Global aspects on Coal Combustion Products

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ABSTRACT

As global energy demand and electrification rates increase, coal remains the most abundantly consumed fossil fuel for the production of electrical power. At the same time, international agreements and local policies are driving a transition towards alternative (nuclear, renewable, ..) energy sources, with a central focus on reducing CO_2 emissions associated with fossil fuel combustion. In some countries, growth in renewable energy is resulting in coal-fired power operators losing base load supply agreements as they are forced to intermittent, lower volume production serving peak demand requirements that renewables are unable to meet. In addition, coal power operators face stricter emission controls from ‘Clean Air’ legislation that require retrofits of existing power stations and design changes for new plants. The shift away from base load power, introduction of retrofits and design changes all impact coal combustion product quality and supply consistency.

Coal combustion by products are well established as valuable, high volume inputs for the manufacture of construction and building materials. They provide functional benefits in these applications and, as substitutes for energy intensive materials such as cement, sand and aggregates, they provide options for lower embedded carbon.

With value as functional materials and recycled, low carbon inputs for the built environment CCP’s present a global opportunity for international trade. Factors inhibiting trade include regulatory constraints, limited export and import infrastructure, supply and demand imbalances in countries with CCP surpluses and – importantly – a lack of general consensus around product standards and limited supply-side knowledge of quality consistency.

Due to the long history of using coal ash in construction materials, relevant standards exist for a range of applications. A compilation of national standards for use of fly ash in cement and concrete has been provided to demonstrate similarities and differences to be considered when ashes are used in other countries.

The paper is jointly written by members of the World Wide Coal Combustion Products Network and is the result of an ongoing, international collaboration between respective country industry associations, being non-governmental organizations (NGO's). Our collective mission is to inform the public, industry and governmental entities about the beneficial environmental, technical and commercial uses of CCPs.

INTRODUCTION

CO_2 emission concerns are creating regulatory and commercial incentives to reduce coal fired generation in many countries around the world. Despite this pressure, the share of coal in global power production remains above 38%, with coal consumption rising over the past few years after a short period of annual decreases. This recent rise in coal consumption is largely driven by economic growth in large developing countries such as China, India and parts of Southeast Asia.

In many developed economies a reduction of coal-fired power generation is underway, with some countries aiming at a total phase out of coal power over the next few decades. The shift away from coal in many countries is accompanied by increased use of fossil fuels such as natural gas, alternative fuels such as nuclear, biomass and increased use of renewables including wind, solar, hydro and geothermal. Energy production choices and the speed of transition to alternatives depend significantly on political, economic and geographical conditions.

Coal Combustion Product (CCPs) production volumes are directly correlated with the combustion of coal in thermal power stations. Their commercial and environmental value is well established as non-virgin, functional inputs in construction material manufacturing and geotechnical engineering applications. Management and utilization of CCP's is similar in most countries, with policymakers encouraging producers and buyers to increase utilization in these applications.

To achieve maximum utilization, producers and policymakers must understand and address regulatory conditions, market demand, product quality and supply consistency. In some countries the majority of CCPs are already consumed in accordance with established product standards or technical guidelines. This has resulted in mature markets with steady demand for quality products used in construction materials and geotechnical applications. In other markets, lack of adequate standards, poor market education and regulatory barriers - such as designation of CCPs as wastes and not resources – are resulting in poor utilization rates with large volumes of CCPs landfilled.

Changing operating conditions of power plants leads to negative impacts on coal combustion product quality, consistency and availability. When the quality aspects are a continuous task of the power plant operators the availability is an issue of market partners with all tools from interim storage, re-use from stock, processing, beneficiation and also export/import for serving existing markets.

The members of the World-Wide CCP Network (WWCCPN) endeavor to continuously inform global stakeholders about developments in the production, utilization and trading of coal combustion products. The most recent data are provided with this paper.

ROLE OF COAL IN ENERGY PRODUCTION

As global supply of CCPs is tied directly to coal power production it is useful to understand the current state and outlook for global coal consumption and future demand.

At present, about 7,700 Mt of coal is used worldwide by a variety of sectors including power generation and other industries like iron and steel production, cement manufacturing etc. An overview of the coal recoverable resources is given in figure 1 where recoverable means to be accessible under current local economic and technological conditions /1/.

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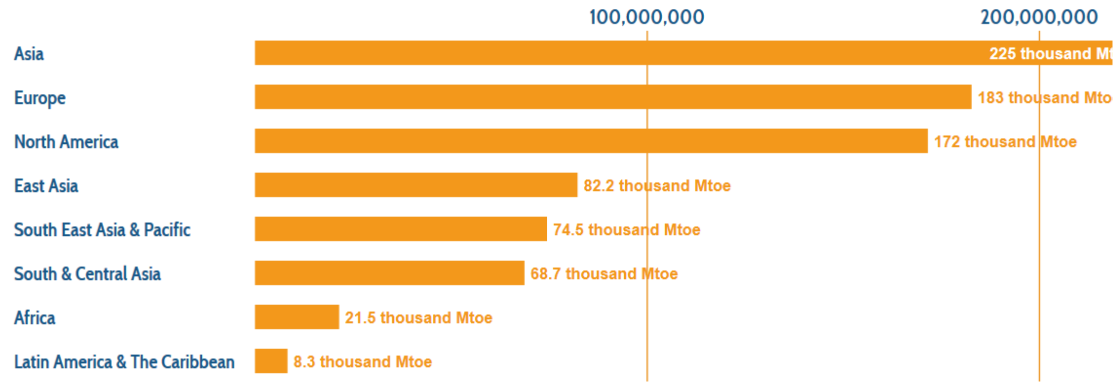

Figure 1 Coal recoverable resources by region /1/

Asia represents the biggest market for coal and currently accounts for 66% of global coal consumption /2/. After several years of declines, coal consumption rose by 1%, or 25 million tonnes of oil equivalent (mtoe), with India recording the fastest growth (4.8%, 18 mtoe). After three years of successive declines, China's coal consumption also increased (0.5%, 4 mtoe) despite substantial coal-to-gas switching in the industrial and residential sectors, as increases in power demand in China consumed additional coal as the balancing fuel /3/.

