CoalTech2051

Changing the face of coal:

a strategy for future coal-related RTD in the European Union

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Preamble

The European Commission's *Coal Regions in Transition Platform* initiative includes a number of activities of relevance to the research community. The EU-supported CoalTech2051 project has developed a future coal-related research strategy with input from many stakeholders. This report details that strategy and gives examples of research projects that are already pushing the boundaries to deliver new solutions that can better position coal and the coal regions for the future.

The CoalTech2051 project partners are grateful for the support of all those who contributed to this report and especially to those who participated in the three project workshops, joined the many working group meetings, responded to Delphi surveys, and provided input for the illustrated research project summaries.

Research Fund for Coal & Steel

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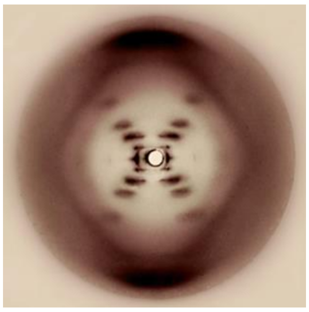
Box 1 – From coal crystallography to unravelling the structure of DNA



The “plate 51” photograph from which the structure of DNA was deduced

After graduating from Cambridge University in 1941, Rosalind Franklin joined the British Coal Utilisation Research Association (BCURA), a new organisation dedicated to research on the production, distribution and use of coal and its derivatives such as coke. She earned her PhD studying the porosity of coal and coke, or “holes in coal” as she described. After the war, she moved to Paris where she mastered and extended the technique of x-ray crystallography, applying this to carbon compounds produced from coal. These, she found, were either graphite-like and soft or very hard, low-density, vitreous carbon crystallites which resisted heat. The latter quickly found industrial applications while her x-ray skills identified the strong cross-links within the carbon crystallites.

Back in the UK, at King’s College London, Dr. Franklin turned her attention from coal to the structure of proteins and DNA – both candidates in the chemistry of heredity. From samples of DNA, she photographed the crucial x-ray diffraction pattern that allowed James Watson and Francis Crick to deduce the double-helix structure of DNA in 1953. They won a Nobel Prize for this discovery in 1962, four years after Rosalind had sadly died of cancer at the age of 38. Her extraordinary experimental work was recognised in 2020 when The Royal Mint issued a commemorative UK fifty-pence coin.

“We dream of an environmentally friendly and climate-neutral European Union that is globally competitive and grows thanks to its industrial potential. We know it requires a transformation of the entire EU economy and that will not happen overnight. Moreover, this transition must be inclusive and fair – we must leave no citizen, no region and no Member State behind.

“Therefore, we have to ensure a secure and worthy future for our coal regions’ residents who will be most affected by this profound transformation. We want old mines and other post-industrial sites to become investment areas generating sustainable and future-proofed jobs; we want parks and recreational areas to be created in place of abandoned post-industrial areas; we want projects aimed at combating smog and energy poverty in the carbon-intensive regions.

“With this in mind – together with the Vice-President of the European Commission, Maroš Šefčovič – we launched the EU Coal Regions in Transition Platform. In addition, I had proposed to establish a special Just Transition Fund – the idea that became now a central part of the European Green Deal under the leadership of Vice-President Frans Timmermans.

“However, all that we dream of depends on technological progress. Here, the Research Fund for Coal and Steel can play its part by looking at coal and the coal-value chain in new ways. Gasification, fuel cells, materials science, bioremediation and other new and innovative technologies from the coal sector can all support our clean energy transformation. Yesterday’s coal scientists are tomorrow’s low-carbon champions.”

Prof. Jerzy Buzek MEP

Introduction

From the earliest days of the industrial revolution, coal has been special. It provides raw energy with security at an affordable cost, often from indigenous resources. Fair markets for coal and steel formed the very basis of European integration under the Treaty of Paris signed in 1951. These same objectives and more are reflected in today's Green Deal initiative of the European Union.

Over the decades, coal research in Europe has inspired progress in many fields. From the British Coal Utilisation Research Association, it was Rosalind Franklin who first photographed the structure of DNA in 1952. More recently, the EU Research Fund for Coal and Steel has supported R&D projects in universities, institutes and industry that have improved the coal sector.

Today, with the recent shift in EU policy away from coal, driven by climate-change concerns, the objectives of coal-related research must be adjusted. Whereas research into health and safety will remain important, alongside energy efficiency and environmental protection, the overriding priorities have become the preservation of natural resources, exploitation of new energy sources and elimination of carbon emissions. As many countries outside the European Union will continue to rely on coal for decades to come, coal research also has an important international dimension.

The aim then is to offer a structure for coal-related research that is aligned with the overall goals of the Union's climate and energy policy, as well as with the specific aims of the European Green Deal. This is not a rigid structure, but one that encourages the many facets of coal-related research, each contributing to policy objectives. New research is already in progress with showcase projects. These and many more are needed if the EU is to meet its tough climate targets.

In this report, you can read about projects that are helping to shape the future of the coal industry. All are important, but some more than others. Carbon capture, use and storage, alternative uses of coal and lignite, and the repurposing of coal-related assets should be given special consideration to deliver and comply with the political ambition of transforming the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use.[1]

Given that most non-EU countries have less climate ambition – with weaker commitments under the UNFCCC Paris Agreement – it will be necessary to introduce appropriate trade protection measures. To produce basic commodities and meet society's energy needs with zero pollution will be more expensive. EU industry must therefore enjoy a captive market for its "green" products, without unfair competition from outside. Thus, socio-economic research may be just as important here as technical research.

Box 2 – "Blue Coal" reduces household emissions in Poland

BLUECOAL
BŁĘKITNY WĘGIEL

The mayor of Jedlina-Zdrój agreed with the Institute for Chemical Processing of Coal (IChPW) in Poland to run a pilot programme aimed at reducing local air pollution from household coal use. The first batch of 400 tonnes of smokeless "Blue Coal" developed by the institute was delivered to residents of Jedlina-Zdrój for their stoves and boilers, while residents of Roszkowa and Krzyżanowice received 200 tonnes. The pilot programme, which included extensive air quality monitoring, has allowed researchers to make a full assessment of this new, low-emission fuel in real conditions, following earlier testing at IChPW in Zabrze.

[1] COM(2019) 640 – The European Green Deal

Perspectives on future coal-related research

Legislation is now in place in the EU to make the future use of coal for power generation and industrial applications increasingly unattractive. The historic trend of declining coal use may therefore accelerate, especially as governments agree phase-out dates for coal use. The ambition in the EU is to eliminate the use of all fossil fuels, to reduce the need for all extractive industries by recycling materials within the economy, and to depend almost entirely on renewable energy sources (RES). However, outside the EU, growing economies are fuelled by coal and other fossil fuels. A two-pronged, coal-related research strategy is thus called for: firstly, a focus on research activities that support EU policy objectives and, secondly, research activities that promote EU leadership and international engagement through climate diplomacy.

> ***"As the EU is transitioning towards a low-carbon economy, the future of regions with large coal sectors must be planned carefully. Transition to a low-carbon economy will require structural changes in coal-producing regions with a strong focus on research and innovation. As the European Parliament's rapporteur for the EU Framework Programme for Research and Innovation, I appreciate that Horizon 2020 is the largest EU research and innovation programme with a budget of €80 billion for 2014-2020 and 35% of resources dedicated to climate-related research. Unfortunately, the recent Council's results on the Multiannual Financial Framework 2021-2027 are a clear 'no' to innovation, decarbonisation and digitalisation. At the beginning of the decade, the EU announced that it would become the engine of technology and the most innovative place in the world. The compromise reached now destroys all ambitions to achieve a 55% reduction in CO_2 emissions in a decade. This objective would have meant transformative changes based on clean coal technologies in our carbon-intensive regions."***
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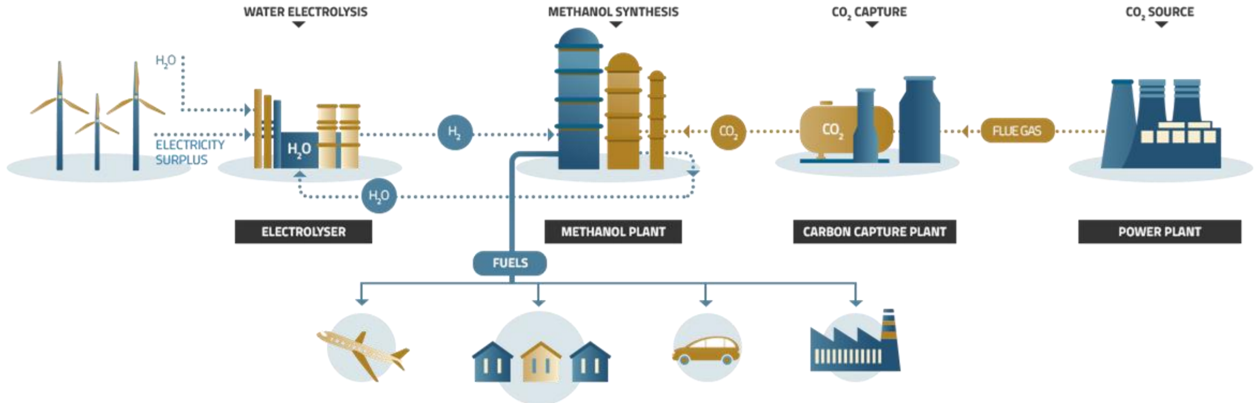
> Dr. Christian Ehler MEP

