Available online at www.sciencedirect.com

ScienceDirect

Progress in Energy and Combustion Science 33 (2007) 19–55

PROGRESS IN ENERGY AND COMBUSTION SCIENCE

www.elsevier.com/locate/pecs

Development of fluidized bed combustion—An overview of trends, performance and cost

Joris Koornneef*, Martin Junginger, André Faaij

Department of Science, Technology and Society, Copernicus Institute for Sustainable Development and Innovation, Utrecht University, Utrecht 3584 CS, The Netherlands

Received 4 October 2005; accepted 20 July 2006
Available online 10 October 2006

Abstract

The goal of this article is to chart and analyse the development and economical performance of fluidized bed combustion (FBC) and its derivates circulating fluidized bed (CFB) and bubbling fluidized bed (BFB). A descriptive overview is given of the technology and the market penetration is discussed. To make further analysis possible a database is constructed. This database comprises technological and economical data on 491 FBC projects. Analysis of these projects shows that the technology variants (CFB and BFB) diffused differently over time. Drivers, which influenced the market diffusion and technological development are market regulation, environmental legislation and RD&D programs. Important drivers for FBC technology are fuel availability, required applications in the market, innovation spill over and competing technologies. In this article technical characteristics are charted, which show improvements in fuel diversification, technical availability, efficiency and emissions. In terms of economical performance the results show a decline in specific investment cost. Finally, the effect of technological learning and experience on the economical performance of FBC technology is analysed using the experience curve method and theory on economies of scale. A problem with applying the experience curve method is that it is not used often for large power plants like FBC plants and with it lacking a methodological standard. A method is therefore suggested. The analyses yielded progress ratios (PR) from 0.42 to 0.93 for different groups of projects (new plant, repower, retrofit, add-on and conversion) and different parts of the capital breakdown (total project price, engineering, procurement and construction price and boiler price). This means that the specific investment prices (in $/kWe) decline with, respectively, 58% and 7% with every doubling of cumulative installed capacity (in MWe). The progress ratio found for new FBC plants lies between 0.90 and 0.93. These values correspond with the average PR of 0.90 found for power plants in the literature. Further results show that economies of scale have a significant influence on the investment price. Scale factors are found in the range of 0.62–0.81 for different groups of projects. According to these scale factors specific investment price decreases, respectively, between 25% and 12% with every doubling of plant capacity (in MWe).

Keywords: Technological learning; Fluidized bed combustion; Development; Scaling up

*Corresponding author. Tel.: +31 30 253 3544x7600; fax: +31 30 253 7601.
E-mail address: j.m.koornneef@chem.uu.nl (J. Koornneef).

0360-1285/$ - see front matter
doi:10.1016/j.pecs.2006.07.001

Contents

1. Introduction

'Getting rid of waste' was the ultimate goal when the fluidized bed combustion (FBC) technology was introduced. This goal evolved over time to 'clean energy for the future'. Since its introduction in the 1970s the technology has gained acceptance in various industrial applications. It is known for its ability to burn low-grade fuels with low calorific value, high ash content and high moisture content. Other advantages are fuel flexibility, emission performance, re-use of non-hazardous by-products (e.g. gypsum) and the possibility of the technology to be implemented in an existing plant (retrofit).

As the technology evolved, three variants of this technology were developed. The bubbling fluidized bed (BFB) was the first version of FBC technology. Practical experience over the past three decades confirms that BFB technology can be well suited to the utilisation of 'difficult' fuels such as high-moisture fuels (e.g. wastes and sludge's), high-ash fuels (e.g. some types of municipal solid waste and refuse-derived fuel) and low volatile fuels (including anthracite, culm and petroleum coke). Although BFB technology has faced increasing competition from the circulating fluidized bed (CFB) variant in recent years, it has maintained an important position in the market. BFB technology is well

Nomenclature

B&W	Babcock and Wilcox (manufacturer)
BFB	bubbling fluidized bed
BOP	balance of plant
C&I	capital and investment
CCGT (NG)	combined cycle gas turbine (natural gas fired)
CCT	clean coal technology program
CER	cost-estimating relationships
CFB	circulating fluidized bed
CHP	combined heat and power
CIBO	the council of industrial boiler owners
COE	cost of electricity
CYMIC®	cylindrical multi-inlet cyclone
DOE	department of energy (USA)
DTI	department of trade and industry (UK)
EPA	environmental protection agency (USA)
EPC	engineering, procurement and construction
EPI	energy products of Idaho (manufacturer)
EPRI	electric power research institute (USA) (1973)
ESP	electrostatic precipitator
EU	European union
FBC	fluidized bed combustion
FBHE	fluidized bed heat exchanger
FW	Foster Wheeler (manufacturer)
GDP	gross domestic product
GNI	gross national income
GT NG	gas turbine natural gas fired
IEA	international energy agency
IGCC	integrated gasification combined cycle
IR-CFB	internal re-circulating circulating fluidized bed
IT	information technology
MW	capacity in mega watts (= 1 million J/s)
MWe net	net electrical capacity of an installation in mega watts
MWe	electrical capacity of an installation in mega watts (gross)
MWth	thermal capacity of an installation in mega watts
NERC	North American electric reliability council
NETL	national energy technology laboratory
O&M	operation and maintenance
OECD	organisation for economic co-operation and development
PC	pulverised coal
PFBC	pressurised fluidized bed combustion
PR	progress ratio, quantifies relationship between cumulative production (as a proxy of experience) and cost/price
PURPA	public utility regulatory policy act (USA) (1978–1983)
P-value	tests for trend in the data versus random dispersion
SF	Scale factor
R&D	research and development
R^2	coefficient of determination: R^2
RDF	refused derived fuel
S(N)CR	selective (non) catalyc reduction

suited to smaller industrial applications as well as to the combustion of waste materials. The CFB variant is derived from the BFB technology and surpasses its predecessor in terms of sulphur removal, efficiency and scale. The application of CFB has changed over time, as the capacity of the installation steadily increased. The result is that it has developed from industrial applications to utility applications. The third variant is a hybrid type of the BFB and CFB. It was developed to combine the advantages of both BFB and CFB and thus found its application to be in medium-scaled (industrial) capacity range. In terms of total installed capacity, the hybrid variant has a small market share compared to BFB and CFB. Because of this, the hybrid variant is excluded from detailed analysis in this study. In the past, numerous companies have built fluidized bed boilers. Each of these firms has developed his own variety of FBC boilers [1]. The number of technology producers has declined due to mergers, takeovers and shakeout. Watson [2] has given an extensive overview of the development of a community of manufacturers of FBC technology. Charting these developments is a novelty, which would be dealt with in this article.

Many improvements have been made to the FBC technology and its derivatives. As the technology matured, the drivers (regulatory, market and technological) for further development changed in nature or by impact. Also the different variants developed differently as they were specifically suitable for different applications (power, cogeneration or steam generation). The main developing areas up to now have been scale-up, environmental compliance and fuel flexibility in design and use. These efforts will be important in the future development of FBC. Further efforts are set to improve plant construction and operation, increase efficiency and reduce capital and operating costs [3].

Gaining experience by learning from the technology often results in the improvement of economic performance. One way of quantifying technological learning and associated cost reductions is the experience curve approach [4–6]. Empirically, it has often been observed that investment costs tend to decline with a fixed percentage with every doubling of cumulative produced units. This cost reduction is expressed in the so-called progress ratio (PR). This concept is widely accepted and used for energy technologies like PV-solar cells, wind power, natural gas combined cycle (NGCC) and supercritical coal power plants [6,7]. A good overview of the results of determining the experience curve concept for energy technologies is given by McDonald and Schrattenholzer [8]. However, for power plants like FBC with such variety in application and fuel use, this concept is not used often. As a result no methodological framework exists for analysing the experience curve concept on these technologies. Claeson Colpier and Cornland [4] determined the effect of experience on the capital and generating cost of combined cycle gas turbines (CCGT) and with it provided some possibilities for applying the concept. De Visser [9] and Junginger [7] applied the concept, respectively, on biofuelled combined heat and power (CHP) plants in Sweden and Danish biogas plants to estimate the effect of experience on capital and production cost. For FBC technology, Scherr and Fuller [10] studied and quantified the effect of cost influencing factors (fuel type, size and completion date) on fuel, operating and capital cost with the use of a small dataset. The US Department of Energy (DOE) [11] has presented the relationship between the development of the FBC technology over time and the capital cost. However, the empirical effect of experience on unit capital cost of FBC has not previously been quantified in the form of a PR.

The PR can be used in energy modelling exercises. Models can create a partial foresight for an energy technology with the use of the estimated relationship between experience and cost and an assumption on experience growth. Roughly there are two model approaches: top down and bottom up. The top-down model (e.g. GEMA) generally is based on macro-economic relationships assumed in the area under investigation. Models based on the top-down approach may neglect the underlying factors for cost development in the past and in the future. The approach for the bottom-up models (e.g. Markal) focuses on assessing future structures of the energy-system by describing cost, performance and technology mix in such a way that a detailed description of energy technologies in a system is presented. The latter inherently needs a better understanding of factors influencing cost, e.g. a estimation of the PR. An advantage of the method suggested in this study is that a range of PRs can be estimated for such modelling exercises to address uncertainty in the cost development of energy technologies.

Research on the development of FBC is certainly not new. However, the approach of charting and quantifying of the development of technological, economical and market state of FBC is a novelty. The goal of this article is first to review the development in FBC technology since its introduction. Secondly, technological, economical and market developments are charted and the drivers behind these developments described. Thirdly, the goal is to analyse cost reductions and provide an indication for future prospects for FBC in terms of performance and cost. The perspective on the developments and trends is based on theory of technological learning and innovations, which includes the experience curve and theory of economies of scale. Subsequently, the methods for analysing and explaining possible cost reductions are derived from this theory.

To achieve this, a database was constructed which includes techno-economical data on almost 500 FBC installations. Technical databases for FBC installations are already available through SFA Pacific [12–14] and CRE Group Limited [3]. These databases were combined and economical data was added. Finally, by combining the separate research goals mentioned above, a more detailed insight on the past, present and future development of FBC and the mechanisms, which cause it, can be given.

2. Technology overview

The technology is named after the state of the matter within the fluidized bed boiler and determines the way in which the combustion process is managed. The fluidisation process begins when a bed of inert material (usually sand), which is a solid granular particle, is suspended by a flow of air or gas (air). This flow is injected into the boiler from the bottom and from the side. When the velocity of the gas stream increases, the flow suspends the individual particles in the bed. At this stage, the fuel with a (optional) sorbent (mainly limestone or dolomite) can be injected into the boiler. All bed particles are now in a 'liquid state' [15].

The base principle has been utilised in two major variants of the FBC technology (BFB and CFB). Although they share the same principle, design parameters of the installations vary considerably. The design of the FBC installation depends mainly on the fuel and required steam conditions, though also influenced by emission requirements, manufacturer and site conditions. The main differences in design parameters are summarised in Table 1. A more detailed overview of design, operating and economical variables of FBC installations is given in the Appendix in Fig. 18. In this section the main components and design parameters of the major variants of FBC, being BFB and CFB, are discussed. Further reading is suggested for detailed insight into the design considerations of the FBC technology (e.g. [17–19]).

2.1. Fuel preparation

Before feeding the fuel into the boiler some preparation might be required. Several techniques are available to process the fuel between storage and combustion. The main functions of these techniques are sizing of the fuel, drying of the fuel and separation of non-combustibles from the fuel. The two last-mentioned functions are mostly necessary when firing waste-like fuels and biomass [19]. CFB generally requires smaller (<25 mm) fuel particles than BFB (<50 mm).

2.2. The combustor

In the BFB combustor, the majority of fuel particles, which are fed under, into or onto the bed, react in the bed with the oxygen in the upward airflow (primary air). The lower combustion zone contains a high density of the mix of fuel, sorbent (optional when firing coal with high sulphur content) and ash. Refractory protects this part of the furnace from high temperatures as well as erosion and corrosion. The bed acts as a heat buffer enabling high heat transfer between the particles. Due to this, the BFB combustor is less sensitive to variations in the fuel moisture content, and is very suitable for biomass and waste firing, with a wide variation of moisture content. This characteristic along with a lower fluidisation velocity (see Table 1) and high residence time of bed material (inert and fuel particles) in BFB systems, allows larger fuel particles and fuels with lower calorific value.

The combustion can be staged in different parts of the furnace. Secondary air is fed above the combustion zone in order to improve the fuel to oxygen ratio and thus the combustion efficiency.