Interestingly, the increase in US production came despite a further fall in domestic consumption, with US coal producers increasing exports to Asia. The world top 10 coal producers are given in table 1 /4/ and TOP 10 coal exporter in table 2 /5/.

nr	Country	amount [million tonnes]
1	China	3,874.0
2	United States	906.0
3	Australia	644.0
4	India	537.6
5	Indonesia	458.0
6	Russia	357.6
7	South Africa	260.5
8	Germany	185.8
9	Poland	137.1
10	Kazakhstan	108.7

Table 1 Top 10 coal producers /4/

nr	country	amount [million tonnes]
1	Indonesia	467.7
2	Australia	394.7
3	Russia	155.5
4	United States	112.7
5	Columbia	82.4
6	South Africa	82.2
7	Canada	40.4
8	Kazakhstan	36.0
9	Mongolia	19.3
10	Korea	18.4

Table 2 Top 10 coal exporter /5/

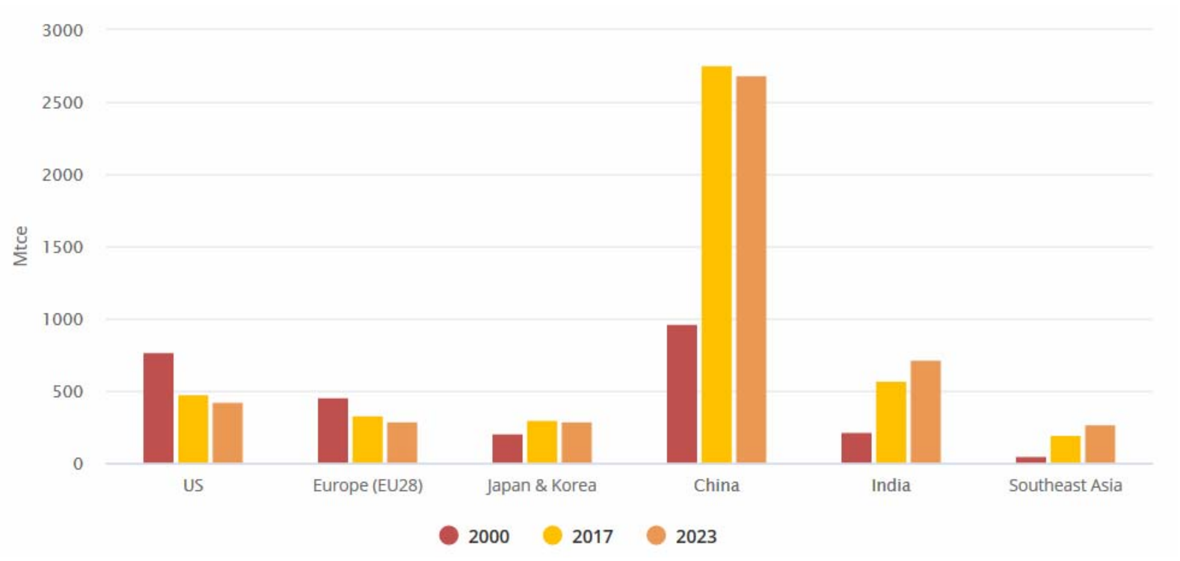

Figure 2 Coal demand in selected countries/regions in 2000, 2017 and 2023 /6/

The growth in coal demand in the near future is concentrated in India, Southeast Asia and a few other countries in Asia. Coal demand is expected to decline in Europe, Canada, the United States and China (see figure 2). As a result of these contrasting trends, global coal demand will only slightly increase over the next decade. Although coal-fired power generation will increase in absolute terms, as a share of the energy mix it is expected to decrease due to growth of renewables and natural gas /6/.