Box 3 – Synthesis of methanol from captured carbon dioxide using surplus electricity



The $MefCO_2$ project with partners from across Europe aims to produce methanol from captured CO_2 and hydrogen produced using surplus renewable energy. Methanol can be used as a fuel in many applications or as a feedstock in the chemical industry. The technology is being designed in a modular format at an intermediate scale, with the aim of being able to adapt it to varying plant sizes and gas compositions.

Methanol is traditionally produced from synthesis gas, obtained by the reforming of natural gas or coal. The $MefCO_2$ project has developed a flexible methanol synthesis process fed with a high-CO_2 concentration input stream from a lignite-fired thermal power station at Niederauβem in Germany. The process could equally well use CO_2 from industrial processes such as steel or cement production. The other synthesis reactant, hydrogen, comes from water electrolysis using surplus renewable electricity which is often available on sunny or windy days.

$MefCO_2$ – an Horizon 2020 project funded under the Sustainable Process Industry through Resource and Energy Efficiency (SPIRE) contractual Public-Private Partnership (PPP)

Coal-related research in support of EU policy objectives

The EU has agreed a climate-protection goal that requires CO_2 emissions to be reduced by up to 95% by 2050, compared with a 1990 baseline, and has the ambition to reach net-zero GHG emissions. Fully replacing the use of fossil fuels in power generation with renewable energy sources is not enough to achieve this climate goal. All sectors of the economy must contribute: the energy used in industry, transport and buildings must be largely decarbonised. The coal-related research community must play its part by exploring imaginative new solutions, building especially on the opportunities to repurpose assets and develop technologies to meet EU policy objectives and decarbonisation ambition.

In the EU, governments and industry are working to completely transform the energy system, shifting away from fossil fuels (coal, oil and gas) to incorporate a significant share of renewable energy sources. At the same time and given the rather uncertain geopolitical situation facing the world, there is a general desire to reduce energy-import dependency, so the EU's large reserves of indigenous coal may continue to play a role for some years to come, supporting a secure and affordable energy transition as well as being an important source of carbon.

For some sectors, the use of carbon is inevitable. For example, carbon is the basic building block of the chemical industry: plastics and all organic chemicals contain carbon. The carbon in limestone must be removed to make cement. Iron and steel both contain carbon. So, even if electricity is carbon-free, there remains an enormous range of products that depend on carbon.

The transformation of the power sector brings its own challenges. Renewable power generation (*e.g.* wind turbines and solar PV) is often intermittent. As the share of renewables grows, managing this intermittency becomes more difficult. Security of energy supply is vital for any modern society, so solutions have to be found: a combination of sufficient back-up power supply and efficient energy storage is needed.

The cost of the energy transition needs to be understood for the whole economy. Researchers must assess the costs of different options, so that decision-makers are aware of the system-wide implications of adopting particular policies.

Box 4 – Lithium-ion batteries smooth power supply in Germany

A 15 MW battery storage system comprising ten containerised units at the 466 MW STEAG Völklingen-Fenne coal-fired heat and power plant in Germany where a 42 MW gas engine also operates on coal mine methane

With the energy transition, the share of renewable energy sources in the EU power mix will continue to grow to meet targets. This already means large fluctuations in power generation from solar PV and wind turbines have to be quickly balanced out. To achieve this, STEAG has invested €100 million in six 15 MW battery systems – with no subsidy – at Herne, Lünen, Duisburg-Walsum, Bexbach, Völklingen-Fenne and Weiher power stations. Each system has a capacity of more than 20 MWh and the six systems together could theoretically provide power for 300 000 households for one hour. As with portable electronic devices, storing large amounts of energy requires multiple batteries. STEAG uses rechargeable lithium-ion batteries linked via a control centre. When partially charged, these systems are ideal for providing primary reserve power.

“Workshop on RFCS energy transition for coal regions certainly constitutes a major economic opportunity in itself, boosting sustainable investments, growth and jobs. Some €379 billion investments needed annually in 2020-2030 period to deliver on climate and energy objectives.”

Ms. Maria Spyraki MEP

The future energy system must continue to integrate more renewable power generation with conventional generation, in a strongly interconnected system that allows energy consumption in industry, transport and buildings to become interlinked through *sector coupling*. The vision is for an “all-electric world”. Power, heat and materials become interchangeable within a “closed-carbon-cycle economy”.

EU trends reflect an ambitious climate and energy policy, and the pursuit of a zero-emission economy under the European Green Deal. Research aims to accelerate and enable this energy transition, with positive impacts on society – leaving no one behind. Even with such ambitions, coal remains a valuable resource in the EU and its potential can continue to be explored and developed. For example, there are many alternative products which can be derived from coal, including chemicals, soil improvers and new products such as graphene and carbon fibre.

There is also much important research needed on coal mine rehabilitation, improved use of resources associated with coal extraction such as methane, reuse of coal mines and mine infrastructure, and on repurposing coal-fired power plants. Carbon capture, use and storage (CCUS) is an important R&D topic that goes beyond high efficiency, low emission (HELE) coal plants, with the potential to eliminate GHG emissions. Other research relates to the decline of coal production and post-mining tasks, as well as the changing nature of the labour market in coal mining regions as coal value chains are replaced.

Supporting the just transition of the coal sector and regions

The coal sector accounts for one fifth of the total electricity production in the EU, and provides jobs for around 230 000 people in mines and power plants across thirty-one regions and eleven member states. The coal regions have valuable assets and infrastructure, as well as highly trained employees. The repurposing of closed or end-of-life coal-related assets, such as:

- coal and lignite mines,
- coal- and lignite-fired power plants,
- coal transport infrastructure,
- coal preparation plants and lignite fuel processing plants, and
- coal-based industrial processes, *e.g.* coking ovens and cement works,

as well as workforce re-training, have the potential for economic restructuring during a socially acceptable transition. Existing infrastructure can provide some of the assets needed for redevelopment and so be part of a smooth transition. This is especially true in the coal regions where workforces are attuned to industrial development and adaptable to new solutions for energy and materials supply.

“The Just Transition Fund has a potential to become a helpful tool in climate transition and climate change adaptation. Coal- and energy-intensive regions must remain attractive for their citizens. Too much restrictions in targeting of JTF finance would be counterproductive. Being open and applying common sense will be crucial.”

Mr. Ondřej Knotek MEP

Carbon capture, use and storage

CO_2 capture, use and storage (CCUS) can be applied to a wide range of industrial sectors, including power generation, steelmaking and chemicals. It includes, for example, the permanent storage of carbon in building materials or plastics. There are many exciting new CCUS opportunities for researchers to explore and these are becoming more important than ever as EU policymakers target carbon neutrality by 2050 under the European Green Deal. For example, algae farming allows CO_2 to be converted to biomass and processed into biofuels.

