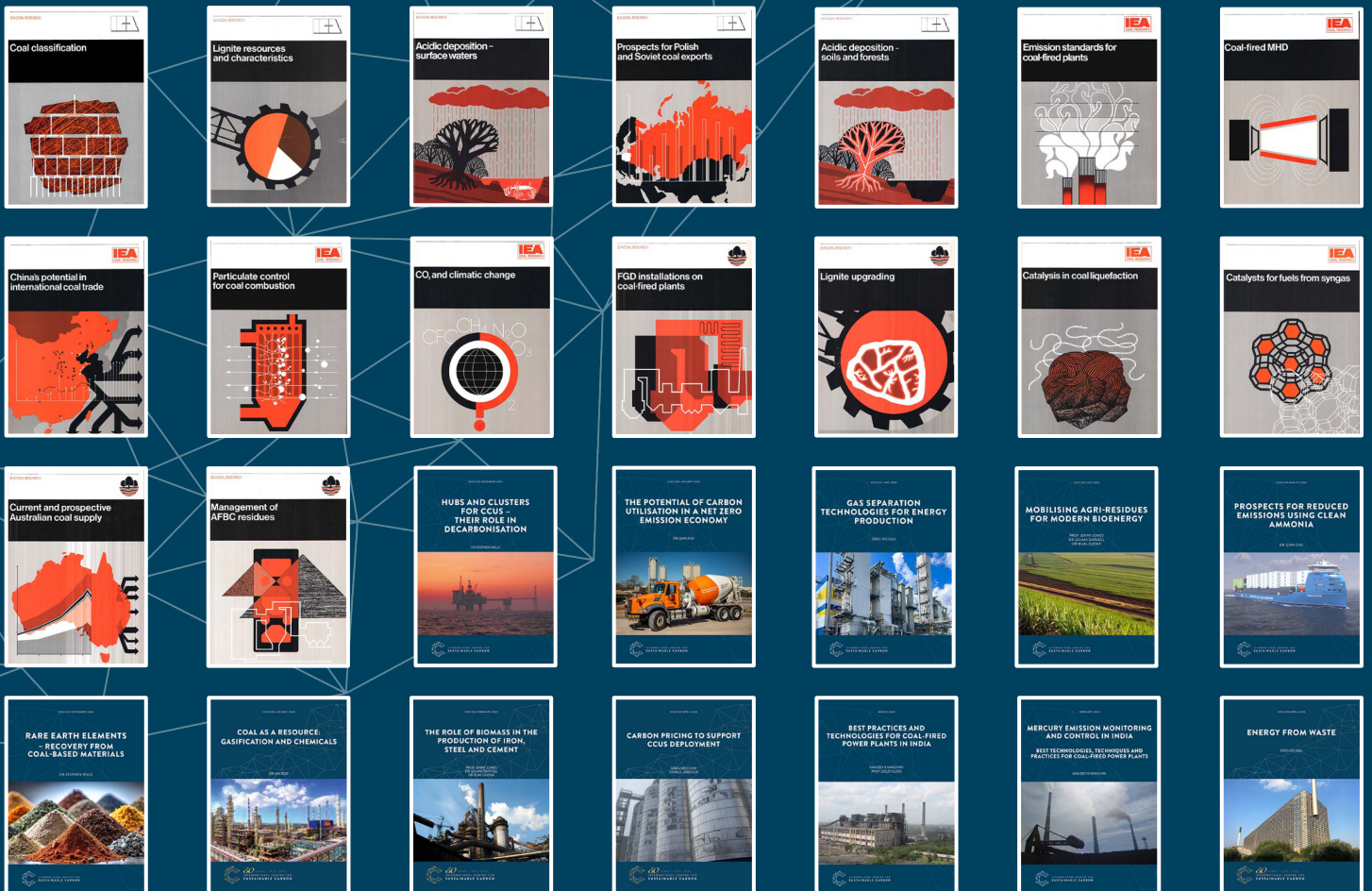


FIFTY YEARS OF COAL RESEARCH

PROGRESS TOWARDS LOW EMISSIONS COAL AND BIOMASS AND THEIR ROLE IN ACHIEVING NET ZERO

DR STEPHEN MILLS
DEBO ADAMS



50 YEARS | 1975-2025
INTERNATIONAL CENTRE FOR
SUSTAINABLE CARBON

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PREFACE

This report has been produced by the International Centre for Sustainable Carbon (ICSC). It should be understood that the views expressed in this report are our own and are not necessarily shared by our member organisations.

The International Centre for Sustainable Carbon was established in 1975 and has contracting parties and sponsors from Australia, China, Italy, Japan, and South Africa.

The overall objective of the International Centre for Sustainable Carbon was to continue to provide our members, the International Energy Agency (IEA) Working Party on Fossil Energy and other interested parties with definitive and policy relevant independent information on how various carbon-based energy sources can continue to be part of a sustainable energy mix worldwide. The energy sources include, but are not limited to coal, biomass and organic waste materials. Our work is aligned with the UN Sustainable Development Goals (SDGs), which includes the need to address the climate targets as set out by the United Nations Framework Convention on Climate Change (UNFCCC). We consider all aspects of solid carbon production, transport, processing and utilisation, within the rationale for balancing security of supply, affordability and environmental issues. These include efficiency improvements, lowering greenhouse and non-greenhouse gas emissions, reducing water stress, financial resourcing, market issues, technology development and deployment, ensuring poverty alleviation through universal access to electricity, sustainability, and social licence to operate. Our operating framework is designed to identify and publicise the best practice in every aspect of the carbon production and utilisation chain, so helping to significantly reduce any unwanted impacts on health, the environment and climate, to ensure the well-being of societies worldwide.

The International Centre for Sustainable Carbon is a Technology Collaboration Programme organised under the auspices of the International Energy Agency (IEA) but is functionally and legally autonomous. Views, findings and publications of the International Centre for Sustainable Carbon do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

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ABSTRACT

From 1975 to 2025, *IEA Coal Research* provided independent information and analysis to a global audience on all aspects of coal – its production, markets, transport, utilisation and environmental impacts. The Centre’s approximately 500 studies provide a legacy of technical, policy-relevant and independent information on how carbon-based energy sources such as coal and biomass, can be sustainable sources of clean energy, compatible with the UN Sustainable Development Goals.

The emphasis of the research evolved with the changing times and from the 1980s onwards there was a focus on how to reduce emissions from using coal and lower other environmental impacts. Methods include incorporating air pollution control technologies, improving efficiency, cofiring with other fuels such as biomass or ammonia, and adding carbon capture, utilisation and storage to power stations and to hard to abate industrial processes to minimise their climate impact.

Coal remains an important fuel for power generation and will do so for decades, particularly in Asia. Worldwide, coal is also a critical input for steel, cement and aluminium production, materials that are essential for economic development and the clean energy transition.

In addition, alternative uses for coal are being developed – as a feedstock for the chemical sector, and as a source of rare earth elements and other critical minerals for example. The by-products from coal combustion also have a value, such as fly ash in cement. On a policy level, the Centre made important contributions towards the development of many national and international regulations, policies and strategies intended to make energy production cleaner and more sustainable, while emphasising that there is ‘no one size fits all’ solution to such global issues. Although IEA Coal Research closed in 2025, its work remains relevant as the role for coal evolves and extends into the future.

ACRONYMS AND ABBREVIATIONS

ARIPPA	Appalachian Region Independent Power Producers Association, USA
AUSC	advanced ultrasupercritical
BECCS	bioenergy with carbon capture and storage
CCGT	combined cycle gas turbine
CCT	clean coal technology
CCUS	carbon capture, utilisation and storage
CFBC	circulating fluidised bed combustion
COP	Conference of the Parties, UNFCCC
CREA	Centre for Research on Energy and Clean Air
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
DOE	Department of Energy, USA
DOS	Department of State, USA
ELV	emission limit value
ESP	electrostatic precipitator
FBC	fluidised bed combustion
FGD	flue gas desulphurisation
HELE	high efficiency, low emissions
IEA	International Energy Agency
IEA CCC	International Energy Agency Clean Coal Centre
ICSC	International Centre for Sustainable Carbon
IGCC	integrated gasification combined cycle
KP	knowledge partner
LNG	liquefied natural gas
NCB	National Coal Board, UK
NDC	Nationally Determined Contribution
NGO	non-governmental organisation
NSCR	non-selective catalytic reduction
NZE	net zero emissions
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PCC	pulverised coal combustion
PFBC	pressurised fluidised bed combustion
RD&D	research, development and demonstration
REEs	rare earth elements
SC	supercritical
SCR	selective catalytic reduction
SDG	Sustainable Development Goal, UN
TCP	Technology Collaboration Programme, IEA
UNECE	United Nations Economic Commission for Europe
UN	United Nations

UNFCCC	United Nations Framework Convention on Climate Change
USC	ultrasupercritical
VRE	variable renewable energy

Note: all monetary values are in United States dollars (\$) unless otherwise stated.

UNITS AND CHEMICALS

°C	degrees Celsius
gCO ₂	grammes of carbon dioxide
Gt	gigatonne
MPa	megapascals
Mt	million tonnes
Mtoe	million tonnes of oil equivalent
MW	megawatt
MWe	megawatt electric
MWh	megawatt-hour
TWh	terawatt-hour

CO ₂	carbon dioxide
NO	nitric oxide
NO ₂	nitrogen dioxide
NO _x	nitrogen oxides
SO _x	sulphur oxides
SO ₂	sulphur dioxide
SO ₃	sulphur trioxide

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1 THE LAUNCH OF IEA COAL RESEARCH

In the 1950s, the use of oil increased rapidly as it became a major driver of industrialised economies. Between 1960 and 1972, its share of worldwide energy consumption increased from 35% to 42%. Thus, when Arab members of the Organization of the Petroleum Exporting Countries (OPEC) imposed an embargo on the USA and several other countries that were supporting Israel during the Arab-Israeli War, the resulting oil crisis of 1973 had a serious impact on the Global North. Petroleum exports to these countries ceased and cuts in oil production were introduced. The result was sudden increases in global oil prices and takeovers of foreign-owned oil production by the producing countries. The vulnerability of many industrialised nations and their heavy dependence on imported oil products was clearly exposed. Henry Kissinger, then US Secretary of State, recognised the importance of international cooperation to strengthen energy security and diversify energy sources and suggested the formation of an International Energy Agency (IEA). As a result, the IEA was founded in November 1974 as a Paris-based autonomous intergovernmental organisation under the framework of the Organisation for Economic Co-operation and Development (OECD) (Figures 1 and 2).



**Figure 1 International Energy Conference 1974 which led to the formation of the IEA.
US Secretary of State Henry Kissinger on left**

The IEA had a broad mandate to foster improved energy security through cooperation on energy policy between major consuming nations. Its initial aims were to avoid similar future shocks by helping to ensure reliable energy supplies, to provide data and statistics about global oil market and energy sectors, to promote energy efficiency, to ensure energy security, and to encourage technological

research and innovation via international collaborative programmes. The original membership included 17 industrialised countries that accounted for 60% of global energy demand.



Figure 2 Signature of the agreement establishing the IEA, 18 November 1974

Over the following decades, the IEA's role expanded to cover many other aspects of the global energy system, encompassing coal, natural gas, nuclear power, renewable energy sources such as biomass, solar and wind, carbon capture, use and storage (CCUS), and hydrogen production and use. More recently, the IEA has included analysis of the sustainable provision of rare earth elements and other critical minerals needed for many of the technologies crucial in driving the energy transition.

IEA member countries are all part of the OECD; association countries are affiliated with the IEA and are allowed to participate in its work but are not members of the OECD – one of the main criteria for IEA membership. As of 2025, the 32 member countries are Australia, Austria, Belgium, Canada, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, South Korea, Spain, Sweden, Switzerland, Türkiye, the UK and the USA. The 13 association countries include Brazil, China, India, Indonesia, Thailand, and Ukraine. The four countries seeking membership are Chile, Colombia, Costa Rica and Israel.

The core activity of the IEA remains the provision of policy advice to its members to support their energy security and advance their transition to cleaner sources of energy. It continues to maintain a focus on supporting global efforts to accelerate a transition to cleaner sources, mitigate climate change, and achieve net zero emissions (NZE). By 2025, two-thirds of IEA member governments had

committed to reaching emission neutrality by 2050 and among association countries, Brazil by 2050, China and Indonesia by 2060, and India by 2070.

1.1 TECHNOLOGY COLLABORATION PROGRAMMES

An important function of the IEA is to provide a structure for international cooperation on topics related to energy technology research, development and demonstration (RD&D). The overarching goal is to bring together expertise and organisations with common aims to jointly address energy-related issues and share their findings.

These initiatives are known as Technology Collaboration Programmes (TCPs). TCPs have contributed significantly to speeding up technological progress and innovation, reducing costs, and have been instrumental in minimising technical risks and avoiding duplication of effort. Effective dissemination of results and findings is an essential part of each TCP. Thus, TCPs can provide significant benefits to researchers, technology developers, governments, and others.

Since the foundation of the IEA, more than 80 collaborative initiatives have been launched, covering nearly every aspect of energy technology – from renewables and smart grids to hydrogen, carbon capture, and next-generation fuels. TCPs are organised under the auspices of an Implementing Agreement, which sets out the purpose, management and implementation of the TCP. Each TCP is overseen by an Executive Committee (ExCo) comprising representatives of each participating member country or sponsor. The ExCo members fund the TCPs, and decide on the work programme and the management of each Programme. In 2024, TCPs involved over 6000 experts worldwide who represented nearly 300 public and private organisations from 55 countries. In 2025, there were around 40 TCPs in operation.

1.2 IEA COAL RESEARCH

The first TCP of the IEA to be launched was IEA Coal Research which opened in November 1975 (Figure 3). The decision was made to base the organisation in London, due to the wealth of relevant expertise and experience within the UK's National Coal Board (NCB) at the time. The ten founding members, known as Contracting Parties, who signed the Implementing Agreement on 20 November 1975 were Austria, Belgium, Germany, Italy, the Netherlands, Spain, Sweden, Turkiye, the UK and the USA.



Figure 3 Leslie Grainger, British Coal Board, Dr Ulf Lantzke (Executive Director, IEA), Alex Eadie MP and Sir Derek Ezra, Chair of the National Coal Board, signing the document that opened the new NCB (IEA Service) Ltd office in London, September 1976

The Centre is best known for its reports, around 500 of which have been published since it opened for business in 1975. The reports cover the whole of the coal chain, including topics such as country studies and coal markets; emissions and control; carbon dioxide (CO₂) mitigation; pollution control technologies; residues and their management; coal properties and analysis; combustion; environmental policy and legislation; mining, production and preparation; power generation; conversion and industrial use of coal; coal gasification; and alternative uses of coal.

It is interesting to look back through the library and see how subjects have waxed and waned. For example, in the last few years, there has been more interest in the integration of coal-fired power generation with variable renewable energy (VRE) than mining and coal preparation. There has also been an increase focus on the ongoing role of coal and biomass in the energy transition. The Centre's first report on the link between CO₂ emissions and climate change was published in 1978, four years before the Earth Summit and before the first assessment report of the Intergovernmental Panel on Climate Change.

In the 2000s, the Centre published various reports on CCUS. Despite calls by the G8 and then G20 to invest in CCUS, the global financial crisis led to a protracted period of lower growth and the anticipated investment in CCUS was not forthcoming. In 2005, the IEA had been asked by the G8 to identify the steps needed to accelerate the implementation of radical technology changes, including in coal use for power generation. With the assistance of the Centre it produced a 'Technology Roadmap: High-Efficiency, Low-Emissions Coal-Fired Power Generation' in 2012.

HELE technologies have the potential to reduce emissions of CO₂ by over 20% if a supercritical plant replaces a subcritical one, and further advances in China have resulted in some plants running at around 50% efficiency (compared to the global average of 37.5%). Another advantage of HELE plant is that all emissions are reduced per kW generated, not just those of CO₂. The Centre has also reviewed the best options for reducing emissions from ‘hard to abate’ industries which remain coal-dependent such as the production of cement, iron and steel – improved efficiency and CCUS should have a major role, as well as some fuel substitution. Other themes to emerge include reducing water stress and ensuring poverty alleviation through universal access to robust and reliable electricity, together with other sustainability and socially-led goals.

The amount of coal used for power generation has decreased in the Global North this century, but interest is growing in alternative uses for coal, such as the coal-to-chemicals sector, high-value carbon-based products such as graphene, and the extraction of rare earth elements (REEs).

Throughout its fifty-year life, supported by a range of national governments and sponsors, the Centre remained the world's foremost provider of information on the clean and efficient use of coal, particularly low emission technologies, in a balanced and objective way, without political or commercial bias. It provided independent information and analysis on coal-related trends and all aspects of coal production, transport, processing, and utilisation, within the rationale for balancing security of supply, affordability, and environmental impacts.

The Centre's main areas of work included:

- In-depth topical reports and reviews on technological developments for the cleaner use of coal, and their impacts on relevant markets and policies;
- Provision of technical, environmental, and policy-related advice to academia, technology developers and suppliers, and governments;
- Maintenance of online databases addressing various aspects of coal research, production, and utilisation;
- Extensive outreach activities, particularly in developing and industrialising economies. For example, participation in the negotiations for the Minamata Convention on Mercury;
- Facilitation of research and development networks;
- Provision of support to industry professionals and others through organisation of international workshops and conferences; and
- Collaboration with other multilateral organisations to facilitate the use of low emissions coal, especially in emerging economies. This included the Asian Development Bank, Electric Power Technology Platform (IERE) of Japan, Euracoal, the IEA Coal Industry Advisory Board (CIAB), the Japan Organization for Metals and Energy Security (JOGMEC), the United Nations Economic Commission for Europe (UNECE), the UN Environment Programme

(UNEP), the US Department of State, US Agency for International Development (USAID), and the US Department of State (USDOS).

The overarching aim of the Centre was to support the use of sustainable carbon as a key part of the global energy mix, partly through the provision of independent information and analysis on how biomass, coal, and wastes could become cleaner sources of energy, compatible with the UN Sustainable Development Goals (SDGs).

1.2.1 Membership

The Centre was a non-profit making organisation, funded predominantly by members' subscriptions. Latterly, funding was also provided by various industrial sponsors and external contracts.

At different times, national governments and industrial partners from many countries were members of IEA Coal Research. Over the years, member countries included Australia, Austria, Canada, Denmark, European Commission, France, Germany, Italy, India, Japan, the Netherlands, New Zealand, Poland, Russia, South Africa, South Korea, Spain, Sweden, the UK and the USA. Sponsors included: Anglo Coal, Banpu, BHEL, BRICC, Coal Association of New Zealand, Danish Power Group, Eletrobras, EPPEI, Schlumberger, SUEK, and Vattenfall.

Members did not always have the same priorities, reflecting the diverse and ever-changing nature of both the global and national energy sectors and their interactions. For example, the USA directed considerable effort towards the development of advanced power systems and low emission coal technologies, and the recovery of rare earth elements from coal-based materials; the UK made significant progress in the development of fluidised bed combustion (FBC) technologies, and Germany developed efficient lignite-fired power generation (Figure 3). China made significant advances in the improvement and deployment of HELE coal power generation, and CCUS. Japan was always at the forefront in the development of ultrasupercritical (USC) coal-fired power generation and integrated gasification combined cycle (IGCC) technologies. As a major global coal producer, Australia made advances in coal mining techniques, primarily through the adoption of advanced automation technology. All such topics were accommodated via realignment of the Centre's work programme, helping to ensure that the requirements of all members were met through the provision of unbiased expert-led studies and supporting activities. As these priorities evolved, the Centre's work programme remained flexible, and expertise was developed so IEA Coal Research was able to adapt to meet members' requirements.

1.2.2 International cooperation

The Centre developed far-reaching and comprehensive connections with the global coal and environmental communities for half a century, leading to extensive international cooperation and forming strong links with a network of like-minded people and organisations from around the world.