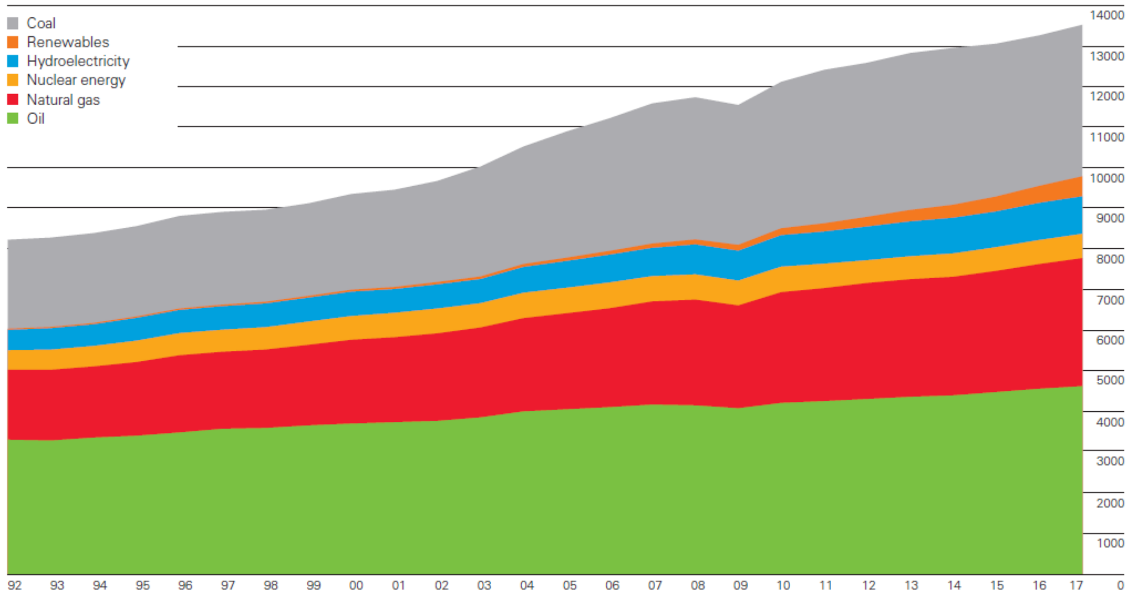

Figure 3 World primary energy consumption (in mt oil equivalent) /2/

World primary energy consumption grew by 2.2% in 2017, up from 1.2% in 2016 and the highest since 2013. All fuels except coal and hydroelectricity grew at above-average rates. Natural gas provided the largest increment to energy consumption at 83 (mtoe), followed by renewable power (69 mtoe) and oil (65 mtoe) (see figure 3 /2/).

The majority of coal is either utilised in power generation, using steam coal or lignite, or iron and steel production that uses coking coal. Coal still provides nearly 40% of the world’s electricity. The increase in world electricity consumption is closely linked with economic growth, and economic growth in turn relies upon dependable sources of power. While coal power can, in several geographies, provide reliable supply, demands for climate change mitigation, transition to renewable energy forms and increased competition from other resources are presenting challenges for the sector.

MAJOR AGREEMENTS IMPACTING COAL

Over the past few decades, national governments have required that coal combustion for energy production meet emissions standards for clean air. This has resulted in emissions reduction technologies for dust (fly ash), NOx and SOx and efforts to improve overall combustion efficiency. Along with these national regulations, global discussions on climate protection have led to international agreements with further regulations applying in signatory countries. The Climate Convention, Kyoto Protocol and Paris Agreement are all well known initiatives which aim at reducing CO2 emissions and mitigating risks of global warming.

UNFCCC

The United Nations Framework Convention on Climate Change (UNFCCC) is the main international agreement on climate action. It was one of three conventions adopted at the Rio Earth Summit in 1992. Its sister Rio Conventions are the UN Convention on Biological Diversity and the Convention to Combat Desertification. The convention entered force on 21 March 1994. It started as a way for countries to work together to limit global temperature increases and climate change, and to cope with their impacts. The 197 countries that have ratified the Convention are called Parties to the Convention (CoP) /7/.

The objective of the Convention is

> *The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.*

KYOTO PROTOCOL

In the mid 1990’s, the UNFCCC realised that stronger provisions were needed to reduce emissions. In 1997, they agreed to the KYOTO PROTOCOL, which introduced legally binding emission reduction targets for developed countries. The participating countries have committed to reducing emissions by at least 18% below 1990 levels. The EU has committed to reducing emissions in this period to 20% below 1990 levels /7/.

When the Convention encourage industrialised countries to stabilize GHG emissions, the Protocol only commits them to do so. Under the Protocol, countries must meet their targets primarily through national measures. However, the Protocol also offers them an additional means to meet their targets by way of three market-based mechanisms, such as International Emissions Trading

Mechanism (ETM), Clean Development Mechanism (CDM) and Joint Implementation projects (JI).

The CDM, for example, allows emission-reduction projects in developing countries to earn Certified Emission Reduction (CER) credits, each equivalent to one tonne of CO_2. These CERs can be traded and sold, and used by industrialized countries to a meet a part of their emission reduction targets under the Kyoto Protocol. The mechanism stimulates sustainable development and emission reductions, while giving industrialized countries some flexibility in how they meet their emission reduction limitation targets. Accepted CDM and JI projects are listed in the UNFCCC CDM data base /8/. One example of a JI project referring to the use of coal ash is the TEFRA project from Poland, involving three installations in different locations, where coal ash is used or planned to be used in the production of hydraulic binders /9, 10/.

PARIS AGREEMENT

On 12 December 2015, parties to the Paris Climate Conference reached a new global agreement on climate change. Article 2 of the Paris Agreement defines the three purposes of the instrument: to make mitigation effective by holding the increase of temperature well below 2°C, pursuing efforts to keep warming at 1.5°C above pre-industrial levels; to make adaptation possible for all parties; and to make finance available to fund low carbon development and build resilience to climate impacts. These three outcomes have an impact on energy developments, primarily through the adoption of commitments labelled as Nationally Determined Contributions (NDCs), which are only “intended” (hence INDCs) until the Agreement enters into force /11/. The Agreement entered into force 4 November 2016 after the conditions for ratification by at least 55 countries accounting for at least 55% of global greenhouse gas emissions were met. All EU Countries ratified the agreement /7/

The temperature target of Paris requires a profound transformation process and an inherently new understanding of our energy systems. Credible and effective national policies are crucial to translate the pledges made at Paris into domestic policy. To meet the Paris obligations, new policies will need to be put in place and old ones aggressively revisited:

- carbon emissions will need to be priced;
- energy production and consumption technologies will be regulated;
- funding for research and development will need to be made available;
- and low carbon assets will need to be nurtured by financial markets.

