Doosan Lentjes

40 Years of Circulating Fluidised Bed (CFB) Power Plant Technology

A review of the history, present status and future potential of the application of an innovative and successful combustion technology

Dedicated to Prof. Dr. Ing. Lothar Reh, brain behind the CFB principle, on the occasion of his 85th birthday

Written by Damian Goral, Reinhard Knittel, Silvio Löderbusch, Dr. Hans Piechura and Dr. Ludolf Plass

Special Print

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Kurzfassung

40 Jahre Zirkulierende Wirbelschicht (ZWS) Kraftwerkstechnologie – eine Übersicht über Geschichte, aktuellen Stand und Zukunftspotential der Anwendung einer innovativen und erfolgreichen Verbrennungstechnologie

Die Kraftwerkstechnologie basierend auf dem fluid-mechanischen Prinzip der zirkulierenden Wirbelschicht (ZWS) war auf Basis ihrer Vorteile bei der Emissionsminderung und Brenstoffflexibilität äußerst erfolgreich, wie nahezu 5.000 Anwendungen weltweit belegen.

Beginnend mit ihren Wurzeln in der metallurgischen Anwendung und von den ersten Ideen der Erfinder ausgehend wird die Entwicklung von stationären hin zu zirkulierenden Wirbelschichten beschrieben, vom Pilotmaßstab und ersten kommerziellen Installationen bis hin zu Kraftwerksgroßanlagen.

Dabei werden auch alternative und konkurrierende Ausführungskonzepte betrachtet, sowie die Entwicklungen auf dem chinesischen Markt. Die Entwicklungen werden mit Beispielen ausgeführter Anlagen und deren Betriebsergebnissen belegt.

Der zweite Teil des Fachbeitrags widmet sich aktuellen und zukünftigen Konzepten der ZWS bei Kraftwerksanwendungen. Neben Beispielen für innovative Ausführungsvarianten der Aufstellung werden Konzepte mit überkritischen und ultra-überkritischen Dampfparametern vorgestellt, sowie die Anwendung auf die Verbrennung von Biomassen.

Abschließende Betrachtungen zeigen die Einbindung einer ZWS-Kraftwerksanlage in ein innovatives Energiekonzept als Beispiel für Anwendungen resultierend aus der Energiewende.

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Introduction

May 31, 2016, marked the 40th anniversary date of the filing of the last base patent for the circulating fluidised bed (CFB) combustion technology for power plant applications. Over the last 40 years the technology passed through a significant development in design, size and applications. With close to 5,000 references around the globe, the process stands for a very successful implementation of an industrial innovation, based on its outstanding features with respect to both fuel flexibility and emissions control capability.

Today, CFB combustion technology stands for the most environmentally-friendly and efficient power plant technology for solid fuels.

After 40 very successful years of application of this technology and particularly, in view of the energy transition taking effect almost worldwide, it is time to review the remarkable history, present the status and the future potential of CFB combustion (CFBC).

The early beginnings of fluid bed applications

Fluid bed gasification, cracking, roasting and combustion

In 1921, Fritz Winkler, an engineer of German BASF developed in the course of the invention of the Haber-Bosch-Process for ammonia production the Winkler Generator for the gasification of fine lignite on the basis of a new gas/ solids reaction principle called "fluidisation" in a stationary, fluidised bed. A first large scale plant went into operation in 1926 and others followed.

During further development of the fluid bed technology it was found that, by operating at higher gas and solids velocities in pneumatic transport regime, certain shortcomings in comparison to "slow" beds could be overcome, in particular scale-up of capacities. However, it was only in 1938 when Lewis and Gilliland filed a first patent based on high-velocity-fluidisation for cracking oil with a concept similar to a CFB. Realisation of this patent in industrial practice has never been reported. [1]

In the 1950's, BASF applied classical fluid bed combustion technology to a process for roasting pyrites with horizontal tube bundles for raising steam while generating electric energy or process heat (Figure 1).

It was then that the company Lurgi Chemie und Hüttentechnik became aware of the technology and intensively used it since 1951 under license in the inorganic chemical and non-ferrous metallurgical industry. End of the 1950's, a first industrial 6 MWe classical fluidised bed boiler with in-bed tube bundles was realised for the Lurgi-Rohrbach process for production of white cement by fluidised bed combustion of oil shale, still in operation at the Lafarge Holcim AG cement plant at Dotternhausen, Germany. [3, 6]

The idea of burning coal in a bubbling fluidised bed certainly crossed the minds of many innovators and scientists. There is a common agreement that it was first pursued and promoted by Douglas Elliott of Central Electricity Generation Board at Southampton, who proposed its use in the UK in 1960's. He recognised the merit of burning high carbon-in-ash residue in fluidised beds to recover thermal energy and to generate steam by immersed boiler tubes. His original idea was soon extended to coal-fired power generation in its entirety. [4]

Metallurgical CFB applications – alumina calcination and iron ore reduction

Though different modes of high velocity fluidisation technology were applied extensively, they did not have a direct entry into the application for steam generation by coal combustion.

Among others also Lurgi found higher velocity fluidisation to be an excellent technique for carrying out reactions with finely grained solids. Based on laboratory-scale work around 1958 with a first direct diesel oil injection fired CFB at 1,100 °C and based on the external doctorate thesis about fluid dynamic similarity of fluidisation in the boundary regime to pneumatic transport by Lothar Reh, during the 1960's, they developed a new alumina calcination process in cooperation with Vereinigte Aluminium Werke AG (VAW). It was tested in a 24 tpd pilot plant in Lünen and was followed by a first commercial plant of 500 tons per day in 1970 there, too.

In alumina calcining, being an endothermic process, gas or oil has been burnt for the first time in an air staged low NO_x emission mode in the CFB calciner. The generated heat was recovered from the product in a multi-stage cooler, whereas waste gases exchanged heat with feed materials. Use of the CFB process allowed uniform control of the calcining temperature within its required limits. As a result of this attractive feature, a large number of CFB calciners were soon put into commercial operation. [5, 6]

In 1975, knowhow for circulating fluidised bed reactors was provided by Lurgi to the developers of the ELRED iron ore reduction process. The ELRED process is characterised by a fluidised bed pre-reduction stage at 950 to 1,000 °C fed with fine ore and coal to produce a partially metallised product also called sponge iron which is then smelted in a DC arc furnace to give a liquid iron product. The off gas from the pre-reduction stage together with that from the electric furnace forms the fuel for electrical power generation.