These connections were instrumental in fully utilising the knowledge base created by the studies programme and other activities. An extensive outreach programme was used to deliver the key messages from Centre studies on all aspects of coal production, transport, and utilisation; to inform the debate on the cleaner use of coal and other fuels; and to encourage the take up of improved technologies, particularly in developing economies. This took the form of specialist workshops and conferences to support international cooperation on various sustainable energy options. The events brought together industry, researchers and academia to share insights and promote beneficial developments. The team also had a significant input to complementary meetings and conferences organised by other bodies.

Collaboration and support were provided to a wide range of government departments, such as the UK Parliamentary Office of Science and Technology, and national and international organisations that included Asia-Pacific Economic Cooperation, Asian Development Bank, Euracoal, Minerals Council of Australia, Sotacarbo, UNECE, UNEP, UNIDO, VGB, and the World Energy Council.

In the USA, input was provided to a range of government departments, sections, and laboratories that included the Department of Energy, Department of State, Environmental Protection Agency, Office of Scientific and Technical Information, National Energy Technology Laboratory, Congressional Research Service, Environmental Defense Fund, Agency for International Development, and US Energy Association. As part of this, several major US-funded projects were undertaken. For example, funded by the Department of State, the Centre evaluated emissions from the Indonesian coal fleet, unit-by-unit, to inform strategic fleet operation and emission reduction strategies, an approach then replicated in Vietnam.

The Centre also made significant contributions to the IEA, the IEA Coal Industry Advisory Board, and other IEA Technology Collaboration Programmes, as well as providing input to innumerable academic papers and reports. For example, a series of case studies were produced on different types of coal-fired power plants around the world for the IEA as part of a remit from the Climate Change Action Plan G8 Summit of 2005. The summit was attended by Heads of States of G8 Governments, together with leaders from African countries, from China, Brazil, India, and Mexico as well as with representatives of the International Monetary Fund (IMF), World Bank, World Trade Organization (WTO), and the IEA. Building on the work of the Centre, the IEA was tasked with producing a global study of recently constructed plants, to assess which were the most cost effective, with the highest efficiencies and lowest emissions. The informative Centre report subsequently produced was circulated widely, providing useful input, observations, and recommendations on the effectiveness and operation of a range of coal-fired technologies, and comparing them with alternative systems.

There was also involvement in Coaltrans conferences that took place in countries that included China, Egypt, India, Indonesia, Spain, Singapore, the UK, the USA, and Vietnam, with the Centre involved in the provision and organisation of various training courses and other outreach activities.

Alongside more formal activities, there were innumerable occasions where the Centre provided private and off-record advice to academia, power plants, utilities, and governments, supplying guidance on best practices and delivering insight on compliance strategies. For example, information and suggestions for effective particulate control systems and strategies were supplied to the South African utility Eskom. These actions were a key part of the Centre's outreach activities that focused on sustainable energy and environmental issues via capacity building and training related to low carbon emissions technologies, especially in developing countries.

Examples of major Centre outreach activities are given in Table 1.

TABLE 1 EXAMPLES OF MAJOR CENTRE OUTREACH ACTIVITIES		
Title	Dates	Location
CARBON MANAGEMENT WORKSHOP	2025	Japan
9 COFIRING BIOMASS WORKSHOPS	2011-2020	China, Denmark, Japan, Netherlands, UK, USA
9 CLEAN COAL TECHNOLOGIES CONFERENCES	2001-2019	Germany, Greece, Italy, Poland, Spain, USA
5 ADVANCED ULTRASUPERCRITICAL POWER GENERATION WORKSHOPS	2012-2017	China, Italy, Japan
15 MERCURY AND MULTIPOLLUTANT EMISSIONS FROM COAL WORKSHOPS	2014-2019	India, Poland, South Africa, USA, Vietnam
UPGRADING AND EFFICIENCY WORKSHOP	2014	China
HIGH EFFICIENCY, LOW EMISSION POWER GENERATION WORKSHOP	May 2016	Japan
SUSTAINABLE COAL USE IN SOUTH AFRICA	April 2017	South Africa
3 ENERGY TRANSITION WORKSHOPS	2022-2024	Italy, South Africa
NEW EMISSION REDUCTION POLICY IN INDONESIA	2021	Indonesia, online
FLEXIBILITY FOR POWER PLANTS	2022	India
CONTINUOUS EMISSION MONITORING	2022	India
STRATEGIES FOR EMISSION REDUCTIONS	2023	Indonesia
IMPROVING ENVIRONMENTAL PERFORMANCE	2023	India

In other work, the Centre established *Flex India*, a collaboration between Indian utilities which meets annually, under EPRI guidance, to discuss coal plant flexibility issues.

Through collaboration and knowledge-sharing, the Centre's work was made freely available and disseminated widely, providing information on the latest technological advances in, for example, coal-fired power generation and low emission coal technologies in general, to countries in desperate need of reliable, affordable electricity.

Many of the Centre's specialist workshops, conferences, training courses, and other outreach activities were embraced by the global energy and environmental communities, and although organisation has since passed to other bodies, they will continue to provide a platform for the dissemination of information on energy and environmental topics that have increasingly taken centre stage over the past few decades.

This report describes the work of IEA Coal Research, and its role in the development and uptake of low emission methods, technologies and policies to encourage the more sustainable use of coal and biomass. The work is divided into key subject areas which illustrate the influential nature of the Centre's output. However, as a short study, it cannot give a comprehensive coverage of the Centre's diverse output.

2 COAL MARKETS

Global coal demand grew rapidly from 1975 to 2025, although the distribution of demand shifted as populations increased in Asia and economies developed. High demand in Europe and North America declined with the rise of natural gas and increased uptake of renewables. In much of Asia, there is less natural gas available, and although there has been an increased use of renewables, growing demand has led to a huge increase in the use of coal. Throughout this period, IEA Coal Research was on hand to provide expert advice and analysis on how to produce and use this resource efficiently to provide reliable power supplies to support economic growth and development.

2.1 GLOBAL COAL DEMAND

The dramatic growth in demand for coal during the period 1975-2025, illustrates neatly the importance of an international organisation such as IEA Coal Research in guiding the use of this vital resource. In 1975, global coal production was 3.29 gigatonnes (Gt), rising to 3.61 Gt in 1980, and 4.15 Gt in 1985. By 2021, the amount of coal used worldwide was nearly 8 Gt. In 2024, global coal demand grew by 1% to an all-time high of 8.77 Gt and the three largest producers – China, India and Indonesia – reached new records for output. Australia is set to become the fourth largest producer by 2027, surpassing the USA and Russia. Although industrial consumption also increased in the early 2020s, the power sector has been the main driver of growth in coal demand, with electricity generation from coal reaching an all-time high of 10,700 terawatt-hours (TWh) in 2024 (IEA, 2024).

Figure 4 illustrates global coal consumption through the 21st century.

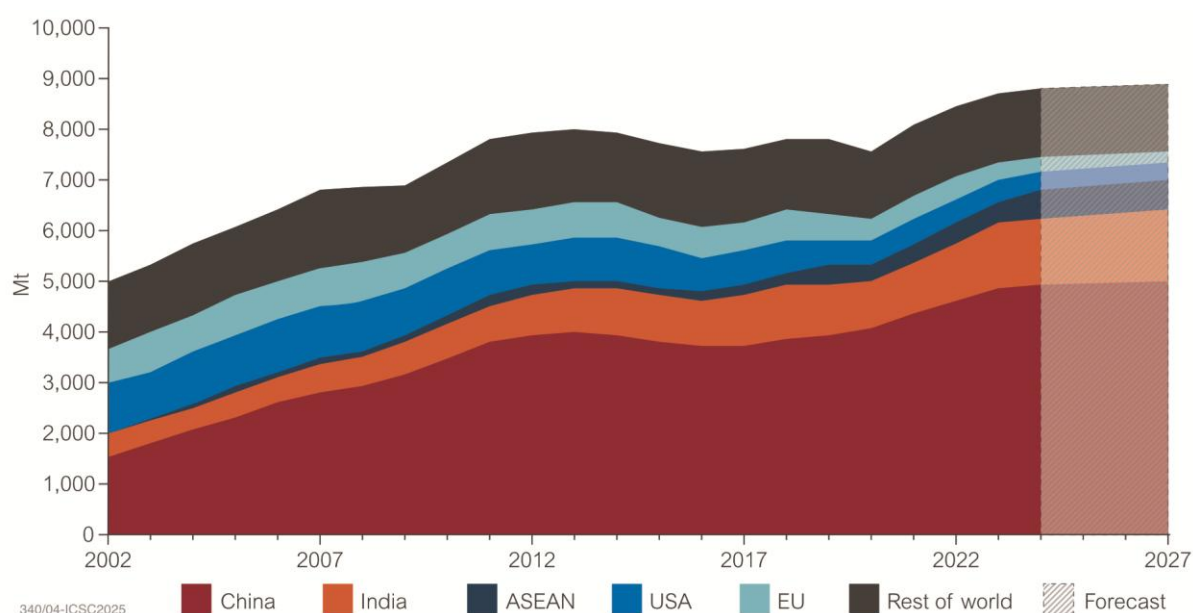


Figure 4 Global coal consumption 2002-27 (IEA, 2024)

Demand from the power generation and industrial sectors has continued to increase in some emerging economies where electricity demand is rising sharply, driven by economic development and population growth (Figure 5). Despite repeated predictions that global demand would plateau in the period up to 2025, this has failed to materialise. Furthermore, as has been seen on several occasions, unforeseen global events could impact energy markets, potentially driving up demand further. Factors can include extreme weather events, fuel price shocks, government policies, pressures on energy markets, international conflict and, global economic activity in general.



Figure 5 Coal train, South Africa (courtesy of Anglo America)

2.2 CHINA

Chinese coal production, in particular, began an upward trend in the 1970s that has continued (Minchener, 2004). Production rose from 483 Mt in 1975, to 620 Mt in 1980, 837 Mt in 1985, and reached a record 4900 Mt (4.9 Gt) in 2024, roughly a 10-fold increase over 50 years (IEA, 2024).

As one-third of all the coal consumed worldwide is burned in power plants in China, the country's electricity sector is the main driver of global coal markets. Electricity demand in China is increasing significantly, due to two main drivers: the electrification of services previously provided by other fuels, such as transport and industrial heat, and emerging industries such as data centres and AI (IEA, 2024).

2.3 INDIA

India has the world's third largest hard coal reserves, after the USA and China. Figure 6 shows the growth in energy supply, population and GDP in India from 1978 to the end of the last century. In 2000, India's population reached 1 billion, hard coal production was 310 Mt, and consumption was

317 Mt. The largest consumers were the electric power sector (67%), iron and steel (13%) and the cement industry (13%). About 75% of India's electricity was generated from coal. Between 2000 and 2022, Indian coal production increased by 166%, and it provided over 70% of electricity generation. Demand grew over 5% in 2024 to 1.3 Gt, a level that only China has reached previously.

In 1975, Coal India Ltd acquired the title to, and the right to manage, all mines owned by the national government. By 2000-2001, with an annual output of 268 Mt, Coal India was the world's second-largest coal supplier after the Russian mining company Rosugol. It had a total workforce of some 562,000 employees at this time, making it the world's second-largest employer after General Motors.

As India's population is 1.36 billion (2025) and the economy is fast-growing, energy demand is increasing rapidly as the country continues to urbanise and the manufacturing sector develops. This growing demand is met through various energy sources, with coal the largest source of energy supply. India is expected to see the largest increase in coal use in the coming years, driven by consumption from the power sector and industry. In addition, the Government of India has made considerable progress in providing access to electricity and clean cooking while implementing a range of energy market reforms (IEA, 2023).

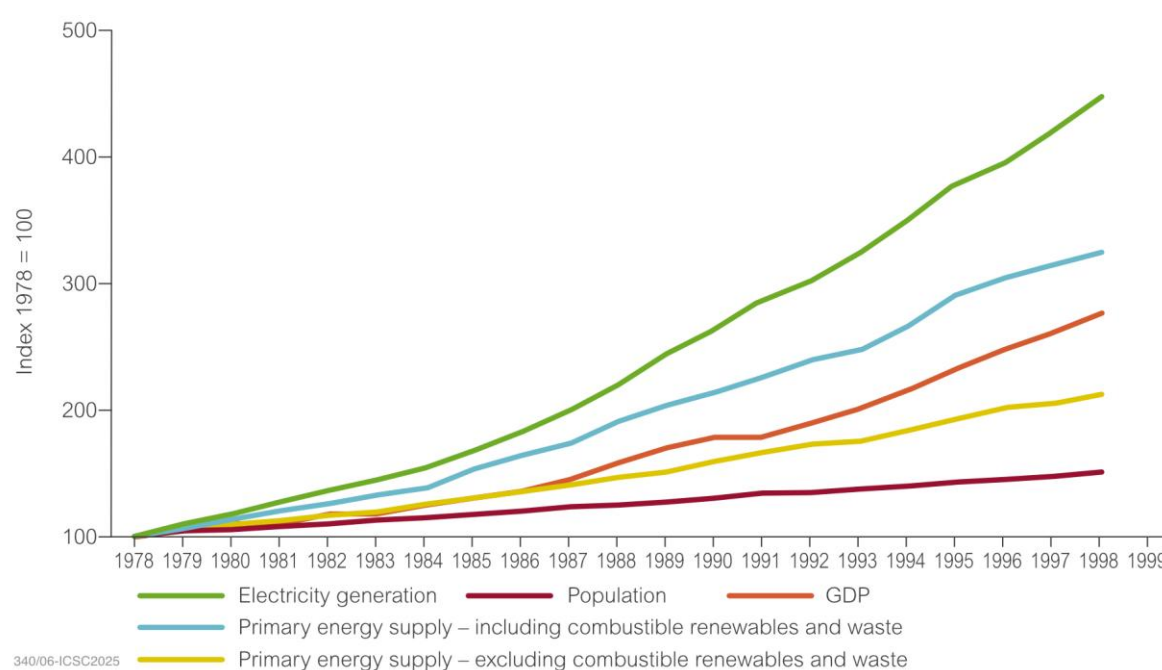


Figure 6 Growth in energy supply, population and GDP (IEA/OECD, 2001)

Figure 7 shows how although coal's share of the energy supply in India has reduced, the total amount of coal used has increased, as demand has expanded.

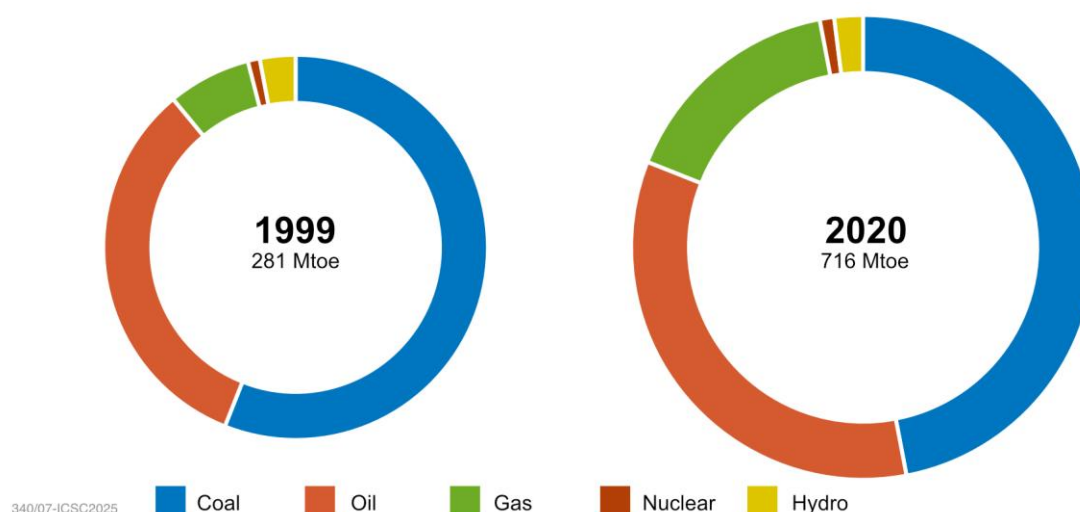


Figure 7 Supply of coal, oil, gas, nuclear energy and hydro (IEA/OECD, 2020)

IEA Coal Research published some important reports about India over the years, including most recently ‘A pathway to reducing emissions from coal power in India’ (Adams and others, 2021), which explored the difficulties in India in meeting emission limits for SO_x and NO_x, and identified solutions. It also examined the potential for CCUS and developments in this sector. Prospects for HELE power plants in India were examined by Barnes (2016).

2.4 EUROPE AND THE UK

Coal demand in most advanced economies peaked a few years ago and is falling, although the trajectory varies by region or country. In Europe, hard coal capacity fell from the 1980s onwards as mines became exhausted and output became uncompetitive against third-country imports (Daniel and Jamieson, 1992). The closure of the last coal power plant in the UK in September 2024 was a symbolic moment for a country where coal had powered the industrial revolution (IEA, 2024). By 2025, the amount of coal consumed in the EU and the USA combined will be less than half the amount used in India (see Table 2).

TABLE 2 COAL PRODUCTION PROJECTIONS, MT (IEA COAL RESEARCH ESTIMATE)				
	1970	1980	1990	2000
Hard coal				
Belgium	11	8	1	–
France	37	20	11	2–5
Germany	117	95	77	37–52
Greece	–	–	–	–
Spain	11	13	20	8–14
UK	145	130	89	30–60
Total	321	266	198	77–131
Brown coal/lignite				
France		3	1	–
Germany		388	356	180–220
Greece		23	50	65–75
Spain		16	16	10–12
Total		430	423	255–307

In Europe, this century, there was a growing reliance on gas piped directly from Russia, although following the latter's 2022 invasion of Ukraine, sanctions reduced EU dependence from 45% in 2021 to 15% in 2023. Despite sanctions, some Russian gas continued to arrive in the EU via third parties in the form of liquefied natural gas (LNG), although Europe's gas supplies increasingly switched to suppliers such as Norway, the USA, North Africa, and Qatar. However, in 2025, the EU remained dependent on gas imports.

2.5 USA

Between 1981 and 2023, the most coal produced in the USA was 1063 Mt in 2008 and the lowest amount was 487 Mt in 2020. In 2023, 526 Mt was produced, less than half the amount produced in 2008 (CEIC, 2021). The US EIA expects that US coal production will continue to decline. While environmental regulations have contributed to coal's decline, most of it is due to economic factors, as natural gas and renewable energy resources have proved less costly to produce electricity. As of 2025, there are just over 200 coal-fired power stations operating, accounting for 16% of total electricity generating capacity, whereas at the turn of the century, it produced about half of US electricity (Proctor, 2025).

In 2009, coal's share in the US power mix was 45%, and gas was 23%. A decade later, the situation had almost reversed, with coal's share falling to 24%, and gas accounting for 38% of the country's power

generation. This change was due largely to the rapid development of shale gas technology which resulted in a dramatic increase in gas production, driving down national and international prices, reducing national oil imports, and helping transform the country's energy landscape. The US shale gas revolution had an impact on the country's coal power sector, as low gas prices became a major factor in reducing coal demand.

2.6 COUNTRY STUDIES

The nature and importance of the global coal sector were recognised through the production of a series of **country and regional studies** that focused on aspects of the international coal trade and global coal production, uses, and consumption. These included assessments of many countries and their prospects for coal and low emission technologies, including Australia, Bangladesh, Bulgaria, Canada, China, Czech Republic, Greece, India, Indonesia, Italy, Japan, Kazakhstan, Malaysia, Mongolia, Mozambique, Namibia, Pakistan, the Philippines, Poland, South Africa, South Korea, Türkiye, Thailand, Ukraine, Vietnam, Zambia, and Zimbabwe and regions such as Africa, Asia-Pacific, Eastern Europe, Western Europe, North America, and Latin America (Figure 8). Individual studies examined energy resources available, coal demand and consumption, coal applications, environmental impacts associated with its use, and potential future demand. This type of study was to remain part of the Centre's output for much of its lifetime.