Key market disruptions will be experienced by market participants and governments alike, including technology innovations and stranded assets /11/.

The changing regulatory environments described above impact operating conditions for power plants which can lead to negative quality, consistency and availability impacts on CCPs for existing users. Power plant operators accordingly face difficulties maintaining reliable CCPs supply and quality consistency for served market partners. Significant research into harvesting of interim storage, recovery from stock, processing, beneficiation and also export/import for serving existing markets have become priorities.

BAT - BEST AVAILABLE TECHNOLOGIES

To ensure natural and economic ecosystems are sustainable it is necessary that we mitigate the negative impact of industrial activities on the environment. Emissions from industrial installations have therefore been subject to national legislation for many years. Clean air requirements for power plants have, inter alia, led to the collection and availability of CCPs. This has been a successful example of pollution reduction technology adoption around the world, with additional environmental benefits accrued through CCPs role as a substitute for natural, energy intensive resources.

There are several requirements for clean air which consider emission limit values round the world. Due to the ongoing information exchange the so-called Best Available Technologies (BAT) are partly referenced in laws and regulations. The Organisation for Economic Co-operation and Development (OECD) has published a report on establishing BAT which describes activities in the different parts of the world /12/.

The report presents a comprehensive analysis of approaches to establishing BAT and similar concepts to prevent and control industrial emissions in a wide range of countries, including examples from: the Russian Federation, Korea, the United States, the European Union, India, the People’s Republic of China and New Zealand. For each country, the report presents extensive information on the procedures for collection of data on techniques for control and prevention of industrial pollution, evaluation of the techniques and identification of BAT. In addition, the report covers international initiatives facilitating the application of BAT, including under the Minamata Convention on Mercury and the Stockholm Convention on Persistent Organic Pollutants. While acknowledging the inherent differences of the policy contexts in which BAT are applied, the report allows for a cross-country comparison of existing approaches to determine BAT.

The policies examined in the report use different terms and definitions to describe BAT. The European Union (EU) Industrial Emissions Directive /13/ defines BAT as "the most effective and advanced stage in the development of activities and their methods of operation, indicating the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where this is not practicable, to reduce emissions and the impact on the environment as a whole". However, some countries also include innovative and cutting-edge techniques amongst their BAT.

The BAT documents in the EU, the Russian Federation and Korea are called BAT reference documents, or BREFs, while they are named Guidelines on Available Techniques of Pollution Prevention and Control in China. All of the above present a list of techniques identified as BAT, while the Indian equivalent – Comprehensive Industry Documents Series (COINDS) – are rather guidelines highlighting the advantages and disadvantages of various available techniques to meet the Minimum National Standards (MINAS).

The revised EU Best Available Techniques (BAT) Reference Document for Large Combustion Plants (BREF LCP) was published in June 2017. The conclusions were published in the Official Journal and give bandwidths for emission limit values which have to be defined by the national regulators when implementing the new requirements. Besides dust, NOx and SOx, limit values for Hg will be defined. These limits may provide guidelines and regulatory certainty that may allow for further investment and effort to continue coal-fired generation in some regions.

In Germany, producers formed the '$Hg_{capture}$ Initiative' to publicly inform about the success when using BAT as defined in the BREF /15/. This is of special importance as the CCPs from hard coal are used nearly completely in the construction industry and as changes in compositions may complicate continued use. The research work currently at lab and pilot scale demonstrate that the expected very low Hg emission values may not be reached with only one BAT. In addition, the systems has different effects in different power plants which has not been considered in the revision phase although commented several times.

COAL COMBUSTION PRODUCTS

Beneficial use of CCPs as raw materials in the manufacture of construction materials is well established. Globally, various terms have been used to describe CCPs. Terms including coal ash, pulverized fuel ash, coal utilisation by-products (CUBs), coal combustion by-products (CCBs), cool combustion resides (CCRs), coal combustion wastes (CWRs) and others are used to describe what are basically the same materials. Precise understanding and consistent definitions are important in drafting effective regulations and standards. In an attempt to facilitate precision and consistency the members of the World Wide Coal Combustion Products Network ('WWCCPN'[1] or 'Network') have collaborated to harmonize terminology and to promote CCPs as the consistent nomenclature. This terminology is a more positive view and is in keeping with the concept of

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[1] http://www.wwccpn.org/ The WWCCPN is a coalition of international Associations interested in information exchange concerning management and use of CCPs.

industrial ecology and circular economy principles being an approach which seeks to reuse one industry's by-products as another industry's raw material. The WCCPN global definitions for coal combustion products are given in table 3 /16/. It is our hope that this harmonization of terminology will not only be adopted, but facilitate clarity and understanding of the properties and utilization options for CCPs in regulatory circles and lead to greater international market acceptance.

Depending on the coal type and production process siliceous and calcareous ashes are produced. In siliceous ashes three predominant elements present: silicon, aluminum and iron. The oxides account for 75–85% of the material. It consists principally of amorphous glassy spheres together with minor crystalline matter and unburnt carbon. Lime content for these ashes is restricted by definition in most standards to less than 10%. Calcareous ashes constitute the same oxides but contain more than 10% of lime.

Numerous standards produced across the globe provide guidance and definitions for CCPs use (these are compiled in a later section). The nature and properties of fly ash are dependent on a variety of factors that include the coal's mineral composition, furnace/boiler temperature, type and fineness of the coal and the length of time the minerals are retained in the furnace/boiler.