The process concept originated from Per Collin at Stora Kopparberg Bergslag AB, a former major steel producer in Sweden who jointly developed it with ASEA AB. Between 1976 and 1979, a CFB reduction pilot plant was built and tested at ASEA's Central R&D Department as part of the overall process development. However, to date, no commercial ELRED process unit has been sold. [7]

The inventor's original ideas, inventor's proposal and patents

In the course of the development work for the ELRED process for the reduction of fine iron ore with fine coal in a CFB in spring of 1974 the four engineers Per Collin (Stora), Sune Flink (ASEA), Lothar Reh and Martin Hirsch (Lurgi) discussed the possibilities of the combustion of fine coke residue after magnetic separation from fine ore. During the informal discussion, Collin drew the intention towards the CFB process. He initiated the idea to place parallel water tubes in the upper part of the combustor for cooling purposes, which in fact Dr. Reh had already considered in earlier roasting plant development works as well. [3]

The ideas had been further discussed and developed into the Inventors Proposal which the German engineers developed for the technical concept and performed for the process calculations. After all they created the term "Circulating Fluidised Bed CFB". The proposal was finally issued on February 4, 1975. [8]

It is remarkable that this early idea already incorporated such advanced features like an external fluid bed heat exchanger (FBHE) with several chambers and both, water cooled combustor and cyclone as well as internal cooling walls. It already includes ideas for desulphurisation with limestone and oxygen enriched combustion.

There are two basic patents that have been granted to protect the CFB boiler inventions. The first patent applied for on September 5, 1975 and titled: "Verfahren zur Verbrennung kohlenstoffhaltiger Materialien" (Process for Burning Carbonaceous Materials) was granted to the four inventors Collin, Flink, Reh and Hirsch and is based on the original inventor's proposal. It already mentioned in-situ SO_2 removal efficiencies of over 90 % in the combustor by addition of fine grained limestone, possible NO_x emissions of less than 100 ppm and use of oxygen enrichment in combustion air. [11]

With a second patent "Verfahren zur Durchführung exothermer Prozesse" (Method of and Apparatus for Carrying out an Exothermic Process) applied for on May 31, 1976, by Lothar Reh, Martin Hirsch and Ludolf Plass the invention was completed. It marks the day of the 40^{th} anniversary of CFBC power plants.

Key of this patent is the external FBHE and its solid recirculation into the combustor. It is remarkable, that the process of a pressurised CFB was already mentioned in that early stage of CFB developments. [12]

In order to verify the new technology and to be in a position to test various fuels and combustion conditions as a basis for the design of the commercial plants various laboratory and pilot size facilities were built and operated, the largest with a capacity of 1.5 MW_{th} and an inside diameter of 0.7 m. The plant has been intensively used for testing and combustion verification until the end of the 90's.

During the commercialisation of the technology and before the first coal burning plant was built, engineers came up with various concepts for first implementations. For example, they developed the Ranstad boiler concept for complete low temperature, oxygen enriched combustion of Swedish oil-shale at 650 °C. Figure 1 shows an artists view. In fact, it is already close to an advanced CFB boiler, even though it contains features we look today with a certain curiosity on. A plant according to this concept was never built.

Commercialisation: the first CFB power plant in Lünen

VAW Lünen – the first coal fired CFB power plant

For the engineers it was only a short step from the calcining technology to the first purely coal-fired boiler at the VAW Lünen works in 1981 (Figure 2). At a capacity

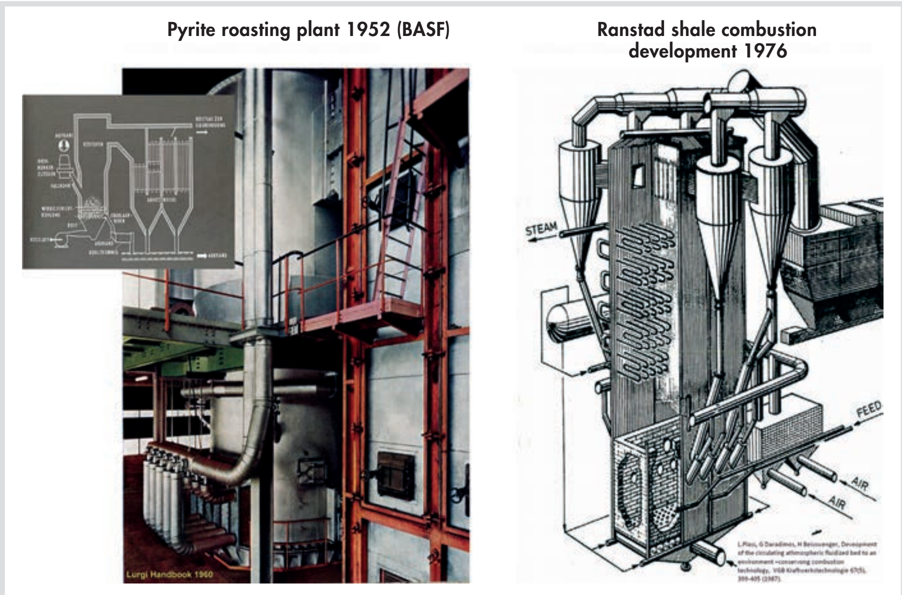

Fig. 1. Early developments of fluidised bed systems – left: Pyrite roasting plant, BASF 1952; right: Ranstad oil shale CFB combustor [9, 10].

Fig. 2. CFB power plant VAW Lünen 1982 [13, 14].

of 84 MW_{th}, it generated steam, power and process heat from high ash coal wash residues for their novel aluminium operation. The very low SO_2 and NO_x values of the first patent were confirmed and the ash was sold commercially for construction purposes.

Undoubtedly, the plant still looked more like a metallurgical application with a round, refractory lined combustor and refractory lined cyclone, an external FBHE reheating molten salt as a heat carrier for the bauxite tube digestion process and a waste heat boiler generating steam with 87 MW_{th} (50 t/h steam production) capacity.

Transformation from coal to waste fuels*

After closure of the aluminium operations the plant was converted to burn coal and waste fuels and subsequently, the firing of coal was phased out completely. To accomplish this transition from coal to waste combustion a number of modifications were required to the boiler.

- 1981, dismantling of the separation cyclone; operation with the recycling cyclone proofed to be sufficient due to extremely high separation efficiency of cyclones with high solids loading.
- 1985, de-commissioning of the FBHE as the salt heat carrier for the bauxite tube digestion was not used any longer.
- 1990, first co-firing of alternative fuels, transition from coal to waste fuels started.
- 1996, retrofit of the plant with a flue gas cleaning system according to German 17. BImSchV
- Approx. 2005, addition of various fuel feeding systems (total of 5 systems installed for liquid, solid, pasty, sludge, dusty and meat sludge waste)
- 2007, addition of after burning zone
- 2015, exchange of the waste heat boiler

The Lünen plant is, as part of the Remondis Lippe Werk recycling activities, in operation until today and exclusively burns a large number of different waste fuels which proves the flexibility in terms of fuel applications and emissions compliance of the CFBC technology (Figure 3).

From pilot plant to utility size

Milestones of CFB development

After the development from the earliest fluid bed technology ideas up to the first commercial combustion plants in the early 1980's, the further implementation of the CFBC technology took off rapidly. Already the second unit had a capacity of close to 100 MW_e and in every decade a new milestone could be reached: 100 MW_e in the 1980's, 250 MW_e in the 1990's, close to 300 MW_e until 2010 and today boilers of 600 MW_e plus are on the engineering tables.