Table 1
Design parameters BFB and CFB [3,12–14,79,80,81]

Design parameter	BFB	CFB
Combustion temperature (°C)	760–870	800–900
Fuel particle size (mm)	0–50	0–25
Fluidization velocities (m/s)	1–3	3–10
Solids circulation	No[a]	Yes
Particle concentration	High in bottom, low in freeboard	Gradually decreasing along furnace height
Limestone[b] particle size (mm)	0.3–0.5	0.1–0.2
Average steam parameters[c]		
Steam flow (kg/s) (range)	36 (13–139)	60 (12–360)
Steam temperature (°C) (range)	466 (150–543)	506 (180–580)
Steam pressure (bar) (range)	72 (10–160)	103 (10–275)

[a]Circulation of (large) unburned particles is possible in the case of bad burnout. However, solid circulation in BFB is compared to CFB a less integrated part of the combustion process.

[b]Applicable in the case when limestone is used for in bed sulphur removal.

[c]Data on steam parameters is collected for ca. 400 FBC installations. The data is as mentioned in Section 4 derived from [3,12–14].

The zone above the combustion zone is called freeboard. In the freeboard the density of solid particles is low. When the furnace operates under substoichiometric conditions, non-oxidized fuel particles are burned in the freeboard after addition of secondary air. Combustion above the bed with the use of secondary air is common when firing fuels with high volatile contents (e.g. biomass).

The basic difference between BFB and its successor CFB is the fluidisation velocity, which is higher for CFB compared to BFB. As a result the solids are entrained in the air flow more equally along the combustor height. The mix is fluidized with primary and secondary air (see number 13 and 14 in Fig. 1). These higher velocities and vigorous mixing in CFB results in a different heat transfer pattern of the flue gas. The heat transfer and particle concentration gradually decreases along with combustor height. It is however more equally distributed with combustor height compared to BFB. This results in a more homogenic temperature distribution in a CFB compared to a BFB combustor.

The combustion temperature in a BFB, compared with CFB, is often lower due to poor fuel quality, greater particle size and high moisture content.

2.3. Particle collection and circulation

With BFB technology the need for collecting ash, bed material or non-combustible solids (glass, rock etc.) under the bed is high, while conglomeration of these solids could prevent the combustor from working properly. Solids entrained in the flue gas can be collected in a cyclone or similar collection device typically at the end of the convective pass. Unburned fuel particles collected here can be fed back into the combustor to improve overall combustion efficiency. The gas is led to an electrostatic precipitator (ESP) (no. 8 in Fig. 1), bag house or other solid collection device to collect remaining fine particles before the gas is emitted by the stack (no. 9).

Due to the higher fluidisation velocities in CFB high concentrations of particles are also found in the upper part of the combustor. The solids (mainly

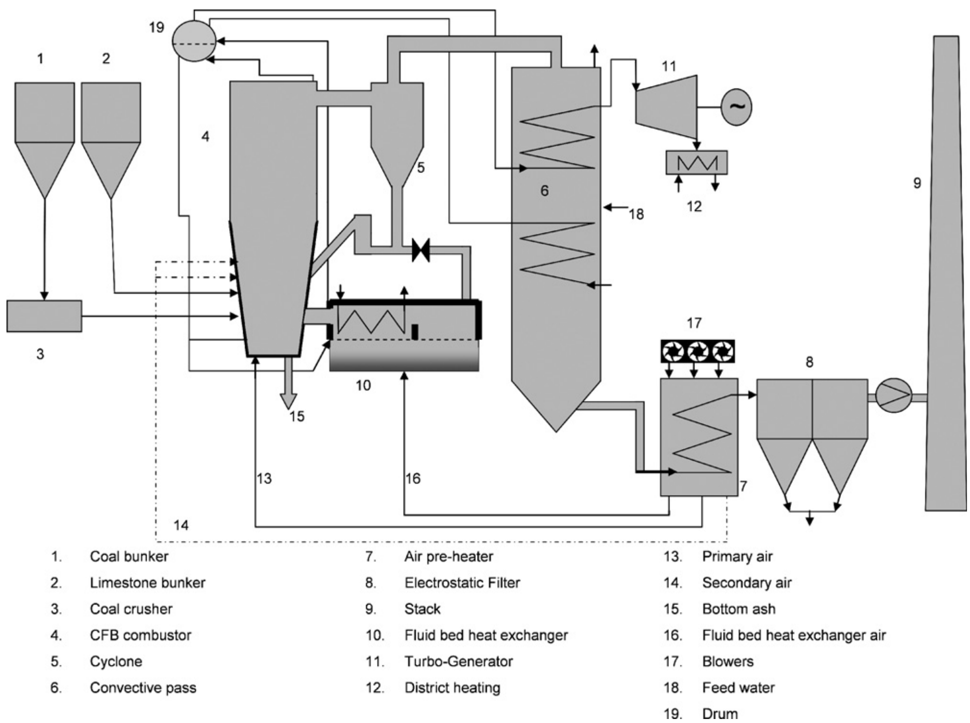

Fig. 1. Schematic representation of a coal-fired CFB plant (courtesy Lurgi Lentjes) [16].

unburned fuel and bed material) must be separated from the flue gas before the hot gas enters the convective pass. The solids are collected in a cyclone (no. 5) or other solid collecting device. In the cyclone up to 100%[1] of the solids are separated from the gas by centrifugal force.

Collected solids can be cooled with the use of an external fluidized bed heat exchanger (FBHE) (10) and fed back into the combustor for a new cycle. Especially when burning low calorific fuel, the bed temperature has to be kept at operational conditions. This can be controlled by adjusting the solids circulation rate and flue gas recirculation rate among others. The name CFB is derived from this circulation of solids.

2.4. Heat transfer surface

Heat transfer surface in FBC combustors are used for evaporative, superheating and reheating duty. Evaporative duty is performed by the wall of the combustor, which consists of bundles of pipes, which are horizontally or vertically arranged. This enclosure of the furnace is comparable for both BFB and CFB design. Also comparable is the convective pass located downstream of the combustor. The hot flue gas that exits the combustor or cyclone enters the convective pass section (no. 6), where heat can be transferred in superheater/reheater and economiser to raise, respectively, the steam and feed water temperature. When the gas leaves the convective section, the heat in the flue gas is generally used for pre-heating of primary and secondary air. Additionally, heat in the flue gas can also be used for fuel drying purposes.

The steam or hot water produced is fed into the steam drum (19). In the steam drum water and steam are separated. The steam is send to the superheater(s) and reheater and water to evaporators. From there the steam is superheated and expanded in a high-pressure steam turbine and (optional) reheated in the convective pass before it is expanded in a low-pressure steam turbine. The steam can also be used as process steam or for district heating. The simultaneous production of electricity and useful thermal energy is referred to as cogeneration.

The heat in a BFB combustor is mainly transferred in the lower part of the combustor. Heat is exchanged for production of steam and is necessary in order to control the temperature in the combustor. In the lower part of the furnace an in-bed heat exchanger[2] is often placed. This heat exchanger is used to control the bed temperature and has evaporative duty. Another way of controlling the bed temperature is by flue gas re-circulation into the furnace. For low calorific fuels, it is possible to omit the in-bed heat exchanger and use a heat exchanger in the upper part of the furnace. This heat exchanger is often used to superheat steam.

Next to the enclosure, in-combustor panels and the convective pass two other locations are available for heat transfer surface. Additionally for CFB technology, the cyclone or other solids collection device may be cooled with steam or water in order to reduce wear of materials. If this is the case, (superheated) steam or hot water is produced. Optional heat transfer surface for CFB is the FBHE[3] (10) into which the collected stream of solids from the flue gas is fed and where internal heat from the solids is transferred to water or steam. This FBHE offers high heat transfer rates and makes it possible to control the heat transfer.

Due to high temperatures in the lower part of FBC combustors, the bed bubble caps (nozzles which distribute primary air in the bed) must be cooled in order to prevent failure. Heat is transferred to the working fluid (water or steam) in the bundles that lie next to or under the bubble caps.

The components mentioned above have to endure high temperatures and pressures. In order to protect them, refractory is added to the surface.

2.5. Design variants of CFB technology

The main manufacturers, Foster Wheeler, Alstom, Lurgi Lentjes, Babcock & Wilcox and Kvaerner, all share a similar basic configuration of the components found in CFB technology mentioned above. Though, there are substantial differences in the design. The different design variants of the CFB technology offered by the manufacturers are summarised in Table 2. The main design differences are

[1]The velocity of the stream (positively), particle size (positively) and size of the cyclone (negatively) influences the collection efficiency of a cyclone.

[2]To prevent corrosion of the in-bed heat exchanger when firing fuels with, for example, high alkali contents, the in-bed heat exchanger can be omitted; however, the bed temperature must be controlled otherwise in such a case.

[3]The FBHE can have evaporative and or superheater duty.

in the external heat exchanger, grid design (the grid of nozzles for feeding primary air into the combustor) and solid collecting systems. The Lurgi Lentjes and Alstom design usually features an external heat exchanger, whereas the second generation Foster Wheeler design has an INTREX internal FBHE [20]. Kvaerner offers the CYMIC® (CYlindrical Multi-Inlet Cyclone) combustor, which does not feature a FBHE. The need for a FBHE is absent as the solids are internally circulated by a cyclone, which is integrated in the combustor. A similar philosophy is materialized in Babcock & Wilcox's version called Internal Recirculating CFB (IR-CFB). This version of CFB features in-combustor beams, called U-beams. Fluidized solids collide with the U-beams and fall back to the bottom of the combustor. Smaller particles, which remain in the gas flow, may collide with a second set of U-beams placed outside the combustor. The fine solids fraction passing the U-beams are collected in the secondary stage of the solids separation system by a mechanical dust collector (MDC) or ESP.

3. History of FBC

In general, the rate of adoption of a new technology often follows a standard pattern. When the rate of adoption is plotted cumulatively against time, the resulting distribution is often S-shaped (which is also termed a logistic substitution or diffusion curve [21]). According to Rogers [22], this rate of adoption and curve are found for most new technologies (see Fig. 2). This curve can be divided into different stages. In the *invention* stage no physical applications have been introduced into the market. The time lag between invention and innovation can range between 10 and 60 years [21]. The rate of adoption in the *innovation* phase is low and confined to the 'innovators'. Next to adopt are the 'early adopters' and then the late majority. The technology has entered the *commercialization* phase and is now fully commercial. The technology diffuses rapidly until the market is saturated and the rate of adoption declines. The technology is *matured* and market growth is often marginal.

The diffusion of the technology is discussed below according to this conceptual framework. The elaboration on historical market development will include some drivers, barriers and important milestones (see Table 3). For further reading the authors would like to refer to extensive publications on the development of FBC by Watson [2] and Minchener et al. [3]. Also, Banales-Lopez and Norberg-Bohm [23] performed an analysis on policy-induced drivers and barriers for FBC innovations in the USA.

3.1. From invention to innovation

In 1922, the development of the FBC started with the Winkler patent for gasification of lignite. The technology has been used for different applications since then. Efforts in the 1960s ultimately resulted in

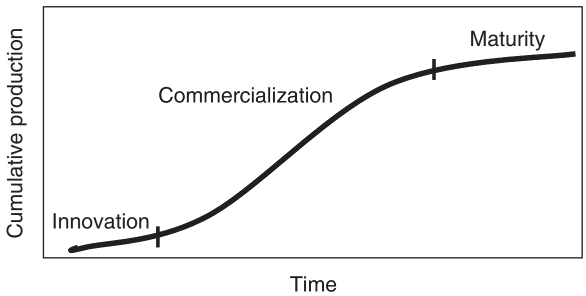

Fig. 2. Typical *S*-shaped curve depicting the diffusion of technologies. Adapted from [21,22].

Table 2
Design variants of CFB technology

Manufacturer	Solid collection	Features
Lurgi Lentjes	Traditional cyclone[a]	External FBHE
Alstom	Traditional cyclone	External FBHE
Foster Wheeler	Traditional cyclone; compact CFB (square cyclone)	Compact CFB: cooled solids separator placed directly next to the combustor, internal FBHE (INTREX)
Kvaerner	Traditional cyclone; CYMIC®	CYMIC®: internal hot cyclone, no FBHE
Babcock and Wilcox	Traditional cyclone; IR-CFB	IR-CFB: two staged internal recirculation by U-beams (impact separator) and MDC, no FBHE

[a]Traditional cyclones may be steam/water cooled or uncooled depending on load schedule, fuel properties, steam parameters and other design criteria [82].