CCUS can have a higher public acceptance than other carbon capture approaches. The carbon that is captured, once paired with hydrogen produced by water electrolysis using surplus renewable electricity, can be converted into useful and valuable products. These include low-carbon transport fuels such as dimethyl ether (DME) and polyoxymethylene dimethyl ethers (OMEn) which have extremely low emissions of sulphur, NOx and soot. Unlike petrol and diesel, DME and OMEn have no carbon-carbon chemical bonds, so carbonaceous particles cannot readily form. The biggest advantage of CCUS is that it can contribute to *sector coupling*, embracing the whole energy-

Box 5 – Handlová fish farm uses water from an active coal mine

Fish farming at Handlová coal mine in Slovakia

Using warm mine water from Handlová coal mine in Slovakia allows African Catfish (*Clarias Gariepinus*) to be bred at the mine's new fish farm built by the mining company HBP. About 100 l/s of water flows freely from the mine at a temperature of 15°C to 18°C, of which 40 l/s are used by the farm. This provides 2.8 MW_{th} of energy which keeps the fish warm at 30°C, drives freezers and provides the fish with plenty of clean water in which to swim. The annual production of fish meat is 1 000 tonnes, making the project the largest indoor fish farm in the European Union. With more than 5 MW_{th} of heat energy available in the mine water, there is the potential to double meat produciton capacity with a second breeding hall.

Box 6 – Optimisation of CO_2 capture technologies for utility scale

CO_2 capture plant at the 2 600 MW Brindisi Sud coal-fired power plant operated by ENEL in Italy

The operability and flexibility of first-generation, post-combustion CO_2-capture processes were demonstrated by TNO, EnBW and ENEL at pilot plants in order to prepare for full-scale demonstration projects. OCTAVIUS established guidelines on operations, emissions, health, safety and environment (HSE), and costs.

In addition, OCTAVIUS demonstrated the DMX™ process on the ENEL pilot plant at Brindisi. This second-generation capture process should enable substantial reductions in the energy penalty and operational costs of CO_2 capture.

OCTAVIUS built on earlier FP6 and FP7 CCS projects, such as CASTOR and CESAR. Results from this clean coal research have assisted the participating technology suppliers, engineering companies and end-users.

OCTAVIUS – a FP7 project on the optimisation of CO_2 capture technology allowing verification and implementation at utility scale (2012-2017) supply system, including the power, chemicals and transport sectors, by using existing infrastructure to transition from fossil fuels to renewable energy sources.

The size of the carbon footprint associated with CCUS depends crucially on the availability of renewable energy sources in the energy mix. As these grow, CO_2 emissions from across the whole energy system can be decreased. As always, it will be necessary for researchers to analyse the life-cycle emissions from all options.

Energy storage

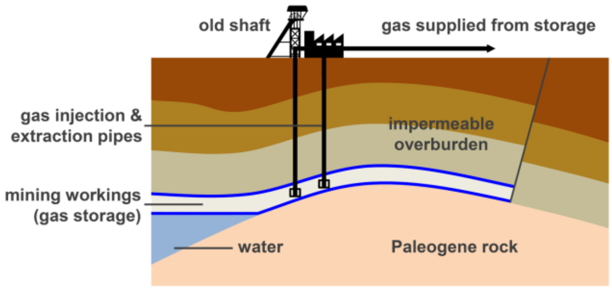
The intermittency or variability of renewable energy sources already creates a high demand for energy storage whereby operators can "make hay while the sun shines". This need will only grow as the share of renewables in the power market increases. The production of synthetic natural gas (SNG) using captured CO_2 and hydrogen from the electrolysis of water offers a way to store and use surplus renewable power. Among the many different types of energy storage, thermal energy storage (TES) offers the prospect of using existing infrastructure at existing coal power plants. The energy storage unit is heated using electricity during periods of peak output from say wind turbines and solar PV, thus storing electrical energy in the form of heat. When power prices are high during periods of peak demand, the heat is recovered and converted back into electricity using the existing steam plant infrastructure and turbo generators. TES increases the flexibility of existing plants, allowing them to play a bigger role in grid-balancing services. In the longer term, when a purely RES-based power system is envisaged, the coal-fired boilers can be closed to leave a fully operational, standalone storage system.

Hydrogen production

The term "hydrogen economy" refers to the vision of using hydrogen (H_2) as a low-carbon energy carrier to replace, for example, liquid fuels for transport and natural gas for heating. Hydrogen is attractive because whether it is combusted to produce heat or reacted with air in a fuel cell to produce electricity, the only by-product is pure water.

Hydrogen gas is not found naturally on Earth, so it must be split from chemical compounds, such as natural gas, coal, biomass or alcohols, or from water by electrolysis. In all cases, it takes energy to produce hydrogen. For that reason, hydrogen is really an energy carrier or storage medium, rather

Box 7 – Gas storage at abandoned mines



Cross section of underground gas storage

Abandoned underground mines offer an ideal place to store gas, given their often large volumetric capacity.

The Anderlus and Peronnes coal mines in Belgium were used for natural gas storage. After mining ended, both mines produced methane (AMM) which was sold via a gas pipeline. Gas storage operations began in 1980 and continued to 1996 at Anderlus and 2000 at Peronnes. Each mine had a large number of shafts – ten at Anderlus and nineteen at Peronnes – making sealing maintenance expensive and ultimately rendering these particular storage operations unprofitable.

New gas storage projects would likely require the installation of a barrier to prevent gas leakage, perhaps using geotextiles to encase underground workings. Although no abandoned coal mine has been used for the storage of pure hydrogen, the potential exists with the right technology.

HyUnder – a FCH JU project to assess the potential, the actors and relevant business cases for large-scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe

Box 8 – Synthetic natural gas production to store electrical energy and recycle CO_2

At the 1 155 MW Łaziska coal power plant in Poland, a car is refuelled with compressed natural gas (CNG) from the SNG pilot plant

In Poland, Tauron and its partners are demonstrating the production of synthetic natural gas (SNG) from CO_2 captured from the flue gas of coal-fired power plants and hydrogen from water electrolysis.

The gas can be easily stored in the gas network (line packing) or storage facilities and can, of course, be used like natural gas for heating and transport applications as well as chemicals production. The 8 MW pilot plant produces 5 MW of SNG and is of a modular design to allow scaling and non-stop maintenance.

Technical challenges include the design of a stable, non-aging catalyst, control of methanation reactor temperature and concepts to integrate the exothermic methanation step with the energy-intensive CO_2 capture step.

CO2-SNG project financed by InnoEnergy, a Knowledge and Innovation Community (KIC) supported by the European Institute of Innovation and Technology which is an independent EU body based in Budapest

than an energy source, and its climate impact depends on the carbon footprint of the energy used to produce it.

The production of hydrogen at existing coal-fired power plants could be one way to deliver *sector coupling* through energy storage. During periods of surplus power, electrolysers at existing power plants could be used to produce hydrogen. The hydrogen could then be used directly in the transport sector or added to natural gas supply (hythane) for use or storage in the existing natural gas pipeline system (line packing).

To add even more flexibility, CO_2 emitted from power plants can be combined with the hydrogen to produce synthesis gas from which many useful chemicals and liquid fuels can be produced.

As more and more new renewable sources of electricity come online, the electricity demand of electrolysers could be met from these new sources. Adding gas turbines would allow surplus hydrogen to be used for power production during periods of low or no renewables generation. With a heat recovery steam generator (boiler), the coal power plant's steam turbine and generator can be integrated into a new clean energy system.

Geothermal energy

New geothermal power plants offer the possibility of re-using the infrastructure that remains after the decommissioning of conventional power plants and coal mines. Such sites are well connected to the electricity grid and many are also connected to heat networks. The production of geothermal energy at these sites offers them a new lease of life which, with heat supply to nearby consumers, can be especially attractive.

Non-energy uses of coal and lignite in support of a circular economy

The expanding role of advanced materials, such as carbon fibre reinforced polymers, means that products made from mined raw materials, such as steel, cement, glass and ceramics, are being replaced with more environmentally friendly alternatives. Carbon chemistry is fundamental to establishing a more sustainable, resource-efficient, low-emission society in which more materials are recycled, complementing the biogeochemical cycles found in nature. In addition, the growing demand for rare earth elements and other scarce materials means that coal resources, including spoil and ash, are being viewed in a new light – as a source of materials for the new economy.