Term	Definition
Coal Combustion Products	Coal combustion products (CCPs) include fly ash, bottom ash, boiler slag, fluidized-bed combustion (FBC) ash, or flue gas desulfurization (FGD) material produced primarily from the combustion of coal or the cleaning of the stack gases. The term coal ash is used interchangeable for the different ash types.
Fly ash	The finer ash produced in a coal fired power station, which is collected using electro-static precipitators. ….. This is also known as Pulverised Fuel Ash (PFA) in some countries. … .About 85+% of the ash produced is fly ash.
Furnace Bottom Ash (FBA)	The coarse ash that falls to the bottom of a furnace. The molten ash adheres to the boiler tubes, eventually falling to the base of the furnace. ….. Usually <15% of the ash produced is FBA
Cenospheres	Hollow ash particles that form in the furnace gas stream. …. They float on water and are usually collected from lagoons, where ash/water disposal systems are being used. ….
Conditioned ash	Where fly ash is mixed with a proportion of water (10 to 20% by dry mass typically) in order that it can be transported in normal tipping vehicles without problems with dust for sale or disposal.
Flue Gas De-sulfurisation	Where a source of calcium is injected into the furnace gas stream to remove sulfur compounds. …. The sulfur compounds convert the calcium carbonate to calcium sulfate, or gypsum, which is used in the wallboard industry for general construction

Table 3 WWCPN global definitions for coal combustion products /16/

Beside their definition also the regulatory classification is important to exchange on positive experiences regarding utilization and transport. Table 4 gives an update on the status of CCPs in countries reported by the WWCCPN /17/.

Countries	Defined as Waste	Defined as haz.waste	Basel Convetion adopted	REACH adopted	IInt'L Treaty on Mercury[3]	Utilis. Env. Condit.
United States	Yes	No	Yes	No	Yes	Yes
Australia	Yes	No	Yes	No	No[4]	Yes
Canada	Yes	No	Yes	Ref	Yes	Yes
China	Yes	No	Yes	Yes[2]	Yes	Yes
Europe	Yes[1]	No	Yes	Yes	Yes[4]	Yes
India	Yes	No	Yes	No	Yes	Yes
Indonesia	Yes	Yes	Yes	No	Yes	?
Israel	No	No	Yes	No	No	Yes
Japan	Yes	No	Yes	No	Yes	Yes
Russia	Yes	No	Yes	No	Yes[4]	Yes
South Africa	Yes	No	Yes	No	Yes[4]	Yes

[1] – in some member states defined as by-products or products
[2] – China REACH is similar to EU REACH
[3] – International Treaty on Hg, under UN Environment Program; [4] – partly not ratified yet

Table 4 Environmental Classification Systems adopted by Country /17/

PRODUCTION

During the course of 2012 the Network agreed to gather, collate and publish production and utilization data provided by members or from publically available and proven sources. The first worldwide compilation of the worldwide production of coal combustion products in 2010 resulted in approximately 780 Million metric tonnes (Mt) /18/, the update was given by Heidrich in 2017 resulting in 1.1 billion metric tonnes /19/.

Table 5 reports on Annual Production, Utilization Rates by Country in 2016. The largest coal combustion product producing countries were China, India, Europe (total production of 140 Mt to be considered as utilization rates only available for EU15) and the USA. The total production estimate for the year totaled nearly 1.2 billion tonnes.

Utilization varies widely in the countries discussed in this paper. Japan had the highest reported effective utilization rate of 99.3% and Africa/Middle East (still) the lowest at 10.6%. Countries ranked with the highest coal combustion product utilization rates were; Japan 96.3%, Europe (EU15) 94.3%, Korea 85%, China 70% and Other Asia 67% or US 56%.

Country/Region	CCPs Production (Mt)	CCPs Utilisation (Mt)	Utilisation Rate %
Australia	12.3	5.4	43.5
Asia			
- China	565	396	70.1
- Korea	10.3	8.8	85.4
-India	197	132	67.1
-Japan	12.3	12.3	99.3
- Other Asia	18.2	12.3	67.6
Europe	140		
-EU15	*(40.3)*	*38*	*94.3*
Middle East & Africa	32.2	3.4	10.6
Israel	1.1	1	90.9
United States of America	107.4	60.1	56.0
Canada	4.8	2.6	54.2
Russian Federation	21.3	5.8	27.2
Total	**1221.9**	**677.7**	**63.9**

Table 5 2016 Annual Production and Utilisation Rates of CCPs by Country /17/

The countries with a high utilization rate also demonstrate an existing market where CCPs are used regularly according to existing regulations and can easily be put into the market. Ashes are mostly used in cement and concrete applications, especially those with siliceous properties (or class F). Furthermore they are used in road construction, especially when stocks are available, and for filling applications. Calcareous ashes are mostly used for reclamation or, due to their hydraulic properties, as binders. FGD gypsum is predominantly used as raw material for the gypsum industry in different applications including manufacture of wallboard and plaster and in the cement industry as a setting regulator. There has been an increase in use of FGD gypsum as a substitute for natural gypsum in agricultural applications, particularly in the United States.

INTERNATIONAL TRADE

Unlike trade in coal, cement and other commodities there are no comparable figures or official statistics on the international trade of coal combustion products. Information collected from Network members and from import/export data resources provides some indication of trade activity.

Based on trade data provided by contributing network members, global trade for 2010 was more than 3.5 Mt of CCPs traded across borders worth over USD $101 million in transaction value. From the 6 countries reporting trade of CCPs during that year, only 4 countries were able to determine value attributable for these transactions. The compilation of CCP's trade data for 2015 suggests global trade of more than 5 Mt /18/. With a very limited number of countries reporting trade data, the annual volumes and trade revenue generated by CCP's is believed to highly underestimate actual volumes.