Figure 8 Bełchatów coal-fired power plant, Poland (courtesy of PGE)

For each country, the influence of government policies and environmental regulations were considered, and the scale and type of technologies that might be deployed were addressed. Their much-reduced emission levels of conventional pollutants and CO₂ attainable by HELE plants were

emphasised. Despite reduced coal power generation in the West, many Asian countries have young coal fleets some of which include HELE plants and will continue to rely heavily on these for many years (Kelsall and Baruya, 2022). In 2025, Asia was home to over 60% of the world's population and relied on fossil fuels for 90% of its energy needs. It was responsible for more than half of global CO₂ emissions emanating from fossil fuels. Asia's coal fleet provided 57% of the region's electricity.

3 ACID RAIN AND AIR POLLUTION

The term acid rain was first used by RA Smith in 1872 in his book *Air and Rain: The Beginnings of a Chemical Climatology*. Awareness of acid rain became widespread in Scandinavia in the late 1960s, when Svante Oden published his Ecological Committee Report (1968) which included a huge body of scientific and policy-relevant evidence that long-distance transport and deposition of acidifying pollutants were causing significant environmental and ecological impacts, even in countries far away from pollutant-emitting source areas in other countries.

Concern grew and an OECD project published a report in 1977, which concluded that “Sulphur compounds do travel long distances in the atmosphere and the air quality in any European country is measurably affected by emissions from other European countries” (OECD, 1977). These conclusions paved the road for a pan-European scientific collaboration on air pollution, the European Monitoring and Evaluation Programme (EMEP) starting in 1977. The findings from the project also formed the basis for the United Nations’ Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (LRTAP) signed in 1979. Eight protocols have been signed subsequently under LRTAP committing parties to take far-reaching actions, with respect to acid rain and several other air pollution issues. Emissions of all key air pollutants have been reduced significantly and for the most important acidifying compound, sulphur dioxide (SO₂) emissions in Europe have decreased by 80% or more since the peaks in around 1980–1990 (Grennfelt and others, 2019).

The threat to European forests was identified in the early 1980s and photos of ‘The Black Triangle’, of dying forests in the border regions between Poland, East Germany and Czechoslovakia, were widespread in the media. In this region, there was combustion of large amounts of brown coal with a high sulphur content. The growing interest in regional air pollution resulted in the Sulphur Protocol signed in 1985 and the Second Sulphur Protocol of 1994. The Gothenburg Protocol of 1999 took a multi-pollutant, multi-effect approach and considered the effects of acidic deposition, nitrogen deposition and ozone (Grennfelt and others, 2019).

The results of the emissions control regulations and actions taken are neatly summarised in Figure 9.

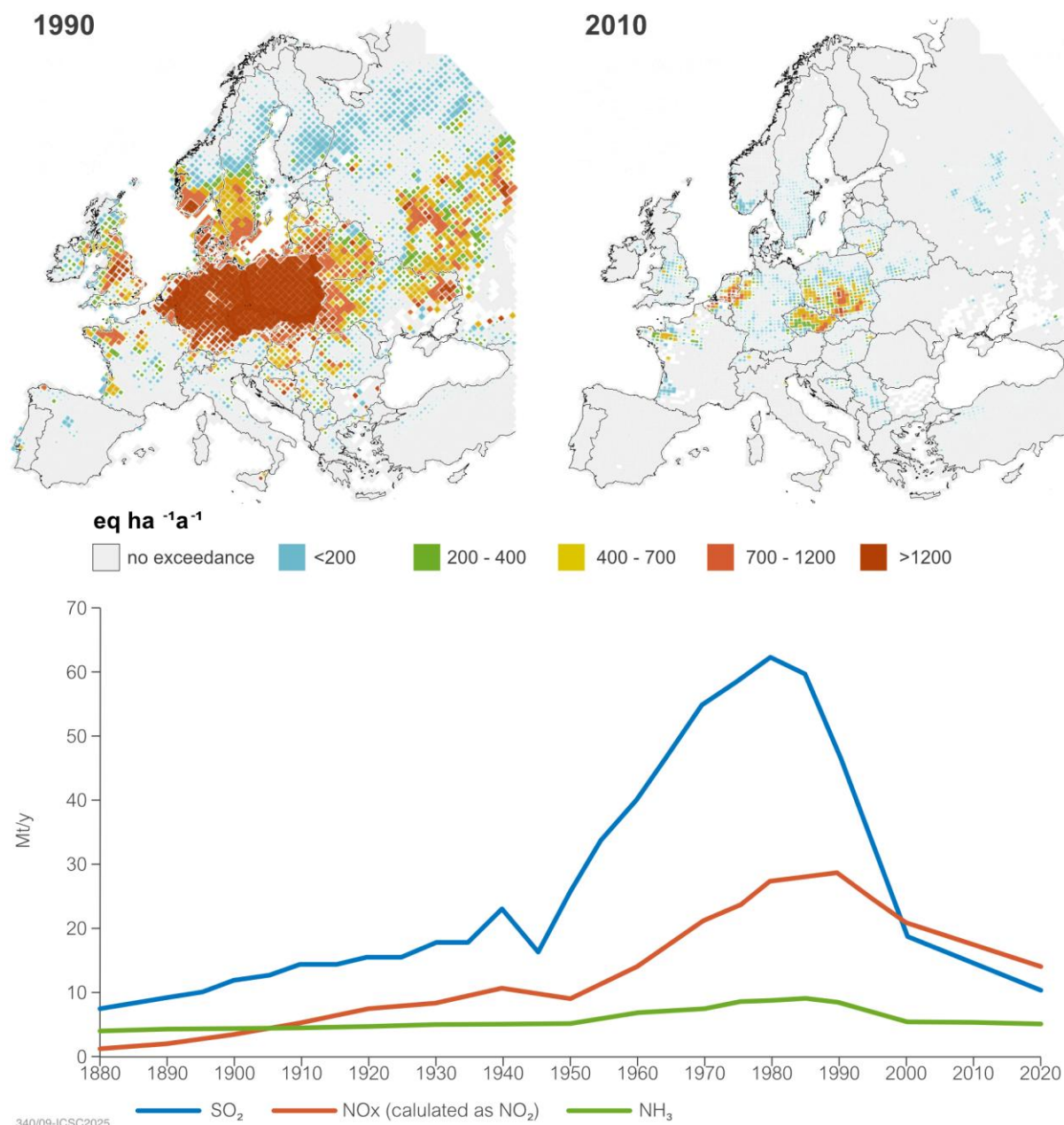


Figure 9 Map of Europe showing the outcome of emission control of SO₂, NO_x and ammonia between 1990 and 2010 (de Vries and others, 2015)

In the USA, a sulphur emissions trading programme for larger power plants was established under the Clean Air Act (Grennfelt and others, 2019).

IEA Coal Research was very active in reporting on the science of air pollutants that contributed to acid rain and promoted the technologies that were developed to control their emissions from coal-fired power plants. For example, the early 1980s were marked by the further development of NO_x control technologies, including the introduction of improved low-NO_x burners for power plants, and selective catalytic reduction (SCR) and non-selective catalytic reduction (NSCR) systems as secondary measures. All of these were the focus of Centre studies. There were also studies on newer techniques

for monitoring and controlling SO₂ emissions. At the time, several flue gas desulphurisation (FGD) variants were being installed in growing numbers around the world (Figure 10), and these and their respective effluent streams were studied. There were also reports examining the impact of different trace species such as alkali metals, halogens, and trace heavy metals released during combustion. Particulate control systems were also gradually improving, and developments to enhance capture efficiency and overall performance were monitored. The impact of ambient concentrations of PM₁₀ and PM_{2.5} (particulate matter smaller than 10 micrometres and smaller than 2.5 micrometres) on human health were also examined, as well as reviews produced on the technologies available for sampling and analysing these species, and their limitations.



Figure 10 FGD unit on UK coal-fired power plant (courtesy of Russell Mills Photography)

Some studies concentrated on air pollution and its control in several geographical locations. This included some of the first in-depth work addressing the environmental impact of the growing use of coal for power generation in South Asia (mainly India), a region characterised by increasing energy requirements, and a consequential growth in coal demand (Henderson, 2003).

Alongside studies that concentrated on practical, technological aspects of these technologies, other work examined the impact of SO₂, NO_x, and particulate emissions on human health, air, surface water, soils, and forests. Much of this work was set against a background of continuing in-depth reporting on coal chemistry and characteristics, and coal combustion mechanisms, necessary for the better understanding of reactions taking place and their impact in the wider world.

3.1 EMISSION STANDARDS

The Centre provided important data that was instrumental in the creation of national and international emission standards for coal power plants and industrial coal users – this was fed regularly into the development of national and international air pollution control policies (Zhang, 2016; Sloss, 2003). The Centre contributed to government efforts in Europe and North America to monitor emission levels and develop and enforce air pollution regulations. For example, in 1980, the US Congress passed the Acid Deposition Act, followed later by the first assessment of acid rain in the USA, provided by the US National Acid Precipitation Assessment Program. Stronger SO₂ and NO_x emission controls were introduced by the US Clean Air Act of 1970, along with similar measures in Europe – Centre studies contributed to many of the decisions taken.

The Centre maintained a database of emission standards relevant to coal combustion. The standards were freely available and aimed to cover the countries that set emission standards, including Australia, China, EU, France, Hong Kong, India, Indonesia, Japan, Kazakhstan, Malaysia, Pakistan, the Philippines, Russia, South Africa, South Korea, Taiwan, Thailand, Turkiye, Ukraine, United Arab Emirates, USA, and Vietnam. Because of their detail and easy availability, they were accessed widely by both government and non-government organisations, utilities, and academia.

3.1.1 Representation in international standards organisations

The Centre was represented on various industry and standards bodies; for example, the International Standards Organisation (ISO) Standards Committee, where advice was provided to compile new international standards for the measurement and monitoring of pollutants including PM_{2.5} and mercury, the European Committee for Standardization (CEN), the British Standards Institute (BSI) committee covering coal analysis, the Expert Committee of the International Conference on Coal Science and Technology, the European Conference on Coal Research and its Applications, and the UNECE expert group on coal mine emissions.

3.2 EMISSIONS CONTROL

As concern about emissions and the environmental footprint of energy production grew, it became evident that more accurate information on emissions of CO₂, SO₂, NO_x, and trace pollutants from fossil fuel power plants was needed, and the Centre assessed and reported on the effectiveness of current emissions monitoring and reporting strategies.

Advances in emission control systems continued to be made. At the time, electrostatic precipitators (ESPs) were the dominant type of particulate control in pulverised coal combustion plant, with fabric filters playing a smaller role. However, in many developed economies, environmental pressures and tighter regulations led to reduced emission limit values (ELV) for particulate matter, increasingly recognised as a threat to human health. A review was subsequently produced that examined emission

standards and control of small particulates from coal-fired power plant. Studies included assessment of particulate levels in parts of India, where excessive levels had been identified as impacting human health and increasing ground-level air pollution (Adams and others, 2021).

Advances continued to be made in the effectiveness and efficiency of FGD systems, although there were still some technical challenges to be overcome. For example, conventional FGD systems traditionally required large supplies of water, and technologies that reduced water demand became more important as large numbers of FGD units were installed to meet tightening emission regulations. Reducing water loss was particularly important in arid regions of the world, and the Centre reviewed commercial and near-commercial low-water systems that showed promise. Other work on FGD systems included assessment of non-calcium desulphurisation technologies, and advances being made in multi-pollutant control, capable of reducing combinations of emissions such as NO₂, NO, SO₂, SO₃, CO₂, particulates, and mercury.

3.2.1 Continuous emissions monitoring

In some cases, there was a focus on addressing specific pressing issues in an individual country. For example, there was a Continuous Emission Monitoring programme held in India in 2022. The coal-fired power sector is one of India's most polluting, with plants responsible for significant emissions of particulates, SO₂, NO_x, and mercury. A robust monitoring system delivered by continuous emission monitors (CEMs) was needed to accurately account for these emissions. The installation of CEMs throughout industrial sectors capable of delivering real-time data directly to the regulators was mandated in 2014, but implementation had been significantly delayed. Various potential issues with CEM installation, calibration, operation, and maintenance were identified, and work was undertaken to assess the status of CEMs in India. As part of this, the Centre proposed new guidelines on best practice in CEMs in India and made recommendations for improving CEM utilisation and data handling, as well as a roadmap for future capacity building among stakeholders. Significant challenges were identified concerning the calibration and reliability of these systems. Without appropriate training, there was a risk that emission data reporting would be inadequate and not sufficiently reliable to ensure that emission limits were met, and air quality goals achieved. To address this, the Centre held four regional workshops, bringing in expert trainers from the USA and Europe to deliver hands-on training with onsite instruments. Each workshop was supported by the regional State Pollution Control Board, ensuring that the training was delivered to both regulators and sources. Over 400 Indian delegates took part in the training.

3.3 MERCURY

Mercury is an element of growing global concern. IEA Coal Research had significant and long-running involvement in global efforts to minimise mercury emissions from the power sector, producing a series of reports that assessed the emerging markets for mercury control, and legislation, standards and

methods for its reduction (Sloss, 2012, 2015, 2017). Since the inception of the Coal Partnership area of UN Environment in 2007, IEA Coal Research, represented by Dr Lesley Sloss, was heavily involved and provided advice through all rounds of negotiation leading to the ratification of the Minamata Convention on Mercury in 2013. It is an international legally binding instrument to coordinate actions to reduce emissions of mercury. Advice continued to be provided throughout subsequent Conferences of the Parties (COPs).

UNEP funding allowed IEA Coal Research to create mercury emission inventories for the coal fleets of China, Indonesia, Russia, South Africa, Thailand and Vietnam, which encouraged them to ratify the Minamata Convention. Important input and advice were also provided to UN Industrial Development Organization (UNIDO) on mercury issues. Mercury emissions had been identified as a particular problem in some Asian countries, and in collaboration with the US Department of State, the situation was reviewed in India and Southeast Asia in the early 2020s.

Subsequent mercury-related Centre studies, led by Lesley Sloss, included:

- Mercury reduction at Indonesian coal plants – Minamata Compliance Strategy;
- Prospects for mercury emission reduction project finance in Indonesia;
- Reducing mercury emissions from the coal combustion sector in Indonesia; and
- Mercury emission monitoring and control in India – best technologies, techniques and practices for coal-fired power plants.

India was the second largest national emitter of mercury in the world, and coal contributed 80% of the country's total mercury emissions. Thus, monitoring and controlling emissions from the coal sector was identified as a priority. The complex behaviour of mercury in a coal plant needed to be understood fully to achieve sustainable cost-effective reduction, but only if the correct techniques and technologies were applied. Centre reporting summarised best practices to measure and reduce mercury emissions from the coal utility sector in India, focusing on the regional challenges. In addition, IEA Coal Research also established and ran 15 international workshops – Mercury and Multipollutant Emissions from Coal (MEC); the last one took place in Jakarta in 2023.

IEA Coal Research expertise and experience with many aspects of coal and its applications were shared widely, allowing comprehensive dissemination of ways to improve efficiency and reduce environmental impact in power generation and industrial applications via the provision of training courses for plant operators, coal researchers, and industry decision-makers. For example, training and capacity building were provided to India, through twelve regional workshops, on emissions monitoring and control on coal-fired plants, training over 1000 individuals, and providing legacy training materials for the future. Other activities in India included a MEC workshop, and a US Department of State energy efficiency workshop held in Chennai in 2015 (Figure 11). Similar activities addressing a range of topics took place in other countries.



Figure 11 Attendees of the MEC workshop held in Chennai on 16-20 November 2015 with IEA Coal Research's Dr Lesley Sloss (3rd from right)

4 HIGH EFFICIENCY, LOW EMISSIONS

Throughout the life of IEA Coal Research, coal power has remained a major source of the world's electricity. Many developed and developing countries depended heavily on coal to drive their power, industrial, and manufacturing sectors. IEA Coal Research studies examined the economics of coal power generation and how to improve efficiency and hence lower emissions per MWh. There was increasing emphasis on techniques to improve generating efficiency through the adoption of technological advances such as hot gas cleanup systems, advanced high-temperature syngas coolers, and the application and development prospects of double-reheat systems. Other studies included the application of increasingly resilient materials for plant construction, and power station upgrading and refurbishment, for example.

4.1 SUPERCRITICAL AND ULTRASUPERCRITICAL UNITS

In the early part of the 21st century, many coal-fired power plants operated on relatively low subcritical steam conditions. However, changes occurred in many power fleets, as operators moved away from older subcritical designs, adopting higher steam parameters offered by supercritical technologies, with the efficiency and environmental improvements they provided (Nicol, 2013) (Figures 12 and 13). Importantly, CO₂ emissions per unit of electricity generated were also reduced. This is neatly summarised in Figure 14.

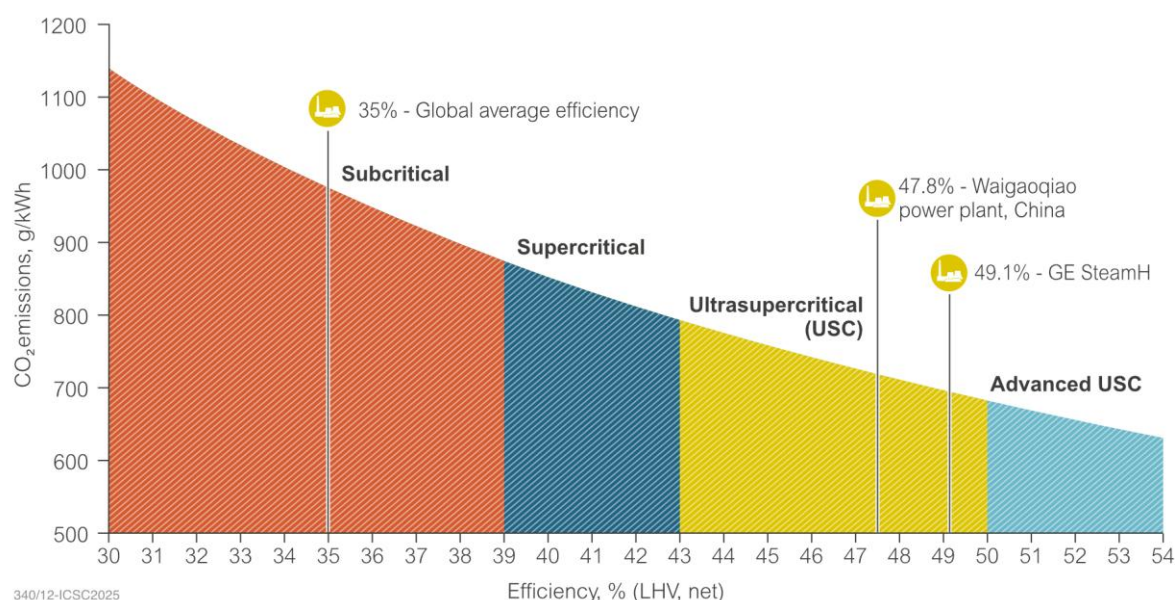


Figure 12 Increasing efficiency of coal-fired units with decreasing CO₂ emissions (IEA CCC, 2018)



Figure 13 1320 MW supercritical Sugoju power plant, Turkiye (courtesy of STEAG)



Figure 14 Supercritical lignite-fired Lippendorf power plant in Germany (courtesy of Alstom)

The first commercial supercritical (SC) steam-electric generating unit became operational in the late 1950s in the USA. However, materials available at the time were generally inadequate to support the technology successfully in these more challenging conditions, and operational problems were encountered. However steady advances in metallurgical technology were made, leading to the widespread acceptance of SC technology as a viable option. The scale of the global SC fleet slowly

increased – the Centre monitored industry developments and reported on the efficiency and environmental performance of these early plants, as well as the R&D initiatives underway, focused on the development of more advanced materials capable of tolerating even higher steam conditions (Wiatros-Motyka, 2016; Barnes, 2019). A supercritical plant is shown in Figure 14.