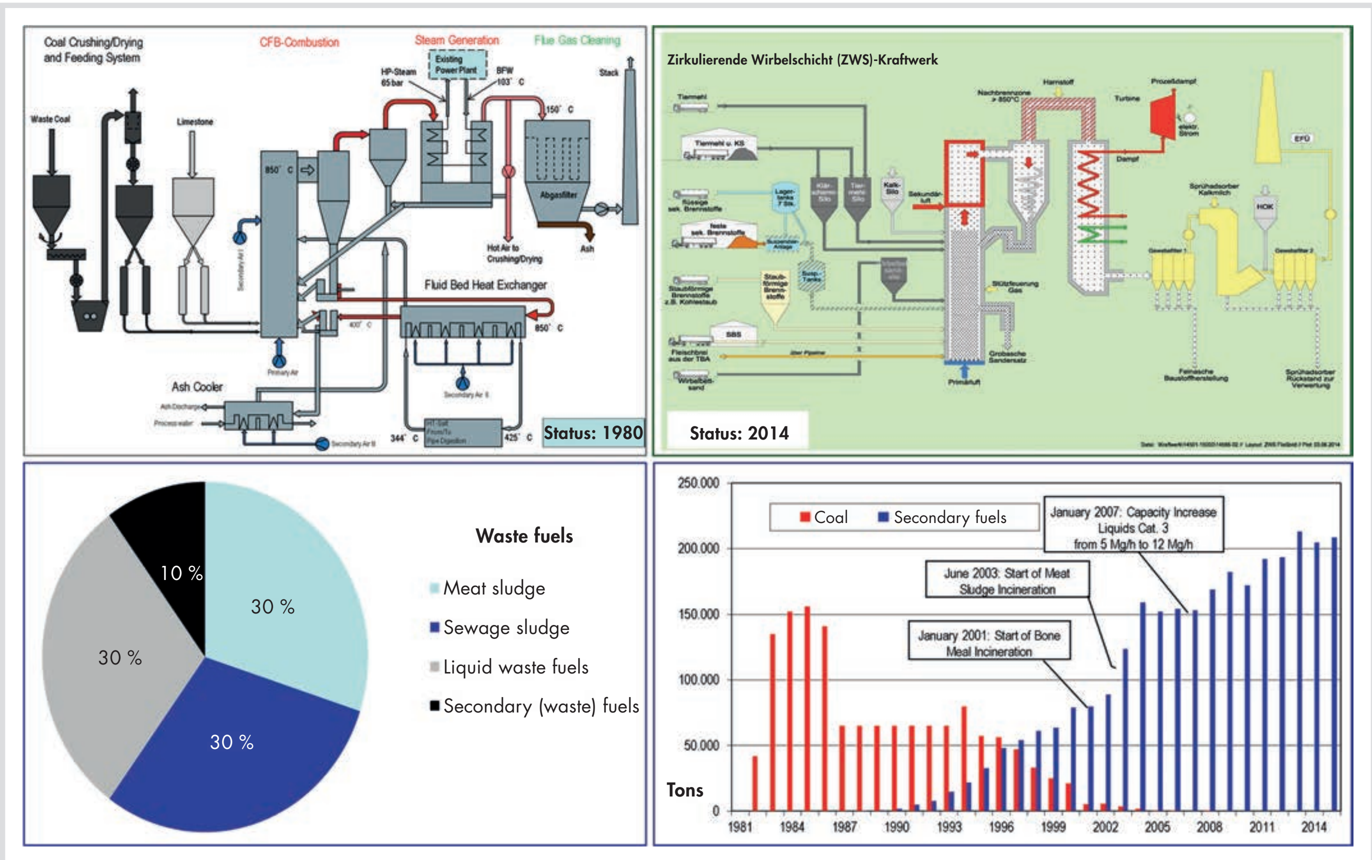

Fig. 3. Lünen (Status 1980 vs. 2014 and transition of fuel usage [15].

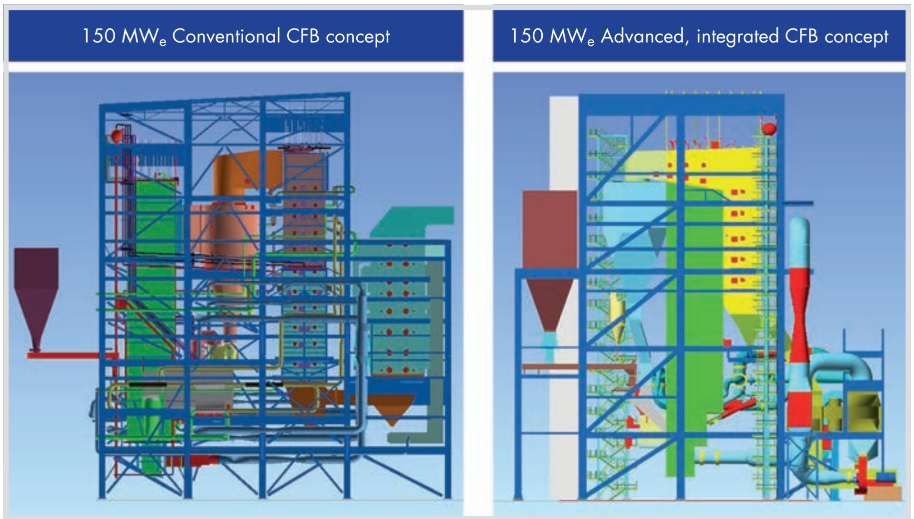

Fig. 4. Concepts for CFBC power plant technology – Conventional vs. integrated CFB design.

The rapid development of the technology also caused standardisation and capacity increase, in particular for utility applications, going hand in hand with a more "power plant" typical design. One cyclone being sufficient up to 100 MW_e was soon succeeded with a two cyclone design up to 200 MW_e (Berlin, Tisova), a four cyclone design up to 350 MW_e (Twin Oaks, Gardanne) and for larger units a sic to eight cyclone design will be mandatory.

Certainly, the CFB technology has changed its face over the years. Starting as a chemical and metallurgical application the overall design had to be adapted to power plant use. The first units still used circular/refractory lined combustors and cyclones, the second generation already had water cooled, square combustors, FBHE's and sometimes even cooled cyclones, however, in a conventional arrangement as illustrated in the left image of Figure 4. Modern designs use extremely integrated arrangements, are entirely water/steam cooled and require reduced space and investment.

Main drivers of the development

One of the major drivers for this new technology in the early 1980's was the debate about the "acid rain" debacle with increasing environmental awareness. Already in August of 1983, the Spiegel Magazine posted an article including major advantages of the new technology: Wirbelnde Zukunft (Fluidised Future) – The latest knowledge about the causes of the acid rain improves the chances of an environmental friendly technology – the "fluidised bed process" for power plants. [16] They are still or even more, the same driving forces today:

The environmental advantage of the process, desulphurisation in the combustion chamber at low temperatures (850 °C) combined with low nitrogen oxides and carbon monoxide, enabled power plants without add-on flue gas cleaning systems, allowing economic, efficient and clean generation of electric power. The most stringent environmental regulations can be met.