Table 3
Important events in the history of fluidised bed combustion

Year	Event
1922	Winkler patent
1965	Start of the Atmospheric Fluidized Bed Combustion Program (between 1965 and 1992) [23]
1965	First BFB test facility commissioned [2]
1972	First contract awarded for Rivesville
1973	EPI provided the first fluidized bed combustion (FBC) system in the US capable of converting waste biomass into usable energy
1976	BFB Rivesville industrial scale demonstration project
1976	Start of large scale R&D program by ERDA (USA)
1978	European Commission starts supporting FBC technology with demonstration projects until 1990 [3]
1979	First CFB industrial scale power plant by Foster Wheeler
1981	First coal fired commercial CFB boiler supplied by Alstrom (now Foster Wheeler)
1981	First commercial BFB fired with biomass as main fuel type supplied by EPI
Mid 1980s	First HYBEX (BFB), Kvaerner
1982	First Lurgi Lentjes CFB is commissioned
1983	First commercial CFB fired with biomass as main fuel type by Foster Wheeler
1986	The Clean Coal Technology (CCT) Demonstration Program started (USA). Ended in 1993.
1988	Large scale (142 MWe net) BFB demonstration project in the USA.
1988	First commercial CIRCOFLUID by Babcock
1990	EU THERMIE (RD&D) programme includes 3 CFB projects, ends 1996
1992	First commercial operation INTREX by Foster Wheeler (CFB)
1994	Model project on CFB implemented in 1994 under Green Aid Programme for Asia-Pacific countries
1994	First CYMIC® Kvaerner (CFB)
1996	First IR-CFB B&W (CFB)
1999	International Energy Agency (IEA) FBC implementing agreement started, now 12 countries are member
2003	First supercritical CFB boiler Lagisza Poland Foster Wheeler with Siemens OTU (once through unit) design. Start-up is planned in 2009

the design of three coal firing test units. The first BFB test facility was commissioned in 1965. This test unit was used to conduct experiments to establish the potential for controlling emissions of sulphur dioxide [2]. In that same year the Atmospheric FBC Program started in the USA. Subsequently, the USA founded the Environmental Protection Agency (EPA) in 1970, which gave the FBC technology with lower emissions the advantage over conventional coal combustion technologies. FBC could meet the new SO_2 and NO_x emission restrictions without the use of auxiliary equipment. The new restrictions concerning environmental control in the USA were regulated by the Clean Air Act issued in 1971 [24].

The development of FBC was not limited to the USA. Other countries like the UK, Finland, Germany and China also started programmes to develop FBC, as they wanted to establish a technology, which was able to burn low-grade fuels with low emissions. Indications for these incentives may be the rising research and development (R&D) budgets for coal technologies in USA and Germany in the period between mid-1970s and early 1980s [25].

R&D of circulating FBC type began in Europe, funded mostly by private industry. The first development work on circulating CFB began in Germany in the mid-1970s, soon followed by work in Sweden, Finland and the USA [26]. However, CFB development was more a product of R&D in Europe than in the USA, where the emphasis was still on the BFB version.

Along with the UK and the USA, China and Germany are the countries, which have abundant quantities of low-grade coals with high sulphur content; this was a main driver for starting the development programs of FBC. Finland differed from the other countries in the early stage of development, as they were especially interested in the technology for burning low-grade fuels like peat, wood waste and sludge. These fuels were by-products of the large domestic pulp and paper industries. FBC is an attractive solution in this industry for two reasons. First this sector has a high-energy demand[4] and therefore autonomous

[4]'The forest and paper, metal and engineering and chemical industries represent about 80% of Finland's industrial production.

produced energy is favourable. Second, waste combustion reduces waste disposal and can replace more expensive fuels used for energy production.

3.2. From innovation to commercialization

BFB installations (<100 MWe) are used in the aluminium and paper manufacturing industry since 1970. Several pilot and demonstration plants have been built by various manufacturers in the power segment in the period 1976–1986. The first application of the BFB technology in the utility (>100 MWe) segment was in 1986, when a 117 MWe net demonstration plant started in Burnsville[5] (USA). Despite that, since then most BFB installations continue to fall in the small-to-medium (25–100 MWe) capacity range. Only a small number of large capacity plants have been built in e.g. Finland (110 MWe), USA (142 MWe) and Ireland (117 MWe). The BFB technology is thus mainly commercialised for industrial applications and not in the utility segment.

The first commercial small size CFB boiler (5 MWe net) started in 1979 and was manufactured by Foster Wheeler [28]. In the utility segment the first use of the CFB technology started in 1985 with the operation of a 90 MWe CFB boiler in Duisburg (Germany).

3.3. From commercialization to diffusion

Fast diffusion of BFB boilers occurred in China, which claimed to have over 2000 BFB boilers operating in the early 1990s. However, the greatest part has a capacity of less than 10 MWth and detailed information is not available. The other countries where BFB technology diffused are Finland, Sweden, India and the USA. In Finland and Sweden, single relatively large-scale (up to 50 MWe) BFB boilers are being used in the pulp and paper industry. The diffusion of BFB started in Finland in the 1980s and for Sweden in the 1990s. The region Scandinavia differs from India and USA in terms of installed units (~60 vs., respectively, ~20 and ~20) and in the type of fuel used. The installations in Scandinavia are mainly fired with biomass or industrial waste and those placed in India and the USA are primarily coal-fired.

CFB boilers gained acceptance for non-utility size applications in the USA in the early 1980s. A driving force for that was the fear for oil crises as they occurred in 1973 and to a lesser extent in 1979/80. As a consequence, research was performed on the possibility to produce power with alternative fuels. A major R&D effort on FBC by the US government follows initiated by the Energy Research and Development Administration (ERDA) in 1976 [29]. The introduction of Public Utility Regulatory Policy Act (PURPA) in 1978 in the USA formed a driving force for the penetration of FBC for industrial use. This act mandated utilities to purchase electricity from particular types of small-scale (up to 80 MWe) power producers, called qualifying facilities (QFs), which included industrial co-generators and renewable sources. The utilities must purchase electricity at avoided cost rates [24]. According to, Banales-Lopez and Norberg-Bohm [23] this act resulted in a growth of installed capacity of FBC in the non-utility sector in the USA, 90% of which was CFB. In the same period only six units were installed in the utility sector. The use of FBC was to be promoted by the Clean Coal Technology (CCT) program. This program was set up in 1986 with the demonstration of a utility scale CFB installation. The CFB technology reached commercial utility scale in the USA in the 1990s but a breakthrough in the utility section was not reached. A total of approximately 30 units have been installed in the utility segment (>100 MWe). Instead the CFB emphasised its niche market in industrial and cogeneration.

3.4. Maturity and prospects

The FBC technology can be considered as a mature technology for cogeneration and industrial sized applications. Possible R&D areas for the future have been indicated by some FBC operators. The three most important areas (in order of importance) for FBC used in industrial applications are materials handling, environmental control technology and boiler reliability. The operators of FBC technology for utility applications indicated boiler reliability, fuel flexibility and environmental control technology as the most important R&D areas [30].

Future technology development of BFB is likely to be limited to ensuring fuel flexibility on existing

(*footnote continued*)
These industries are very energy-intensive, and the forest and paper industry alone accounts for 63% of industrial energy consumption [27].'

[5] Northern States Power Company owns the installation, which was built by Foster Wheeler.

designs for the increasing use of biomass and/or waste as feedstock with, or instead of, coal. Ensuring a firm market share in the niche market of small and cogeneration units seems to be the most viable option for BFB technology. Contrary to CFB, there are no major industrially focused international R&D projects under way for BFB.

For CFB, several opportunities remain to support further development of (supercritical) CFB and the pressurised version (PCFB) (6 units operating at present) [31]. Further development in efficiency improvement, fuel flexibility, effective scale-up and reducing capital cost is needed for CFB to remain a competitive technology (see also Scale-up section) and gain market share in the utility segment.

The total installed capacity of BFB worldwide is surpassed by the capacity of CFB. This is mainly due to the rapid diffusion of CFB, which started at the end of the 1980s. According to Minchener et al. [3] 1130 CFB installations were operating worldwide in the year 2000 with a total thermal capacity of 65.5 GWth. The largest share is installed in China with 830 CFB units (~25 GWth). The installed units in Asia represent 52% of thermal capacity. North America is second with 26%, followed by Europe with 22%. Hupa [32] reports that in 2003 the cumulative number of worldwide installed BFB and CFB boilers is, respectively, about 200 (~15 GWth) and 360 (~50 GWth). Engstrom and Pai [28] report that about 300 CFB projects were in operation or under construction in 1999 and for BFB, approximately, 200 in the year 2002.

On a worldwide basis, a potential market up to 2020 of some 150 GWth is estimated [3]. This additional capacity is expected to be primarily coal-fired and localised in China (125 GWth), North America (17 GWth) and India (6 GWth)[6]. Scott and Darling [33] add that China is planning to install about 15 GWe (~40 GWth) per year of new generating capacity (not FBC specific).

The OECD[7] and IEA[8] [34] estimate the demand for additional coal-fired electricity generating capacity to be as high as 1400 GWe for the period 2003–30. The majority is expected to be built in Asia with 150 GWe in India and 550 GWe in China. These figures all indicate a large growth potential for coal fired CFB if it is possible to obtain a share of the total required additional capacity. The same holds for BFB technology. The additional required capacity for electricity generating from biomass and waste is possibly 70 GWe [34]. The suitability of BFB for firing these types of fuel can result in the addition of BFB capacity worldwide.

[6]This estimate is based on the assumption of 5% market penetration of FBC technology in India. Total coal fired capacity addition of ~120 GWth is estimated by Minchener et al. [3] for India.

[7]Organisation for Economic Co-operation and Development.

[8]International Energy Agency.

4. Trends in development quantified

In this article a techno-economical database is constructed using technological databases from SFA Pacific [12–14] and CRE Group Limited [3] supplemented with reference lists from some manufacturers (Alstom, Babcock & Wilcox, Babcock Borsig, Bharat Heavy Electricals, Energy Products of Idaho, Foster Wheeler, Kvaerner Pulping and Lurgi Lentjes). The reference lists are provided by the companies or derived from conference proceedings and industry journals (e.g. Modern Power Systems).

Economical data was derived from the following sources:

Trade journals: Modern Power systems, Power Engineering and other trade journals connected with the Gale Group were used as source for contract prices.

Conference proceedings: Conference proceedings on FBC have been used. Data is collected from proceedings from 1970 to 1999. The proceedings mainly consist of publications from manufacturers, research institutes or reports on (demonstration) projects. The emphasis in those reports is on technological information. Detailed cost breakdowns are given for hypothetical projects and demonstration projects. The publications from manufacturers comprise experience overviews and occasionally contract prices.

Manufacturers: Price data for FBC projects were found in press releases on awarded contracts and their (rough) values. These press releases were gathered through Internet search.

Governmental programs reports: As governmental funded programs are often obligated to publish the cost of the project, the quality of the data is very detailed and comparable. The CARNOT program of EU, Altener program of EU and CCT program by DOE (USA) provided some data[9] for the database.

[9]The disadvantage of this data lies in the fact that sponsored programs are often pilot or demonstration (RD&D) projects.

Table 4
Variables included in techno-economical database

Variable	Type	Scale of measurement	Unit[a]
Technology	String	Nominal	CFB, BFB
Location	String	Nominal	
Country	String	Nominal	
Region	String	Nominal	Asia, Australia, Eastern Europe, Mid/South America, North America, Scandinavia and Western Europe
Manufacturer	String	Nominal	
Year of commissioning	Numeric	Interval	
Number of boilers	Numeric	Ratio	
Capacity	Numeric	Ratio	MWe net
Steam pressure	Numeric	Interval	Bar
Steam temperature	Numeric	Interval	Degrees Celsius
Steam flow	Numeric	Ratio	Kilogram per second
Main fuel type	String	Nominal	
Fuel characterisation (see Fig. 9)	String	Ordinal	Standard design, no challenges, some challenges, multiple challenges
Application	String	Nominal	Power generation, cogeneration, district heating
Project price	Numeric	Ratio	USD (2003)
EPC price	Numeric	Ratio	USD (2003)
Boiler price	Numeric	Ratio	USD (2003)
Type of project	String	Ordinal	New plant, add-on, retrofit, repower, conversion

[a]For ordinal and nominal scales of measurement the categories are given in which installations are subdivided.

Existing databases: like Coal's Resurgence in Electric Power Generation Database [35] and GADS database from the North Electric Reliability Council [36], respectively, provided data about cost and reliability.

The developed database includes 19 variables (see Table 4), which provide techno-economical information on 491 FBC projects, in the time frame 1976–2006[10], of which CFB represents 311, BFB 146 and HYBRID 34 projects. Based on figures from literature [3,28,32], our estimate is that the collected sample covers ~70% of worldwide installed capacity excluding endogenous FBC technology installed in China[11]. It was not possible to integrate these Chinese installations as detailed data on both economical and technical characteristics is lacking. Due to data limitations on the Hybrid variant, detailed analysis was not possible and this variant was excluded from the analysis. Regarding the technological data almost all variables are covered with data; although data for the steam parameters for installations build by Alstom (70 projects) are mostly lacking.

4.1. Diffusion of FBC variants

The diffusion of the FBC technology and its three variants are shown in Fig. 3. The figure shows an *S*-curve for the cumulative number of installed boilers for both variants. BFB shows a more steady growth of installed units than CFB, which shows exponential growth rates from 1986 to 2003. Rapid increase of installed BFB units starts in the early 1990s.