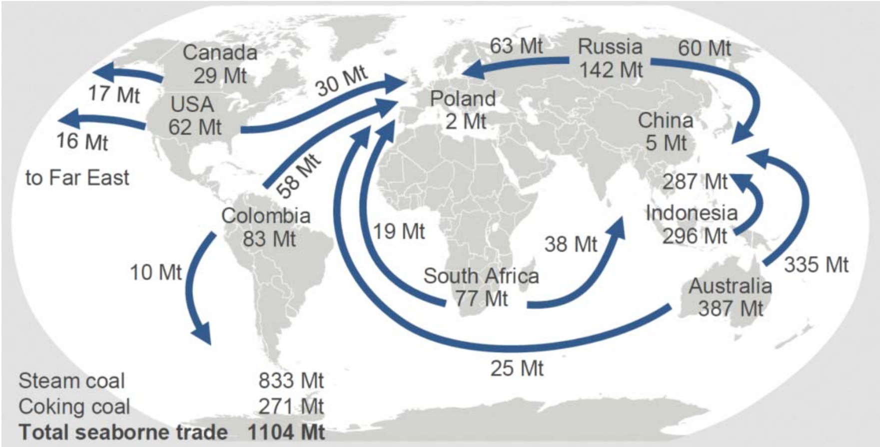

Figure 4 World traded coal flows in 2015 /20/

Despite having a designated HS code, coal combustion by products have not yet gained substantial trade volumes status from a global import/export perspective.

Given increased interest in global CCPs trading observed it is believed that volumes and value of global CCPs trade have increased substantially over the last decade /19/.The growth is driven by several market changes including changes in power production in the US with a switch to gas and in the Western part of Europe with a switch to increased production by renewables as well as in the middle east areas were the use of CCP's has developed. In addition, the CO_2 trading scheme for the industries led to increased requests by the cement industry as ashes and slags are accepted and long term established replacement materials as supplementary cementitious materials. In Europe, ECOBA reports on annual basis the cross border transport which since 2012 is on a constant level of nearly 3 million tonnes /21/.

Considering ship transports of the cement industry, ash transport into the US and cross Europe as well as those to the middle East, the trade volume of coal ash is estimated to be about 6 million tonnes annually and this figure is still seen as a minimum.

Domestic market demand in countries with a net surplus of CCPs consumes much of the supply located closest to export facilities. This increases the total delivered cost of the products as supplies need to be transported from more distant production facilities.

Accordingly, global trade in ashes and gypsum (FGD) is increasing slowly.

INTERNATIONAL STANDARDS

As the use of CCPs is either standard or project related the national regulations for the use in different applications have to be considered. The easiest way to serve existing markets is via product standards with definitions, properties and partly also use information for the materials. Therefore, a compilation of standards for the use of coal ash in cement and/or concrete of the most CCP producing countries is given in this report as this high value application may lead to increased international transport.

Combustion of different types of coal in different types of boilers produces coal combustion products with different characteristics. The use of hard coal, bituminous and subbituminous coal in dry bottom boilers leads to siliceous fly ash with pozzolanic properties. In some countries this is referred to as Class F ash. When burning lignite coals with higher lime and sulfur content also ashes with hydraulic properties are produced. Due to the higher lime (calcium) content these are referred to as calcareous ashes or Class C ashes in some countries.

The definitions and related properties are covered in standards and regulations governing and guiding utilization. The following international standards from Europe: EN 450-1 /22/; USA: ASTM C 618 /23/; Australia/New Zealand: AZ/NZS 3582 /24/; Japan: JIS 6201 /25/; India: IS 3812-1 /26/; China GB/T 1596 /27/ and Russia: GOST 25818 /28/ are compiled to avoid misunderstandings in cross border trade and to inform about options for increased utilisation through exchange of information on existing studies and long term experience. It has to be noted that the standards are used in combination with application standards and other regulations, including environmental requirements.

Basically all standards deal with fly ash or pulverized fuel ash from coal (Europe, Australia/New Zealand and Japan), specifically anthracite, bituminuous, sub-bituminuous and lignite (USA, India and China) or also blended coal mixtures (Russia). These standards contain chemical and physical properties of the ash.

Only the European Standards cover co-combustion of defined materials in specific amounts to ensure ashes characteristics are within a defined range. In addition, processing is covered for ashes which basically follow EN 450-1 standard except for fineness and LOI. Ashes can be processed in suitable production facilities through classification, selection, sieving, drying, blending, grinding or carbon reduction, or by a combination of these processes. Such processed fly ash may consist of fly ashes from different sources, each conforming to the basic definitions required to meet the criteria of the standard. South Africa uses the EN standard in full and Israel has implemented it with minor deviation by exclusion of co-combustion and quality control systems.

