelled plants, and instead encourage utilising commercially available, cost effective supercritical pulverised coal plants. The energy penalty associated with carbon capture and sequestration was also noted.

The DOE and JCOAL CCT programs have examined a wide range of coals to fuel various power generating plants, brought improvements in the environmental impact of current coal-fuelled subcritical plants, and contributed to the development and commercialisation of higher efficiency future plants. The DOE and JCOAL strategies are ultimately for future zero-emissions coal-fuelled systems that will include hydrogen in hybrid technologies based on enhanced coal gasification.

The US and China have undertaken a collaborative approach within the Clean Energy Research Centre, a program that encourages top researchers from both countries to develop technologies for clean energy. The program seeks technologies needed for an efficient and low-carbon economic future. This is wide ranging and includes advanced coal-fuelled technologies, and energy efficiency for buildings.

The uptake of higher efficiency SC and USC coal-fuelled plants has increased in China and Japan. Germany initially constructed SC and USC plants with steam temperatures of ≥550°C. Japan started constructing SC plants due to the 1970 oil crisis, and these power plants accounted for a significant proportion of generation plants in 1996, with an average annual growth of 27.3%. USC plants were introduced by 1993 and Japan was the driver of USC technologies during this period. China is reported to have built ten SC units during ~1990s, growing to 27 by 2010. From 2010 to 2020, larger power plants in China will be required to be SC, and about half of the new power plants will be USC (Horach et al., 2014). China has progressed the clean coal project, which includes USC coal-fired plants exceeding 100 GW, and the operation of a 250 MW integrated gasification combined-cycle demonstration power plant; the program includes water slurry gasification, dry feed pressurised gasification technology with a >2000 ton/day capacity, and the demonstration of CO_2 capture and storage, including enhanced oil recovery. Research on high temperature heat resistant alloy material has led to the demonstration of a 600 MW USC unit, which exceeds 700°C, to enable a system efficiency of 50-52%. A considerable proportion of China's coal reserves are low-rank coal and research is also ongoing to improve the quality of this coal.

Advanced higher efficiency coal-fuelled plants are developed by major suppliers of power generation plants. General Electric is part of a consortium undertaking a US DOE-led project to develop materials for USC plants that would operate with high pressure steam at 760°C. Siemens is developing new materials and turbines to operate at 600-700°C. Alstom reports a design-ready 500 MW turbine to operate at 700°C, but are concerned with the costly alloys required for such a plant (We, 2011). SC and USC plants operate with high generating efficiencies, and where applicable, combined heat and power may provide up to 90% total thermal efficiency (Mohn, 2008; Santoianni, 2015).

The IEA has undertaken a study of how high efficiency, low emission coal-fired power plants may contribute to the reduction of carbon dioxide emissions in the major coal user countries: Australia, China, Germany, India, Japan, Poland, Russia, South Africa, South Korea and the USA. These countries have differing coal-plant fleet ages and efficiencies, and different local conditions and policies which impact on the capacity to implement advanced technologies. The study provides an overview of the differing trends for these countries, showing their dependence on an aging coal-fuelled fleet, and the prospects for growth, or decline, in coal-sourced electricity (Barnes, 2015).

The advanced power generation plant uses expensive alloys operating at high temperatures and pressures, and it is imperative that the coal used to fuel such plants does not cause the corrosion or fouling of heat transfer surfaces. Most coals, and especially low rank coals, contain aggressive ash-forming constituents that may cause corrosion, erosion and fouling of boilers. High moisture in low rank coals is also unwanted. Effort is required to produce high quality, non-fouling and low-cost fuel for new power generation plants. A plethora of physical and chemical approaches to upgrading all coals have been performed by various organisations, and the major ideas are discussed in this volume. Various organisations have examined novel ways to utilise low rank coal, particularly by upgrading high-moisture low rank coal by drying, but few (if any) of these are commercialised. Modern drying technologies have been developed in Germany and the US. RWE's WTA dryer and GRE's DryFining™ system have been demonstrated successfully at a commercial scale, while Vattenfall's PFD dryer has reached pilot scale. Dry lignite has been used to fuel a new power station in Grevenroich-Neurath near Cologne; this operates at 43% efficiency with a flexible response to demand. These are major advances in developing high efficiency lignite-fuelled power stations (World Coal, 2014).