There was growing interest in many national power fleets in ways to increase the performance and effectiveness of coal-fired plants. Supercritical steam parameters became the norm for new plants, and attention turned increasingly towards the adoption of ultrasupercritical (USC) and advanced ultrasupercritical (AUSC) conditions.

The rate of uptake of supercritical technologies differed around the world - some countries remained hesitant, concerned about the higher Capex involved, and the need for more advanced materials (Mills, 2021). During this period, most materials available widely were operating at the limit of their capabilities, and subcritical plants continued to be the norm in some economies where they were established and understood, and where cost remained an issue. But as the availability of newer more advanced materials increased, there was a distinct upward trend in the uptake of SC technology (Lockwood, 2021a).

Steam conditions increased further over the years, and materials capable of operating under USC conditions were developed and became available commercially from multiple suppliers. USC offered even greater operational advantages than SC and came to be adopted for a growing number of plants. The first commercial coal-fired USC plant, the John W. Turk Jr. plant in the USA, came online in 2012. Other notable USC plants followed such as the 400 MW Nordjyllandsværket plant (Unit 3) in Denmark, the 750 MW Lunen plant in Germany, and the Isogo new 600 MW Units 1 and 2 in Japan (Figure 15). The latter operated at 600/620°C reheat, achieving 45% efficiency. Not only did they achieve significantly higher efficiency than earlier designs, but in the case of the Isogo units, emission levels were reduced to those of a natural gas-fired combined-cycle plant (NGCC). Combined, the two new units emitted 50% less SO_x, 80% less NO_x, 70% less particulates, and 17% less CO₂ than the older subcritical units they replaced.



Figure 15 Isogo USC units 1 and 2, 1200 MW coal fired plant, Tokyo Bay, Japan (courtesy of J-Power)

By 2013, there were 165 USC plants in operation around the world, together with 645 SC units, compared with 7880 subcritical units (Breeze, 2017). The uptake of SC and USC technologies was encouraged further by both government and multilateral agency intervention. For example, the OECD introduced stringent financing rules in 2015 that made subcritical plants ineligible for funding except for units under 300 MW in International Development Agency (IDA)-eligible countries. For plants between 300 and 500 MW, USC was preferred although SC was permitted, again limited to IDA-eligible countries. For plants of 500 MW or more, the financing rules allowed funding only for USC plants.

Table 3 gives the global total of subcritical, SC and USC units, by MW, as of 2025 (Global Energy Monitor, 2025).

TABLE 3 GLOBAL TOTAL OF COAL-FIRED POWER PRODUCTION, BY CAPACITY AND TECHNOLOGY (GLOBAL ENERGY MONITOR, 2025)				
	Subcritical	Supercritical	Ultrasupercritical	Total
Announced	3,199	9,550	67,180	79,929
Pre-permit	2,900	17,110	50,176	70,186
Permitted	5,795	17,220	115,840	138,855
Total pipeline (all 3 above)	11,894	43,880	233,196	288,970
Construction	6,232	35,043	197,826	239,101
Shelved	8,380	13,748	70,775	92,903
Cancelled since 2010	166,862	551,165	303,578	1,021,604
Operating	1,029,421	566,371	476,847	2,072,639

As of 2025, no AUSC plant has been built, but in China there are units operating at almost 50% efficiency. These plants have been described at various Centre workshops, such as the third Energy Transition Workshop, Cape Town, 2024 (ICSC, 2024). For example, Pingshan Phase II, is a 1350 MW USC double reheat coal-fired unit, at 32.5 MPa/510/630/623°C. In a performance test, it ran at more than 49.2% efficiency (Li, 2024).

The Centre undertook studies examining the development and potential of high efficiency, low emissions (HELE) power generation technologies, covering topics such as the types of technology available, their efficiency, environmental impact, and global prospects. Compared to older coal-based power generation systems, modern HELE power plants became an increasingly attractive proposition in some economies. They provided cleaner affordable electricity and were capable of flexible cyclical and low load operation, increasingly needed to compensate for the fluctuating input from VRE supplying the same grid.

Various countries were active in developing proposals for new coal-fired power generating capacity, and the Centre, via a series of studies, workshops and conferences, actively encouraged and promoted the selection of HELE technologies, rather than older, less efficient, more polluting systems. Their potential to provide much-needed electricity to populations suffering energy poverty was emphasised, as even smaller-scale projects could have a major impact, particularly in emerging economies. Effective, affordable electricity remains a prerequisite for driving meaningful social and economic development.

As these systems began to find commercial application, the Centre monitored and reported on what were, at the time, the world's cleanest and most efficient power plants, comparing their improved performance and environmental impact against older technologies (Lockwood, 2021a). Their future potential was assessed and reported on for a range of countries and economies at different stages in their development.

The Centre's workshops and conferences helped disseminate the latest industry developments and encouraged utilities, governments, and other decision-makers to adopt them. For example, the Centre held a workshop on HELE coal-fired plant in Tokyo in 2016. This built on the success of previous workshops on efficiency upgrading and covered all aspects of high-efficiency coal power research and emissions abatement technology. Topics addressed included materials and designs for supercritical and AUSC power plant, new technologies for improving power plant efficiency and flexibility, developments in IGCC and fuel cells, advanced power cycles such as the supercritical CO₂ cycle, advanced pollutant controls, and policy and financial mechanisms to promote uptake of HELE power plant.

4.2 COAL COMBUSTION DEVELOPMENTS

During the 1970s and 1980s, interest increased in possible alternatives to pulverised coal combustion, the technology adopted for much of the world's coal power generation, as they offered improved efficiency and/or lower environmental impact.

4.2.1 Fluidised bed combustion

Although now well established, from the start of the century, fluidised bed combustion (FBC) technology emerged as a viable alternative to pulverised coal combustion for utility-scale coal power generation (Wu, 2003; Zhu, 2013). There was widespread deployment of FBC boilers of up to 300 MW, which became commercially available from various major international suppliers. Bubbling FB units were deployed in growing numbers, often used for industrial applications or as small captive power plants. However, circulating FBC (CFBC) was often selected for power generation or cogeneration applications, increasingly firing combinations of coal with biomass and/or waste materials (Barnes, 2013, 2015). An important driver was the dramatic increase in oil prices at the time, with many users substituting cheaper solid fuels for expensive oil. Pioneering work was undertaken in Germany, the USA, and by the Coal Research Establishment in the UK. FBC systems also demonstrated good load-following performance and offered the possibility of low NO_x and SO₂ emissions without recourse to special DeSO_x or DeNO_x equipment. For example, in 2005, the US DOE achieved a significant milestone in its *Clean Coal Technology Demonstration Program* by completing a utility-scale project in Florida, where the Northside Generating Station was converted to CFBC, becoming one of the lowest emission coal-fired power plants in the world. At its core was a 300 MW CFBC unit that was three times bigger than any of its predecessors. Many similar examples followed in different parts of the world. And increasingly, SC conditions began to be adopted for some applications, spurred on by the successful demonstration of units of up to 600 MW. In 2025, the world's biggest CFB boilers were two 660 MW USC units in China at Weihe in Guizhou province, and at Binchang in Shanxi province. These were designed and built by Dongfang Boiler Group Co. Ltd and Harbin Boiler Co, Ltd, respectively.

Often suitable for retrofit applications, CFBC in particular has since been scaled up to utility-scale cogeneration and power generation operations (Figure 16).



Figure 16 Turów CFBC power plant, Poland (courtesy of PGE)

Although the capacity of installed CFBC boilers for power generation is only a small percentage of total world capacity, the technology has been readily developed over the last two decades, particularly in China. In the 2000s, more than 600 CFBC units were operating worldwide, with a total 40,000 MWe generation capacity (World Bank, 2008). Typical CFBC boilers are up to 300 MWe (Utt and Giglio, 2012). An example of a large CFB boiler is the 460 MWe Łagisza power plant in Poland which began operation in 2009. It is also the world's first once-through unit supercritical CFB boiler (Boughton, 2013).

The Centre monitored the ongoing development of the different types of FBC, comparing their economics and efficiency, and addressing issues such as the application of FB boilers for industry and power generation, their environmental performance when firing coal and/or coal-waste mixtures, and management of the solid residues produced.

4.2.2 Integrated gasification combined cycle

Integrated gasification combined cycle uses a high-pressure gasifier to turn coal into a pressurised synthesis gas. This enables removal of impurities from the fuel prior to generating electricity, thereby reducing emissions of SO₂, particulates, mercury and, in some cases, CO₂. The first successful demonstration of the basic IGCC concept at a commercial scale was the 1984 Cool Water Project, part of the US DOE's Clean Coal Technology Program. This was followed by other projects that achieved operational success during their lifetimes. In the USA, these included the 260 MW Wabash River Coal Gasification Repowering Project, the 250 MW Tampa Electric Project, and the 618 MW Duke Energy Edwardsport Project. Plants elsewhere included the 330 MW ELCOGAS plant in Spain, the 253 MW

Willem Alexander plant at Buggenum in The Netherlands, the 250 MW GreenGen Project in China, the 400 MW Vresova plant in the Czech Republic (Figure 17), and the Nakoso IGCC Demonstration in Japan.

The advantages of IGCC are the high thermal efficiency, low non-carbon greenhouse gas emissions, and capability to process low-grade coal. The disadvantages include higher Capex and Opex, and the amount of CO₂ released if pre-combustion capture is not included. The Centre produced a series of studies comparing the effectiveness and operation of the different designs of gasifiers being offered commercially, including products offered by Texaco, Shell, Lurgi, BGL, GE, Dow, and KBR (Smith, 2009; Barnes, 2013, 2019; Fernando, 2014).



Figure 17 400 MW Vresova IGCC plant in the Czech Republic (courtesy of SUAS)

The air-blown Nakoso project came online after several decades of development and was one of a number of advanced coal-based projects developed in Japan that included two 500 MW-class IGCC plants at the Nakoso site, and one at the Hirono Power Station. The high efficiency achieved translated into carbon cuts – at the time, the global average for CO₂ emissions from coal-fired power plants was 950 gCO₂/kWh at the generator terminal, although IGCC emissions were around one-third lower at 650 gCO₂/kWh. Later developments included the multi-phase oxygen-blown Osaki CoolGen Demonstration in Japan's Hiroshima Prefecture that incorporated CO₂ capture and fuel cells and had the overall aim of achieving NZE. Experience gained from the initial tranche of plants was fed into the design of later variants. Centre studies examined the operability, continuity of operation, environmental performance, load variation/change, durability, reliability, and maintainability of these and other advanced projects.

Throughout their operational lifetimes, the performance and effectiveness of all such projects based on different configurations and gasification technologies, was monitored and compared via a series of studies. Their environmental performance was also monitored; for example, methods of minimising water usage and discharge – particularly how low emission technologies such as IGCC plant might achieve zero water discharge. These reports were some of the first to highlight the impact of water use and the increasing strain that global water supplies would face in the future.

5 CLIMATE CHANGE MITIGATION

The Centre produced its first reports on global warming as far back as the 1970s (Smith, 1978), years before the first publication of the Intergovernmental Panel on Climate Change (IPCC). The Centre's report crucially flagged up the possible impact of CO₂ emissions from coal power and industrial plants, identifying this as “an unresolved problem” and strongly recommended improved energy efficiency as a no-regrets measure. This early identification of what would eventually be recognised as a global issue provided significant impetus for many national and international studies and projects that followed.

5.1 THE 1990S

Years later, in 1992, the Earth Summit took place in Rio de Janeiro, attended by representatives from many nations. After this event, governments formulated their initial responses and strategies to the prospect of climate change. For example, the USA announced plans to stabilise its greenhouse gas emissions, the first of many such pronouncements. Climate change was to become an increasingly important topic throughout much of the Centre's lifetime and led to a succession of studies over the decades that examined the scale of the problem, the contributions from different coal-consuming sectors, and ways to mitigate emissions.

The emissions and control of non-CO₂ greenhouse gases from coal was analysed at the turn of the century and the Centre also examined coalbed methane emissions, capture and utilisation over the years. Greenhouse gas emissions from hard-to-abate industries such as the manufacture of cement, iron and steel were described. Cement is the second most widely used material after water, and it, together with iron and steel are critical to all economies. The adoption of various techniques and strategies for reducing the associated environmental impacts was suggested, such as improving the efficiency of production, co-utilisation of alternative fuels with coal, and the addition of CCUS.

In the 1990s the Centre reported that there was growing confidence and acceptance that a global warming trend was underway, but that most climate models available needed further development to provide accurate predictions of future climate change. Centre studies on this topic were distributed widely and helped raise awareness at government level of what was becoming a major global issue. Guidelines for compiling national emissions inventories were produced to show how GHG emission factors for coal could be used to estimate detailed emission data for specific technologies and fuels. These emission factors were studied for regional inventories and used to compare various fuel and technology options for energy production. CO₂, methane and nitrous oxide emission factors were reviewed throughout the coal chain, from coal production to end use.

Against this background, various countries increased efforts to understand and control rising GHG levels. For instance, the USA unveiled the Climate Change Action Plan, emphasising voluntary

measures to stabilise GHG levels. This was followed by a series of programmes such as the US Climate Change Research Initiative, the National Climate Change Technology Initiative, and the Carbon Sequestration Leadership Forum, aiming to bring together ministerial-level representatives to discuss the growing body of scientific research on GHGs.

5.2 CARBON CAPTURE, UTILISATION AND STORAGE

As the science around climate change became widely accepted, while reliance on fossil fuels continued, interest grew in carbon capture utilisation and storage (CCUS). A succession of in-depth studies from the Centre examined both technical and policy/strategies focused on reducing GHG emissions. The effectiveness and potential impact of adopting clean coal technologies and CCUS systems were addressed, and estimates provided of the potential emissions reductions achievable through efficiency improvements and plant replacements using such modern systems – it was concluded that major CO₂ emissions savings could be made, and the potential was assessed for both developed emerging economies. For example, this included a review of the various options being pursued to reduce carbon intensities in five developing countries, namely Brazil, China, India, Indonesia, and South Africa.

5.2.1 Decarbonisation of power generation

GHG mitigation studies were produced for both traditional pulverised coal power generation, as well as more advanced systems such as IGCC. The effectiveness and applicability of both pre-combustion capture of CO₂ in IGCC plants, and post-combustion capture systems and oxyfuel combustion were studied and compared. Although numerous other systems had been proposed, these three remained the focus of most RD&D efforts. The prospects for the commercial deployment of CCUS were also examined for specific countries. For example, the challenges and opportunities for China were examined, where CCUS was an RD&D priority. Activities underway in China encompassed work on most capture options, transport, and storage, and were characterised by a high level of international cooperation. There were significant large industrial-scale trials funded and implemented by various Chinese power generation, coal, and oil companies, and the Centre reported on many of these.

A review was produced on the status of coal-fired CCUS demonstration plants (Mills, 2013a). This considered activities focusing on the eventual large-scale deployment of CCUS on coal-fired power plants (Figures 18 and 19).

The deployment of a carbon capture system on a coal power plant inevitably carries an energy penalty, reducing the plant's overall output, and a series of studies examined ways in which this penalty might be minimised via the further refinement of existing technologies such as amine-based capture, or using novel schemes such as hybrid carbon capture systems. Alternative solutions were also examined such as capturing and storing CO₂ with other air pollutants, power plant flue gas treatment to enhance

capture rates, and advanced plant heat integration schemes to reduce the energy penalty (Carter, 2010).

A major issue often cited as limiting the uptake of CCUS schemes was the capital and system operating costs. These topics were explored and ways to expand deployment suggested (Henderson, 2015; Metzger, 2020; Kelsall, 2020; Lockwood, 2021). As well as promotion via national and international policies and strategies, the availability of different types of climate finance worldwide were identified by the Centre, such as development finance, green bonds, and carbon markets. Studies examined the barriers to CCUS deployment, potential ownership models, business models, policies, and revenue streams that could incentivise its use. Ways to minimise economic and market risks, policy risks, and regulatory risks were suggested.



Figure 18 ECO₂ post-combustion 1 MW pilot demonstration at R.E. Burger Plant in Ohio, USA (courtesy of Powerspan)



Figure 19 CSIRO amine-based post-combustion pilot project, Loy Yang, Australia (courtesy of CSIRO)

5.2.2 Industrial decarbonisation

As the take up of CCUS at power plants has been relatively slow, there has been more focus on decarbonising hard-to-abate industries (Carpenter, 2012, 2013; Kelsall, 2023; Jones and others, 2025). However, decarbonising individual industrial facilities via the deployment of CCUS systems may prove to be prohibitively expensive. Consequently, there was increasing interest in developing the ‘hubs and clusters’ model, where industries and power generators feed their CO₂ to a central carbon hub, after which it is transported for utilisation or storage (Mills, 2023). The model could enable the development of affordable, shared infrastructure, capable of handling CO₂ harvested from clusters of facilities. Open access to such shared systems would reduce the costs and risks for individual emitters, helping promote decarbonisation and potentially supporting the retention of industrial activity in a particular area. The Centre studied the concept and reported on projects proposed or being developed around the world. This included activities in Australia, Canada, China, Germany, India, Indonesia, the UK and the USA. And in 2024, Japan announced plans for seven advanced ‘role model’ projects. Hubs and clusters could be a cost-effective means for driving decarbonisation of the industrial and power sectors, contributing towards meeting national and international CO₂ reduction targets.

6 INTEGRATION WITH RENEWABLE ENERGY

This chapter reflects on the increased use of wind and solar power and the role of biomass and newer zero carbon fuels such as ammonia and hydrogen.

6.1 VARIABLE RENEWABLE ENERGY

Historically, most large-scale coal-fired power plants operated on baseload, running continuously, often at near full capacity. This type of operation began to change as more variable renewable energy (VRE, mainly wind and solar) was fed into the grid and prioritised, meaning that coal-fired power plants were increasingly expected to adopt more flexible modes of operation. This frequently involved regular ramping up and down to meet fluctuating demand patterns, or to accommodate the growing levels of electricity being fed into grids from VRE. There were industry concerns that many plants would be unable to operate effectively under these conditions, and that constant changes in load would adversely impact major plant components, leading to premature failure and outages. The Centre undertook many studies that examined these issues, providing useful operational and other data for utilities, plant operators, and developers. This work facilitated the increased adoption of VRE as a means to reduce emissions of CO₂ from the power sector (Sloss, 2016).

Naturally, coal power was not without competition from alternative generating systems such as natural gas, nuclear power, and renewables such as hydro, solar, and wind power. Although the use of renewables, especially for electricity generation, is often considered a relatively recent phenomenon, competition with coal power began, albeit in a small way, in the late 1970s. At the time, apart from hydropower, the use of renewables for electricity generation was considered relatively niche, although R&D in the USA and other countries had increased, triggered largely by the oil crises of the 1970s. For example, in 1978, the US Public Utility Regulatory Policies Act was introduced, requiring companies to buy a certain amount of electricity from renewable energy sources, and by the 1980s, the first utility-scale wind farms began operation in California. More modest developments were also being pursued in parts of Europe. This growing trend was recognised by the Centre, and initial studies compared the cost of coal-based generation with renewables, a prelude to the series of reports that encompassed a variety of renewable and non-renewable sources.

The growing deployment of such VRE systems over the following years had an increasing impact on the scale and makeup of many national energy sectors, often at the expense of coal power (Figure 20). The Centre followed these developments closely, and proposed various ways in which coal power could support and contribute to low emissions power generation, either through increased efficiency and reduced environmental impact, or via the integration of coal power with VRE (Mills, 2013b, 2017).