Box 9 – Hot houses for tomatoes in Slovakia and district heating in Germany

Tomato greenhouse heated using geothermal heat and energy from waste mine water

Hot water (9 l/s at 66°C) from deep boreholes and heat from mine water are both used for growing tomatoes at the HBP Nováky underground coal mine in Slovakia. The geothermal borehole and residual heat from the mine water are used to heat two industrial greenhouses where tomato plants grow in a hydroponic culture, without the use of pesticides or chemical sprays. One of the installed heat pumps is the biggest in Slovakia, with an output of 1.6 MW_{th}. From an area of three hectares, the annual tomato crop is around 1 500 tonnes or one eighth of Slovakia's annual tomato consumption. Separately, heat from the mine water is also used in the winter to heat the mine's incoming ventilation air.

In Germany, the Ruhr area has a vast subterranean infrastructure of tunnels and shafts associated with its former hard coal mining industry. Some coal mines reached a depth of 1 400 metres. Significant volumes of mine water – around 61 million cubic metres every year – have to be pumped from mines at six sites to protect groundwater. As this water is quite warm (20-30°C), the plan is to use it in heat pumps to provide district heating of up to 800 GWh_{th} per year. The "Grubenwasser-Ruhr" (GW-Ruhr) consortium aims to implement a number of publicly funded projects in the Essen area and hopes that its findings can be adapted to other former coal-mining regions in Europe with similar geothermal potential.

Among these non-energy uses of coal is the production of carbon fibre from coal tar pitch, a cheaper precursor to carbon fibre than the traditional polyacrylonitrile (PAN) fibre derived from petroleum. It is already effectively deployed in applications where its stiffness, lightweight and strength are advantages, not to mention its high thermal conductivity and low electrical resistance. The market for lightweight structural materials is growing, providing an opportunity for carbon pitch fibre in applications such as aerospace, electric vehicles and robotics.

New electrochemical methods can directly convert bituminous coal to nanocarbon, exploiting the amorphous-crystalline structure of coal. Materials made of nanocarbon, such as graphene sheets, carbon nanotubes (CNT) and quantum dots can replace steel and other materials. CNT are essential in some energy-storage applications, such as improved lithium-ion batteries and for hydrogen storage. Nanotubes could also replace copper wires, given their higher electrical conductivity. Furthermore, coal can be the low-cost raw material for industrial electrodes and carbon cathodes in batteries and supercapacitors.

Activated carbon is a microporous material used in water filtration, gas purification and to remove contaminants in processes such as pharmaceutical drug synthesis. Its role in coal power plants is promising because, apart from the removal of mercury, it is a possible alternative to high-cost amines for CO_2 capture. Beyond that, the recovery of raw materials, including rare earth elements, from mining wastes, mine-water discharge and power station ash, offers much scope for innovative research linked to a circular economy.

The production of humic acid is another interesting, non-energy use of lignite as it can be used as a carbon-neutral plant fertiliser in the agricultural sector. According to the UNCCD *Global Land Outlook* report, one third of the Earth's land is severely degraded and fertile soil is being lost at the rate of 24 billion tonnes each year, of which 970 million tonnes is lost to erosion across Europe.

Box 10 – A carbon-based circular economy

CFOAM® material systems replace conventional building and insulation materials (left) and X-MAT prototype first-generation X-TILE™ (centre and right)

With a "circular economy" in mind, the biogeochemical cycles found in nature – principally water (hydrogen and oxygen), carbon, nitrogen, phosphorous and sulphur – provide a guide to what is truly sustainable. For example, human beings are one fifth carbon by mass. Material use outside of these cycles requires the extraction of raw materials from the Earth. Already, carbon is being used to replace many traditional engineering and construction materials: carbon-based composites account for around half the mass of the latest aircraft – aluminium accounts for just 20%. Concrete and steel can also be replaced with more eco-friendly, carbon-based products such as carbon foams and ceramics. Ultimately, even glazing could be replaced with manmade, diamond-like materials made of pure carbon.

There are exciting prospects for the way we use carbon, not in a decarbonised world, but in a world built of carbon. A hurdle that researchers must overcome is future energy demand. EU policy sets targets for member states to use less energy, but new materials or alternative ways of making traditional materials with lower CO_2 emissions require vastly more electricity. For example, steel made using green hydrogen requires 1400% more electricity than steel made using coal.[1] To shift from traditional ironmaking to "green" steel in the EU would require 586 TWh of electricity each year – all from green sources. This is more power than France currently generates from all sources, including nuclear. Similarly, to decarbonise the German chemicals sector would require 628 TWh annually – more than Germany currently generates from all sources.[2] To remain competitive, industry has stated that this power would need to be priced at 4 €c/kWh and without any taxes or levies. To be sustainable, the power must come from renewable energy sources.

[1] SSAB Capital Markets Day, Oxelösund, Sweden, 4 December 2019
[2] "Working towards a GHG neutral chemical industry in Germany", DECHEMA and FutureCamp for Verband der Chemischen Industrie e.V. (VCI), September 2019

This desertification needs to be reversed if land is to remain fertile enough for food production and reforestation. The production of artificial soils from lignite offers a solution of interest to policymakers and the coal-related research community.

Co-firing coal with biomass and conversion of power plants to biomass

Biomass co-firing with coal or even 100% biomass firing at repurposed coal power plants in the EU allows these important assets to move away from fossil fuels, while continuing to provide stability and reliability to electricity grids. Net-zero GHG emissions are possible with biomass use as CO_2 emissions from combustion are balanced by CO_2 absorbed during biomass cultivation. With CCS, emissions can be negative. Many sources of biomass are available: coppiced wood, energy crops, agricultural waste, manure, forestry residues, mill residuals and scrap wood. Technical challenges with biomass combustion include reduced boiler capacity and efficiency, and the impact on pollution control catalysts. Biomass gasification at dedicated plants offers further opportunities to use clean, gaseous fuel. However, the repurposing of existing facilities may offer the most viable solutions during the energy transition.

Box 11 – Alternative uses of lignite

Innovative products from lignite produced in Turkey

TKİ Hümas is a natural organic soil regulator produced in Turkey from lignite mined by Turkish Coal Enterprises (TKİ). It contains humic and fulvic acids produced from leonardite – a black or brown oxidation product of lignite that is a soft waxy, shiny vitreous mineraloid, easily soluble in alkaline solutions. What distinguishes TKİ Hümas from other soil conditioners is the high ratio of humic and fulvic acids.

In addition to fertilisers, TKİ also produces the upmarket TKİ Elegance range of cosmetics from lignite.

Box 12 – Biomass co-firing and CCS at Drax for negative GHG emissions

Biomass domes at Drax power plant, Yorkshire, UK

The 4 GW coal-fired Drax power station in the UK is one of Europe's largest. The last of six 660 MW units at the station was commissioned in 1985, followed in 1993 by a fully operational FGD plant to meet international and EU emission limits. Reducing emissions of CO_2 have been the more recent imperative – Drax is a major player in the EU emissions trading system. Biomass co-firing has been gradually increased to the extent that four units now operate with 100% sustainable biomass at what is the largest decarbonisation project in Europe. Looking ahead, Drax Group and Mitsubishi Heavy Industries Group of Japan have agreed a new bioenergy with carbon capture and storage (BECCS) pilot project at the power plant, with construction expected to start in autumn 2020. The project will help researchers and engineers to understand the technologies for delivering negative GHG emissions.

Improving health and safety

The health and safety of workers employed in the extractive industry as well as of people living in post-mining regions is a social challenge. Issues concerning safety at active or closed coal mines as well as in coal supply and use with a view to improving working conditions, occupational health and safety, as well as environmental issues deleterious to health, all demand further research with the aim of eliminating workplace accidents and fatalities.

Box 13 – Monitoring, assessment, prevention and mitigation of hazards in coal mines

Physical modelling of ground stresses around a roadway in an underground coal mine

The MapROC project aimed to improve mine safety by developing and field-testing rock-burst and gas-outburst prevention techniques, based on the use of large diameter boreholes with alternative stress and gas pressure relief techniques such as blasting, slotting and high-pressure water injection. A method of making short-term predictions of rock bursts and gas outbursts using seismic monitoring and other data, coupled with modern neural network and fractal dimension analysis, allowed a practical risk-assessment tool to be developed.