4.1.1. BFB

The diffusion of BFB started in North America (see Fig. 4) with the use of fuels, which did not require major alterations[12] in the basic components. Diffusion of BFB in North America declined in

(*footnote continued*)
These projects are partially designed to test various operating conditions rather then for economical optimized operation. The economics details may thus not be representative for other (commercial) FBC installations.

[10]For projects under constructing the estimated start-up date is used.

[11]This number does not take into account ca. 830 CFB installations with a combined capacity of ca. 25 GWth in China (Minchener et al., 2000) as detailed data is lacking. In China relatively small capacity units are installed. According to Minchener et al. ca 250 units of >50 MWth, 180 units of ~25 MWth and 400 units of <15 MWth are built. FBC projects in China are only included if build by the manufacturers mentioned.

[12]In Fig. 9 the design of FBC installations for various coal ranks is characterized as 'no challenge' and 'standard design'.

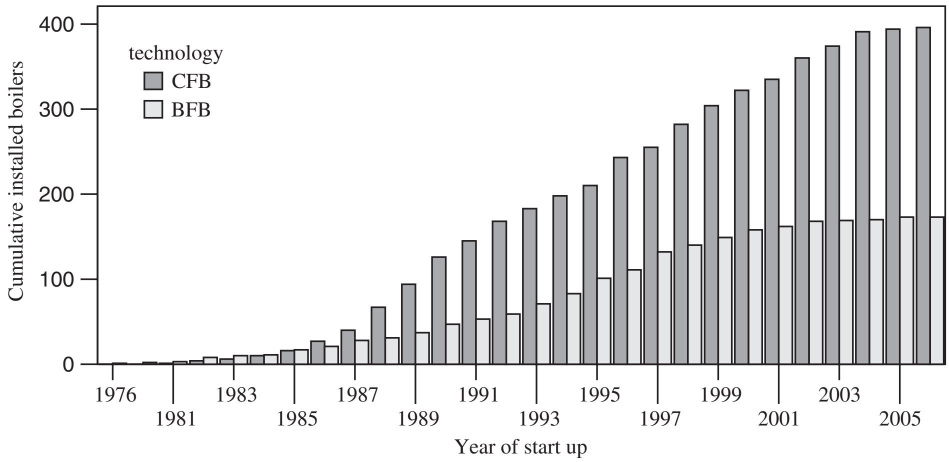

Fig. 3. Diffusion of FBC technology by variant [3,12–14].

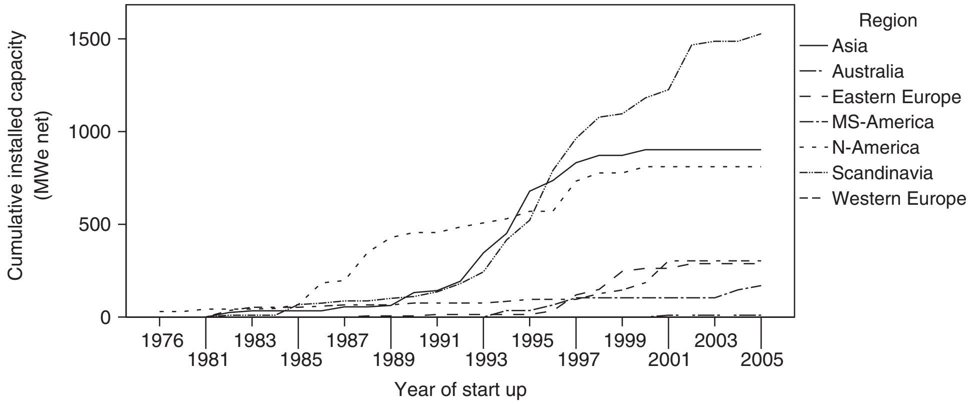

Fig. 4. Diffusion of BFB for different regions [3,12–14].

1990, when CFB became the technology of choice, until 2000 when the last BFB was installed in North America. In the same period when addition of BFB capacity in North America slowed, Asia and Scandinavia started to increase their capacity in BFB. Scandinavia focused primarily on BFB installations for burning mainly biomass. A possible driver for this is a tax based on the carbon content of the fuel which accelerated the use of biomass (used in BFB) in Sweden [37].

In Asia BFB shows somewhat the same trend as in North America, where first low grade coals were used as fuel and later on biomass took over the majority in installed capacity. For all regions the trend is that since 1992 almost only biomass-fired BFB installations are added, most of them in Scandinavia.

The application of installed BFB technology was first focussed on power generation, but after 1983 cogeneration took over the largest part in installed units. However, in terms of cumulative installed electricity generating capacity (in MWe net), power and cogeneration are equal.

Fuel used in BFB technology started with industrial waste and coals. Biomass is commercial fired since 1985 and is now the dominant fuel (see Fig. 7 for further details).

4.1.2. CFB

Rapid diffusion of CFB technology also started in North America where the largest part of cumulative capacity is installed (Fig. 5). Western Europe followed with the diffusion of coal fired plants, but it levelled out in the early 1990s. Since

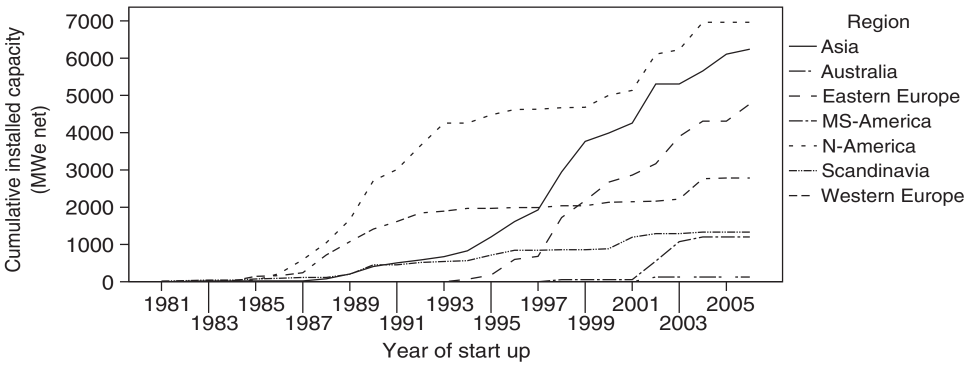

Fig. 5. Diffusion of CFB for different regions [3,12–14].

then little capacity has been added. The levelling was probably caused by the anticipation of plans for economic restructuring of the coal industry in Germany[13]. The execution of these plans in 1994–96 and during the second restructuring in 1997–98 led to a decrease in subsidies to indigenous hard coal production [38]. The CFB capacity, which is added in Germany since, consists of mainly small (<20 MWe) biomass fired and small (<50 MWe) bituminous coal fired plants. This is due to a regulation, which only provides remuneration for small biomass fired plants (IEA) [1]. Another example of regulation influencing size of capacity is the PURPA in the USA. This law resulted in keeping the average size of installed CFB technology below 100 MWe until 2000 (see Fig. 14) while the technology was already available above 400 MWe net.

Scandinavia and Asia started the diffusion with steady growth of capacity in the mid 1980s and Scandinavia continued that growth. However, CFB technology diffused rapidly in Asia from the beginning of 1990s. In the same period Eastern Europe, especially Poland and the Czech Republic, emerged. There, new coal-fired plants were built and old installations were retrofitted with CFB technology.

CFB started with installations build mainly for cogeneration and this is still the main application. CFBs build for power generation started in 1985 and although fewer units compared to cogeneration were built, the growth in installed capacity in MWe net was almost equal until the end of the 1990s. In 1998, the cumulative capacity of power generating CFB became dominant over cogeneration and currently almost doubles the capacity (in MWe) of cogeneration.

The fuel used in CFB technology was already diversified in the beginning of the diffusion. First, main fuel types used (in MWe net installed capacity) were lignite and bituminous coals. Later, also anthracite, sub-bituminous coal, petroleum coke, and biomass were used.

In North America, at first coal was the dominant fuel type used. In Asia and Eastern Europe it still is. Western Europe recently focussed more on biomass and waste materials as fuel type like Scandinavia did from the beginning of the diffusion process. North America also recently installed some biomass and waste-fired CFB installations. Although the trend seems to go towards (co)firing more biomass and waste materials, the dominant fuel is still coal and in particular bituminous coal (for further details see Fig. 8).

4.2. Manufacturers and competition

In the figure below an overview is given of the development of the manufacturer industry (Fig. 6). It clearly shows a series of take-overs and mergers as companies adjusted their strategies. This was necessary due to the pressure on the market by competing manufacturers as well as by competing technologies such as CCGT and traditional boiler technologies. Extensive research on this topic has been done by Watson [2]. He presents a very detailed overview of the development of the market since the introduction of FBC, focussing on the role of events and actors and their decisions. The competition has narrowed the field of FBC manufacturers significantly resulting in four major

[13]Germany has the largest installed capacity in Western Europe.

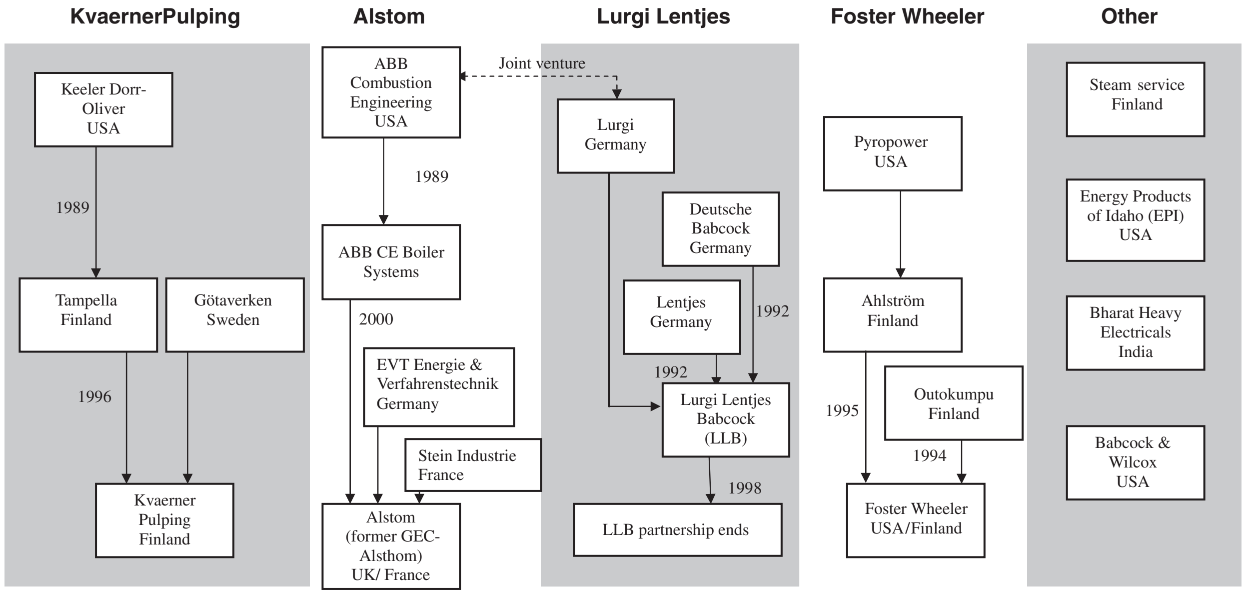

Fig. 6. Overview joint ventures, takeovers and mergers in BFB and CFB manufacturing industry 1985–2003.

Table 5
Overview of installed technology, capacity and market entry for the selected manufacturers included in the database

Manufacturer	Technology	Installed capacity in Mwe			# of boilers	# of installations	Start up year
		Minimum	Maximum	Total			
Alstom	BFB	17	142	355	12	7	1988–99
	CFB	2	520	8229	75	51	1986–2005
Babcock and Wilcox	CFB	3	76	580	25	22	1982–2002
Babcock Borsig	BFB	0	35	88	7	5	1982–2000
	CFB	9	120	408	13	10	1989–99
Bharat Heavy Electricals	BFB	5	50	392	28	18	1987–98
EPI	BFB	10	45	185	10	9	1981–93
Foster Wheeler	BFB	0	117	1229	57	51	1976–2002
	CFB	0	460	10648	199	161	1981–2006
Kvaerner Pulping	BFB	6	117	1762	59	56	1985–2005
	CFB	0	240	1375	41	32	1984–2002
Lurgi-Lentjes	CFB	9	225	2182	43	35	1982–2004
Totals for selected manufacturers	BFB	0	142	4011	173	146	1976–2005
	CFB	0	520	23422	396	311	1981–2006

Data is derived from manufacturers reference lists and [3,12–14].

market players Alstom, Foster Wheeler, Lurgi-Lentjes and Kvaerner Pulping.