While a large number of low rank coal drying processes have been examined, few chemical methods have undergone extensive research to produce high quality coal. A process developed by Clean Coal Technology Pty Ltd, and an R&D program in collaboration with La Trobe University (CCT/LTU R&D), is discussed in this volume; this process chemically removes ash constituents at elevated temperatures and then uses the same heat to lower the moisture in coal. This process may also be used to add catalysts to low rank coals. The CCT/LTU R&D Program, which deals solely with the treatment of low rank coals, has defined process conditions to produce three high quality products with high heater content: (1) non-fouling coal, suited for high efficiency coal-fuelled plants such as SC and USC, (2) zero-ash coal suitable for direct coal-fuelled turbines, and (3) a catalytically loaded coal suited for the steam gasification of coal. The process is designed to be integrated with high efficiency coal-fuelled power generation plants, and is also integrated with gasification plants to produce high quality syngas.

Classifications of Coal and its Properties

Coal upgrading and beneficiation processing conditions are primarily based on the properties of the various coals, which are ranked as fuels based on their heat content. The low rank coals are peat, brown coal, lignite, and sub-bituminous, and the high rank coals are bituminous and anthracite. Table 1-1 shows the classification adopted by Coal Marketing International. Table 1-2 provides a range of properties for the majority of low rank coals. The US Geological Survey produced a detailed classification system for coals that includes elemental analysis, heating content, and accessibility for mining (Wood et al., 1983).

The heterogeneity of the coals poses considerable difficulties in developing chemical processes to improve their quality. Coal beneficiation has been practiced for a considerable period, with the majority of processes used to lower the ash content of high rank coals; some of these techniques may be applicable to sub-bituminous coals and lignites. The techniques for coal beneficiation are broadly physical, although recently chemical methodologies have been examined and discussed in the literature. The techniques discussed here are mostly for low rank coals, but occasionally high rank coal processes are also mentioned for illustration purposes.

An inexact, but useful, classification for coal processing is a division into two broad categories, namely hydrophilic (attracts and retains water) and hydrophobic (repels water). Low rank coals are hydrophilic due mainly to a greater proportion of oxygen functional groups within the organic coal matrix; these coals can be treated using aqueous acid-based chemistry. Hydrophobic coals can be washed with water to remove unwanted constituents, and as water is not absorbed by the coal, the treated coal can be separated from water without reducing the heating content. Hydrophilic coals will retain water and this must be removed after treatment to ensure a high quality product is obtained.

Table 1-1. Coal Properties and Rank*

	Moisture (ar)[a]	Volatile Matter (daf)[b]	Carbon (daf)	Calorific Value (ar)[c]	Oxygen (daf)
Peat	~75%	69 – 63%	<60%	3,500 kcal/kg	>23%
Lignite	35 – 55%	63 – 53%	65 – 70%	4,000 – 4,200 kcal/kg	23%
Sub-bituminous C	30 – 38%	53 – 50%	70 – 72%	4,200 – 4,600 kcal/kg	20%
Sub-bituminous B	25 – 30%	50 – 46%	72 – 74%	4,600 – 5,000 kcal/kg	18%
Sub-bituminous A	18 – 25%	46 – 42%	74 – 76%	5,000 – 5,500 kcal/kg	16%
High volatile bituminous C	12 – 18%	46 – 42%	76 – 78%	5,500 – 5,900 kcal/kg	12%
High volatile bituminous B	10 – 12%	42 – 38%	78 – 80%	5,900 – 6,300 kcal/kg	10%
High volatile bituminous A	8 – 10%	38 – 31%	80 – 82%	6,300 – 7,000 kcal/kg	8%
Medium volatile bituminous	8 – 10%	31 – 22%	82 – 86%	7,000 – 8,000 kcal/kg	4%
Semi-Anthracite	8 – 10%	14 – 8%	90%	7,800 – 8,000 kcal/kg	3.5%
Anthracite	7 – 9%	8 – 3%	92%	7,600 – 7,800 kcal/kg	4.5%
Meta-Anthracite	7 – 9%	8 – 3%	>92%	7,600 kcal/kg	5%

a – as received, often as-mined; b – dry ash free; c – kcal/kg= 0.0041868 MJ/kg.

As indicated by Tables 1-1 and 1-2, coal composition varies greatly, and coals can be found with properties outside those depicted in these Tables. Good quality high rank coals are exported, and their quality (and price) is

* For additional information see: http://www.coalmarketinginfo.com/advanced-coal-science/.