MapROC – a RFCS project on monitoring, assessment, prevention and mitigation of rock burst and gas outburst hazards in coal mines (2015-2018)

Safety is a key value of the leading coal mining companies. Despite considerable efforts in many countries and significant achievements, most notably in OECD countries, the rates of death, injury and disease among the world's coal mineworkers remain unacceptably high. Replicating the high levels of work safety found at, for example, coal mines in Australia, is an ongoing task around the world.

The EU's long history of occupational health and safety (OHS) improvements at coal mines means that it has many best-practice solutions to offer. Safety systems and processes have grown and evolved, but have not reached the point where coal mining operations are completely safe. It remains important to reduce risk exposure by designing a safe working environment with appropriate equipment, tools and materials. "Mine safety by design" includes gas control and strata monitoring with a view to improving underground conditions and hence health and safety. Digital products, services and solutions, based on modern IT systems, automation and remote control, can be used to enhance safety. For example, a heavy-duty underground monitoring robot with autonomous drone capabilities is being built and tested as part of the UNDROMEDA project funded by the European Institute of Innovation and Technology.

An interesting new direction is the application of Industry 4.0 techniques which offer opportunities to integrate production processes and systems, exchanging information between them to improve diagnostics and identify potential problems before they can cause harm.

Box 14 – Training future miners using virtual reality

An immersive experience of work in a coal mine via virtual reality using WorksiteVR™ Quest

As mining companies innovate to enhance safety, the use of virtual reality (VR) has become increasingly attractive. An example of the positive use of VR is a training platform which allows mining companies to safely train employees within a real-time, 3D experience. Miners can operate equipment and feel fully engaged in a virtual environment that mimics the real one found underground.

The VISION ZERO project of the International Social Security Association (ISSA) aims to prevent accidents and diseases in mining through leadership training and education. The ISSA mining section has prepared a list of future research topics with the aim of reaching zero accidents and fatalities in the mining sector.

> ***"In Poland, we estimate that the additional cost of transition from 2020 to 2050 will amount to an average of 2.6% to 4.3% of GDP or over €500 billion. This burden is 1.7 to 2.3 times higher than the European Union average. Please also remember that in Poland we have the Silesia region which is linked with the mining sector. 200 000 people work in and around this sector. However, creating one job in new sectors costs €250 000 according to data from regional academic institutions."***
>
> Mr. Grzegorz Tobiszowski MEP

Minimising the environmental impacts of the coal sector in transition

Researchers seek to minimise the impacts of coal mining operations and coal use on land, air and water within the framework of an integrated pollution management strategy. In the case of coal mining, the aim is to secure resources for future generations, while minimising the environmental impacts of active coal mines, coal mines in the closure process and closed coal mines.

Methane control

Methane, a powerful greenhouse gas (GHG), is the second-largest cause of global warming today and comes from a range of manmade and natural sources, including oil and gas production and coal mining. In 2019, the oil and gas sector emitted an estimated 82 million tonnes (2.5 $GtCO_2e$). Coal mining emitted less than half this quantity. Methane control across all sectors, including agriculture – the largest emitter – and waste disposal, will be critical to reaching climate targets.

Methane emissions during coal mining pose a safety risk as the gas can be explosive. Yet, methane is also a potential fuel for clean heat and power generation, or a precursor for useful chemicals such as methanol. Upgrading the methane found in mine ventilation air (VAM) is the subject of ongoing research on advanced thermal/catalytic reverse-flow reactors, membrane reactors and combustion devices for low-concentration methane.

Box 15 – World's first International Centre of Excellence on Coal Mine Methane

Directional drilling is used to extract coal mine methane prior to coal mining

Located at Katowice in Poland, the International Centre of Excellence on Coal Mine Methane (ICE-CMM Poland) was founded in 2017 by the Central Mining Institute (GIG), the Polish Oil and Gas Company (PGNiG), the Polish Geological Institute (PIG-PIB) and the Oil and Gas Institute (INiG-PIB).

This expert institution operates under the auspices of the United Nations Economic Commission for Europe (UNECE) and aims to develop new technologies for capturing and using coal mine methane as a valuable energy resource. In so doing, mining safety and efficiency can be improved through research, as well as reducing the overall GHG footprint of the coal sector.

Methane emissions do not stop when deep coal mines close. In the EU, coal mine methane (CMM) and abandoned mine methane (AMM) will persist for decades. Elsewhere, AMM could account for one quarter of all methane emissions from coal by

2050. In China, for example, there were 24 800 active coal mines in 2005 and 7 000 by 2017. Research is needed to map abandoned mines to determine coal type, date of closure, closure procedure and the status of any flooding. Research results can provide a better understanding of gas-in-place and the shape of the gas production decay curve – crucial information for decision making.

Box 16 – Exploiting coalbed methane to supplement dwindling EU natural gas production

Surface facilities at a coal mine methane project in northern France

La Française de l'Energie SA has obtained the necessary exploration permits to assess the extent of the coalbed methane resources available in France. Thanks to the geological surveys carried out over the years, as well as modelling work, the company has been able to identify the most promising areas to exploit.

In total, coalbed methane reserves equivalent to six years of gas consumption in France have been discovered by La Française de l'Energie which already has many years of experience in methane extraction from France's abandoned coal mines.

Managing mining waste

The transition to a more circular economy is part of the European Green Deal for a modern, resource-efficient and competitive economy where economic growth is decoupled from resource use. A more holistic approach to mining and mineral processing is called for, one that takes into account environmental and social costs and benefits.

Mine spoil and tailings can contain potential soil and water pollutants, so new ways of treating mine waste are under consideration to help with the remediation and reuse of coal mine sites. New research directions aim to apply biotechnological solutions using microbes, bioremediation with algae and phytoremediation. The conversion of solid mine waste residues into building materials attracts research interest, as does the recovery of the residual energy content of spoil and tailings.

Coal ash in construction, land reclamation and for rare earths

Annual coal use results in over one billion tonnes of coal fly ash (CFA) and bottom ash. Once considered wastes, demand for these useful by-products has grown and there is a growing international market as coal consumption shifts from Europe and North America to Asia. The main use of CFA is in the construction industry where it can substitute for cement clinker. Bottom ash is used for low-density manufactured aggregates, blocks, bricks, concrete and geopolymers. As cement production is the largest industrial emitter of CO_2, CFA substitution for cement can reduce the environmental impact of the construction industry.

As an alumina silicate, the crystalline structure of CFA could be adapted to replace widely used zeolite catalyst supports – important in water and gas purification – whereas cenospheres from CFA are a valuable, low-density product in demand as a filler material to reduce material costs.

CFA, when combined with manure, can be added to soils where it has benefits, including controlling soil acidity, improving the texture, and enhancing water retention. Fertilisers that combine coal ash and sewage sludge are already applied to contaminated lands and waste landfill sites to provide essential nitrogen and phosphorus for plant growth.

Rare earth elements (REE), present in relatively high quantities in some coals, are even more concentrated in coal fly ash. Demonstration projects aim to economically extract REE from coal ash as a substitute for the restricted, worldwide supplies.

Box 17 – Construction of a new water-treatment facility at Profen mine

Profen mine-water treatment plant

The municipal water treatment works at Predel in Saxony-Anhalt has been expanded with a €27 million mine-water treatment plant to treat water from the Profen lignite mine operated by MIBRAG. Since the project was completed in July 2017, only clean water has been pumped into the Weiße Elster River. The mine-water treatment plant can handle up to 129 cubic metres of water per minute. The total iron content of the pumped water is reduced to the stringent 1.5 mg/l limit set by the German authorities. Compliance with all statutory water-quality parameters is now guaranteed.