Figure 20 Solar array (Pixabay)

Much of the success of VRE was because of strong policy support, provided in many countries for more than a decade, coupled with further technological development, learning-by-doing, and falling capital costs. These factors helped take renewables such as solar and wind power from subsidised niche markets to the mainstream.

6.2 COFIRING

There has been continual interest in producing energy from coal in combination with other materials such as biomass and wastes. This was not limited to combustion, and studies examined coprocessing coal and wastes to produce gas and liquid fuels and chemical feedstocks. Some of the specific approaches considered included gasification/cogasification of sewage sludge, liquefaction of papermaking wastes, and the use of straw and wood wastes and scrap plastics. Centre studies helped raise awareness of the impacts resulting from the uncontrolled production of materials such as plastics and suggested ways they could be co-utilised with coal, thereby reducing the overall environmental impact. These studies provided useful early groundwork for decision-makers involved in energy production and efforts to mitigate environmental damage and helped raised awareness of what would eventually be recognised as a significant global problem. Co-utilisation of coal with other materials was to remain a key area of work that would assume even greater importance in later years.

6.2.1 Biomass

Cofiring biomass with coal started in Europe, decades ago, and great expertise developed in Denmark, the Netherlands, the UK and other countries. Cofiring biomass at rates of 10–20% was common, although Drax power plant in the UK trialled 50% cofiring before converting to 100% biomass

(see Figure 21). Some of the other plants subsequently converted to 100% biomass whereas others closed. Cofiring increased in several countries, especially in Asia where expansion was rapid (Baruya, 2015). By the start of the 2020s, cofiring was underway in China, India, Japan, Malaysia, South Korea, and Vietnam. This was driven by efforts to reduce fuel costs, improve national energy security, minimise pollutant levels, and reduce CO₂ emissions. In the 2010s, the Centre ran a series of workshops on cofiring biomass, two of which were held at Drax, as there was much interest in other countries to learn from the European experience.

Operating experience of cofiring coal with different forms of wastes, biomass, and low-grade fuels was the focus of several studies (Zhang, 2019; Zhang and Meloni, 2020). These examined a range of associated topics that included the sustainability of cofiring biomass with coal, considered one of the simplest ways of reducing GHG emissions from coal power plants. However, partly due to its heterogeneity, the use of biomass can be problematic, and the Centre examined the technical issues that could arise when cofiring at high ratios, such as availability of fuel, storage and handling, milling, slagging, fouling, corrosion, and ash characteristics. Follow-up studies examined enabling and supporting mechanisms and incentives for coal/biomass cofiring in countries that had substantial operational experience or showed potential for its wider uptake.



Figure 21 Drax power station, UK (Shutterstock – Clare Louise Jackson)

Other drivers included efforts to reduce local air pollution – for example, China deployed cofiring to reduce the impact of unregulated dispersed burning of agricultural and forestry wastes and sludge, as well as to contribute towards decarbonising its coal fleet. In Japan, some older coal-fired power plants adopted cofiring as a means for achieving the 44.3% electricity efficiency standard required by March 2031. In India, increased cofiring of agricultural wastes was pursued as a way to reduce stubble burning,

thereby improving the long-running problem of poor localised air quality. The Centre regularly reviewed developments and activities in this field, reporting on biomass characteristics and pretreatment, options for cofiring, impact on plant emissions, progress made, operational and supply considerations, and activities taking place in various countries and regions. Studies also encompassed technology transfer from the West, support mechanisms available, and technical options such as cofiring in CFB boilers, cogasification, and oxyfuel cofiring.

Studies also explored the role that sustainable biomass and wastes might play as part of the decarbonisation of the iron and steel and cement sectors (Jones and others, 2025). Biomass or biomass products can supply, or supplement process heat provided by coal, and in the case of iron and steel, act as a reducing agent and supplement or substitute for coal or coke. Reports also examined the important role that biogenic sources could have in displacing coal use in cement manufacturing, a process already underway in some parts of the world. Factors influencing the scale and cost effectiveness of using such fuels as a means for decarbonisation include combinations of technical, environmental, and national and regional supporting policies and regulations.

The potential of bioenergy with carbon capture and storage (BECCS) as a means for reducing GHG emissions was examined (Jones and others, 2023) (Figure 21). By 2023, limited use was being made of the technology, deployed on a number of power generation, energy-from-waste, and cement manufacturing facilities, with uptake expected to increase significantly over the following decade; new projects were planned at Drax in the UK, Norway, the Netherlands, and Sweden. The status and potential of the different BECCS approaches being made, particularly in Canada, China, Europe, India, Japan, the UK, and the USA, were examined. The technologies addressed were state-of-the-art solvent-based carbon removal methods, as well as developing technologies such as chemical looping combustion, oxyfuel combustion, carbonate looping, and gasification with physical absorption. The wider uptake of BECCS could make a useful contribution towards global efforts to decarbonise power generation and major industrial emitters.

6.2.2 Ammonia

The study of the effectiveness and potential of cofiring was extended to include the use of ammonia (Zhu 2022, 2024). Ammonia has properties that make it suitable as an energy storage medium, a hydrogen carrier, and a fuel. In 2025, it was the second most-produced chemical in the world. Technologies for production, handling, transport, and storage of ammonia are mature and global supply and distribution infrastructure already exist; hence ammonia has potential as the basis of an integrated energy storage and distribution solution and is a zero-carbon fuel for power generation. Centre studies explored the extensive RD&D programmes underway, and developments in ammonia combustion technologies (Zhu, 2024). By 2024, significant progress had been made, with a commercial demonstration at 20% ammonia in a Japanese coal-fired power plant. Analyses confirmed that substituting fossil fuels with low-carbon ammonia for power generation could reduce CO₂ emissions,

contributing towards the decarbonisation of the power sector, an important step in the energy transition and move towards NZE.

7 HARD TO ABATE INDUSTRIES

Although power generation was a consistent theme throughout the Centre's life, studies also monitored and addressed the issues associated with coal use in industrial sectors such as the production of iron and steel, cement, aluminium, and chemicals (Carpenter 2012, 2013; Kelsall, 2022; Jones and others, 2025). In 2024, it was estimated that industry produced about 8000 MtCO₂/y of direct emissions, 70% of which came from the cement, iron and steel, and chemical sectors.



Figure 22 UK blast furnace (courtesy of Corus Group plc, now Tata Steel Europe Ltd)

As the global energy transition moved forward, focus increased on ways to reduce global coal consumption, minimise emissions, and decarbonise. In 2024, the industrial sector remained a major CO₂ emitter, but efforts to decrease emissions had stalled as some activities remained particularly difficult to decarbonise – for example, cement production. In 2024, coal provided around 90% of the energy consumed by cement plants around the world – the cement industry consumed around 4% of global coal production, roughly 330 Mt/y. Similarly, despite industry moves towards the greater use of technologies such as electric arc furnaces, coke produced from coking coal remained vital for producing much of the world's iron and steel (Figure 22). Eliminating coal use in such sectors will be challenging and likely to take many years.

The Centre examined how effectively coal-based industries would be able to operate as countries progressed towards NZE, and suggested ways in which they might achieve this. For example, plants equipped with CCUS technology could play an important part in the decarbonisation process. Although overall industrial coal use will inevitably reduce, perhaps by as much as 80% from the 2024 level of 5 Gt/y, between 0.6 and 1.4 Gt/y is still forecast to be used in 2050, largely in heavy industry.

8 COAL PRODUCTION AND BY-PRODUCTS



Figure 23 Lignite mining operations, West Macedonia, Greece (courtesy PPC)

8.1 LOW RANK COALS

The Centre examined the global potential of utilising low-rank coals, considering their scale, location and major uses, and addressed the individual countries where they currently played, or were expected to play an important role in energy production (Dong, 2011; Mills, 2011, 2016) (Figure 23).

It was estimated that around half of the world's estimated recoverable coal reserves comprised low-rank/value coals. These included large deposits of lignite, although its relatively low economic value due to high moisture content and low calorific value, limited its use mainly to power generation at, or close to, the respective power plants. Indian bituminous coals and lignite typically have a high ash and high moisture content, so the aim is to use the coal locally, to avoid substantial transport costs for a material with a low calorific value. Despite this, lignite is still an important source of energy in several countries, although not widely traded. Centre studies examined and compared the cost-effectiveness and operating experience of using various low-grade fuels in both pulverised coal combustion and FBC technologies.

8.2 COAL MINING

During the 1970s – 1990s when coal was a major driver of energy production and economic growth in many nations, a major area of study at the Centre was coal mining and production methods, and related topics (Hessling, 1991; Clarke, 1995; Walker, 1996). These included both surface and underground

mining; prospecting, surveying, and mine planning; seam exploration techniques; shaft sinking and drivage; longwall mining control; strata control; and geophysical examination of coal deposits. Issues of safety and efficiency were also addressed through reports on the monitoring of machines and mining systems, coal transport, equipment testing, and potential mining hazards such as the prediction and monitoring of methane levels (Walker, 2001; Sloss, 2017a; Chapman, 2022).

8.3 LEGACY OF MINING

By its very nature, coal mining can have significant effects on local environments. In addition to the physical disruption of landforms and ecosystems, mining can also leave behind a legacy of secondary detrimental effects such as leaching of acid and trace elements from discarded materials (Figure 24). Studies examined the environmental impacts from emissions of dust and acid runoff on land use, highlighting emerging techniques capable of limiting and reducing these negative effects (Sloss, 2013, 2017b). Focus increased on ways to remediate both deep mine and opencast mine sites, with in-depth examinations of reclamation methods, back-filling issues, drainage, and restoration.



Figure 24 Part of the Loomis culm bank at Nanticoke, Pennsylvania, USA (courtesy of ARIPPA)

8.3.1 Coal wastes

The legacy of more than a century of coal mining in some countries meant that large legacy deposits of associated waste materials had accumulated, sometimes of gigatonne proportions (Figure 24). There is growing pressure to reduce the environmental impacts produced by the large-scale storage of such wastes. Reprocessing and clearing dumps can eliminate many of these and allow the land previously occupied to be restored and turned over to productive use. Where site clearance includes coal

recovery, income from coal sales can contribute towards the remediation costs. Some wastes can be used directly in several types of combustion system, or alternatively, their residual coal can be recovered and used as fuel. Some require minimal pre-treatment, whereas others may need upgrading or blending with other materials prior to use. A number of medium-sized power plants have been developed capable of successfully firing materials such as anthracite culm and bituminous coal waste sourced from previously dumped deposits. Most such plants adopted FBC technology (Figure 25) and as well as generating electricity and/or heat, had the added benefit of reducing the scale of legacy waste deposits, thereby minimising their ongoing environmental impact, sometimes allowing previously blighted land to be returned to productive use.



Figure 25 Nanty Glo West waste dump, Pennsylvania, USA (courtesy of ARIPPA)

The Centre explored the situation in most major coal-consuming countries, covering the scale and types of waste generated in each, their use, and their current and future potential. Centre studies considered the options for remediation and explored the potential for combining site cleanup with the sustainable and cost-effective recovery of residual coal content, thereby generating a useful income stream that could be directed towards site cleanup (Mills, 2018).

8.4 COAL COMBUSTION BY-PRODUCTS

Another significant source of waste is the residues generated by coal combustion. In coal power plants, this generally takes two forms: bottom ash and fly ash. Historically, much of this was simply landfilled or stockpiled, creating significant long-running environmental problems. Coal ash is an inherently variable material due to differences in the mineral content of the source coal, combustion conditions, and ash collection and handling methods, and this affects its marketability. However, fly ash has

become a useful resource, and it is becoming increasingly environmentally and economically advantageous to maximise its commercial use (Reid and others, 2020; Zhang and Meloni, 2020).

8.4.1 Fly ash

Fly ash is a by-product of pulverised coal combustion, formed when mineral impurities in the coal, such as clay, feldspar, quartz and shale, fuse in suspension. The fused material cools and solidifies into spherical glassy particles, called fly ash. It is collected in mechanical or electrostatic separators. Centre studies addressed methods for classifying fly ash, standards and specifications applicable, and quality assurance procedures, providing important data for both ash suppliers and industrial product manufacturers.

The global amount of fly ash used has steadily increased. In 2010, around 780 Mt were produced, of which only about 54% were utilised, the rest going to storage or disposal sites. By 2020, this had increased to over 60%, although it approached 100% in certain regions. However, as coal power has declined in the Global North, there is less fly ash available, and shortages have begun to occur. In the USA for example, the production of fly ash is declining, while the proportion used has tended to increase this century (see Figure 26). Concrete producers and consumers would like to use more, but several regional markets are affected by shifting supply dynamics, associated with closures of coal-fired power plants (ACAA, 2023). By 2023, international fly ash exports from Asia and Eastern Europe were estimated at \$100 million per year.

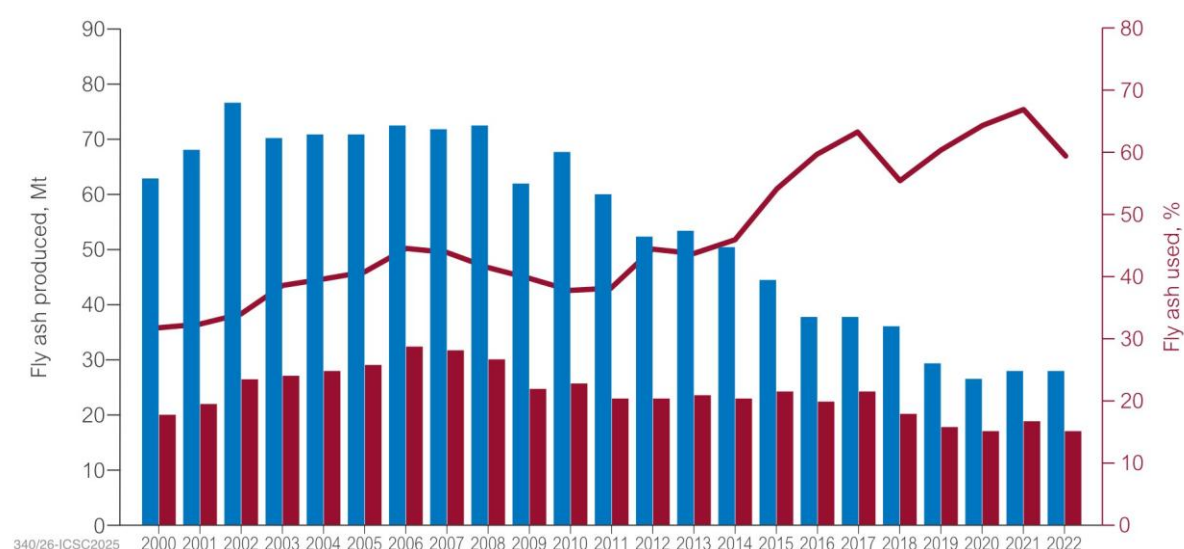


Figure 26 Fly ash production and use, 2000–2022, USA (ACAA, 2023)

Fly ash has many applications including mine backfill, stabilisation of soils and aggregates, land reclamation, road subbase, and agricultural uses such as acting as a soil amendment. However, its biggest market remains the production of cement and concrete, an industrial sector that was closely monitored and reported on by the Centre (Smith, 2005). Cement products such as concrete, bricks,

and blocks can contain up to 50% fly ash – this is one of the most significant industrial means to reduce carbon intensity in the construction industry due to the high energy demand of cement manufacture.

Centre studies followed these developments and also examined the potential use of fly ash in the production of advanced materials such as geopolymers, composites, ceramics, fillers, zeolites, and proppants (used in fracking). Fly ash and other coal wastes and by-products also have potential as a source of rare earth elements, and potential production techniques and markets were addressed.

Fly ash markets in different countries were regularly monitored with respect to production, opportunities, and obstacles to its further utilisation resulting from changing practices in power plant operation as a response to the demands of tightening environmental regulations (Dong, 2010; Barnes, 2011). For example, increased deployment of NO_x control systems sometimes increased the residual carbon content in ash, affecting its marketability. Other changes resulted from the increasingly common practice of cofiring with other fuels such as biomass and wastes.

8.4.2 Other residues

Although ash from coal power generation was the focus of most studies, that from other combustion systems was also considered – for example, residues from CFBC and IGCC plants. CFBC ash showed potential for concrete, as structural fill, for remediation of acid mine drainage, as a soil amendment, and in pollution control. IGCC residues also showed potential and could be utilised as aggregate, in road bases, and specialised cements.

Studies were not limited to combustion residues. For example, these included the management and utilisation of FGD residues from wet scrubbers, semi-dry, and dry scrubbers. Their production in different regions was addressed, as well as detailed assessment of their chemical and physical properties, and barriers and opportunities for their increased use.

9 ENERGY TRANSITION

As much of the world came to accept the reality of climate change, significant changes started to be made in many national power fleets, driven largely by a combination of economics and policy initiatives. Especially in Western economies, electricity produced using fossil fuels began to be replaced with increasing amounts from VRE, predominantly wind and solar (Garwood, 2024). This impacted coal power plants feeding into the same grid, meaning that operational changes were increasingly needed. Historically, many had run almost continually on baseload, but they were now expected to repeatedly ramp up and down in response to variable input from renewables. Inevitably, this had an impact on overall generating efficiency, emissions, and profitability (Henderson, 2014; Wiatros-Motyka, 2019). Especially with some older plants, it also had detrimental effects on major plant components, leading to premature failures and plant outages. These issues were addressed via Centre studies and outreach activities that helped identify the main areas of concern and recommend ways to mitigate potential problems.

Despite growing aspirations by many governments to eliminate coal power, this is not a viable option for some countries, and many continue to meet at least part of their demand using coal, a situation that is likely to continue for many years. This is the case for some Eastern European countries for example, as well as China, India and much of Asia (Figure 27).

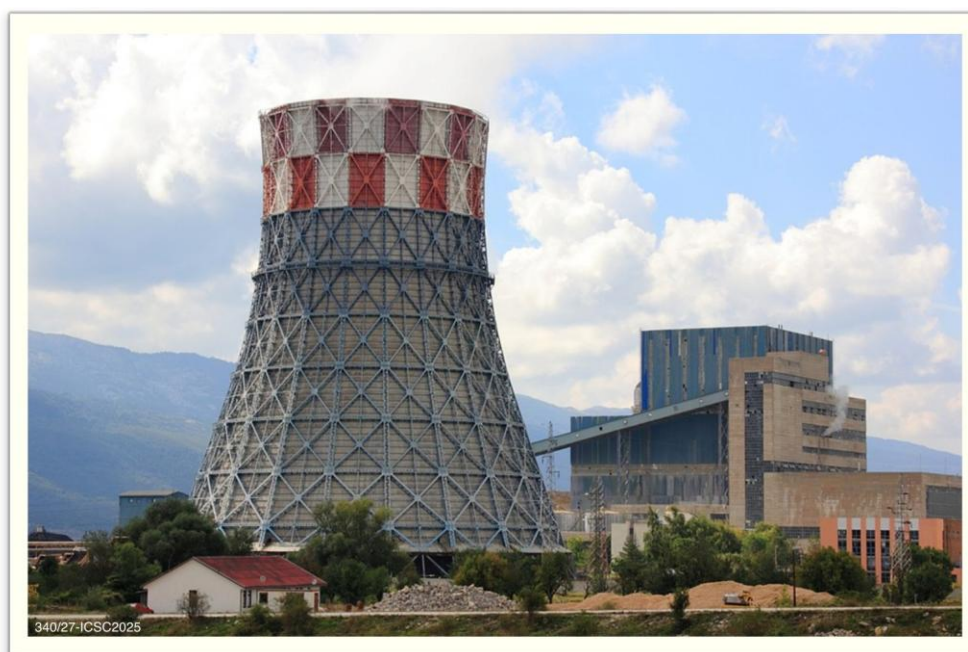


Figure 27 Bosnian lignite-fired power plant (Pixabay)

The energy transition has an increasing strategic impact on operational issues and consequently, this became a major aspect of the Centre's work programme. This was not limited to power plants and

encompassed other aspects such as system flexibility, smart grids and virtual power plants, digitisation of electricity grids, distributed generation, as well as the need to economically integrate CCUS under such conditions. This included operation of power grids with very high capacities of variable renewables, where integrating dispatchable fossil power with CCUS to provide the necessary stability in a cost-effective, very low carbon manner.