The high fluidising velocities made it possible for the first time to scale-up to larger unit sizes and apply the technology to utility sized power plants.

The intense mixing behaviour of the process with excellent heat and mass transfer capability allowed to use all kinds of solid fuels or fuel mixtures, even very low quality fuels such as washery wastes, petroleum coke, biomass and waste fuels to be efficiently and environmentally burnt. It allowed reduced electric energy generation cost by use of abundant waste fuels, a particular advantage also in developing countries with increasing energy needs.

The CFB boiler development history

Alternative CFBC power plant technologies

From the original developments of Lurgi the CFB technology spread out to a wide network of suppliers. From 1984 to 2000 an extensive licensing program was undertaken in lack of own power boiler technology. The extensive market volume could not be handled alone and a number of suppliers were obliged to agree to license payments in their dis-regard of the original patents. As a side effect of the policy and the related know-how transfer, the technology was spread to a number of companies, some of them becoming emerging competitors later.

Today, the original technology is mainly represented by a group of companies such as Doosan Lentjes and is usually including an external FBHE, although arrangements without FBHE are possible.

A second group, originally avoiding the external heat exchanger, EHE, developed around a Finland-based technology. In 1976, the Finnish company started works to develop a CFB boiler, unaware of the existing patents and without applying for own patents. They became inspired by a lecture of Prof. Arthur Squires given in Stockholm and by experience as supplier of classical roaster boiler equipment. In 1979, a plant with 15 MW_{th} to burn bark, wood waste and coal was started up and several plants followed in 1981. Their innovative design of today is a compact water/steam cooled solution using an external heat exchanger.

The need to avoid infringement of existing patents gave way to the development of alternative CFB concepts:

In the Circofluid® CFB, the circulation loop does not maintain full temperature over the height of the combustor, but uses heat transfer surfaces to reduce the temperature in the top of the combustor and consequently uses a cold cyclone design in the recycle loop. It mainly lives on in India and China on the basis of former licenses.

The Studsvik System has a distinct difference to all the other technologies by using so-called U-beam separators instead of the traditional centrifugal or cyclone separators in the circulation loop and finalising the solids separation in a cold recycle by a multiclone separator arranged in the back pass. [17]

The CFBC technology was also applied to waste incineration starting out from Austria and Germany with mostly industrial references, particularly in the pulp and paper industry. In China, numerous applications were realised with co-combustion of household waste and coal in order to boost the low calorific value of the waste. In overall utilising CFBC for waste incineration was not really a success story as the fuel properties causing effects such as corrosion, fouling and agglomeration demanded specific solutions, which were technologically feasible but made the projects far less economic.

The Chinese CFBC story

A comprehensive look at the world wide history of CFB power plants cannot neglect the developments in China. Due to early contacts (1975) to Germany concerning alumina calcination and tube digestion, three Chinese institutes started to develop their own boiler design, based on international technology. All these concepts were developed for a standard size series, were limited to below 150 MW_e and did not have EHE's. 11 major boiler manufacturers built over 3,000 plants based on the local technology, mostly small sizes (35 t/h, 75 t/h etc.).

As Chinese technology could not be expanded to larger sizes without external help, various Chinese boiler companies later concluded license agreements for capacities from 150 to 300 MW_e, including concepts with EHE's. At least,over twenty 300 MW_e units are already in operation.

Based on the 300 MW_e concepts provided by the licensors, one Chinese boiler manufacturer developed and implemented a 600 MW_e CFB unit with supercritical steam parameters at Baima/China in follow-up of a national development program. The design clearly shows advanced features of the technology such as pant leg design and integrated FBHE's. Environmental achievement is over 97 % SO_2 emission reduction, around 100 ppm NO_x emissions and 9 mg/Nm^3 dust emissions. [18]

Track record of CFBC boilers

An estimated total number of approx. 800 CFB power plant units with a total capacity of app. 50 GW_e are installed across the world excl. China. In China approx. 4,000 CFB boilers exist with approx. 70 GW_e combined capacity, designed and manufactured by Chinese boiler companies (thereof 2,000 with capacities below 25 MW_e).

CFB power plants are under operation with unit sizes ranging from app. 15 to 600 MW_e. The average capacity is approx. 75 MW_e with a trend to larger capacities for air pollution reasons. Largest sizes under construction and operation are ultra-supercritical boilers with 550 MW_e (Samcheok, Korea) and 600 MW_e (Baima, China) and design concepts are available up to 800 MW_e.

Hereafter a review of major milestones of CFBC power plant references:

Milestone projects

Stadtwerke Duisburg CHP 1 – 1985 – the world record plant

Being the second commercial CFB power plant, the unit 1 of CHP (Combined Heat and Power Plant) Duisburg is a real champion:

- First CFB worldwide to apply Benson (once-through) boiler principles, even though it was still with sub-critical conditions.
- First CFB boiler delivering in co-generation mode heat to a large city district heating network. By high yearly average efficiency of close to 70 % it already reduced CO_2 emissions considerably.
- First 100 MW_e CFB worldwide! This capacity was considered the utmost possible at that time.
- Commissioned in September 1985 and with over 230,000 operation hours Duisburg is the longest continuously running CFB boiler in the world (Figure 5).

Berlin, Moabit (Vattenfall) – 1990 – the first Benson type CFB

The Berlin plant with 100 MW_e was another huge step forward. It was the first CFB close to 200 bars on Benson (once-through) principle (Figure 6). And the first CFB worldwide with steam cooled cyclones and FBHE's. This outstanding plant was honored with the International Power Plant

Fig. 5. Stadtwerke Duisburg CHP 1 1985.

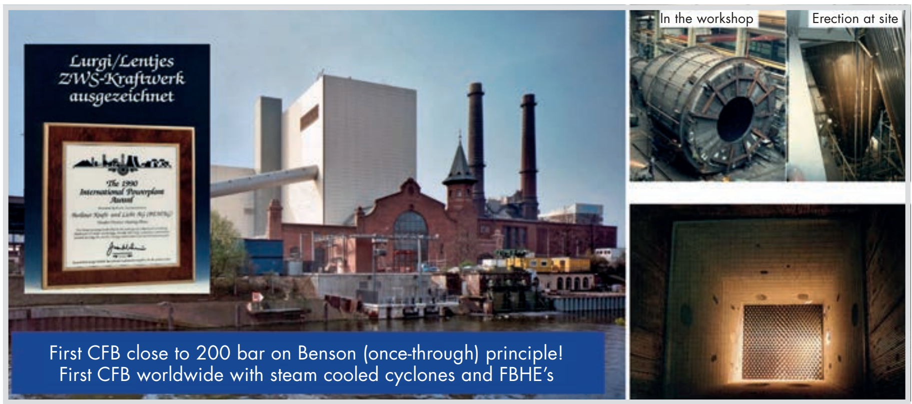

Fig. 6. Berlin Moabit (Vattenfall) 1990.