Mine drainage

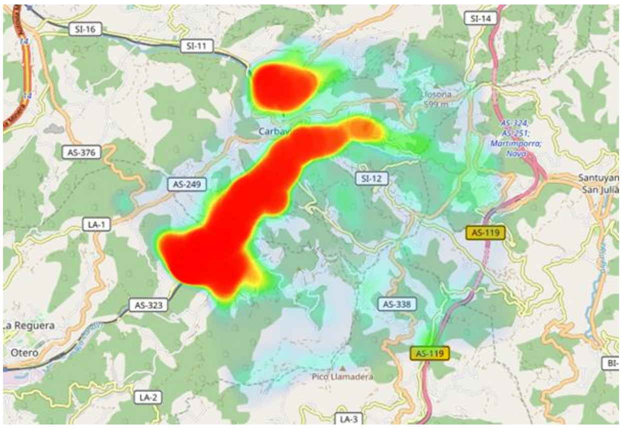
Coal mining can change hydrological and topographical conditions, sometimes drastically, influencing the quality and quantity of subsurface aquifers and surface water features around mine sites. A proper water management system to reduce environmental impacts and risks is an essential part of the mine planning process and must continue long after mine closure. For example, modern mine-water treatment offers opportunities to recover minerals and supply water for agricultural use.

Hydrological and water-quality monitoring, data collection and analysis, including with computer modelling, are important for cost-effective water management. Every mine site is unique and so good water management requires an understanding of many site-specific factors. To achieve the best outcomes, ongoing research is essential.

Post-mining opportunities and challenges

Post-mining reclamation is the process of restoring land that has been mined to a natural or economically useful state. Although the reclamation process only begins once mining is completed, mine reclamation activities are planned prior to a mine being permitted. Reclamation creates new landscapes that meet a variety of goals ranging from the restoration of natural ecosystems, farmland and forests to the creation of industrial estates, commercial centres, residential housing, transport infrastructure and community resources such as parks and lakes. Modern mine reclamation minimises and mitigates the environmental impacts of mining by leaving a lasting legacy.

Box 18 – Management of environmental risks during and after mine closure



Flood probability at the Mosquitera and Pumarabule underground coal mines in Asturias, Spain

The MERIDA project led by the Central Mining Institute (GIG) in Poland has examined the foreseeable environmental risks associated with the closure of underground coal mines. Previously, there had been a lack of detailed information on the management of these risks. Now, the project provides specific guidance on appropriate approaches, tools and techniques for the closure of underground coal mines, with due account of economic issues. All this is included in best-practice guidelines for practitioners and policy makers.

MERIDA – a RFCS project on the management of environmental risks during and after mine closure (2015-2020)

Avoiding subsidence damage

Land subsidence due to coal mining has various environmental impacts, including changes in land morphology, disturbance of hydrological conditions and damage to surface infrastructure, especially in urban areas. Society expects mining to be largely invisible which means controlling rock masses to ensure safe conditions without significant or unforeseen damage.

Digitalisation has provided ever-more sophisticated ways to develop the monitoring, analysis and prediction of rock mechanics (*e.g.* more accurate data on the structure, deformation and seismicity of the rock mass). Computer simulations linked to spatial planning enable the development of urban areas following risk assessments that avoid conflicts with current and historic mining activities.

As patterns of land use become more complex, research on avoiding subsidence damage to all types of infrastructure is essential, for operational reasons at active mines and also to understand and manage land settlement around closed mines, now and in the future.

Box 19 – European Plate Observing System

EPOS
ERIC
EUROPEAN RESEARCH INFRASTRUCTURE CONSORTIUM

Europe is home to some of the planet's most complex and dynamic geological systems. Understanding these is essential to the security, livelihoods and economic well-being of EU citizens. To this end, scientists have led in the understanding of stratigraphy (the timing and distribution of sediment layers) and plate tectonics. As Earth monitoring evolves, with new sensors located above and below ground as well as in outer space, more information will be available for decision making.

Launched in November 2018, partners from twenty-five countries collaborate in the European Plate Observing System (EPOS) project funded under the EU Horizon 2020 research programme. The aim is to combine national Earth science facilities and the associated data and models, together with the scientific expertise into one integrated delivery system. Polska Grupa Górnicza S. A. (PGG – Polish Mining Group) is the only industrial partner in the Polish National Consortium (EPOS-PL).

Since 2017, the consortium has researched seismic events due to coal mining at three coal mines. In this way, EPOS draws attention to the management of geo-hazards associated with resource exploitation.

EPOS – a European Research Infrastructure Consortium with support from Horizon 2020

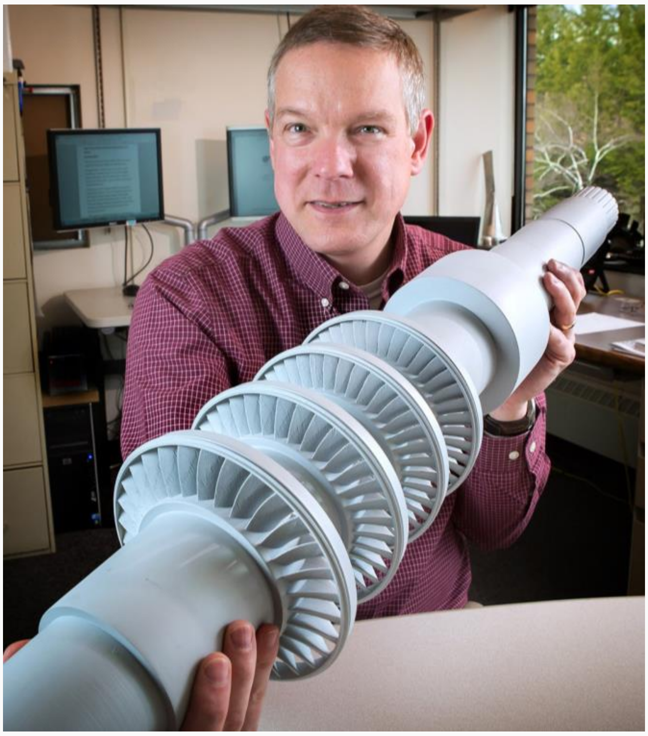
Coal-related research with an international outlook

Action in the EU alone will not solve the climate challenge. In 2019, fossil fuels met 84.3% of global primary energy demand, while wind power and solar PV provided 3.3% (assuming renewable power is 2.5× more "valuable" than fossil energy). The renewables revolution will undoubtedly see this share rise, but reputable projections from the International Energy Agency, the US Energy Information Administration and BP plc all show a continuing demand for billions of tonnes of coal over the coming decades. Coal accounted for 27.0% of global primary energy supply in 2019 – a share which has grown since the 1970s – and 36.4% of global electricity supply. About 70% of world steel production depends on coking coal feedstock. In consequence, there will be a large, global market for coal-related technologies, especially those that address the climate and environmental concerns of coal use.

For this reason, ongoing R&D efforts aim to improve coal power plant efficiency, reduce emissions from coal use and extend the commercial availability of coal resources. The latter means improving exploration with the latest geological-mapping technologies and improving the exploitation of coal resources.

From a geopolitical perspective, the greater the availability of energy, the lesser is the risk of conflict over energy resources. Moreover, climate risks will persist until CO_2 emissions from coal use are

Box 20 – Allam cycle generates electricity using a supercritical CO_2 turbine



Prototype 10 MW supercritical CO_2 turbine is one tenth the size of an equivalent steam turbine

A combined cycle gas turbine (CCGT) power plant burns natural gas or gasified coal with air to drive a gas turbine and then uses the hot exhaust gas to heat water and so drive a steam turbine.

Invented by a British engineer, the Allam cycle uses a single turbine, driven by a working fluid consisting of mainly CO_2 and some steam. This is achieved by burning the fuel in pure oxygen.

The turbine exhaust gas is cooled in a heat exchanger, the steam condenses and water is drained from the cycle. The CO_2 is compressed and a small amount removed to balance the CO_2 created by fuel combustion. The rest is reheated in the heat exchanger and recycled to the combustion unit where it continues to form the vast majority of the working fluid.

With only a single turbine, the Allam cycle can potentially achieve efficiencies of around 51–52% (LHV) on gasified coal because, in its supercritical state, CO_2 is very efficient for driving a turbine. Also, the energy losses associated with the phase transitions of water (latent heat) are avoided.

High power density and the ability to capture pure CO_2 very easily with no efficiency penalty should make the capital costs of power plants based on the Allam cycle lower than conventional alternatives. A 25 MWe demonstration plant for electricity generation using the Allam cycle is being tested at La Porte, Texas.

massively reduced. Without a global effort, this could take many decades. It is therefore in the EU's interest to engage in research that can promote the cleaner use of coal by countries outside the EU.