Alstom and Foster Wheeler are now the two largest producers of CFB technology (see Table 5). Both are active in various regions worldwide and have their largest part of installed capacity placed in North America. Foster Wheeler is market leader in 5 of the 7 defined regions. It also was first-to-market in both CFB and BFB technology.

Kvaerner is market leader regarding BFB technology followed by Foster Wheeler. Both have their capacity primarily placed in Scandinavia. In that region, Kvaerner is by far the market leader, as it is in Western Europe. Foster Wheeler is further active and market leader in Asia and North America. BFB manufacturers that are only active in their own region are Bharat Heavy Electrical (India, Asia) and EPI (North America).

The table also shows that not all manufacturers are active in both technology types and when they are, they seem to have focussed on one type: Alstoms main product is CFB; Kvaerners main product is BFB but has built an almost equal number of CFB boilers; Foster Wheelers main product is CFB, but also has a large market share in BFB.

4.3. Fuel flexibility

A development, which makes FBC an attractive technology for burning solid fuel, is its *fuel flexibility*. During the past three decades, FBC (BFB and CFB) in its various forms has been used to burn all types of coals, coal wastes and a wide variety of other fuels, either singly or co-fired with coal (see Figs. 7 and 8). One of its main advantages is that the technology can burn a wide variety of low-grade fuels; however, variations in design are necessary to obtain fuel flexibility or optimise the technology for a certain fuel.

Design varies with the fuel used in the installation due to a number of fuel quality factors. The main factors are: heating value, ash content, corrosion potential of combustion by-products (i.e. the fuel's chlorine content) and the preparation the fuel requires [39]. A categorisation of fuels regarding the associated challenges on the design of the installation is shown in Fig. 9 following [40].

Experience with firing difficult fuels started early in the development of FBC. The first biomass fired FBC is claimed by EPI in 1973. Though the first unit was built in the USA, most of the development took place in Finland and Sweden. The majority of FBC installations (mainly BFB) burning biomass are placed in these two countries. The lessons learned from firing biomass and other difficult fuels led to modifications in design and operation parameters. These include:

- *Fuel feeding and preparation*: larger fuel particles can block the fuel preparation and feeding parts, which results in a non-homogeneous fuel feeding.

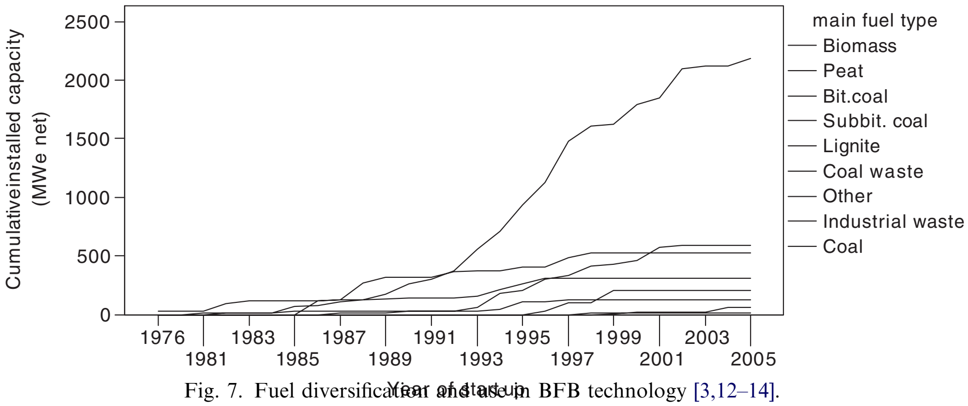

Fig. 7. Fuel diversification and use in BFB technology [3,12–14].

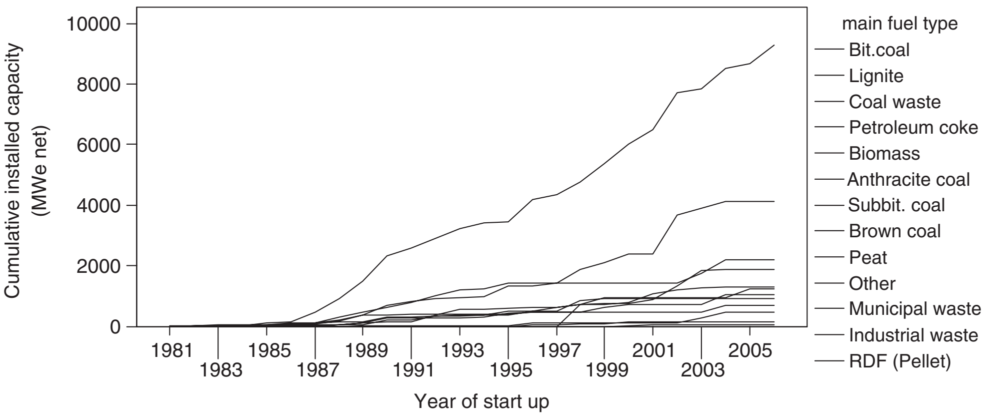

Fig. 8. Fuel diversification and use in CFB technology [3,12–14].

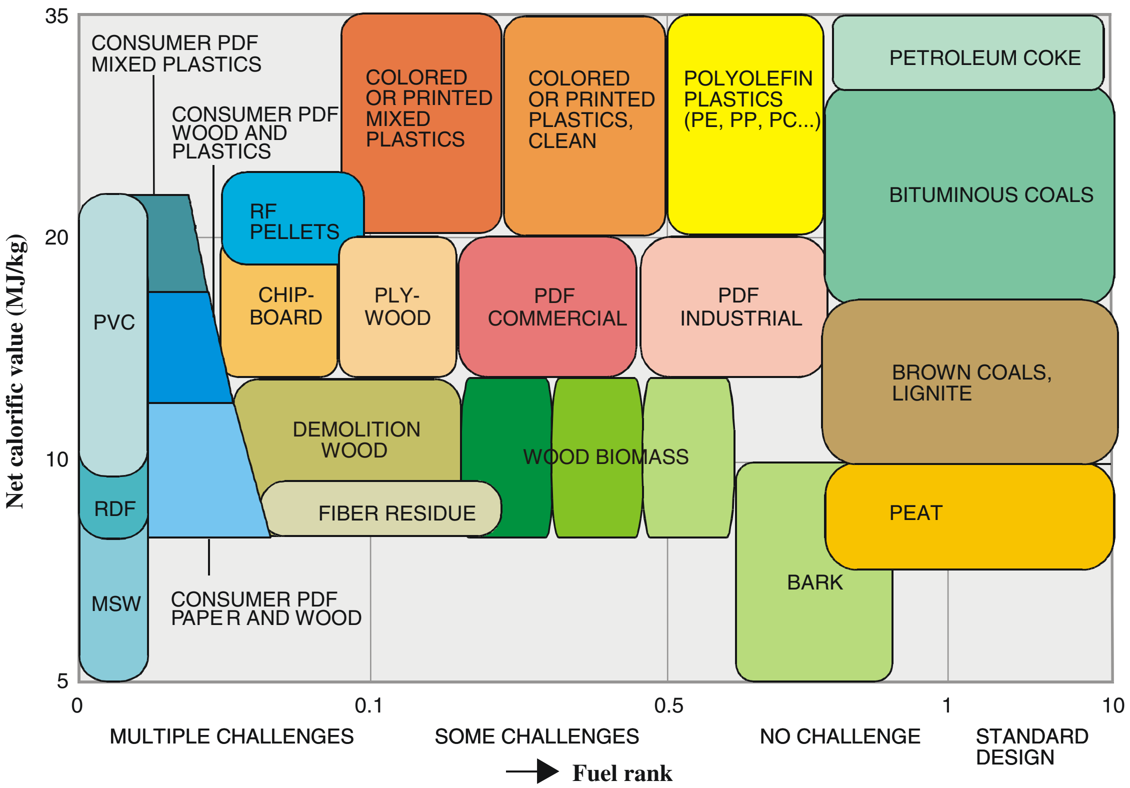

Fig. 9. Fuel range applicable for fluidized bed combustion. At the right fuels that can be used with standard boiler design, moving to the left the fuel characteristics cause more challenge for multi-fuel operation and boiler design (courtesy Hämäläinen) [40].

- *Coarse removal*: large particles in the boiler can negatively influence fluidisation of the bed, which results in problems with combustion and heat transfer.
- *Preventing agglomeration (sintering or slagging) of bed material or ash in order to maintain proper fluidisation*: the agglomeration of particles in the boiler depends on the fuel used. If agglomeration occurs it can cover the nozzles, which provide the air for fluidisation, cover the furnace wall or affect homogeneous fluidisation. These problems affect the combustion process and heat transfer. Research on the mechanism of agglomeration, learning on site and proper maintenance reduced down time caused by agglomeration [17,18].
- Alkali[14] removal to prevent corrosion of the furnace wall.

Modifications in fuel preparation and feeding were necessary to maintain the combustion process, and subsequently emission control and efficiency, at the desired operating conditions. The other three modifications had impact on the maintenance—or if not carried out failure—of the installations, which in its turn influences the reliability and availability.

[14]Biomass fuels often contain alkali metals.

4.4. Availability

A commonly used performance indicator for power plants, known as availability, is calculated by dividing the number of hours a plant is able to generate output by the total number of hours for a given period of time [2]. The availability can be used to measure the reliability of a design or the effectiveness of operation and maintenance (O&M). However, it is difficult to measure them independently as information on availability and O&M is often not given. Down time can thus not be allocated to the scope of problems or the effectiveness of maintenance as they are related to each other. A poor design would lead to high maintenance, but this can be compensated or fortified by (poor) maintenance. If maintenance is carried out effectively the planned outage is shortened and forced outage can be reduced.

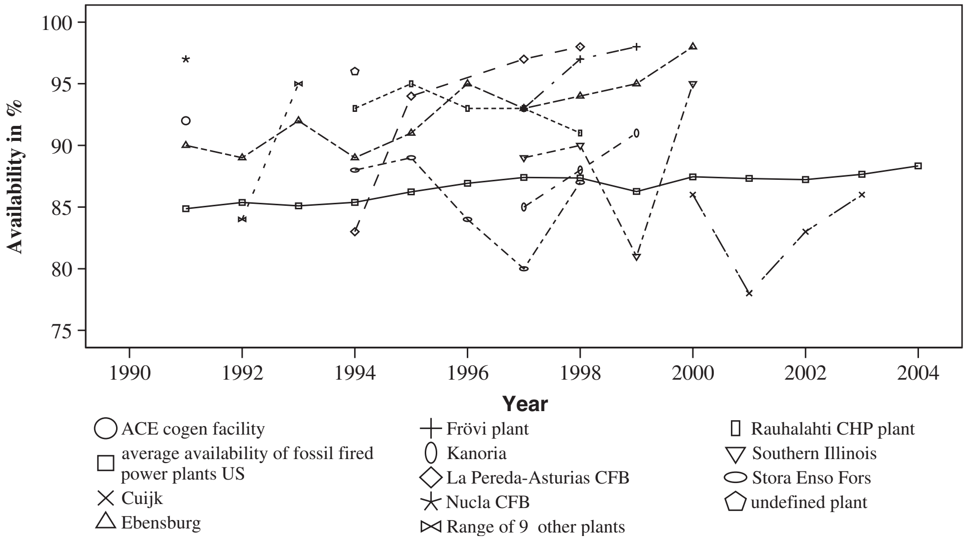

Fig. 10. Availability of FBC plants and industry average for fossil fired power plants in the USA. The mean of 9 plants is given as one data point [2,42–45].

The availability is reduced due to forced outage (problems) and planned outage, together called down time. Major problems that caused down time were problems with the boiler section and fuel feed and preparation section [19]. Problems in the boiler are caused by erosion and corrosion of the furnace walls, agglomeration of ash and bed particles and tube failure in the steam production section. Early problems with erosion and corrosion were dealt with by adding refractory to exposed parts. Development in the material used for refractory and boiler design reduced the thickness of the material and overall failure rates.

Regardless of maintenance and design, the availability in the first year of operation is often low. Testing, minor modifications and fine-tuning are responsible for this down time. A study on the effects of learning-by-doing on nuclear power plant operating reliability revealed that capacity factors[15] increased with 5% for each year of operation. Another result from this study was that new plants showed higher first year capacity factors as they learned from previous gained experience [41]. Analysis of the database provided by NERC [36] showed that the average availability[16] of fossil-fired power plants in the USA increased from 80% in 1982 to 87% in 2002. These numbers show a steady increase over time as more experience is gained.

No specific database as NERC exists for FBC technology. Therefore, an attempt is made to chart the development of availability of FBC technology by combining data of various sources (see Fig. 10). It includes data for 12 FBC plants and is supplemented by 2 data points which reflect the average of 9 unidentified FBC plants (derived from Watson [2]). The used data sources did not always specify the used calculation method to obtain the availability values presented may thus not be optimal for comparison between installations. The figure does however provide indications for trends within a installation and rough industry trends.