As global reliance on intermittent renewables and biomass grew, operators of coal plants increasingly sought ways to increase efficiency and extend their working lives by improving their operational flexibility and reducing environmental impact. Centre studies examined the possibilities of combining some types of renewable systems with coal-fired power plants – for example, using solar energy to preheat coal plant feedwater (Figure 28) (Mills, 2017). And various other options were also identified such as cofiring biomass and/or wastes. Both options could help reduce operational and fuel costs, lower conventional plant emissions, and where the biomass was sourced sustainably, also lower CO₂.



Figure 28 The Cameo Generating Station, Colorado, USA. This coal-solar hybrid used parabolic trough solar collectors to collect sunlight (courtesy of Xcel Energy)

Several policy-relevant workshops augmented the studies programme, covering the impact of sustainable carbon on the energy transition. Such outreach activities engaged with many other organisations. The first workshop on the energy transition was held in Italy in collaboration with the Centre’s Executive Committee member, Sotacarbo, and others followed in South Africa, with a focus on the perspective from a developing nation. These major international events were important for sharing information and insights into both technical and non-technical aspects of energy production. For example, the 3rd Energy Transition Workshop, held in Cape Town in 2024 examined practical routes to achieving net zero. It was organised jointly by the Centre and South African utility, Eskom

(Figure 29). Topics addressed included policies and realities, practicalities of improving coal-fired generation, CCUS, integration of energy sources, and coal in a circular economy. As with other Centre-led gatherings, there were very positive outcomes – important information was made widely available to numerous outside bodies, knowledge-sharing was boosted, and collaborative activities enhanced.



Figure 29 3rd ICSC Energy Transition Workshop, Cape Town, South Africa, 2024

All such events were widely supported and addressed a range of issues that covered policy topics, energy security, the realities affecting the energy transition, just energy transitions, and the future for coal in ever-changing energy markets. Practical routes to achieving net zero were also explored, encompassing topics such as the practicalities of improving coal-fired generation, CCUS, integration of different energy sources, and coal use in a circular economy. Thus, the Centre continued to raise awareness amongst governments, industry, academia, and international organisations about the potential of low- and zero-carbon technologies and their interplay to attain carbon-neutral energy systems. A key aspect was to highlight the differences in such applications between OECD countries and developing nations, reflecting on the heterogeneous nature of energy availability and use.

The energy transition resulted in the closure of many coal mines and power stations, and as coal power declined in the Global North, studies addressed the growing problem of redundant sites. The USA and Europe witnessed the most rapid changes, and the Centre explored possible options for remediating and/or repurposing the growing number of sites. Although clearance was one possibility, alternatives were identified that could better support the energy transition – for example, as sites are often well located and have existing grid connections, they could become the location for alternative energy-based options such as small modular nuclear reactors, wind or solar power, and/or battery

storage. Studies reviewed the advantages and barriers to reusing such sites, highlighting those solutions already technically proven and adopted and describing progress in ecological restoration programmes being pursued (Reid, 2023).

10 ALTERNATIVE PRODUCTS FROM COAL

For decades, coal was used predominantly to supply markets for power generation, metals, and chemicals production, although it was increasingly regarded as a resource, equally useful for non-combustion applications. From the 2010s, interest has been increasing in the repurposing of coal as ‘carbon ore’ and its growing use for non-energy applications (Minchener, 2011; Nalbandian-Sugden, 2014).

As many countries transitioned to lower emission forms of energy, a number of new carbon-based industries and technologies emerged in energy storage, aerospace, and composite materials to take advantage of the particular properties of carbon. Some types of coal and coal wastes hold great promise as a source of feedstock for many of these low emission applications, viewed as crucial in reaching NZE goals.

A series of Centre studies examined the production of various advanced materials from coal and/or coal wastes, reporting on possible manufacturing techniques, production challenges, costs involved, and the potential for market acceptance. Materials considered included activated carbon products, carbon electrodes, graphene, carbon fibre and composite production, carbon nanotubes, and graphene (Reid, 2018). All hold significant promise for the future.

Some coal-based materials also showed great potential in the agricultural sector, where climate change and industrial farming practices have impacted soil fertility, biodiversity, and food production (Reid 2020, 2023).

An alternative to conventional nitrogen-phosphorous-potassium (NPK) fertilisers may be lignite-based ones, which are in development and gaining commercial success. The largest commercial product is the conversion of lignite to potassium humates which also offer slow-release nitrogen. Centre studies considered different solutions offered by coal and coal technologies, how they influence soil properties, enhance carbon sink attributes and soil fertility. These concluded that low-rank coal products could augment resources and offer a means to lower chemical fertiliser use, potentially opening up large global markets.

10.1 COAL TO CHEMICALS

For more than a century, the coal-to-chemicals sector produced a range of materials from coal tar pitch that included dyes, preservatives, fungicides, and liquid and solid resins (Song, 2005; Fernando, 2008; Minchener, 2011). Although some products were later supplanted by equivalents made from petroleum feedstocks, production continued.

Syngas generated via coal gasification can be used to make key products generally obtained from petrochemicals, including hydrogen and ammonia, benefitting from flexibility in syngas composition.

China dominates this market, using 400 Mt/y of coal in 2024 for coal to chemicals; India and Indonesia have also developed an interest in coal gasification. A more recent development is the growth of a market sector based on gasifying coal to produce methanol for olefin manufacture, particularly in China. Here, coal-to-chemicals was a relatively new industry evolving from initial production trials in 2008 and growing quickly, especially between 2018 and 2024. China's strategy focused on maximising the use of its indigenous coal to provide stability and protect its economy from wide variations in the price of imported fossil fuels. The Centre continued to monitor and report on such developments around the world (Reid, 2025).

10.2 RARE EARTH ELEMENTS

Another increasingly important area that coal and/or coal wastes could potentially service is the production of rare earth elements (REEs) and other critical minerals, a rapidly expanding market sector. These have attained strategic importance in many economies and are vital components for many high-tech consumer devices and defence applications (Reid and others, 2020). They are also a crucial element of the energy transition and are used in renewable energy technologies such as solar panels, wind turbines, electrolyzers, and electric vehicles.

China dominates global production and supply of REEs, and this situation raises concerns over cost and security of supply, especially in the Global North. Thus, other countries are urgently seeking to develop alternative sources from conventional mineral ores (Figure 30) and also via REE recovery from coal-based materials such as hard coal, lignite, coal refuse, mine drainage, and coal combustion by-products such as fly ash, some of which contain viable amounts of REE. Many of these materials are readily available in large quantities.



Figure 30 Mountain Pass rare earths mine in California, USA (courtesy of M P Materials)

A range of techniques continue to be explored for extracting REEs from these, and the Centre studied possible production techniques, RD&D activities underway, the costs involved, environmental impacts, and the potential for scaling up selected processes to economically viable commercial operation (Mills, 2024). There is a substantial incentive to achieve viable REE recovery from coal-based materials – successful development would diversify sources, easing concerns over current and future market domination, and help progress towards the widespread deployment of technologies effective in meeting the challenges of climate change. Centre studies into this evolving field contributed significantly towards meeting this important goal but further work is needed to explore the commercial viability of individual projects.

10.3 HYDROGEN FROM COAL

Another route being pursued towards NZE is the use of hydrogen as an alternative to fossil fuels. Hydrogen can be made by a variety of means including coal gasification (Collot, 2003; Kelsall, 2021; Zhu, 2023). Studies suggest that global demand is set to increase rapidly, reaching more than 500 Mt/y by 2050; this will be difficult to achieve. Although coal gasification-based hydrogen production is the most carbon-intensive, the addition of CCUS could reduce CO₂ emissions substantially. When the best available technologies are adopted, this option can have life cycle environmental impacts close to those achieved in the production of renewable hydrogen. However, it will not be possible to meet global demand by renewable hydrogen production alone, at least in the near to medium term. Therefore, low-emission hydrogen production from coal with CCUS, which costs significantly less than renewable electrolytic hydrogen, could be a vital tool in bridging the gap. The Centre examined regional

variations in hydrogen demand and supply, and the possible role of coal in helping to meet future demand, concluding that producing low-emission hydrogen from coal with CCUS would be a low-cost option in regions with abundant coal, access to CO₂ storage, and limited renewable energy availability.

10.4 AMMONIA FROM COAL

Some properties of ammonia make it suitable for use as an energy storage medium, a hydrogen carrier and as a fuel. Ammonia is the second most produced chemical in the world. There are three main commercial technological routes for ammonia production: steam methane reforming (SMR) accounting for 72% of global ammonia production, coal gasification accounting for 26%, and the water electrolysis-based Haber-Bosch process produces less than 1%. Ammonia production processes are energy intensive and create emissions of large volumes of CO₂ as almost all ammonia is currently produced from unabated fossil fuels, and textiles.

Low-carbon ammonia can be produced by capturing both process and utility CO₂ from ammonia production. Capturing and storing process CO₂, a pure stream of CO₂ generated from the SMR process, is relatively easy as it is ready for sequestration. Capturing utility CO₂ which is the CO₂ emitted during the generation of steam, heat and electricity needed by ammonia production, requires the installation of carbon capture equipment with the associated additional cost.

For ammonia producers that use grid electricity to power the production process, collaboration with a power generator will be needed to decarbonise power generation to minimise the carbon footprint of the ammonia. The industry has experience in CCS over decades with many commercial demonstration CCS projects in operation and more commercial CCS plants under construction around the world. Carbon capture technologies have been evolving and are ready to roll out to assist in producing ammonia from abated fossil fuels as part of the energy transition. (Zhu, 2022, 2024).

11 UN SUSTAINABLE DEVELOPMENT GOALS

Much of the Centre's work was aligned with the United Nations (UN) Sustainable Development Goals (SDGs), 17 interconnected goals that act as a blueprint to address the most urgent global challenges. In 2016, the SDGs of the UNs' *2030 Agenda for Sustainable Development* came into force. Via a series of activities, there was an aspiration to end all forms of poverty and improve the quality of life for many populations by 2030.

Sustainable energy supply is an important element of the UNs' Goals, fundamental in driving the further advancement of human civilisation. Population growth is leading to accelerated development of many regions, something that will increase energy demand for many years. The Goals call for action by all countries to promote prosperity whilst protecting the planet. They recognise that ending poverty is linked strongly with economic growth, but that climate change and environmental protection must be factored in. They include the need to address the climate change mitigation targets as set out by the UN Framework Convention on Climate Change (UNFCCC). SDGs are being implemented through individual countries' own sustainable development policies, plans, and programmes, providing direction and allowing national plans to be allied with their global commitments.

Estimates vary but suggest that in 2024, between 760 million and 1.18 billion people still lacked access to electricity. The IEA estimated that 775 million people will still be in need by 2030, mainly in sub-Saharan Africa. This region and South Asia are home to five out of six of the world's poorest people. Lack of electricity impacts healthcare, education, food security, public safety, economic development, and opportunity.

The Goals that are most relevant to the work of the Centre are summarised in Table 4.

TABLE 4 SELECTED UNITED NATIONS SUSTAINABLE DEVELOPMENT GOALS (SDGS)	
Goal	Aims
7 – Affordable clean energy	Ensure universal access to affordable, reliable and modern energy services by 2030. This includes enhancing international collaboration to facilitate access to clean energy research and technology, including cleaner fossil fuel technology
9 – Industry, innovations and infrastructure	Build resilient infrastructure, promote sustainable industrialisation, and foster innovation. The aim is to upgrade certain aspects of industry by 2030 in order to make them more sustainable, with increased resource-use efficiency, whilst adopting clean and environmentally sound technologies
12 – Responsible consumption and production	Ensure sustainable consumption and production patterns. Aims include the environmentally sound management of wastes throughout their life cycle, and significantly reducing any adverse impacts on human health and the environment
13 – Climate action	Take urgent action to combat climate change and its impacts
17 – Partnership for the goals	Revitalise the global partnership for sustainable development through improved international cooperation on topics that include energy technologies with a low environmental impact

The wider uptake of high efficiency and low emission technologies would help meet these goals:

Goal 7

The provision of affordable, clean energy remains a pressing need in many developing nations. Modern power systems, including coal-fired power plants can provide reliable, low-cost electricity capable of transforming people's lives and driving economic development.

Goal 9

The replacement of outdated, low-efficiency power plants with newer, more advanced systems would encourage sustainable industrial development. The upgrading of older coal power fleets through the adoption of newer more advanced technologies helps make them more sustainable, of higher efficiency, and of lower environmental impact. It also promotes innovation. Provision of CCUS transport and storage infrastructure will complement such endeavours and help deploy CCUS technologies to industrial sectors such as chemicals, steel and cement.

Goal 12

Reducing the environmental impact of coal-fired power plants is an aspect of Goal 12, which includes measures to reduce the release of pollutants and wastes. Modern coal power plants can incorporate state-of-the-art emission control systems, capable of reducing emissions to air to very low levels.

Furthermore, they generally operate much more flexibly than older systems, allowing them to maintain higher levels of efficiency and lower emissions over a much wider operating range.

Goal 13

The high efficiency achievable by modern power plants means that less coal is needed to generate a unit of electricity than traditional alternatives, thereby minimising emissions to land and air. CO₂ emissions are also lower, contributing towards reducing the impact of climate change. In the longer term, CCUS has the potential to reduce CO₂ emissions even further. These will be most cost-effective when fitted to modern coal-fired plants and long-life industrial assets such as blast furnaces, alumina refineries and cement plants. Such applications will be particularly important in Asia, where the average age of these assets is around 14 years (as of 2025).

11.1 ENERGY POVERTY

Energy poverty has long been acknowledged as stifling economic development and holding back improvements in people's quality of life. Much of Africa experiences economic and energy poverty so all SDGs remain relevant. It is unlikely that Africa will be able to develop energy security and economic resilience without the use of its own coal resources – the Centre recommended that providing advice and assistance to use them cleanly and efficiently would be more appropriate than ceasing to finance their exploitation. Cleaner coal-fired power generation could make a significant contribution to reducing global energy poverty (Baruya, 2022).

Thus, there is considerable pressure to provide modern sustainable energy to a growing population which is expected to almost double by 2050, whilst simultaneously bringing millions out of energy poverty. The situation in several African countries was reviewed by the Centre including Botswana, Morocco, Nigeria, South Africa, Mozambique, Tanzania, and Zimbabwe. Other reports considered the issue of energy poverty in parts of Eastern Europe, where various countries rely heavily on their indigenous coal resources to power their respective economies. Despite this, many populations lack a reliable affordable source of electricity, greatly reducing their quality of life.

The Centre noted that at a time of pressing need, an increasing number of financial institutions were reducing their exposure to coal-related investments, and international aid was increasingly focusing on wind and solar power. It was argued that as a means for reducing Africa's general economic and energy poverty, countries with abundant coal supplies should exploit these natural resources responsibly to facilitate their development, adopting the most efficient technologies that could be afforded, thereby driving sustainable economic and social development.

Coal has the potential to play a major role in alleviating global energy poverty, a persistent problem across much of the developing world, but particularly severe in sub-Saharan Africa and developing Asia – together, these account for 95% of people in energy poverty. But increased access to coal power

has already made a real difference in many countries – for example, between 1990 and 2010, about 1.7 billion people gained access to electricity, thanks in large part to coal (Mills, 2021).

12 THE FUTURE FOR COAL

Despite considerable rhetoric from various governments, non-governmental organisations (NGOs), environmental groups, and others, eliminating coal from global energy production will continue to be challenging. Coal has numerous well-established advantages including:

- Coal resources are readily available and accessible in many parts of the world;
- In comparison, oil and gas often come from politically unstable regions and are less extensive;
- Coal's widespread availability has been particularly important in times of upheaval. For example, it partially replaced Russian gas following the invasion of Ukraine in 2022;
- Coal's use for power generation and industrial applications is often based on established, proven technologies;
- In developing economies still in the process of electrification, coal power can provide affordable and reliable electricity. (This is recognised, for example, in the OECD guidelines for export credit assistance related to coal-fired power plants - guidelines that were informed by the Centre's HELE research);
- Most alternatives to coal have a higher capital intensity per Megawatt, making them less attractive for low- and middle-income countries;
- Much of the world's coal power plants are relatively young and were built this century. Power plants have high initial capital costs which need to be amortised throughout the plant's lifetime – this can be up to 50 years;
- Modern plants can operate at over 45% efficiency, compared to a global average of 37.5%. When coupled with cofiring of biomass or ammonia and CCUS, they can have very low emissions of CO₂; and
- Coal power can provide stability and backup to grids incorporating a high degree of input from intermittent renewables.

Furthermore, the coal industry is deeply rooted in the culture and the economy of many countries, and phase-out could have a significant localised impact on employment. In 2023, the IEA estimated that globally, around 8.4 million people worked in coal value chains, including 6.3 million in mining, processing and transportation, and 2.1 million in power generation.

However, coal use is clearly not without its problems. Older power plants, particularly in countries that do not have strong regulatory requirements, often lack adequate pollution control systems needed to consistently and effectively control emissions of SO₂, NO_x, particulates, and mercury, species that can have significant negative externalities on human health and the environment. Coal combustion also contributes towards global warming, and many governments consider that its elimination will be

a key step to achieving the goal of keeping the global average temperature increase below 1.5°C or 2°C.

Phasing out coal has become a priority in much of Europe and some other countries, and political debates focus increasingly on how it can be eliminated over the course of the next few decades. Some economies are well advanced along this trajectory, whereas others are likely to continue their reliance on coal for power generation and industrial uses for a considerable time – affordable, sustainable alternatives may simply be lacking. Furthermore, some current national emission reduction commitments, known as Nationally Determined Contributions (NDCs) which are submitted by countries participating in the UNFCCC Conferences of the Parties (COPs,) of major coal-producing and coal-consuming countries do not always appear adequate and lack clear routes for a coal exit.

Set against this background, global coal consumption has continued an upward trend. Repeated claims that ‘peak coal demand’ has been reached have proven incorrect as global coal consumption increased from 3.29 Gt in 1975 to a record of 8.77 Gt in 2024, an increase of 1.4% from 2023-24. China alone accounted for more than 50% of global coal demand, and at 4.66 Gt, is the world’s largest coal producer. Furthermore, capacity for coal power plants in development increased by 16% between 2023 and 2024. Coal consumption in much of Asia is likely to continue increasing for some time.

Despite climate change mitigation pledges struck at various COPs and other international gatherings, and innumerable press reports over recent years suggesting that coal’s time as a source of energy is coming to an end, this has not been borne out by events. Whereas it is true that coal consumption in the USA and much of Europe has declined, this has been offset by continued demand growth in countries such as China and India, as well as many others in developing Asia. In 2024, global coal capacity and consumption reached new levels as Asian demand growth outpaced cuts in Western economies.

In 2024, more than 100 countries and 2000 major entities were using coal across roughly 13,800 coal units and there are many more units using coal in various industrial applications. Some 204 new coal power plants were under construction, another 93 projects had been announced, and 260 new facilities were at the pre-construction stage. China accounted for over 70% of planned coal capacity worldwide and had approved more new plants than those operating at that time in the USA. In 2022, China approved for construction six times more coal power projects than the rest of the world combined, and at the end of 2024, over 200 new coal power projects with a total capacity of 243 GW were under construction or permitted. As well as Chinese developments, over forty other countries also had coal-based power projects in the pipeline, many in Asia. Major coal-fired power capacity additions and plants under construction in 2024 are shown in Table 5.

On a smaller scale, but with potential and growing are the alternative, non-energy uses for coal, for example in the production of chemicals, soil improvers and other products needed for the energy transition such as graphene and rare earth elements.