International collaboration is vital to creating world-class research with real impact. Researchers in the EU should have the ability, support and resources to collaborate with the best partners – wherever these may be. Especially in the case of clean coal technologies, there is expertise and progress outside the EU that is relevant to current global challenges, with well-funded coal research programmes in Australia, Canada, China, India, Japan, South Korea and the USA.

The US Department of Energy (DoE) has a long history of supporting R&D to improve the performance of coal power plants. DoE programmes have resulted in the development and demonstration of advanced coal technologies such as gasification and fuel cells, emission control systems for criteria pollutants (*e.g.* SOx, NOx and particulates), and coal by-product upgrading. The latest R&D programme is Coal FIRST (Flexible, Innovative, Resilient, Small and Transformative), with US$81 million DoE funding announced in May 2020. Coal FIRST will pursue technologies that offer secure, stable and reliable power generation from small, modular plants (50-350 MW) with carbon capture, use and storage (CCUS). The programme also aims to develop alternative uses for coal in the construction sector and elsewhere.

In China, coal industry development follows the 13th five-year plan (2016-2020) published in December 2016 by the National Energy Administration. The plan aims to:

- improve end-use coal quality and vigorously promote quality-based coal use;
- promote the demonstration of deep coal processing;
- renovate coal-fired power plants for ultra-low emissions and energy-savings; and
- reduce the environmental footprint of small-scale coal use.

Closer to home, Russia, Ukraine and Turkey have large coal mining industries that should be a target for the R&D activities carried out in the European Union.

Carbon capture and storage – an opportunity for global deployment

Burning coal releases almost 14 billion tonnes of CO_2 each year to the atmosphere, mostly from power generation. As such, carbon capture and storage (CCS) will be key to reducing global CO_2 emissions, not only from coal, but also from natural gas and energy-intensive industries. CCS involves the geological storage of CO_2, typically 2-3 kilometres deep, as a permanent solution. Large-scale CCS projects are operational in Norway, Algeria, Australia and North America, each storing millions of tonnes of CO_2. The cost of CO_2 capture – as much as 100 €/tCO_2 – can be offset by delivering the CO_2 for productive use. For example, the Petra Nova CCS project in Texas, USA is the world's largest post-combustion CO_2 capture facility, delivering 1.4 million tonnes of saleable CO_2 a year from the 3.65 GW coal-fired W. A. Parish power plant. The CO_2 is sent by pipeline for enhanced oil recovery.

At conventional power plants, the technologies to capture CO_2 are still too costly and too energy-intensive. In its *Energy Technology Perspectives* publication, the International Energy Agency notes that, "CCS is advancing slowly, due to high costs and lack of political and financial commitment." The research challenges are to lower the cost and energy penalties, and to commercialise CCS technologies so that coal use remains economic with low and eventually near-zero emissions.

Clean coal technologies for lower emissions

The term "clean coal technologies" increasingly refers to supercritical (SC) and ultra-supercritical (USC) coal-fired power plants with efficiencies of 42-48% – well above the 35% global average. These plants are also known as high-efficiency, low-emission (HELE) power plants. The capital cost of HELE technology is 20-30% greater than conventional subcritical technology, but the higher efficiency reduces emissions and fuel costs by about 25%. A supercritical steam generator operates at very high temperature (about 600°C) and pressure (above 22 MPa or 220 bar) such that the liquid and gas phases of water are no longer distinct. In Japan and South Korea, about 70% of coal-fired power comes from modern, supercritical and ultra-supercritical power plants. HELE also includes emission control technologies for air pollutants, sometimes reducing these below the emission levels from gas-fired power plants. Looking to the future, even higher efficiencies are possible with coal gasification and fuel cells.

> ***"R&D is crucial to improve the performance of coal power plants. R&D and consequent scale up could offer technologies for coal power plants with lower carbon emissions and with acceptable ROI. Current 'climate hysterical' EU political majority is more or less sceptical of such technologies. However, this can change in five to ten years and the availability of such technologies could be a decision factor to postpone phase out of coal-fired operations."***
>
> Mr. Ondřej Knotek MEP

Box 21 – Coal gasification with fuel cells in Japan boosts efficiency with near-zero emissions

Osaki CoolGen integrated coal gasification fuel cell combined cycle (IGFC) with CO_2 capture demonstration project in Japan

Gasification is a well-established technology that uses heat, pressure and steam to convert any carbon-based raw material into synthesis gas or "syngas". Composed primarily of carbon monoxide and hydrogen, syngas has a wide variety of uses: it can be refined into pure hydrogen, used as a precursor in the chemical industry, converted into ultra-clean transport fuels, transformed into plastics and fertilisers or used to generate electricity with near-zero emissions. Already today, gasification is used in more than twenty industrialised countries. In the EU, gasification technology can help meet the political ambition to decarbonise the means of production.

The advantages of gasification, particularly when it is linked to electricity generation from coal, biomass and wastes, make the technology increasingly important to the global energy sector. The EU's political ambition for a circular economy, where waste is treated as a resource, can *only* be met with gasification technology.

Power plant flexibility

The "deep modernisation" of existing coal power plants with state-of-the-art HELE technologies can be an economic way to control pollution. In the case of existing coal power plants, the challenge is to operate these as flexible backup to variable renewable energy sources, such as wind turbines and solar PV, in a way that reduces emissions while still ensuring supply security. Large-scale batteries can provide a short-term solution, but they add to grid balancing costs. Consequently, coal- and gas-fired power plants must operate more flexibly, with fast start-ups and rapid ramp up and down over a wide load range. Biomass co-firing with coal offers a route to further reduce CO_2 emissions, and can even make a power plant carbon-negative if combined with CCS.

Box 22 – Coal gasification leads towards a near-zero emission, circular economy at the Vresová IGCC power plant

Oxygen separation plant at the Vresová IGCC power plant in the Czech Republic

Although not originally designed as such, the 400 MWe coal power plant operated by Sokolovská uhelná, a.s. (SUAS) at its Vresová gasworks in the Czech Republic is one of the world's largest coal-fuelled integrated gasification combined cycle (IGCC) power plants. Twenty-six Lurgi-type fixed-bed gasifiers built by ZVU process brown coal from nearby mines. The raw gas from the gasifiers is treated by the Rectisol process and fed into two GE 9E gas turbines, one of which was upgraded to a 9EMax at the end of 2018.

Vresová gasworks began operation in 1969, supplying town gas to the western part of the Czech Republic. With the introduction of natural gas, the market for town gas diminished rapidly and a new market had to be found. Various options were studied, including methanol production, but electricity generation was favoured. The two CCGT units were commissioned in 1995 and 1996.

Further development of the complex includes a Siemens liquids gasifier to provide additional syngas from the tars produced in the fixed-bed gasifiers. Today, liquid wastes can also be safely handled and converted to useful power. In summary, SUAS has been able to transform its Vresová gasworks into an important centre for clean energy and a circular economy.

Coal gasification and the circular economy

Looking beyond the current extractive model of industrial production, a *circular economy* aims to redefine growth, focusing on positive, society-wide benefits. It entails gradually decoupling economic activity from the consumption of finite resources by recycling waste. The circular model is based on three principles: designing out waste and pollution, keeping products and materials in use, and regenerating natural systems.

Gasification is the key to using coal and other carbon-based resources for the production of high-purity chemical feedstocks via chemical synthesis. The gasification route opens up a variety of new markets for coal, such as synthesis gases (carbon monoxide and hydrogen), basic chemicals (*e.g.* methanol and ammonia), liquid and gaseous fuels (*e.g.* DME, OMEn and synthetic natural gas) and waxes. Projects that begin by gasifying coal can, as time passes, substitute the coal with biomass, wastes and residues. Thus, gasification is the starting point for a sustainable, circular economy in which carbon is recycled.

The synthesis step of the chemical process even allows hydrogen from other sources to be integrated, turning CO_2 from the gasification process into useful products. As the supply of hydrogen from renewable sources grows, so more biomass, wastes and residues can be fully converted into useful chemical products, thus lowering the carbon footprint to zero.