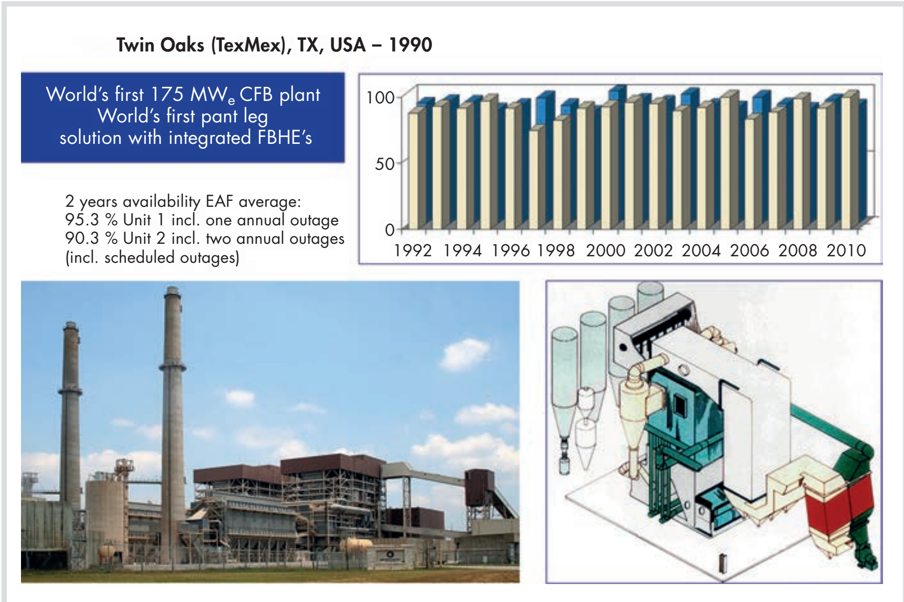

Fig. 7. Twin Oaks (TexMex) design concept and availability record.

Award by Power Magazine in 1990 for outstanding environmental achievements.

Twin Oaks (TexMex), TX, USA – 1990 – new features

A milestone in American CFB history: TexMex (today known as Twin Oaks) was the world's first 175 MW_e CFB and the world's first pant leg solution with integrated water-cooled FBHE's (Figure 7). The plant posts an outstanding availability record over many operating years and burning various fuels including Texas lignite and petroleum coke.

Gardanne, France – 1995 – multi fuel application

Gardanne in the French Provence was the world's first 250 MW_e CFB plant and the largest CFB worldwide for many years. Originally designed for local lignite and later converted to bituminous coal combus-

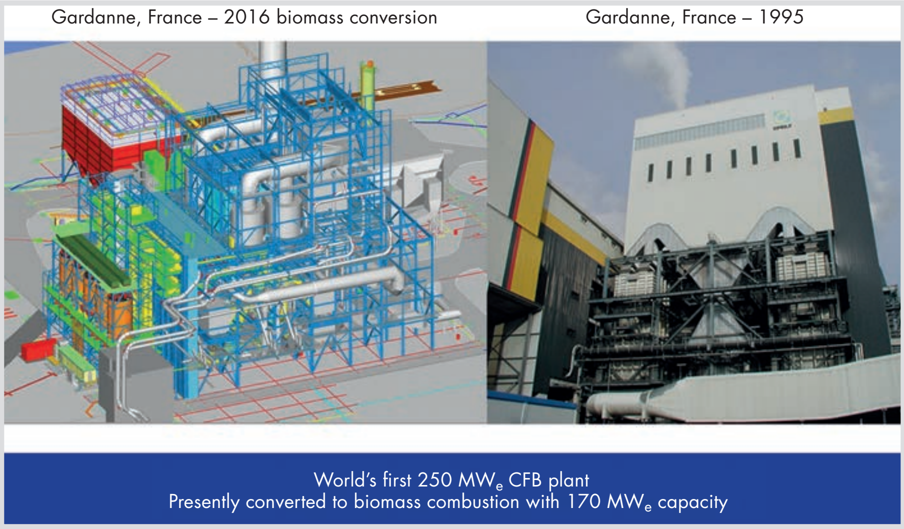

Fig. 8. Gardanne, France biomass conversion 2016.

tion, the unit was recently converted to biomass combustion with a capacity of 170 MW_e (Figure 8). The plant proves the great flexibility of this technology, in particular with FBHE application.

Neyveli, India – 2009 – the 300 MWe class

Presently, the India-based local lignite-fired power plants Neyveli and Bhavnagar are Doosan Lentjes' largest references: each plant has two units with a capacity of each 280 MWe.

Tisova, Czech Republic – first application of integrated CFB design/fuel quality

The 100 MW_e lignite burning plant Tisova is an early example of an integrated plant arrangement concept with pant leg, integrated FBHE's and compact boiler arrangement. At a site with decreasing lignite fuel quality the flexible plant ensures reliable plant operation, availability and energy generation. The arrangement of the plant serves as a basis for state-of-the-art integrated boiler designs.

Actual and future challenges for the application of CFB Combustion Technology

Market

The decision to reduce greenhouse gas emissions, especially CO_2 – just recently confirmed in Paris – resulted in a ban of fossil fuel utilisation for power production consequently followed up by rich western countries, especially of the European Union and the USA. [22]

It is still a question whether and how CFB-based power plants will be required in the future in Europe and the US. Even if renewable-based energy will be available in sufficient amounts, temporary lack of those energy may still have to be compensated by proper storage capabilities and/or conventional energy resources. Certainly, the boundary conditions for fossil fuel power plants will change – e.g. cycling of the operation and perhaps higher flexibility towards fuels and co-combustion of biomass may have to be taken into consideration.

Even though developing countries are intending to support the policy of enhancing renewable energy production as well, the economy in these countries will not allow an aggressive engagement and the associated high investments and resulting high energy prices. These countries might represent the future market but involve challenges.

Nowadays, the World Bank is rather restrictive when it comes to providing support for fossil fuel-fired power plant projects leaving those opportunities to developing countries in order to assist their economy [19]. Additionally, in 2015, the OECD has agreed on new rules on official support for coal-fired power plants, including restrictions on export credits for low efficient coal-fired power plants with the effect that, with increasing capacity increasing efficiency will be required to qualify for export credits. Subcritical boilers will only be supported in developing countries for capacities up to 300 MW_e. Above 300 MW_e at least supercritical boilers and above 500 MW_e ultra-supercritical boilers with related efficiencies will be required. [20, 21]

Apart from utilising financing via World Bank or export credits, new power plant projects optionally will be based on IPP strategy leaving financing, building and operating to private IPP's. Refinancing will be done by selling the produced power on the basis of fixed tariffs according to power purchase agreements – and often these tariffs are rather low.

Both low tariffs and a great competition, especially by Chinese IPP's and EPC's, will create challenges for those projects. High quality at low prices is requested, even if competing against Chinese EPC's and IPP's.

Developing countries do often need smaller size, decentralised power plants meeting the local demand and the limited capacity of the infrastructure. Capacities ranging from 100 to 300 MW_e are rather standard power plant sizes. Decentralised power plants may be required in the future even in developed countries to meet the local spot demand to compensate temporary lack of renewable energy. Then those plants will definitely have to be designed for cycling conditions.