Fig. 10 shows an increase of availability of FBC technology over time as well as for individual plants. In the period 1985–90 the availability ranges from 50% to 70% and since then availability did not fall below ~80% and averaged ~90%.

The trend in availability can be explained with the concept of technological learning (see Box 3, Section 5.2). Learning from a technology can improve the availability for an individual plant. The employees learn from problems, which caused failure and thus downtime. The operating and maintenance of the plant can then be adjusted or improved to prevent downtime and increase availability. Learning-by-interacting may give an

[15]Capacity factor is dependent on availability factor as a plant can not produce when it is not available.

[16]Availability is defined as: available hours/ period hours. This factor does not take into account the planned outage, forced outage and maintenance outage.

Table 6
Thermal efficiency of FBC technologies

Technology	Size (in MWe)	Fuel	Thermal efficiency (in %)	HHV or LHV[a]	Source
CFB	20	Biomass	33	Unknown	[83]
	150	Coal and biomass	37	LHV	[61]
	160	Lignite	41	LHV	[61]
	250	Coal	39	HHV	[84]
	297.5	Coal	36	HHV	[47]
	2×233	Coal	37	LHV	[61]
	460 supercritical[b]	Coal	>43	Unknown	[51]
	600 supercritical	Coal	46	LHV	[61]
BFB	25	Biomass	30	LHV	[85]

[a]HHV = higher heating value. LHV = lower heating value. The latter does not account for the enthalpy in water vapour remaining in flue gas, as this is often not converted into useful energy. HHV does account for this enthalpy and efficiencies are subsequently lower when HHV of fuel is used.
[b]To be build by Foster Wheeler in Poland, expected start-up in 2009 [51].

explanation for the general increase of availability for multiple plants. The interaction between manufacturer and plant owner may result in knowledge transfer about problems causing downtime. The manufacturer can then improve the design of the installation to prevent this downtime. Knowing the problem, the manufacturer still must have the means to overcome these problems. For example, these means can be provided by innovations in building techniques, design, materials (refractory) and operating equipment (IT spill over). These innovations can be the result of fundamental and applied R&D.

4.5. *Efficiency*

In literature on FBC technology, the most published data are those of combustion-, boiler- and thermal efficiency.

The combustion efficiency is the ability of a furnace to burn carbon. For CFB, this is generally higher (up to >99%) than for a BFB boiler. Better mixing of bed mixture and smaller fuel particles are the main factors, which contribute to that difference [15]. An indicative experiment, which studied the combustion of three biomass fuels revealed that the combustion efficiency varies with the type of fuel used [46]. The combustion efficiency is typically higher for reactive fuels (e.g. biomass) than for less reactive fuels (e.g. coal) [19].

The boiler efficiency is defined as the amount of heat energy absorbed by the working fluid (water/steam) divided by the total amount of heat energy of the fuel entering the boiler [19]. The boiler efficiency for FBC boilers ranges from 75% to 92% (HHV) [19,47]. The characteristics of the fuel, primarily the moisture content[17], have significant negative impact on the boiler efficiency. Other heat losses which contribute to the reduction of boiler efficiency are radiation and convection, heat losses due to the moisture from the combustion of hydrogen, exit temperature of flue gas, sensible heat losses from residues[18] and the temperature of the combustion air (primary/secondary air) [48]. Also, other factors like steam parameters and capacity influence the boiler efficiency. With increasing the capacity of a boiler (by scaling-up) the boiler efficiency increases.

Thermal efficiency is defined as the amount of electricity generated minus endogenous electricity requirement divided by the energy input. An overview of thermal efficiencies of FBC technologies is given in Table 6.

The thermal efficiency can be improved by, among others, raising the superheated steam pressure (towards supercritical conditions), raising superheated steam temperature and adding a steam reheat cycle.

In Figs. 11 and 12[19] the development of steam characteristics (pressure and temperature) of both variants is shown. For the CFB variant a trend of increasing main steam pressure and temperature towards supercritical conditions can be seen. The

[17]Biomass and wood often have high moisture content (up to 60%).

[18]Ash cooling heat exchangers can be used to reduce this heat loss.

[19]In both figures the steam parameters of a supercritical unit, which is to be build by Foster Wheeler, are included with the start up year 2006. This unit is actually planned for commissioning in 2009.

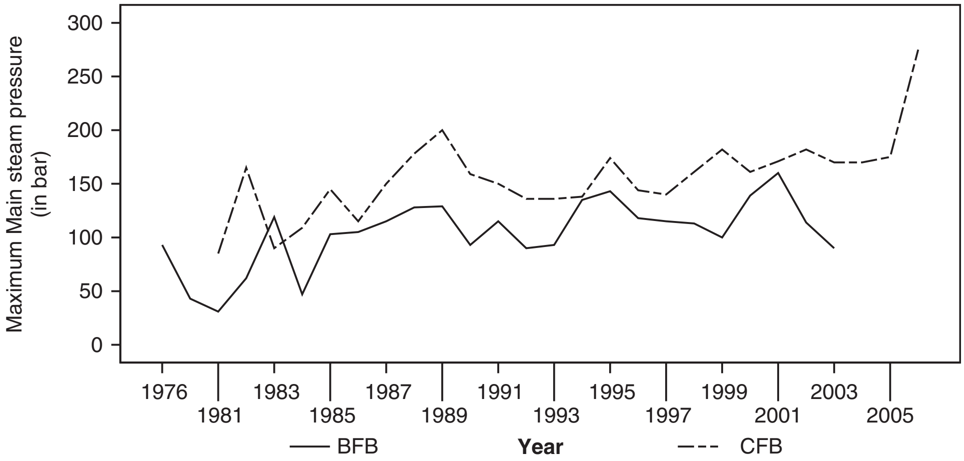

Fig. 11. Development of maximum values for main steam pressure for CFB and BFB installations.

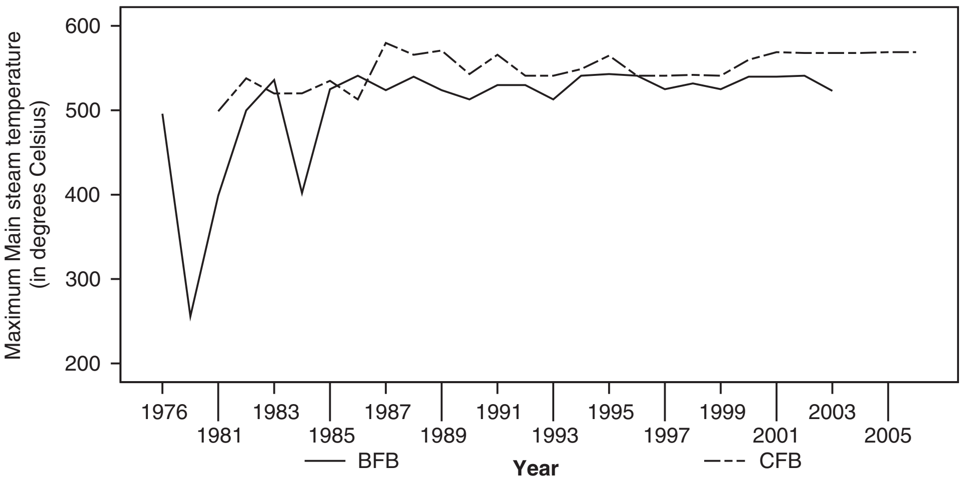

Fig. 12. Development of maximum values for main steam temperature for CFB and BFB installations.

same graphs show also for BFB a gradual improvement of steam conditions, albeit that both the maximum main steam pressure and temperature are lower for BFB than for CFB. These graphs indicate an improvement of thermal efficiency over time by raising the steam quality and show that typically the thermal efficiency of BFB is lower compared to that of CFB.

The steam cycle for CFB and BFB is comparable to that of pulverised coal (PC) installations. They all use a Rankine steam cycle; the main difference lies in the steam parameters, which are often supercritical for PC. These supercritical PC installations are commercially available, where the commercialization of the supercritical version of CFB is yet to come. The efficiency of this supercritical CFB can be as high as 43% according to Foster Wheeler [49]. Alstom claims that 41% efficiency (HHV) is feasible [50]. Although CFB can achieve efficiencies comparable to that of PC, the higher endogenous energy use (for fluidisation) limits CFB reaching higher thermal efficiency then PC installations. Knowledge gained in the development of PC installations, which are developing towards ultra supercritical steam parameters (700 °C/388 bar) can be used to increase thermal efficiencies even further up to 50–55% [51]. The development of improving steam quality was and is dependent on R&D in metallurgical industry. High steam quality requires materials, which can withstand high temperatures and pressures [52]. Thus, development of coal-fired CFB efficiency is expected to improve, but parallel to that of PC installations.

4.6. Emissions

The need for energy technologies with low emissions of NO_x and SO_2 boosted the development and adoption of FBC in the 1970s and 1980s. Especially in the USA, the advantage was given to FBC technology over conventional coal-fired technologies by changing emission levels for NO_x and SO_2. This driver was and is not present in all regions as emission limits were absent or not a challenge for energy technologies [53]. The concern about climate change boosted the use of biofuels in the 1990s as they are considered to be CO_2 neutral. This trend is mainly seen in Western Europe and Scandinavia. In North America also efforts have been made to use biomass as primary fuel in BFB installations and for co-firing in coal-fired CFB plants [54].

Low primary emissions are intrinsic to FBC. The emission of SO_2 are much lower for FBC compared to PC installations without gas cleaning (flue gas desulphurization) facilities. Sulphur dioxide removal can be achieved by injecting limestone into the furnace. The sorbent and the sulphur in the fuel react through a series or reactions[20] to a solid by-product, gypsum.

Advantages in emission performance also resulted in the change from BFB to CFB as CFB outperforms BFB when burning fuels with high sulphur content. The CFB is more effective in in-bed sulphur removal, while the mixture in the bed is more homogeneous than in BFB. In a CFB bed, the chance of a limestone particle colliding with a sulphur particle therefore is higher then for BFB, resulting in better sulphur removal. The current state of the technology is such that in a CFB boiler more than 95% of sulphur can be removed with the use of in-bed sorbent injection.

NO_x emissions in FBC are mainly dependent on the nitrogen content in the fuel used[21]. A second source of NO_x formation is the oxidation of nitrogen in the combustion air (thermal NO_x). Thermal NO_x increases with rising temperature, nitrogen concentration in the flame, oxygen concentration and gas residence time [55]. CFB and BFB operate at relative low temperatures resulting in virtually no formation of thermal NO_x. When regulations require lower NO_x emissions, SNCR[22] (selective non-catalyc reduction) can be used to reduce the emissions with 50%. If further reducing (up to 90%) is required, SCR[23] (selective catalyc reduction) is the appropriate measure. However, this is often not necessary due to the low NO_x formation in FBC boilers.

Contrary to NO_x, low combustion temperatures enhance the formation of N_2O (nitrous oxide). Other important factors influencing the formation of N_2O are excess oxygen, sorbent addition and fuel characteristics. Especially, low volatile content in the fuel (e.g. with petcoke) contributes to higher N_2O emissions. The formation of N_2O when firing biomass fuels is subsequently less as these fuels often contain high volatile contents. Reduction of N_2O can be achieved by increasing the volatile content of the fuel, air staging, NH_3 injection and sorbent addition (e.g. limestone) [3,55,57,58].

Next to the gaseous emissions, solid emissions (e.g. ash and gypsum) are also formed. The solid emissions are collected under the bottom of the bed and in a CFB boiler additionally at the end of the cyclone. Another point where solids are collected for both CFB and BFB is in the bag house or ESP. Fine particles are removed from the flue gas in that section. The collected solids can often be re-used. In 2002, 77% of the produced ash by FBC technology in America was re-used. This ash is used in the cement industry. Gypsum is used as building material. A problem is that the solids are collected simultaneously and separation of ash and gypsum is difficult. Compared to a PC installation, where the streams are collected separately, the economical value of the solids derived from CFB or BFB is lower [59].

4.7. Cost of electricity

The cost of generating power has three components—the capital and investment cost (C&I) of the facility, the operating and maintenance cost of the facility (O&M) and the cost of the fuel (F). In the

[20] $S + O_2 \rightarrow SO_2$ and $CaCO_3 \rightarrow CaO + CO_2$ to $SO_2 + 1/2O_2 + CaO \rightarrow CaSO_4$ (solid).

[21] N can form NO_x in stoichiometric conditions. In substoichiometric conditions less NO_x is formed, N particles form the harmless N_2 in that condition. Staged combustion in CFB boilers with substoichiometric O_2 in the bottom section leads to less NO_x formation.

[22] SNCR uses ammonia inserted into the boiler to cut NO_x emissions up to 70% [56].