"One of the most effective and impressive technology research example is the Sokolovská uhelná, a.s. (SUAS) in the Czech Republic, which has been able to transform its Vresová gasworks into a modern and effective energy enterprise."

Mr. Ondřej Knotek MEP

"The 21st December 2018 was a very emotional moment for many people in the Ruhr area: the Prosper-Haniel mine in Bottrop, the last active hard coal mine in the Ruhr area, closed. After the last coal had been extracted in regular operation on the 14th September 2018, the mine was shut down with a festive ceremony: hard coal extraction in Germany was finally stopped.

"The entire value chain in the Ruhr area must continue to be maintained in the future. Now, we can start to plan specifically for the time after coal-fired power generation in the Ruhr area. This means major changes for all coal-fired power plant locations.

"Glückauf! – 100% Ruhrgebiet für Europa!"

Mr. Dennis Radtke MEP

Box 23 – Environmental protection

Measures such as the UK Clean Air Act 1956 and US Clean Air Act 1970 brought coal power plant emissions under public scrutiny. More recently, in Europe, the Large Combustion Plants Directive of 1988 and its revision in 2001 placed limits on SOx, NOx and particulate emissions from power plants, with little leeway for plants that fail to meet the strict limits – reduced operation and plant closure being the only alternatives to the desired installation of pollution control equipment. Trace elements such as mercury are increasingly being targeted for control.

The Integrated Pollution Prevention and Control Directive of 1996 aimed to improve the quality of air, water and land in the EU. This directive was based on the principle of "best available techniques" (BAT), replacing the earlier BATNEEC principle of 1984 – BAT not entailing excessive costs. The extant Industrial Emissions Directive (IED) of 2010 aims to prevent, reduce and as far as possible eliminate pollution, taking into account the economic situation and specific characteristics of the location where an industrial activity takes place. The BAT principle continues, but contained in supplementary BAT reference documents that authorities are obliged to consider when granting permits. The IED is an example of EU law-making at its best and has successfully controlled pollution from coal use down to levels that are now a small fraction of past excesses.

Beginning with modest action programmes in the 1970s, the European Commission has relied on the expert input of researchers during the development of what is now a far-reaching set of environmental legislation. In 2019, the European Green Deal proposed a new ambition, namely zero pollution for a toxic-free environment. Researchers must now help the Commission to develop a zero-pollution action plan for air, water and soil, and find ways to satisfy this political ambition as part of a new industrial strategy, all at an affordable cost for EU citizens.

Recommended priorities for future coal-related R&D in the EU

This strategic report has been compiled with the input of expert stakeholders. It shows that there are a number of key research topics to be pursued as part of a coherent response to the climate challenge within an international context. The current objectives of the RFCS research programme are described in Council Decision 2008/376/EC:

- improving the competitive position of Community coal;
- health and safety in mines;
- efficient protection of the environment and improvement of the use of coal as a clean energy source; and
- management of external dependence on energy supply.

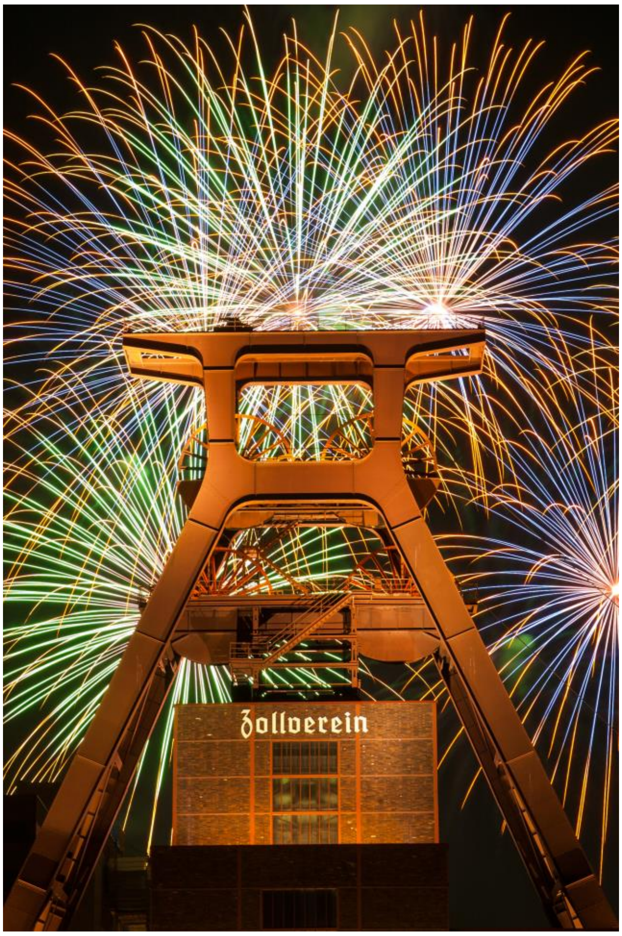
Looking to the future, the RFCS should support an ongoing collaborative research programme with annual proposal calls for industrial research to:

- support the just transition of the coal sector and regions,
- improve health and safety, and
- minimise the environmental impacts of the coal sector in transition.

In addition, the Research Fund for Coal and Steel's trustees should consider financing some "big-ticket" projects that help the coal industry to navigate the energy transition and sector coupling. Within the EU, a growing surplus of renewable energy and policy ambitions under the European Green Deal mean that novel approaches to energy storage, gasification and circularity will all have a role to play in moving the coal sector forward into new areas.

The climate challenge requires a solution for the eight billion tonnes of coal used around the world each year. Hence, the coal industry also calls for targeted support to deploy technologies with global impact, working especially on carbon capture, use and storage and clean coal technology projects with non-EU partners.

Box 24 – Development of a UNESCO world heritage site at a coal mine and cokery



Zollverein coal mine near Essen in Germany

Underground coal mining in Germany ceased at the end of 2018 with the closure of Prosper-Haniel coal mine. The once dominant coal industry has left behind an industrial legacy which is now finding new purpose, especially in the Ruhr and Saar regions. In Essen, headquarters of the former coal mining company RAG, the Zollverein mine became a UNESCO world heritage site in 2001. The site, which also includes a former coking works, has seen much redevelopment by the state of North Rhine-Westphalia, including a cultural centre, museum and business park. The Bauhaus architecture of what was the central mining facility has been saved, along with the iconic *Doppelbock* headgear. Two of the mine complex's twelve shafts are used today to pump mine water from the abandoned mine – a task managed by the RAG Foundation that will go on for eternity. Here, innovation in environmental management will be as important as innovation in coal exploitation.

Abbreviations and acronyms

AMM	abandoned mine methane
BAT	best available techniques
BATNEEC	best available techniques not entailing excessive costs
BCURA	British Coal Utilisation Research Association
BECCS	bio-energy with carbon capture and storage
CCGT	combined cycle gas turbine
CCS	carbon/CO_2 capture and storage
CCUS	carbon/CO_2 capture, utilisation/use and storage
CFA	coal fly ash
CMM	coal mine methane
CNT	carbon nanotubes
CO_2	carbon dioxide
CoalFIRST	Flexible, Innovative, Resilient, Small and Transformative coal R&D programme
DME	dimethyl ether
DNA	deoxyribonucleic acid
DoE	US Department of Energy
EU	European Union
FGD	flue gas desulphurisation
GHG	greenhouse gas
H_2	hydrogen
HELE	high-efficiency, low-emission
HSE	health, safety and environment
IED	Industrial Emissions Directive
ISSA	International Social Security Association
JTF	Just Transition Fund
LHV	lower heating value
NOx	oxides of nitrogen
OECD	Organisation for Economic Co-operation and Development
OHS	occupational health and safety
OMEn	polyoxymethylene dimethyl ethers
PAN	polyacrylonitrile
PV	photovoltaic
R&D	research and development
REE	rare earth elements
RES	renewable energy sources
RFCS	Research Fund for Coal and Steel
ROI	return on investment
SC	supercritical
SNG	synthetic natural gas
SOx	sulphur dioxide (and other sulphur oxides)
TES	thermal energy storage
UNCCD	United Nations Convention to Combat Desertification
UNECE	United Nations Economic Commission for Europe
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USC	ultrasupercritical
VAM	ventilation air methane
VR	virtual reality

CoalTech2051

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