Indigenous fossil fuels of those countries are often characterised by low quality as for example the large lignite reserves in Turkey or India, Anthracite in Vietnam or the discard coals in South Africa. Certainly the CFB technology with its flexibility towards the fuel quality especially at low calorific values and high ash coals is of great advantage against PC technology. The future will show whether and in how far those fuels will be acceptable with respect to public financing requirements. Only projects based on financing by independent international banks will be more free to choose their project design basis (Figure 9).

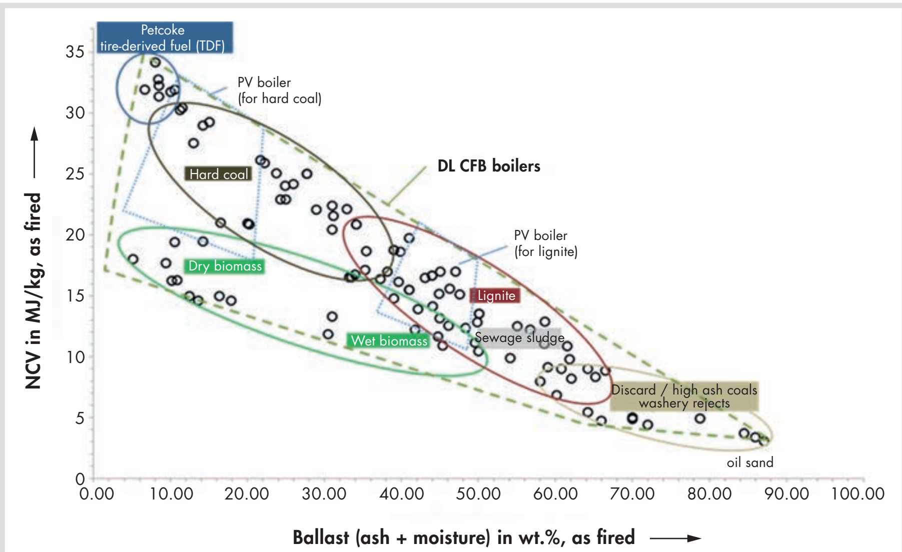

Fig. 9. Reference fuels applied in CFB boilers.

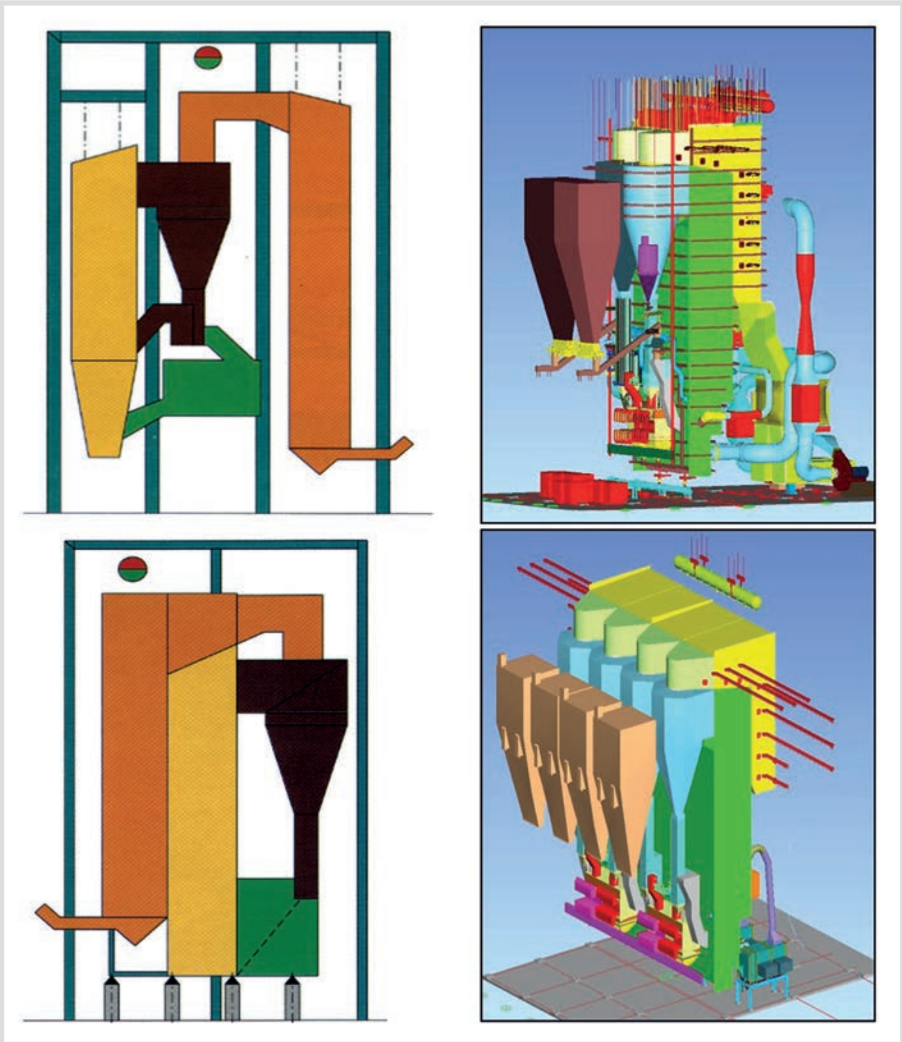

Fig. 10. Left side: Developments towards compact design.
Right side: 150 MW_e 2 Cyclone compact design and 300 MW_e 4 Cyclone compact designs.

Modern status of CFB technology

The first CFB boilers were based on subcritical conditions, hot refractory lined components such as cyclone and FBHE, external, separated components such as the FBHE. They worked quite successfully over the years. But early optimisations were applied such as steam or water cooled cyclones, Benson type boiler design and the pant leg design which allowed applying 4 and more cyclones per boiler unit (Figure 10).

These improvements have been applied in a number of plants resulting in a kind of first compact design demonstrated in the plants of Tisova and Starobeshevo.

The "conventional design" still has been chosen for CFB boilers due to preferences of customers.

The shift of the CFB market to Asia and other low cost markets forced to combine all those improvements to come up with a lean cost competitive concept utilising

- combined combustor – back pass
- water/steam cooled cyclones and ash returns
- integrated water cooled FBHE's
- top support of entire boiler

mainly avoiding sophisticated and expensive expansion joints between the former "hot" parts, significantly reducing the refractory and allowing for a significantly reduced compact, modular arrangement in comparison with that of the conventional design (Figure 10).

The four cyclone inline compact design resulted from modular arrangement of the two cyclone design and is applicable for the 300 MW_e class boilers. Generally the pant leg design is applicable for four cyclones as well and particularly may be applied for more than four cyclones.

Boilers for the 150 and 300 MW_e class will be usually designed as sub-critical boilers. Since plant efficiency is of growing importance, they are applied with increased steam parameters with temperatures of up to 565 °C and steam pressures of up to 175 bars.