TABLE 5 MAJOR COAL-FIRED POWER CAPACITY ADDITIONS AND PLANTS UNDER CONSTRUCTION IN 2024 (CREA, 2025)

Country	Capacity added in 2024, MW	Under construction in 2024, MW
Bangladesh	1260	2640
China	30,525	204,208
India	5810	29,480
Indonesia	1902	8583
Kazakhstan	–	130
Laos	–	660
Mongolia	200	530
Pakistan	660	–
Philippines	450	635
Serbia	350	–
South Africa	800	–
South Korea	1050	1050
Vietnam	716	4043
Zimbabwe	335	1470

12.1 ASIA

Although coal use has declined in the West, as noted, its use has increased steadily in Asia. Whereas Western nations are generally high-income countries with slow-growing, service-based economies, stable populations, and the options of nuclear power, relatively cheap natural gas, and renewables, much of Asia depends on coal for energy security, thanks to its relatively cheap price and ready availability. Asia is home to over 60% of the world's population and relies on fossil fuels to meet 90% of its energy needs. It is responsible for more than half of global CO₂ emissions from fossil fuels. Asia's large coal fleet is young, with a unit average of around 14 years (in 2024); this provides 57% of the region's electricity. A significant number of these coal plants will remain in operation for many years.

Asian countries tend to have relatively fast-growing economies and populations, which are also becoming more urban, driving up energy demand. For example, in 2025, the sheer growth in electricity demand in India necessitated a continued reliance on thermal power. The Indian Ministry of Coal projected coal demand was likely to reach 1462 Mt by 2030, and 1755 Mt by 2047, from 1245 Mt in 2024. These numbers should be compared with coal demand of 89 Mt in 1975, according to Coal India Ltd.

There are other economies in Asia that are expected to grow quickly in the coming decades, as will their demand for electricity. For example, in 2025, countries such as Pakistan, Bangladesh, and Southeast Asian countries consumed roughly the same amount of electricity each year for a population of 2.4 billion people as the EU does for a population of 450 million.

To counter the overall environmental impact of this growing demand, the Centre repeatedly recommended the closure of the region's small, inefficient and unabated coal power plants, replacing them with cleaner more efficient variants ideally based on USC conditions and best available pollutant controls. Plants based on these technologies would also be more amenable to retrofitting with CCUS in the longer term. Similar studies examined the region's industrial sectors such as iron and steel, chemicals, and cement production. With a view to reducing emissions of CO₂ and traditional pollutants, recommendations were made such as deployment of CCUS; fuel switching to hydrogen, biomass and electricity where available at a competitive price; improved energy efficiency; and the increased use of scrap steel and aluminium. There is little doubt that coal will remain key through any transition to net zero emissions in power generation or the industrial sector.

12.1.1 China

Taking China as a case study, as the country dominates coal consumption, in 2024, thermal power generation, mainly fuelled by coal, reached a record high, despite a surge in renewable energy installations. Growing coal consumption increase is driven by increasing power demand and the need for reliable baseload power sources. Between 2000 and 2020, China's coal demand increased significantly, and its electricity generation from coal soared from 1000 TWh to 4775 TWh. Thermal power generation increased by 1.5% in 2024 from 2023 to a record high of 634 TWh. In 2024, coal generated around two-thirds of the country's electricity.

Since the 2010s China has required all new coal-fired units, with some exceptions, to be 1000 MW USC units. China also sought to close smaller subcritical plants and improve the efficiency and add pollution controls to the remaining subcritical units. Efforts have also been made to close smaller, inefficient steel works.

Chinese growth in coal consumption has so far defied views that coal use is peaking for the world's biggest coal consumer. Many industry observers anticipate that despite the deployment of increasing amounts of renewable energy, coal will remain the backbone of the country's energy system for the foreseeable future. Given the country's importance in global energy production and use, the Centre maintained a lengthy and comprehensive engagement with China and Chinese organisations. Studies monitored and reported on many aspects of Chinese power generation and industrial sectors, and there were numerous in-person visits, workshops, capacity-building, knowledge-sharing, conferences, and other cooperative activities. Executive summaries of reports from the Centre were made available from the website in Mandarin.

12.2 REFLECTIONS

In 2024, coal was the single largest energy source in the world. It still generated over a third of the world's electricity, reaching a new record of 10,440 TWh. It will not be feasible to eliminate unabated coal in much of Asia or Africa for several decades at least; hence the Centre consistently encouraged the widespread deployment of high efficiency low emissions coal technologies and CCUS, and cofiring with biomass or low-emissions ammonia. Even though coal use has declined in the USA and Europe, it will remain vital in the Asian economies of China, India, Indonesia, Pakistan, Bangladesh, the Philippines, and Vietnam among others. Combined, in 2024, these accounted for 70% of global coal consumption and most of the world's new coal power projects. In the 2020s, coal production was concentrated predominantly in China, Indonesia, the USA, Australia, India, and the Russian Federation – between them, they accounted for almost 90% of global production. At this time, production in some countries was still increasing.

Investment in the coal sector has increased in the 2020s as some key investors are convinced that a global coal phaseout or phase-down, and decarbonisation of the world's energy sector will take longer than predicted, while demand for reliable electricity continues to increase. This is likely to occur at different speeds between the Global North and Asia, especially China and India. Geopolitical and numerous other developments were repeatedly highlighted over many years by the Centre via a succession of in-depth reports, surveys, interviews, blogs, webinars, workshops, and training and outreach activities.

Coal power plants have proven their worth in times of global upheaval such as the Russian invasion of Ukraine and the subsequent reduction of Russian gas supplies to Europe. To replace the loss of gas-fired capacity, many coal power plants either mothballed or slated for early retirement were quickly made available. Various EU states also increased their reliance on coal power during this period, including Austria, Czechia, France, Hungary, Italy, the Netherlands, and Spain. Coal power also proved its worth in Romania, where Sebastian Burduja, the Minister of Energy, commented in March 2025 that:

*“COAL WAS THE RESOURCE THAT SAVED US IN THE
DIFFICULT EPISODES DURING RECENT YEARS AND
REMAINS A RELIABLE RESOURCE”.*

The upheaval in European energy markets caused by the war in Ukraine illustrated the folly of overreliance on a single source of energy and a single supplier – in this case, Russian gas. This had been regularly promoted by many European governments and other organisations as a sustainable ‘bridge’ between the phasing out of coal and the creation of an energy sector heavily reliant on VRE backed up

by gas-fired plants. However, these events made this option untenable and created significant difficulties for energy providers.

The Centre always argued that a sustainable, reliable, affordable national power sector should comprise a balanced portfolio of different technologies, rather than relying solely on one source of energy or a single main supplier.

13 CLOSING THOUGHTS

Throughout its lifetime, the Centre was always a centre of excellence, providing independent reporting and analysis of the highest level. Produced by a team of experts and analysts from many countries, that brought together extensive international expertise in coal science, industrial experience and applications, power generation, and environmental knowledge. Latterly, the scope of activities broadened to encompass national and international energy policy, market developments, and coal's future in a carbon-constrained world. Throughout this period, the Centre's team provided expert advice and recommendations up to ministerial level.

Global coal production and consumption increased three-fold during the Centre's 50-year lifetime. In 2025, it was still a major energy provider and a primary source for electricity generation. Over the course of half a century, the studies programme was regularly refocused and redirected to reflect the major changes taking place within global energy markets. The work had a broad geographic focus, reflecting the heterogeneous nature of global energy use – there was, and still is, no 'one size fits all solution' to the energy and environmental challenges being faced worldwide.

The Centre's output was highly respected and offered a broad energy and environmental framework of independent support for a wide range of critically important topics and issues that were valued by many official bodies and outside organisations. It covered:

- Independent, peer-reviewed studies, that were disseminated via publications, and the website;
- Complementary work for external like-minded organisations;
- The development and promotion of carbon-based energy technologies that were clean, reliable, with high efficiencies and minimal environmental impact, in line with the UN SDGs, while being commercially competitive;
- Technologies that created high-value carbon-based non-energy products;
- The processing of coal to produce critical minerals including rare earth metals for use in advanced technologies; and
- The production of reviews and analyses of markets for low- and near zero-carbon technologies with low overall environmental impacts, together with enabling policies and regulations required to accelerate their global market introduction.

Output from these studies was freely available and disseminated via traditional channels and social media. Main activities included:

- Regular webinars that supported the published studies, backed up by blogs on related energy and environmental issues;

- Outreach activities that focused on sustainable energy, including capacity building and training related to low carbon emissions technologies, especially for developing countries;
- Specialist workshops and conferences to support international collaboration on various sustainable energy options, especially the impact of limiting emissions. These comprised both Centre activities directly for its members, together with complementary work organised by other organisations;
- Consultancies in both developed and developing countries, for the IEA Coal Industry Advisory Board, for individual member countries of the Centre such as Australia and the USA and other countries as well;
- Publications in academia and scientific and industry journals; and
- Extensive website development to further disseminate key aspects and successes of the overall programme, including the Knowledge Partners Network. The website made Centre output readily available to users worldwide, with growing numbers of visitors from countries that included Australia, China, France, Germany India, Japan, South Africa, the UK and the USA.

Through these activities, the Centre kept policymakers, scientists, engineers, other professionals, and stakeholders informed about the latest developments and how and why they should be implemented in order to promote energy security at an affordable cost and with minimal environmental impact.

Changes in global energy markets and political direction meant that the Centre's study programme evolved, increasingly directed to the cleaner, more sustainable use of coal and other carbon-based materials. Ways to minimise and control traditional emissions were augmented by a comprehensive programme of studies examining and monitoring the impact of climate change and how coal would retain its role as an important source of energy. The issue of global warming was identified by the Centre as far back as the 1970s, long before its importance was widely recognised. This early work helped inform decision-makers and was instrumental in laying the foundation for the creation of a new wide-ranging sector focused on tackling the problem.

The Centre continued to contribute to the debate, informing, advising, and providing expert input and insight into quantifying the scale of the problem, identifying the contributions made by different sectors, and offering recommendations on how to mitigate the effects of climate change. This included studies of techniques to reduce the impacts of coal use through the adoption of measures such as increasing the efficiency of coal power plants, reducing their conventional emissions to very low levels, limiting their water demand, and the deployment of CCUS technologies capable of significantly reducing greenhouse gas emissions. These studies provided valuable insights into a global problem and were frequently fed into the development of national and international greenhouse gas and other environmental policies and strategies.

Over the lifetime of the Centre, huge changes took place, especially in the power generation sector, and these were reflected in the direction and scope of the studies programme and outreach activities.

Developments in the sector were monitored closely, and a comprehensive series of reports explored virtually every aspect of electricity generation. These encompassed technological advances to improve plant efficiency and operability, enhanced flexible modes of operation, plant rehabilitation and upgrading, repowering options, and ways to reduce emissions to air, water, and land.

The programme also concentrated on the growing deployment of supercritical and ultrasupercritical steam conditions as they were increasingly adopted by the power sector. Studies closely followed developments taking place, surveying and reporting on the operational experience and success of plants using these conditions. These were augmented by conferences and workshops aimed at boosting international knowledge-sharing and cooperation on the topic. This included events on supercritical and other clean coal technologies held in many countries including China, Germany, Greece, Italy, Poland, South Africa, Spain, the UK and the USA. The outcomes of these studies and activities were disseminated widely within Centre member countries, but crucially, were also made available to governments, utilities, and project developers in emerging economies, giving them direct access to information on the latest technological advances on coal-based systems, and unbiased comparison of the different systems offered by major technology providers – these included advanced supercritical systems, IGCC technologies, and state-of-the-art emissions controls.

The IEA was originally founded in response to the oil crises of the 1970s and their impact on global energy markets. The Centre also responded quickly to global events in the energy world, quickly producing reports and briefing documents needed to bring decision-makers up to speed. For example, Russia's invasion of Ukraine and the loss of imported Russian coal and gas into Europe prompted in-depth examinations on the effectiveness of sanctions, other sources of fossil fuels, and Russian attempts to find viable alternative markets. The impact of the war on European and global energy markets was studied, and national and international strategies to replace Russian fuels were monitored. This work complemented other Centre studies that focused on the future of coal in Europe, most notably in parts of Eastern Europe, where it continued to be a major provider of secure, affordable electricity. Information and analysis from studies such as these was directed to decision-makers and used to raise awareness of developing situations, emphasising the importance of retaining some coal power capacity as part of a secure and balanced national portfolio of energy resources, something the Centre had always recommended.

For half a century, the Centre helped promote and encourage the wider uptake of the best available coal- and biomass-based technologies as these could offer cost savings, improved efficiency, and greatly reduced environmental impacts. Best practice in all aspects of resource production, transport, processing, and utilisation was consistently promoted. Energy trilemma issues focused on the need to

balance security of supply, affordability, and environmental impact were at the forefront of the study programme and other activities. The overall objective of the Centre's work was to provide a combination of technical and definitive, policy-relevant, independent information on how carbon-based energy sources such as coal, biomass, and organic wastes, could become cleaner sustainable sources of energy, compatible with the UN SDGs.

This chapter in the Centre's long productive life may have come to an end but its legacy in the form of a huge bank of expert knowledge and data will remain a useful asset for many years to come. The information and analysis on technical developments and advances, and that on policy, strategy, and future direction in global energy markets published over the course of half a century will remain freely available to help inform, focus, and direct future work.

On a policy level, the Centre made important contributions towards the development of many national and international regulations, policies, and strategies intended to make energy production cleaner and more sustainable, whilst emphasising that there is 'no one size fits all' solution to such global issues, and that a tailored approach is often the best way forward, reflecting the realities of the varying aspirations and affordable resources available to economies at different stages in their development.

The key messages from the Centre's work will continue to help, advise, and direct government policy and research and development towards achievable outcomes, capable of accommodating the realities faced by both developed and developing economies in their efforts to provide clean, affordable, sustainable energy to their respective populations.

REFERENCES

- ACAA (2023) *Coal combustion products production and use reports*. Available from: <https://acaa-usa.org/publications/production-use-reports/> American Coal Ash Association (2023)
- Adams D, Lockwood T, Baruya P, Wiatros-Motyka M, Zhu Q (2021) *A pathway to reducing emissions from coal power in India*. IEA-CIAB. Available from: <https://www.sustainable-carbon.org/report/a-pathway-to-reducing-emissions-from-coal-power-in-india-ieacc-ciab/> London, UK, IEA Clean Coal Centre, 157 pp (Feb 2021)
- Barnes D I (2011) *Ash utilisation – impact of recent changes in power generation practices*. CCC/176. Available from: <https://www.sustainable-carbon.org/report/ash-utilisation-impact-of-recent-changes-in-power-generation-practices-ccc-176/> London, UK, IEA Clean Coal Centre, 51 pp (Nov 2011)
- Barnes D I (2013) *Recent operating experience and improvement of commercial IGCC*. CCC/222. Available from: <https://www.sustainable-carbon.org/report/recent-operating-experience-and-improvement-of-commercial-igcc-ccc-222/> London, UK, IEA Clean Coal Centre, 52 pp (Oct 2013)
- Barnes D I (2015) *Operating experience of low grade fuels in circulating fluidised bed combustion (CFBC) boilers*. CCC/253. Available from: <https://www.sustainable-carbon.org/report/operating-experience-of-low-grade-fuels-in-circulating-fluidised-bed-combustion-cfbc-boilers-ccc-253/> London, UK, IEA Clean Coal Centre, 68 pp (Jun 2015)
- Barnes (2016) *The prospects for HELE power plant uptake in India*. CCC/271. Available from: <https://www.sustainable-carbon.org/report/the-prospects-for-hele-power-plant-uptake-in-india-ccc-271/> London, UK, IEA Clean Coal Centre, 54 pp (Nov 2016)
- Barnes D I (2019) *HELE technologies and outreach in Japan and South Korea*. CCC/293. Available from: <https://www.sustainable-carbon.org/report/hele-technologies-in-japan-and-south-korea-2/> London, UK, IEA Clean Coal Centre, 68 pp (Mar 2019)
- Baruya P (2015) *World forest and agricultural crop residue resources for cofiring*. CCC/249. Available from: <https://www.sustainable-carbon.org/report/world-forest-and-agricultural-crop-residue-resources-for-cofiring-ccc-249/> London, UK, IEA Clean Coal Centre, 66 (May 2015)
- Baruya P (2022) *Power and coal prospects in developing Africa*. ICSC/319. Available from: <https://www.sustainable-carbon.org/report/power-and-coal-prospects-in-developing-africa-icsc-319/> London, UK, International Centre for sustainable Carbon, 115 (May 2022)
- Breeze P (2017) *Critical thinking: Ultra and supercritical technology focus*. Available from: <https://www.powerengineeringint.com/coal-fired/critical-thinking/> *Power Engineering International* (24 March 2017)
- Carpenter A (2012) *CO₂ abatement in the iron and steel industry*. CCC/193. Available from: <https://www.sustainable-carbon.org/report/co2-abatement-in-the-iron-and-steel-industry-ccc-193/> London, UK, IEA Clean Coal Centre, 11 pp (Jan 2012)
- Carter L D (2010) *Capture and storage of CO₂ with other air pollutants*. CCC/162. Available from: <https://www.sustainable-carbon.org/report/capture-and-storage-of-co2-with-other-air-pollutants-ccc-162/> London, UK, IEA Clean Coal Centre, 19 (Jan 2010)
- CEIC (2021) *United States Coal Production, 1981–2023*. CEIC Data. Available from: <https://www.ceicdata.com/en/indicator/united-states/coal-production>) London, UK

- Chapman G (2022)** *Global thermal coal supply fundamentals*. ICSC/318. Available from: <https://www.sustainable-carbon.org/report/global-thermal-coal-supply-fundamentals/> London, UK, International Centre for sustainable Carbon, 89 pp (Feb 2022)
- Clarke L B (1995)** *Coal mining and water quality*. CCC/94. Available from: <https://www.sustainable-carbon.org/report/coal-mining-and-water-quality-ieacr-80/> London, UK, IEA Clean Coal Centre, 99 pp (Jul 1995)
- Collot A-G (2003)** *Prospects for hydrogen from coal*. CCC/78. Available from: <https://www.sustainable-carbon.org/report/prospects-for-hydrogen-from-coal-ccc-78/> London, UK, IEA Clean Coal Centre, 76 pp (Dec 2003)
- CREA (2025)** *Major coal-fired power capacity additions and plants under construction in 2024*. Centre for Research on Energy and Clean Air (CREA). Online database. Available from: <https://energyandcleanair.org/> (accessed 17 February 2025)
- Daniel M, Jamieson E (1992)** *Coal production prospects in the European Community*. IEACR/48. Available from: <https://www.sustainable-carbon.org/report/coal-production-prospects-in-the-european-community-ieacr-48/> London, UK, IEA Coal Research, 81 pp (Mar 1992)
- Davidson R M (2012)** *Hybrid carbon capture systems*. CCC/204. <https://www.sustainable-carbon.org/report/hybrid-carbon-capture-systems-ccc-204/> London UK, IEA Clean Coal Centre, 25 pp (Sep 2012)
- De Vries W, Hettelingh J-P, Posch M, eds (2015)** *Critical loads and dynamic risk assessments: Nitrogen, acidity and metals in terrestrial and aquatic ecosystems*. Environmental pollution series, vol 25. Dordrecht: Springer. ISBN 978-94-017-9507-4; 10.1007/978-94-017-9508-1
- Dong N S (2010)** *Reducing carbon-in-ash*. CCC/167. Available from: <https://www.sustainable-carbon.org/report/reducing-carbon-in-ash-ccc-167/> London, UK, IEA Clean Coal Centre, 64 pp (Aug 2010)
- Dong N S (2011)** *Utilisation of low rank coals*. CCC/182. Available from: <https://www.sustainable-carbon.org/report/utilisation-of-low-rank-coals-ccc-182/> London, UK, IEA Clean Coal Centre, 92 pp (Apr 2011)
- Fernando R (2008)** *Coal gasification*. CCC/140. Available from: <https://www.sustainable-carbon.org/report/coal-gasification-ccc-140/> London, UK, IEA Clean Coal Centre, 56 pp (Oct 2008)
- Fernando R (2014)** *Developments in modelling and simulation of coal gasification*. CCC/232. Available from: <https://www.sustainable-carbon.org/report/developments-in-modelling-and-simulation-of-coal-gasification-ccc-232/> London, UK, IEA Clean Coal Centre, 77 pp (Feb 2014)
- Garwood M (2024)** *Maintaining a stable electricity grid in the energy transition*. ICSC/CIAB. Available from: <https://www.sustainable-carbon.org/report/maintaining-a-stable-electricity-grid-in-the-energy-transition-icsc-ciab/> London, UK, International Centre for sustainable Carbon, 87 pp (Jan 2024)
- Global Energy Monitor (2025)** *Boom and Bust Coal 2025. Tracking the global coal plant pipeline*. Available from: <https://globalenergymonitor.org/report/boom-and-bust-coal-2025/> 23 pp (accessed 25 February 2025)
- Grennfelt P, Engleryd A, Forsius M, Hov Ø, Rodhe H, Cowling E (2019)** *Acid rain and air pollution: 50 years of progress in environmental science and policy*. Ambio 2019, Sep 21; 49(4) 849-864
- Henderson C (2003)** *Improving efficiencies of coal-fired power plant in developing countries*. CCC/70. Available from: <https://www.sustainable-carbon.org/report/improving-efficiencies-of-coal-fired-power-plant-in-developing-countries-ccc-70/> London, UK, IEA Clean Coal Centre, 71 pp (Jan 2003)