	Europe	USA	Australia/ New Zealand	Japan	India	China	Russia
	EN 450-1	ASTM C 618	AZ/NZS 3582	JIS 6201	IS 3812-1	GB/T 1596	GOST 25818
type of coal	coal	anthracite, bituminous, subbituminuous, lignite	coal	coal	anthracite, bituminous, subbituminuous, lignite	anthracite, bituminous, subbituminuous, lignite	coal or coal mixtures
	co-combustion materials; -max 40 or 50 % by mass in case of green wood; -ash amount from CCM max 30 % by mass				from burning of ground or pulverized or crushed coal or lignite		
	covers processing (of FA from fresh prodution)		covers "conditioned" ash (humidity for handling)		covers processing to modify physical or chemical characteristics		
definition	fine powder of mainly spherical, glassy particles, derived from burning of pulverised coal, with or without co-combustion materials, which has pozzolanic properties and consists essentially of SiO2 and Al2O3	class F typicallly produced by anthracite and bitmuninous class C typically produced by subbituminuous and lignite	solid material extracted from the flue gases of boiler fired with pulverized coal	ash collected by the dust collector from the flue gas of the pulverized coal combustion boiler	siliceous pulverized fuel ash for use with $CaO_{react.}$ less than 10 %; from anthrazit or bituminous coal / calcareous pulverized fuel ash for use with CaOreact. Not less than 10 %; from lignite or sub-bituminous coal	class F fly ash from combustion of anthracite or bituminous coal; Class C fly ash from combustion of lignite of sub-bituminous coal	siliceous fly ash from pulverized coal with CaOreact. less than 10 %; calcareous fly ash for use with CaOreact with more than 10 %
excluded	municipal and industrial waste incineration ashes do not conform to the definition		fly ash from fluidised bed combustion			ashes from municipal and industrial waste incineration; ashes from fluidised bed combustion	
comment	also used in Israel (SI1209); deviating for fuel and conformity control	information in Note to definition class C: class C typically has higher CaO content than class F			requirement for bottom ash, pond ash and mound ash are given in IS 3812-2		ashes are subdivided by types of coal resulting in siliceous and calcareous ash, as well as for use in 4 diffornt anplciations:

Table 6 Scope and definitions of worldwide used standards for fly ash in cement and concrete

The definitions all address the collection of fly ash from the flue gas by electrostatic precipitators or other collection methods. They address siliceous and/or calcareous ash (Europe, Japan, India, Russia) or Class F and Class C depending on the coal burned in the USA and China. Characterization of calcareous (class C) fly ash from siliceous (class F) requires that the amount of reactive calcium oxide in the Class C ash is greater than 10%. In Australia, the limit is 10% total lime where in New Zealand the amount of total lime is 25 % without reference to a specific subtype of siliceous or calcareous. The USA standard mentions in a note that the amount of lime of Class C is typically higher. Although recently being published the standard is again under revision where the lime content in the ASTM standard will be defined to 18 % /22/. With this it is doubted whether the lime levels and associated experiences can be compared as the lime content in class F may have been more than 10 % and only the reference to the used coal may be valid for this. In Europe, the cement standard EN 197-1 defines two types for calcareous fly ash: a W1 class with reactive lime content of 10 to 15 % and reactivity test as for siliceous type ash; and a W2 class with more than 15 % of reactive lime considered as a binder with own compressive strength requirement. In addition, there are rules for consideration higher sulphur contents. For durability reasons of concrete, especially when looking to alkali-silica reaction and sulphate attack, the lime content is of importance.

The compilation of the formal parts of the standards is given in table 6.

The chemical and physical requirements of the standards are compiled based on their reactivity evaluation for siliceous (class F) or calcareous (class C) and for the fineness or the intended use for concrete types. The European and Japanese standard cover siliceous fly ash only. EN in addition covers also two categories for fineness. The Australian/New Zealand, the Chinese and the Russian standard specify up to three different grades of fineness. In the Russian standard the different grades are decisive for the use in different types of concrete. Beside fineness requirements for particle density, water demand, reactivity with lime or in mortars (activity index), setting time and for soundness are defined in most but not in all standards.

Other chemical requirements include proportion of main oxides (SiO_2, Al_2O_3 and Fe_2O_3), as well as sulfur content. Requirements for MgO have to be considered in Europe, India and Russia and for alkali-equivalence in Europe and India. In Europe, phosphate content must also be tested in cases of fly ash from co-combustion.

The compilation of the chemical and physical requirements is given in Annex 1.

SUMMARY/OUTLOOK

Coal is used for energy and steam production all around the world. The natural resources, the global development as economic and population growth will lead to increased primary energy consumption which is also likely to be based on coal. In the near future, the use of coal is expected to grow in South-East Asia and India and to stabilize or slightly reduce in China, Japan and Korea and to be further reduced in America, Europe and Australia.

Coal use in energy production is under considerable scrutiny using current combustion technology and resulting CO_2 emissions with the main driver being climate change. New technologies such as High Efficiency Low Emissions (HELE) afford significant emission reductions, but the energy policy uncertainty across the globe continue to retard investment. Clean Air Acts and agreements for effective use of coal and requirements for flue gas cleaning exist for long time. Only few of them are cited given the worldwide framework as followed of the countries. The most important is the United Nations Framework Convention on Climate Change (UNFCCC) with more precise outcome CO_2 reduction by the KYOTO protocol and a temperature limit of 1,5° for global warming by the Paris Agreement. Signatory countries informed about their approaches to reduce CO_2 emission.

Consequences are observed with construction of more efficient coal-fired power stations, retrofits with de-NOx and de-SOx installations as well in switches to other fossil fuels and phase-out of coal by replacing production capacities by other less CO_2 emitting technologies, e.g. nuclear or renewables. New construction and retrofits as well as associated legal requirements for emissions are subject to state-of-the-art technologies which are used worldwide. However, the so-called Best Available Technologies phrased and used in different parts of the world are only partly comparable and the use has to be tested and adjusted in every single station.

The worldwide production of coal combustions production is greater than 1.2 billion tonnes, almost doubling over the last 5 years. The utilization rates vary widely in the countries due to different regulatory environments, market education and market conditions. Due to existing markets with lower production and less developed markets with high production it was expected that the international trade will rise. The most recent evaluation considering ship transports of the cement industry, ash transports into the US, across Europe and into the middle East results in reported trade volume of 6 million tonnes. This is only moderately higher than reported in 2017 though nearly double when compared to the first evaluation in 2013.