CFB Future Developments

For future applications and in view of the current market developments, as well as the requirements of financing institutes, the design of the 300 MW_e class as supercritical CFB boilers will be critical. In former times, Benson type CFB boilers have been designed and built (e.g. CFB plants Duisburg and Berlin Moabit) but used sub-critical steam conditions. Nowadays, only few CFB boilers are designed and built on supercritical steam conditions such as Lagisza and Baima. Presently, South Korea-based Doosan Heavy Industries is developing an ultra-supercritical CFB technology with a gross capacity of 600 MW_e and super-heated steam parameters of 610 °C/281 bar (abs).

The standard design platform will apply low emissions limits of 150 mg/Nm^3 SO_2 and 100 mg/Nm^3 NO_x according to the environmental requirements in South Korea. According to the design fuel, SO_2 limits will be met only with the CFB typical in-situ desulphurisation while meeting NO_x emissions limit will require a SCR system.

Currently, modern design platforms are available for the 150 MW_e and 300 MW_e class for coal. For very low calorific lignites

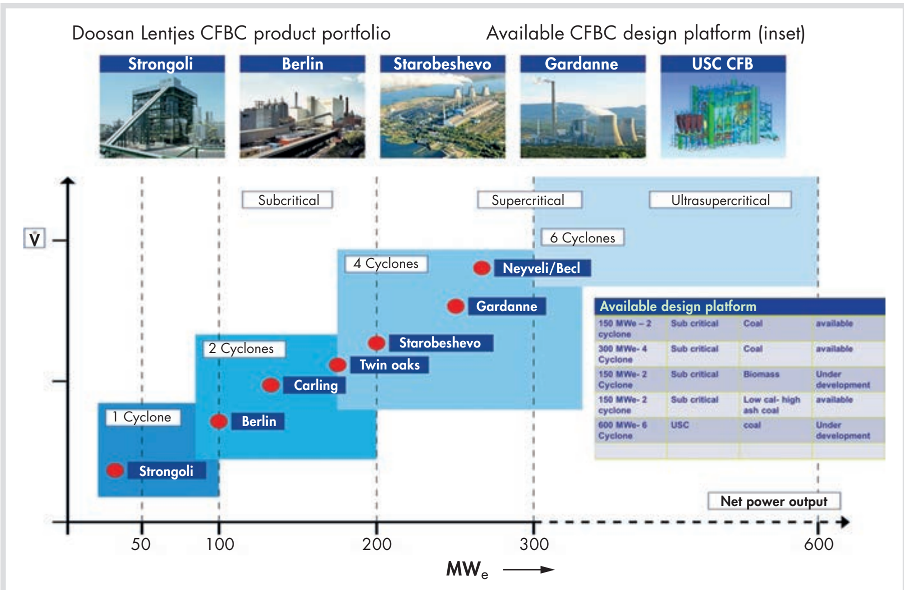

Fig. 11. CFBC Product portfolio and design platform.

as known from Turkey, a concept based on an adiabatic combustion is advantageous and principally available but, as already mentioned, the future will show whether those low quality fuels will continue to be acceptable with respect to both new financing requirements and economic feasibility (Figure 11).

Since biomass as substitute for coal is of growing importance – even if the number of applications will be limited – applications of the CFB technology are requested in the market for up to approx. 150 MW_e and with Teesside in UK even a 300 MW_e biomass CHP plant is under execution. Certainly, the CFB design has to be adapted to the specific requirements of each individual biomass. It is common knowledge that biomass combustion causes a range of challenges: Corrosion that results from chlorine contents of certain biomasses and the agglomeration and fouling due to alkali contents. These challenges are even greater when co-firing waste derived fuels.

Future emission requirements also have to be taken into consideration in the design concepts but principally the required processes are available:

SO_2 emissions down to 200 mg/Nm^3 can easily be met with in-situ desulphurisation with limestone based on coals not too heavily containing sulphur. In case of lower emission values, a second, tail end desulphurisation mainly by dry or semi-dry type systems may be required.

Due to the CFB specific concept of temperature control and staged combustion, thermal NO_x formation can quite sufficiently be suppressed so that in most cases emissions limits down to 200 mg/Nm^3 can be met. For high volatile fuels such as lignite or biomass, as well as NO_x values well below 200 mg/Nm^3, an implementation of SNCR or even SCR systems may be required.

In the future further limitations may be expected, i.e. most probably that of Hg emissions. Flue gas cleaning processes limiting Hg emissions are available, such as the dry type Circoclean® process utilising activated carbon or similar adsorbent for heavy metal and PAH removal.

Energy transition: Key goals

Secured and economic energy production at all times: … but
– 2050: Power generation based only (?) on renewable energy (RE)
– 2020: CO_2 reduction by 40 % against 1990 (-40 mio. t CO_2)
– 2020: Decarbonise traffic sector by adding 10 % RE

Energy transition: Key challenges:

– 2050: Fossil energy (FE) reduced (but to which level ?)
– 2020: Increasing competition between renewable energies (RE)
– 2015: 1 bn € payed for "unused power", in 2016: 1.5 bn € expected very low power prices (app 25 €/MWh)
– 2050: 90 to 140 TWh/y strongly fluctuating surplus power expected

Energy transition: The solution

– "Off grid" power produces methanol via recycled CO_2
– RE and FE jointly produce "green" methanol with CO_2 recycling
– 7,000 to 8,000 h/y operating time: competitive against bioethanol
– 20 % EE in transport sector achievable
– 3 % MeOH blending into gasoline allowed by EU today.
– 15 % MeOH blending used in China without damage to the engines

Fig. 12. Energy transition.

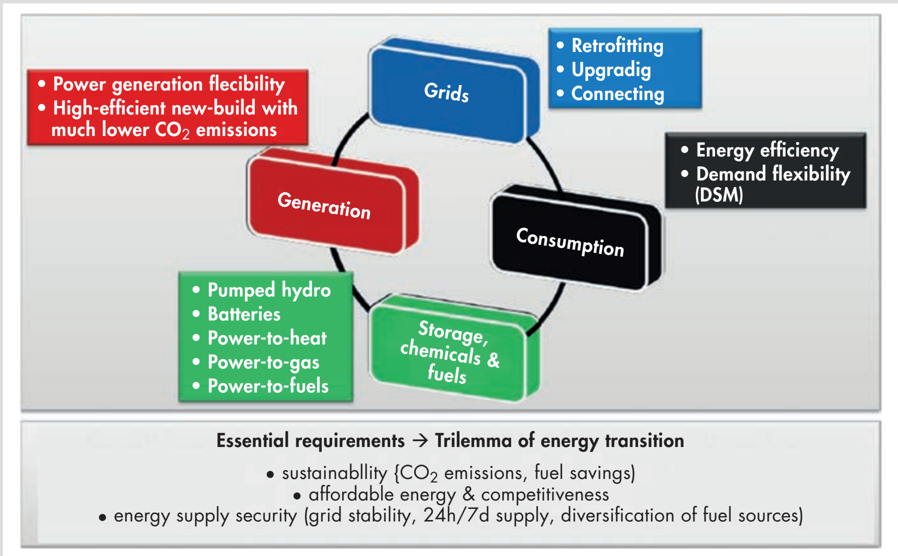

Fig. 13. The challenge of future power generation [23].