- Henderson C (2014)** *Increasing the flexibility of coal-fired power plants*. CCC/242. Available from: <https://www.sustainable-carbon.org/report/increasing-the-flexibility-of-coal-fired-power-plants-ccc-242/> London, UK, IEA Clean Coal Centre, 57 pp (Oct 2014)
- Henderson C (2015)** *Power plant CO₂ capture heat integration*. CCC/260. Available from: <https://www.sustainable-carbon.org/report/power-plant-co2-capture-heat-integration-ccc-260/> London, UK, IEA Clean Coal Centre, 50 pp (Dec 2015)
- Hessling M (1991)** *Mine productivity*. IEACR/25. Available from: <https://www.sustainable-carbon.org/report/mine-productivity-ieacr-35/> London, UK, IEA Clean Coal Centre, 106 pp (Mar 1991)
- ICSC (2024)** *3rd ICSC Energy Transition Workshop. Practical routes to achieving net zero*. Available from: <https://www.sustainable-carbon.org/workshop/3rd-energy-transition-workshop-ctn/> ICSC and Eskom, in Cape Town, South Africa, 24-25 April 2024
- IEA/OECD (2001)** *Energy Balances of non-OECD Countries 2001*. Available from: https://www.oecd.org/en/publications/energy-balances-of-non-oecd-countries-2001_energy_bal_non-oecd-2001-en-fr.html International Energy Agency/Organisation for Economic Co-operation and Development, 599 pp. (2001)
- IEA/OECD (2002)** *Coal in the Energy Supply of India*. Available from: https://www.oecd.org/content/dam/oecd/en/publications/reports/2002/07/coal-in-the-energy-supply-of-india_g1gh2a9e/9789264175945-en.pdf International Energy Agency/Organisation for Economic Co-operation and Development, 118 pp (2002)
- IEA (2023)** *Energy system of India*. Available from: <https://www.iea.org/countries/india> International Energy Agency, Paris, France (accessed 10 June 2025)
- IEA (2024)** *Coal 2024. Analysis and forecast to 2027*. Available from: <https://www.iea.org/reports/coal-2024/executive-summary> International Energy Agency, Paris, France, 127 pp (Dec 2024)
- IEA (2025)** *Membership*. Available from: <https://www.iea.org/about/membership> International Energy Agency, Paris, France. (2025)
- Jones J, Darvell L, Gudka B (2025)** *The role of biomass in the production of iron steel and cement*. ICSC/336. Available from: <https://www.sustainable-carbon.org/report/the-role-of-biomass-in-the-production-of-iron-steel-and-cement/> London, UK, International Centre for sustainable Carbon, 117 pp (Feb 2025)
- Kelsall (2020)** *Carbon capture utilisation and storage – status barriers and potential*. CCC/304. Available from: <https://www.sustainable-carbon.org/report/carbon-capture-utilisation-and-storage-status-barriers-and-potential-ccc-304/> London, UK, IEA Clean Coal Centre, 99 pp (Jul 2020)
- Kelsall G (2021)** *Hydrogen production from coal*. ICSC/313. Available from: <https://www.sustainable-carbon.org/report/hydrogen-production-from-coal-icsc-313/> London, UK, International Centre for sustainable Carbon, 109 pp (Aug 2021)
- Kelsall G (2023)** *The resilience of coal-based industries in the transition to net zero*. ICSC-CIAB. Available from: <https://www.sustainable-carbon.org/report/the-resilience-of-coal-based-industries-in-the-transition-to-net-zero-icsc-ciab/> London, UK, International Centre for sustainable Carbon, 141 pp (March 2023)
- Kelsall G, Baruya P (2022)** *The role of low emission coal technologies in a net zero Asian future*. ICSC-CIAB. Available from: <https://www.sustainable-carbon.org/report/the-role-of-low-emission-coal-technologies-in-a-net-zero-asian-future/> London, UK, International Centre for sustainable Carbon, London, UK, 218 pp (Feb 2022)

- Li L (2024)** A Feasible Three-steps Technological Route for Coal-fired Power Units to Achieve Carbon Neutrality Target. Presented at: 3rd ICSC Energy Transition Workshop – Session 3. Available from: <https://www.sustainable-carbon.org/workshop/3rd-energy-transition-workshop-programme/> (2024)
- Lockwood T (2021a)** *A Technology Roadmap for High Efficiency, Low Emissions Coal Power Plant*. CCC/309. Available from: <https://www.sustainable-carbon.org/report/a-technology-roadmap-for-high-efficiency-low-emissions-coal-power-plant-ccc309/> London, UK, IEA Clean Coal Centre, 92 pp (Mar 2021)
- Lockwood T (2021b)** *A review of cost estimates for carbon capture and storage in the power sector*. ICSC/317. Available from: <https://www.sustainable-carbon.org/report/a-review-of-cost-estimates-for-carbon-capture-and-storage-in-the-power-sector/> London, UK, International Centre for sustainable Carbon, 72 pp (Dec 2021)
- Metzger S (2020)** *Carbon prices and their impact on coal power*. CCC/308. Available from: <https://www.sustainable-carbon.org/report/carbon-prices-and-their-impact-on-coal-power-ccc-308/> London, UK, IEA Clean Coal Centre, 90 pp (Sep 2020)
- Mills S (2011)** *Global perspective on the use of low quality coals*. CCC/180. Available from: <https://www.sustainable-carbon.org/report/global-perspective-on-the-use-of-low-quality-coals-ccc-180/> London, UK, IEA Clean Coal Centre, 80 pp (Jan 2011)
- Mills S (2013a)** *Coal-fired CCS demonstration plants*. CCC/207. Available from: <https://www.sustainable-carbon.org/report/coal-fired-ccs-demonstration-plants-2012-ccc-207/> London, UK, IEA Clean Coal Centre, 114 pp (1 Jan 2013)
- Mills (2013b)** *Combining renewable energy with coal*. CCC/223. Available from: <https://www.sustainable-carbon.org/report/combining-renewable-energy-with-coal-ccc-223/> London, UK, IEA Clean Coal Centre, 117 pp (1 Aug 2013)
- Mills (2016)** *Low quality coals – key commercial, environmental and plant considerations*. CCC/270. Available from: <https://www.sustainable-carbon.org/report/low-quality-coals-key-commercial-environmental-and-plant-considerations-ccc-270/> London, UK, IEA Clean Coal Centre, 111 pp (Sep 2016)
- Mills S (2017)** *Combining solar power with coal fired power plants, or cofiring natural gas*. CCC/279. Available from: <https://www.sustainable-carbon.org/report/combining-solar-power-with-coal-fired-power-plants-or-cofiring-natural-gas-ccc-279/> London, UK, IEA Clean Coal Centre, 91 pp (Oct 2017)
- Mills (2018)** *The use of coal-derived wastes as a source of energy*. CCC/288. Available from: <https://www.sustainable-carbon.org/report/the-use-of-coal-derived-wastes-as-a-source-of-energy/> London, UK, IEA Clean Coal Centre, 79 pp (Jul 2018)
- Mills S (2021)** *Potential markets for high efficiency, low emissions coal-fired power plants*. CCC/312. Available from: <https://www.sustainable-carbon.org/report/the-use-of-coal-derived-wastes-as-a-source-of-energy/> London, UK, IEA Clean Coal Centre, 133 pp (Jul 2021)
- Mills S (2023)** *Hubs and clusters for CCUS – their role in decarbonisation*. ICSC/329. Available from: <https://www.sustainable-carbon.org/report/hubs-and-clusters-for-ccus-their-role-in-decarbonisation-icsc-329/> London, UK, International Centre for sustainable Carbon, 101 pp (Dec 2023)
- Mills S (2024)** *Rare earth elements – recovery from coal based materials*. ICSC/334. Available from: <https://www.sustainable-carbon.org/report/rare-earth-elements-recovery-from-coal-based-materials/> London, UK, International Centre for sustainable Carbon, 96 pp (Nov 2024)

- Minchener A (2004)** *Coal in China*. CCC/87. Available from: <https://www.sustainable-carbon.org/report/coal-in-china-ccc-87/> London, UK, IEA Clean Coal Centre, 59 pp (Jul 2004)
- Minchener A (2011)** *Coal-to-oil, gas and chemicals in China*. CCC/181. Available from: <https://www.sustainable-carbon.org/report/coal-to-oil-gas-and-chemicals-in-china-ccc-181/> London, UK, IEA Clean Coal Centre, 49 pp (Feb 2011)
- Nalbandian-Sugden H (2014)** *Non-fuel uses of coal*. CCC/236. Available from: <https://www.sustainable-carbon.org/report/non-fuel-uses-of-coal-ccc-236/> London, UK, IEA Clean Coal Centre, 80 pp (Jun 2014)
- Nicol K (2013)** *Status of advanced ultra-supercritical pulverised coal technology*. CCC/229. Available from: <https://www.sustainable-carbon.org/report/status-of-advanced-ultra-supercritical-pulverised-coal-technology-ccc-229/> London, UK, IEA Clean Coal Centre, 57 pp (Dec 2013)
- OECD (1977)** *The OECD programme on long range transport of air pollutants. Measurements and Findings*. Available from: https://projects.nilu.no/ccc/reports/paris_1977.pdf Organisation for Economic Co-operation and Development, Paris, France, 332 pp (1977)
- Reid I (2018)** *Non-energy uses of coal*. CCC/291. Available from: <https://www.sustainable-carbon.org/report/non-energy-uses-of-coal-report-ccc291/> London, UK, IEA Clean Coal Centre, 90 pp (Nov 2018)
- Reid I (2022)** *Prospects for coal in agriculture*. ICSC/325. Available from: <https://www.sustainable-carbon.org/report/prospects-for-coal-in-agriculture-icsc-325/> London, UK, International Centre for sustainable Carbon, 78 pp (Sep 2022)
- Reid I (2023)** *Repurposing coal assets*. ICSC/328. Available from: <https://www.sustainable-carbon.org/report/repurposing-of-coal-assets-icsc-328/> London, UK, International Centre for sustainable Carbon, 85 pp (Oct 2023)
- Reid I (2025)** *Coal as a resource - gasification and chemicals*. ICSC/335. Available from: <https://www.sustainable-carbon.org/report/coal-as-a-resource-gasification-and-chemicals/> London, UK, International Centre for sustainable Carbon, 77 pp (Jan 2025)
- Reid I, Carpenter A M, Masili A (2020)** *Beneficial uses of coal fly ash*. CCC/303. IEA Clean Coal Centre, London, UK (Apr 2020)
- Rousaki K, Couch G (2000)** *Advanced clean coal technologies and low value coals*. CCC/39. Available from: <https://www.sustainable-carbon.org/report/advanced-clean-coal-technologies-and-low-value-coals-ccc-39/> London, UK, IEA Coal Research, 76 pp (Nov 2000)
- Sloss L (2003)** *Trends in emission standards*. CCC/77. Available from: <https://www.sustainable-carbon.org/report/trends-in-emission-standards-ccc-77/> London, UK, IEA Clean Coal Centre, 64 pp (Nov 2003)
- Sloss L (2012)** *Mercury emissions from India and South East Asia*. CCC/208. Available from: <https://www.sustainable-carbon.org/report/mercury-emissions-from-india-and-south-east-asia-ccc-208/> London, UK, IEA Clean Coal Centre, 42 pp (Oct 2012)
- Sloss L (2013)** *Coal mine site reclamation*. CCC/216. Available from: <https://www.sustainable-carbon.org/report/coal-mine-site-reclamation-ccc-216/> London, UK, IEA Clean Coal Centre, 70 pp (Feb 2013)
- Sloss L (2015)** *The emerging market for mercury control*. CCC/245. Available from: <https://www.sustainable-carbon.org/report/the-emerging-market-for-mercury-control-ccc-245/> London, UK, IEA Clean Coal Centre, 74 pp (Feb 2015)

- Sloss L (2016)** *Levelling the intermittency of renewables with coal*. CCC/268. Available from: <https://www.sustainable-carbon.org/report/levelling-the-intermittency-of-renewables-with-coal-ccc-268/> London, UK, IEA Clean Coal Centre, 71 pp (Jul 2016)
- Sloss L (2017a)** *Emerging markets for pollution control retrofits*. CCC/274. Available from: <https://www.sustainable-carbon.org/report/emerging-markets-for-pollution-control-retrofits-ccc-274/> London, UK, IEA Clean Coal Centre, 82 pp (Feb 2017)
- Sloss L (2017b)** *Environmental and other effects of coal mining and transport*. CCC/281. Available from: <https://www.sustainable-carbon.org/report/environmental-and-other-effects-of-coal-mining-and-transport-ccc-281/> London, UK, IEA Clean Coal Centre, 98 pp (Dec 2017)
- Smith R A** - Air and Rain, the Beginnings of a Chemical Climatology. London: Longmans Green; 1872
- Smith I M (1978)** Carbon dioxide and the "greenhouse effect" : an unresolved problem. ICTIS/ER 01. London, UK, IEA Clean Coal Centre (Feb 1978)
- Smith I M (2005)** *Cement and concrete – benefits and barriers in coal ash utilisation*. CCC/94. Available from: <https://www.sustainable-carbon.org/report/cement-and-concrete-benefits-and-barriers-in-coal-ash-utilisation-ccc-94/> London, UK, IEA Clean Coal Centre, 70 pp (Jan 2005)
- Smith I M (2009)** *Gas turbine technology for syngas/hydrogen in coal-based IGCC*. CCC/155. Available from: <https://www.sustainable-carbon.org/report/gas-turbine-technology-for-syngas-hydrogen-in-coal-based-igcc-ccc-155/> London, UK, IEA Clean Coal Centre, 51 pp (Oct 2009)
- Song C (2005)** *Premium carbon products and organic chemicals from coal*. CCC/98. Available from: <https://www.sustainable-carbon.org/report/premium-carbon-products-and-organic-chemicals-from-coal-ccc-98/> London, UK, IEA Clean Coal Centre, 88 pp (Jun 2005)
- Umbach F (2024)** *Still waiting for peak coal*. Available from: <https://www.gisreportsonline.com/r/peak-coal/> GIS, Geopolitical Intelligence Services AG, Liechtenstein. (5 Feb 2024)
- Utt J, Giglio R (2012)** The introduction of Foster Wheeler's 660 MWe supercritical CFBC technology for the India market. *Power-Gen India and Central Asia Conference*, New Delhi, India. 20 Apr 2012, 11 pp (2012)
- Walker S (1996)** *Comparative underground coal mining methods*. IEACR/85. Available from: <https://www.sustainable-carbon.org/report/comparative-underground-coal-mining-methods-ieacr-85/> London, UK, IEA Clean Coal Centre, 94 pp (Mar 1996)
- Walker S (2001)** *Experience from coal industry restructuring*. CCC/48. IEA Clean Coal Centre, London, UK (1 July 2001)
- Wiatros-Motyka M (2016)** *An overview of HELE technology deployment in the coal power plant fleets of China, EU, Japan and USA*. CCC/273. Available from: <https://www.sustainable-carbon.org/report/an-overview-of-hele-technology-deployment-in-the-coal-power-plant-fleets-of-china-eu-japan-and-usa-ccc-273/> London, UK, IEA Clean Coal Centre, 75 pp (Dec 2016)
- Wiatros-Motyka M (2019)** *Power plant design and management for unit cycling*. CCC/295. Available from: <https://www.sustainable-carbon.org/report/power-plant-design-and-management-for-unit-cycling-2/> London, UK, IEA Clean Coal Centre, London, 94 pp (Sep 2019)
- Wu Z (2003)** *Understanding fluidised bed combustion*. CCC/76. Available from: <https://www.sustainable-carbon.org/report/understanding-fluidised-bed-combustion-ccc-76/> London, UK , IEA Clean Coal Centre, 42 pp (Oct 2003)

- Zhang X (2014)** *Management of coal combustion wastes*. IEACR/38. Available from: <https://www.sustainable-carbon.org/report/management-of-coal-combustion-wastes-ccc-231/> London, UK, IEA Clean Coal Centre, 68 pp (Feb 2014)
- Zhang X (2016)** *Emission standards and control of PM2.5 from coal-fired power plants*. CCC/267. Available from: <https://www.sustainable-carbon.org/report/emission-standards-and-control-of-pm2-5-from-coal-fired-power-plant-ccc-267/> London, UK, IEA Clean Coal Centre, 80 pp (Jul 2016)
- Zhang X (2019)** *Support mechanisms for cofiring biomass with coal*. CCC/294. Available from: <https://www.sustainable-carbon.org/report/report-support-mechanisms-for-cofiring-biomass-with-coal/> London, UK, IEA Clean Coal Centre, 60 (Jun 2019)
- Zhang X, Meloni S (2020)** *Technology developments in the cofiring of biomass*. CCC/305. Available from: <https://www.sustainable-carbon.org/report/technology-developments-in-cofiring-biomass-ccc-305/> London, UK, IEA Clean Coal Centre, 80 pp (Aug 2020)
- Zhu Q (2013)** *Developments in circulating fluidised bed combustion*. CCC/219. Available from: <https://www.sustainable-carbon.org/report/developments-in-circulating-fluidised-bed-combustion-ccc-219/> London, UK, IEA Clean Coal Centre, 60 pp (Jun 2013)
- Zhu Q (2022)** *The potential role of ammonia in a clean energy transition*. CSC/323. Available from: <https://www.sustainable-carbon.org/report/the-potential-role-of-ammonia-in-a-clean-energy-transition-icsc-323/> London, UK, International Centre for sustainable Carbon, 75 pp (Aug 2022)
- Zhu Q (2023)** *The hydrogen economy and the role for coal*. ICSC/CIAB report. Available from: <https://www.sustainable-carbon.org/report/hydrogen-economy-and-the-role-for-coal-ciab-report/> London, UK, International Centre for sustainable Carbon, 106 pp (Mar 2023)
- Zhu Q (2024)** *Prospects for reduced emissions using clean ammonia*. ICSC/333. Available from: <https://www.sustainable-carbon.org/report/prospects-for-reduced-emissions-using-clean-ammonia-icsc-333/> London, UK, International Centre for sustainable Carbon, 89 pp (Aug 2024)