[23] SCR uses a catalyst to reduce NO_x emissions up to 90%.

form of a formula:

$$COE = \frac{C\&I + O\&M + F}{\text{annual production of electricity}}, \quad (4.1)$$

where COE is the cost of electricity (\$/kWh), C&I the annualised cost of Capital & Investment (\$), O&M the operating & maintenance cost per year (\$), F the fuel cost per year (\$), annual production the total produced kWh per year ($\sum$kWh).

An overview of breakdowns of coal power plants into the three components is given in Table 7. The table shows that the breakdowns vary. This is due to various factors, which influence the three components of COE. These three components and the factors, which influence them, will be discussed in the following section.

4.7.1. Cost of fuel

An overview of fuel prices is given in Table 8. The efficiency of the plant determines how much MJ of fuel is needed to produce a functional unit (kWh or steam). Low-grade fuels often are cheaper but can result in lower efficiencies (lower combustion efficiency, energy needed for preparation (see Section 4.5), higher O&M cost and higher capital cost (fuel preparation, lower availability). The fuel choice has also influence on the choice of technology and subsequently efficiency. The fuel, which is chosen to be fired determines cost of fuel directly and also the part it represents in the breakdown of COE as it influences also O&M and C&I cost.

Table 7
Breakdown of COE for coal fired power plants

Description	Fuel (%)	C&I (%)	O&M (%)	Source
Coal fired power plants (no technology specified)	41	32	27	[86]
Coal fired power plants (pulverized coal)	29	52	19	[87]
100 MWe net CFB retrofit	26	61	13	[45]
Average for 5 standard grade coal fired FBC plants generating electricity	25	57	18	[10]
Average for 8 scrap[a] coal fired FBC plants generating electricity	15	56	29	[10]
Coal fired FBC	31	50	19	[2]

Average is calculated with average cost data (mills/kWh) for capital (for determination of capital cost see [10]), fuel and operating, maintenance & disposal cost (OM&D) from Scherr and Fuller.
Note that assumptions used for determining this breakdowns may vary per study and as a consequence this data must be approached with caution. For further elaboration the authors would like to refer to the original publications.
[a]Scrap anthracite coal or scrap bituminous coal.

4.7.2. O&M cost

Operation cost is the compound of labour cost for keeping the plant running and the variable operating cost. Variable operating cost comprises the cost of disposal (solid and gas emissions), limestone and bed material and is related to the production of the plant. Maintenance cost is the aggregation of labour cost and construction material cost which can be allocated to prevention or reparation of failures in the production process.

O&M as a component of COE varies with each plant as the factors, which influence it vary. The cost of the construction materials, emission disposal and labour are different for each plant. The region where a plant is located can also have an impact on labour cost and labour efficiency.

In general, labour efficiency, automation (influences capital cost) and cost of labour interrelate with each other, while in low labour cost regions automation is less implemented and less necessary due to the low cost of labour. In regions with high labour cost, the efficiency of labour should be high in order to reduce cost, hence more automation [59]. Next to labour cost, automation and efficiency, the region can also have influence on the emission and

Table 8
Minimum, maximum and average fuel prices (including taxes) in 18 European countries in 1999 [88]

Fuel type	Min. €/GJ	Max. €/GJ	Average €/GJ
Forest residues	1.02	8.33	3.42
Industrial by products	0.58	9.07	2.38
Firewood	1.01	14.00	5.26
Wood wastes	−4.00	3.31	0.97
Refined wood fuels	3.24	18.22	8.37
Other biomass resources	0.83	12.00	4.68
Peat	2.10	3.75	2.83
Heavy fuel oil	1.40	12.00	4.26
Light fuel oil	3.10	14.30	6.74
Natural gas	1.10	16.21	5.80
Coal	1.19	12.78	4.53

Note that the maximum and average prices of natural gas and coal are somewhat high. For comparison: the coal prices for industrial users in the Netherlands ranged between 1.4 and 3.3 €/GJ in the period 1969–2004. In that same period the natural gas price ranged between 0.5 and 6.4 €/GJ [89]. In Europe during the first half of 2005 the price ranges between 2.85 and 8.65 €/GJ for natural gas [90].

corresponding regulation and with that cost of disposal (see Box 1).

Another factor, which has an impact on the O&M cost, is the availability. As stated before the availability of a plant is dependent on the design. Weinstein [60] suggested a relation between availability and maintenance cost. The maintenance cost is expected to grow with improving availability. They add that the perfect balance of maintenance and availability varies per case.

Technological learning (see Box 3) can be incorporated in this balance. Experience in maintenance and operating the plant can lead to better planning of maintenance and with it improves availability and reduce maintenance cost. By improving the availability the share of O&M cost in COE can decrease as the production of the plant increases.

In the sections above, an indication has been given for the contribution of O&M to total cost of power. Factors have been mentioned which can influence that contribution. However, the actual cost of O&M has not been investigated. The actual cost of O&M for commercial FBC plants is not well documented. Some estimations and governmental funded R&D programs may provide some insight into the relative O&M cost. The annual cost of O&M for these projects or estimates have been summarised in Table 9.

As far as conclusions can be drawn from this small sample, it shows that O&M cost have not changed much over time in terms of share of total investment. Annual O&M cost at a level of 2.5% of total investment cost should be a good estimate.

4.7.3. *C&I cost*

The breakdown of C&I cost into three sections comprises: engineering, procurement and construction (EPC) cost, capital cost and financing cost. The three summed up form the total project cost. EPC forms the largest part of the total project cost (for an example of the breakdown of EPC see Table 10). In a recent publication [61] the total overnight construction cost of CFB power plants, which is comparable to EPC cost, ranged between 1208 and 1351 $/kWe (2003$). Cost of capital and financing together make up for the remaining part. The variation in capital and financing cost is caused by the variation in the scope of the project and economical situation of the future owner.

Box 1
Example of labour efficiency and automation.

The FBC installations in Cuijk in the Netherlands (25 MWe net, commissioned in 1999) have an operating staff of ca. 3 people, who mainly guide the fuel acceptance. The combustion process is highly automated and is monitored remotely [42]. This staff size contrasts the 43 employees of a FBC installation (100 MWe net) in the USA (commissioned in 1989).

Table 9
Annual O&M cost for FBC plants

Plant (capacity, technology, location)	Start up year	Annual O&M cost as percentage of total investment cost (%)	Remarks
200 MW CFB boiler USA	1984	2.5	Hypothetical project [91]
5 MW FBC[a] boiler	1986	2.5	Hypothetical project [92]
100 MWe net CFB boiler Nucla (USA)	1989	2.6	Coal fired [45]
97.5 MWth BFB Nykoping	1994	1.7	Total investment 45 Million ECU, O&M + fuel estimate of 1.5–2 ECU/MWh (380 GWh/ year)
50 MWe CFB	1997	5	Waste-to-energy facility [93]
34 MWth (8.3 MWe)	1999	6.6	Waste-to-energy facility
25 MWe net BFB boiler Cuijk	1999	<2	O&M budget is <1 Million Euro, investment is 50 Million Euro [42], biomass fired
112.5 MWe net CFB boiler	2000	2.5	Hypothetical project [94]

[a]Technology variant undefined.

4.7.3.1. Comparing breakdowns. A problem occurs when comparing cost breakdowns as a consistent method of presenting the different subsections of the breakdown seems to be lacking. Constructing a consistent breakdown of C&I cost component is more complex than for the former discussed components of COE (O&M and Fuel). This is due to various factors, which influence the components. Scherr et al. [10] identified that the type of fuel, plant size and year of completion affects the cost of C&I. Factors which can also affect C&I but not included in Scherr's study are type of combustion technology and project type (retrofit, re-power and new plant). These factors are already mentioned in a report from the US DOE [11], which adds the region as an important factor as it determines environmental regulations and labour cost and techniques. The DOE also emphasises the effect of the factor 'project type' on capital cost. The project type determines the scope of work, which should be carried out. A report from the Electric Power Research Institute [26] adds supplemental factors

Table 10
Breakdown of total project cost of FBC plants [19,44,45,56,95–102]

Component of total investment	Subcomponent	Ranges for conversion, retrofit, re-power, add-on and new plants		Examples for new plants ($/kWe)			
		Range of percentages of total investment (%)	Range of specific investment ($/kW)	13 MWe BFB[a]	40 MWe BFB[b]	18 MWe CFB[c]	500 MWe CFB[d]
	Boiler section	28–82	144–1436	538		1111	212
	Fuel handling	4–23	61–618				
	Steam turbine section	7–15	90–243				
	Instrumentation and control equipment	2–5	10–75				
	Emission control	2–6	30–60				
	Balance of plant	21–23	317				
	General plant facilities	10–15	141–486				
Total EPC		70–94	186–3045		1000	1500	1046
	Initial working capital	1					
	Contingency	6–12					
	Development fee	3–7					
	Start-up	1					
	Owner's cost						
	Initial debt reserve fund	9					
Total capital cost		86–94					
	Interest during construction	10					
	Financing fee	2					
Total project cost		100	1400–3200	1769	1300	1667	1692

Note: The presented ranges found in literature are collected separately for the different components; therefore they might not add up to 100% or to the totals for each sub section (total EPC, total cost of capital and total project cost). Moreover, the data is collected for different project types (conversion, retrofit, re-power, add-on and new plants). Both columns should thus be considered as an indication for specific investment cost for each component and emphasize the variation of investment cost for different plants and projects. The four columns from the right represent the plants.

[a]Forssan Energia Oy, Finland, 1996, main fuel: biomass [103].
[b]Borås Energi AB, Sweden, 2005 main fuel: biomass [104,105].
[c]Manitowoc Public Utilities, USA, 1991 main fuel: bit. coal [106].
[d]AES Puerto Rico Guayama, Puerto Rico 2002, main fuel: bit. coal [13,107,108].

to the already mentioned factors above. EPRI states that comparison of capital cost is not adequate unless accompanied by a detailed comparison of power plant efficiency and environmental performance, reliability, O&M cost, and financial/economic assumptions. Compromising on one or more of the above design requirements can potentially reduce the capital cost requirements by a few hundred $/kW. The empirical effects of most factors mentioned above on C&I cost has not been previously investigated.

4.8. Scale-up

FBC installations are currently available commercially in the capacity range 1 MWth–500 MWe net. From both versions of FBC technology, CFB has the highest maximum capacity (520 MWe). The BFB version follows (142 MWe) with typically lower-maximum capacity in MWe net per boiler and per plant. Scaling-up can be accomplished by two means. The first is scaling-up through the use of multiple boilers, thus the boiler capacity remains equal. The second is scaling-up by increasing boiler capacity. As the scale-up of the different versions of FBC developed, this process will be discussed for both versions.

4.8.1. BFB

The capacity of bubbling bed installations manufactured during the past three decades has varied significantly [3] over time (see also Fig. 13). In the early 1980s boiler capacity remains low and virtually no scale-up occurred until 1986 when the CCT program started with the utility scale BFB installation. This scale-up was followed by a BFB boiler of 142 MWe net, built in 1988 by ABB Combustion Engineering, which is now Alstom. After that the trend of scaling up BFB towards utility size stopped. This is due to the increasing competition with CFB, which had at that time surpassed the scale of BFBs.

The BFB version then obtained a market position in niche markets as the technology is well suited for smaller industrial applications as well as for the combustion of waste-type materials. Scale-up reoccurred in the 1990s, when relative large-scale BFB units were supplied, although not in large numbers, primarily to large northern European pulp and paper mills and power producers.

Comparing Figs. 13 and 14 reveals that less scale-up occurred in BFB technology compared to CFB. The largest BFB installation in 1986 was a scale-up of an earlier build pilot plant. Problems with operating this installation can probably be allocated to the scale-up. The problems, which compromised performances, were mainly the result of the undersizing of several components. For example, the fuel preparation and feeding systems jammed and could not maintain a homogeneous flow. The sorbent use was also higher than expected which led to problems in sorbent feeding and waste disposal. Another problem was that the temperature in the freeboard was higher than anticipated and as a consequence the design lacked enough heating surface. In general, the main problem when scaling-up BFB is the geometry of the boiler.

With increasing capacity of a BFB boiler the cross section of the boiler must be enlarged. This leads to problems in fluidisation of the combustion mix and a shortage of heat transfer surface between bed and working fluid. The need for further scale-up of BFB was also absent as the CFB technology was easier to scale-up [59].

4.8.2. CFB

Scaling-up the CFB version from pilot scale to 500 MWe took approximately 20 years (Fig. 14). As can be seen in the figure, the technology scaled up steadily over time, though only minor scale-up was achieved in the 1990s.

The main driver for increasing capacity was to use CFB for power production in the utility sector (e.g. CCT program). In order to achieve scale-up, problems in design and operation had to be conquered. Main considerations with increasing boiler capacity were [28,62]:

- Fluidisation in large cross-sectional areas.
- Separation efficiency of large hot cyclone collectors.
- Distribution of fuel and air flow in lower furnace.
- The placement of heat transfer surface (steam cooled).