Challenges of actual energy transition

The United Nations Frame Work Convention on Climate Change, agreed by more than 200 states, decided to limit global warming below 2 °C, preferably to 1.5 °C above pre-industrial levels, by sufficient reduction of greenhouse gas emissions. [22]

One of the main measures to achieve this goal is to significantly reduce utilisation of fossil fuels for power production and for traffic and to utilise renewable sources instead.

Energy from renewable sources such as wind and solar energy are well established in Europe and rapidly developing in other countries. The development of renewable energy production has been strongly supported by subsidies in Europe. This led to an unexpected, temporaryly excessive supply of power from renewables resulting in serious drop of prices. This mainly hit fossil fuel-based power production and its economics, but due to the fluctuating availability of wind and solar energy, fossil fuel generated power is still required to keep the grid stable (Figure 12).

There are two main challenges in terms of the efficient transition from fossil fuel-based power to renewable power: On the one hand, the lack of power storage capabilities and on the other hand the adaption of power supply to the current demand while ensuring compliance with environmental standards (Figure 13).

Today, various power storage systems are under development but especially systems with higher capacities are either not available yet or not accepted such as pumped storage hydroelectricity systems.

The conversion of electrical power to chemical fuels such as hydrogen or methanol could serve as high potential strategy to compensate short term as well as long term fluctuation of renewable power availability.

Combining the strengths of fossil fuel-based power production,

– high availability and
– source for carbon from "Off gas CO_2" as basis for chemical feed stock,

with the strength of renewable energy generation:

– low-cost, CO_2 emissions free and
– excessive power that can be used for electrolytic generation of hydrogen,

allows for conversion of electric power to chemical fuels such as methanol, methane and hydrogen which should solve the problem of fluctuation in the generation of renewable energy. Furthermore, the use of these fuels for powering cars can significantly reduce CO_2 emissions from traffic (Figure 14). [24]

These integrated systems are under development around the world and will help to manage a Smart Grid integrating and controlling all parameters of future energy systems. The systems ideally use flexible CFB

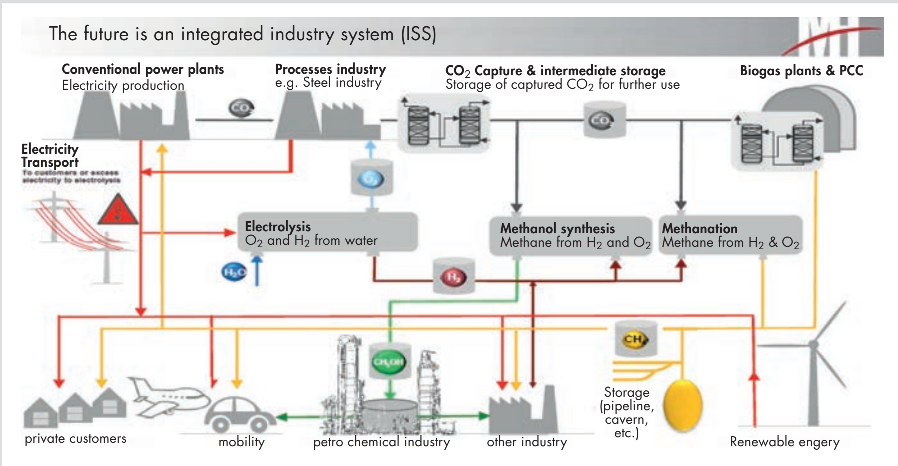

Fig. 14. Model for integrated use of fossil and renewable energy [25].

Methanol from "Renewable" (RE) and Fossil Energy (FE) utilizing CO_2 recycling out of biogenic und fossil sources allows economic use as feed stock for chemical synthesis as well as liquid fuel.
(Source : Fraunhofer ISE 2014)

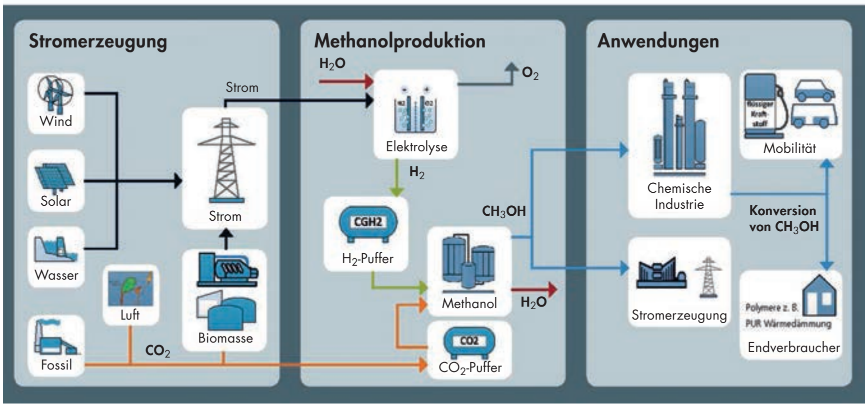

Fig. 15. Methanol from „Renewable"(RE) and "Fossil" Energy (FE) [26].

Left: Guests at the 40 Years Patent Event on June 14, 2016 in Ratingen Germany
Right: The inventors (left to right): Prof. Dr. Lothar Reh, Dr. Ludolf Plass, Dr. Martin Hirsch

Dr. Plass outlined the CFB technology as a promising solution that meets the requirements of future power generation: "Plant operators face demanding future challenges in terms of their used fuel types as well as framework conditions, which means power production plants need to be flexible when it comes to efficient combustion of changing fuels – even those with the most difficult properties. CFB plants can reliably deliver on these requirements, making them the solution of choice for both efficient and environment-friendly future energy generation."

Fig. 16. 40 Years Patent Event – CFB Power Plants.

boilers for energy generation from a wide range of solid fuel types and can be a chance for future CFB boiler appllications (Figure 15).

Summary

The "40 Years Patent Event" (Figure 16) on June 14, 2016 at Germany-based Doosan Lentjes, united not only the three inventors of the technology, but also major contributors and scientists, plant owners and operators. During the event, one of the inventors, Dr. Plass, outlined the CFB technology to be a promising solution that meets the requirements of future power generation: "Plant operators face demanding future challenges in terms of their used fuel types as well as framework conditions, which means power production plants need to be flexible when it comes to efficient combustion of changing fuels – even those with the most difficult properties. CFB plants can reliably deliver on these requirements, making them the solution of choice for both efficient and environment-friendly future energy generation."

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Doosan Lentjes is a global provider of processes and technologies for energy production from both renewable and fossil fuels. Our specific areas of expertise include circulating fluidised bed boilers, key technologies for the generation of energy from waste, and flue gas cleaning systems. We have been pioneering energy solutions for 90 years and convert millions of tonnes of waste into energy every year.

Doosan Lentjes is part of a powerful combination of companies united under the Doosan Group to deliver complementary **technologies, skills and value to customers the world over.**

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