Besides quality, established standards and a favorable regulatory regime the availability of material and export/import infrastructure has to be considered. To overcome some of the challenges of dealing with dust emissions at ports of loading and unloading, some importers have begun conditioning ash with 12-15% moisture. This allows geared ships or ports with grab bucket facilities to load and unload vessels with minimal environmental impact.

For the utilization of CCPs legal and technical requirements have to be considered. The dislocation between jurisdictions across the globe continues with some continuing to refer to CCPs either as waste, non-hazardous wastes, solid waste, inert waste, or resources, by-products or products and used widely in construction applications. Through the WWCCPN we continue to promote classify by-products of coal combustion as coal combustion ‘products’ (CCPs). This latter terminology is a more positive view and is in keeping with the concept of industrial ecology, an approach which seeks to reuse one industry’s by-products as another industry’s raw material. A compilation of the definitions and the physical and chemical requirements in standards for fly ash for concrete round the globe showed comparable definitions for siliceous or Class F and calcareous or Class C fly ashes. The differentiation is partly based on the reactive or the total lime content being 10 %. With this the use of fly ash in different countries is possible but national requirements for application have also to be considered.

The members of the World Wide Coal Combustion Products Network will continue to promote, coordinate and inform the public, industry and governmental entities about the beneficial environmental, technical and commercial uses of Coal Combustion Products.

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COUNTRY	Europe		USA		India		Australia			China		Russia		Japan
Standard	**EN 450-1**		**ASTM C 618**		**IS 3812-1**		**AS 3582.1**			**GB/T 1597**		**GOST 25818**		**JIS 6201**
Classification	Cat N	Cat S	Class F	ClassC	siliceous	calcareous	spec.grade	grade1	grade2	Class F	ClassC	siliceous	calcareous	
							fine	medium	coarse					
Loss on ignition, max,%	<5; <7; <9 (cat A;B;C)		6.0 (12.0)	6	5.0 (7.0[2])		3	4	6	≤5; ≤8[1]; ≤10 (class I; II; III)		<10;<15 (type I;II)[1]	<3;<5 (type I;II)	5
CaOfree, max,%	1.5 (>1.5)									≤ 1.0	≤ 4.0		<5 (type I;II)	
SO3, max,%	3.0		5.0		3.0 (5.0[2])		3			≤ 3.0 (≤ 3.5[1])		<3;<5 (type I;II)	<5 (type I;II)	
Cl, max, %	0.1				0.05									
CaO, %				(> class F)			<10 (AS) / < 25 (NZS)							
Reactive CaO, max,%	10				< 10	> 10						< 10	> 10	
Reactive SiO2, min,%	25				20									
SiO2, min %					35	25								45
SiO2 + Al2O3 + Fe2O3 min,%	70		70	50	70	50	70 (AS) / 60 (NZS)			≥ 70	≥ 50	≥ 70		
Na2O equ., max,%	5				1.5							< 3	< 1,5 (type I;II)	
MgO, max,%	4				5							< 5		
P2O5 sol., max, mg/kg	100													
P2O5 %	5													
Moisture %			3.0		2.0		0.5			≤ 1.0		≤ 1.0		1
Amount retained on 45µm, max,%	40 (+/-10%)	12	34 (+/-5%)		34 (50[2])		15	25	45	≤12; ≤30; ≤45 (class I; II; III)				
Amount retained on 80µm, max,%												<20;<30 (type I;II)	<20 (type I;II)	
Fineness: specific surf. area cm²/g					min. 3200[1] (2000[2])							>2500/1500(type I/II)	>2500/2000(type I/II)	min. 2400[1]
Particle density, kg/m3	+/- 2001)		5%[1]							≤ 2.6				
Specific gravity, min														1.95
Soundness, max	10 mm[2]		0.8%[2]		0.8%						≤ 5 mm			
Setting time, max minutes to ref.	120[3]													
Strength (Activity) Index ß7d min,%			75[3]											
Strength (Activity) Index ß28d min,%	75[4]		75[3]		80					≥ 70				60
Strength (Activity) Index ß90d min,%	85[4]													
Strength (Activity) Index ß91d min,%														70
Relative Strength, Mpa min							105% (1)	75% (1)						
Lime reactivity Mpa					4.5									
Water requirement, max, % of cont	95[5]		105		105					≤95; ≤105; ≤115 (class I; II; III				
Water content ratio, %														102
	1) max. deviation from declared value		1) max. deviation form average value		1) fly ash of fineness 2500 cm²/g can be used by intergrinding with clinker		1) Relative strength not a measure of performance but for reactivity in a given blend (blend by trials)			1) for fly ash for cement use		Type I: for reinforced concrete acc. GOST 26663; Type II concrete structures and lighweight concrete		1) the finess shall not differ by 450 cm²/g
	2) only when CaOfree content is >1.5%		2) According to ASTM C-1012, Fly ash/Cement: 20/80, equal slump		2) for ashes according IS 3812-2 (bottom ash; mound ash, pond ash, …)							1) for fly ash from hard coal <20;<25 (type I;II) for fly ash from anthrazite		
	3) to be tested with mix of 25% flyash:75% cement		3) According to ASTM C-311, Fly ash/Cement: 20/80, equal slump											
	4) according to EN 196, no fixed fly ash /cement ratio, W/C:0.5													
	5) Only for fineness category S													

Table A1 Compilation of chemical and physical requirements in fly ash standards