In the development phase scale-up without experience or extensive knowledge occurred and led to problems in fluidisation, fuel feed, sorbent feed and solid circulation which were followed by problems in controlling emissions and combustion [63]. All problems can be divided in technical challenges comprising two major components of the CFB technology.

The *boiler* geometry affects the mixing and fluidisation of fuel, air and sorbent. When increasing the boiler capacity the geometry changes and thus effecting earlier-mentioned factors. Another problem, which occurred by changing the geometry was the ratio of heating transfer surface to volume. Scaling up is typically achieved by increasing the height and the width of the boiler [64]. This means a decline in the ratio; therefore, heating transfer surface had to be added in order to retain the same heat transfer performance. A way of increasing heating surface is by adding in-furnace heating transfer surface and, for large CFB boilers, an external FBHE.

The *cyclone* efficiency decreases when cyclone size is increased, due to a reduction in centrifugal force. When scaling-up the size of the boiler, the cyclone is increased accordingly up to a point where the size negatively impacts gas velocities and solid circulation. To cope with this problem more smaller cyclones are placed when increasing boiler size [65].

The back pass section has not been a limiting factor in scaling-up. Larger back pass sections were already available for other technologies such as PC combustors.

Further scaling-up in the 700–1000 MWe range is difficult because of the large number of fuel-feeding points; such sizes requires to ensure uniform distribution of the fuel in the bed [66]. A non-technical factor which can influence further scale-up of CFB is that utilities are risk avoiding. In a liberated energy market utilities are not likely to choose for one large boiler for which operating experience is absent. Failures in such a large boiler will result in significant loss of income and thus affect profits. As a consequence, according to Lurgi Lentjes, 250 MWe will remain the size ceiling for a while. Babcock Borsig stated that advanced technologies like CFB have a small role in near future added generation capacity and states that improvements in these technologies are hindered due to lack of investment capital. Alstom on the other hand continues to work on scaling-up towards 400–600 MWe and is developing a supercritical CFB boiler of 550 MWe [67]. The first supercritical boiler is expected to be commissioned in 2009 in Poland. It has a rated output of 460 MWe net and is supplied by Foster Wheeler [68]. Further research is done by VTT in co-operation with Foster Wheeler to scale-up further into utility applications with a capacity up to 800 MWe [69].

Scale-up of both CFB and BFB technology is primarily limited to the installations that are used for power generation and have no fuel challenges (see Fig. 9). Further, the largest installed size of technology is different per manufacturer. Alstom and Foster Wheeler are the only two manufacturers who installed (or are planning to) capacities above 400 MWe net. This is almost double the size of the maximum installed capacities of the other manufacturers.

5. Further analysis of cost development

One of the goals of this article is to analyse cost reductions and provide an indication for future prospects for FBC in terms of performance and cost. The perspective used in the analysis for quantifying developments and trends is based on theory on technological learning and innovations, which includes the experience curve and theory on economies of scale. Using the concept of the scale factor and the experience curve, a relationship between development and cost can be estimated.

5.1. Economies of scale

According to the theory, economies of scale can induce cost decline and with that a decrease in price can be expected. One form of achieving economies of scale is by scaling-up individual plants (see Figs 13–15). An analysis is made to estimate the price reduction with doubling the size of the plant, by estimating the scale-up factor (SF) for FBC technology (see Box 2).

The dataset is split in both technology types and only new plants are taken into account to reduce some price variations. Then only samples were used which provided multiple data points within 1 year[24]. These selection criteria resulted in two usable samples (first two rows in Table 11). Next to estimating the scale factor with the use of information in the database, another data source is used (last two rows in Table 5-1). This source presented price indications from manufacturers for both BFB and CFB boilers of different size [19].

The estimated scale factors presented in Table 11 (last two rows) show that the reduction in boiler price is somewhat higher when scaling-up CFB plants than BFB plants. This can be explained by the fact that scaling-up of CFB technology is easier

[24]It is not possible to calculate scale factors using data from a larger time frame, as this would intermingle the scale effect with the other learning effects.

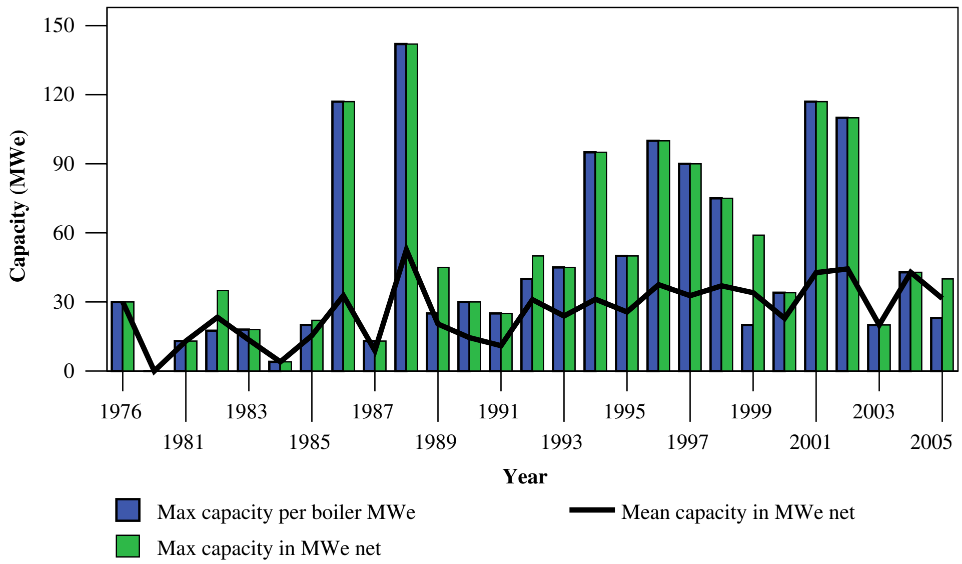

Fig. 13. Maximum-installed capacity of BFB installations and boilers over time [3,12–14].

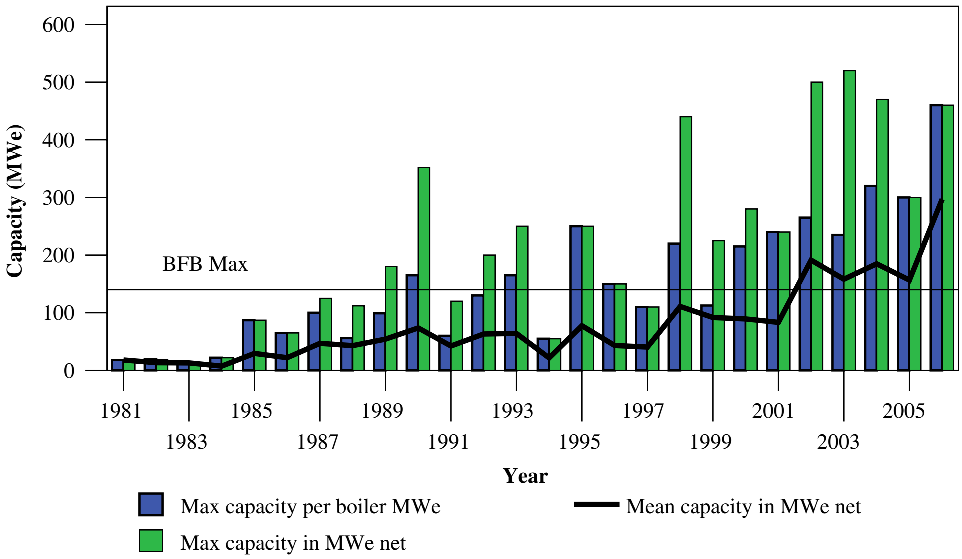

Fig. 14. Maximum-installed capacity of CFB installations and boilers over time [3,12–14].

and has given more attention in the development as mentioned in Section 4.8. Further, the results indicate that the scale factor declines (improves) when the boiler price represents a larger part of the price (EPC and boiler price) (see Table 11). This suggests that the price reduction due to scaling up is mainly accomplished in the boiler section. Earlier performed research on the scaling-up of biomass fired moving grate boilers yielded a scale factor of 0.62, which is very much comparable with the results found here [70]. Another comparable scale factor is found for coal-fired installations by Joskow and Rose [71]. Their findings suggest a decrease in engineering and construction cost of 20% with each doubling of unit size (350–700 MWe). This equals a scale factor of 0.68.

For the category 'project price' no SF was estimated due to data limitations. However,

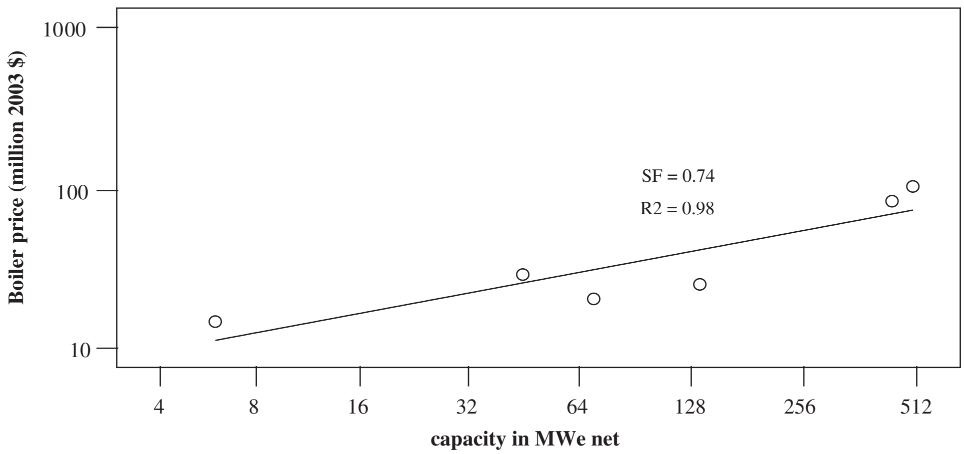

Fig. 15. Relationship between capacity and the boiler price of new CFB plants commissioned in 2002.

Box 2

Economies of scale and the scale factor.

Economies of scale

A common theory in economics is the theory of economies of scale or returns to scale. Mainly, there are three ways of achieving economies of scale:

1. Scaling-up production units (increasing capacity in the case of energy installations) The learning effect of scaling-up can be quantified in the formula:

$$\frac{\text{Cost 2}}{\text{Cost 1}} = \left(\frac{\text{Size 2}}{\text{Size 1}}\right)^{\text{SF}}, \tag{5.1}$$

   where Cost 1 is the cost of installation, Cost 2 the cost of scaled up installation, Size 1 the size of installation, Size 2 the size of scaled up installation and SF the scale factor.
2. Consecutive repetition or mass production. According to Tassey [76], standardisation makes this type of learning possible.
3. Continuous operation, which combines scaling-up and mass production in a plant.

Learning or experience is needed in order to achieve above-mentioned developments. For a more detailed description of the effect of experience or learning on the economic performance of a technology see Section 5.2 Experience curves.

the scale factors for project price would probably be higher than that of EPC. Indications for this assumption are: first, the scale factor is lower (i.e. better) for boiler price than for EPC and second, the theory suggests that economies of scale are hard to achieve for large power plants as these plants require extensive on site production. This negative economy of scale will affect project price to a larger extent than EPC and boiler price.

5.2. Experience curves

One way of measuring technological learning or experience in a technology is by defining the economical performance of a technology. The IEA states that price is the most important measure of performance in a new technology [6]. The measuring of learning and experience (see Box 3) can be a useful tool to analyse the trend of cost reduction of new energy technologies.

Table 11
Scale-up factors for new plants for two cost categories and the technology variants BFB and CFB

Selection steps (price component, technology)	Component	Scale factor	R^2	p-value	Sample size	Year	Price reduction (%)	Source
EPC	CFB	0.81	0.99	0.11	4	2002	12	Database
Boiler	CFB	0.74	0.98	0.01	6	2002	16	
	BFB	0.64	0.98	0.01	5	1994	22	[19]
	CFB	0.62	0.99	0.02	4	1994	23	

Note: The scale factors calculated with the use of data from (Tennessee Valley Authority 1994) are based on MWth (X-variable) and US$(1994)($Y$-variable). The scale factors calculated with data from the database have MWe net (X-axis) and US$(2003) ($Y$-axis) as variables. Price reduction is calculated with equation 5.1 assuming doubling of the size.
R^2 is used as an indicator for the goodness-of-fit measure for the used equation.
p-value$\leqslant$0.05 is considered significant (see Box 3 for more details).

A problem with applying the experience curve method on FBC is that there is no methodological standard for large power plants like FBC plants. The capital cost of these plants and cost of electricity vary strongly due to a number of price influencing factors, such as scope of contract, fuel used, technology variant, application, region, and manufacturer (see also Junginger [7]).

The goal was to analyse the experience effect on comparable plants. To cope with the variations, the collected data is *categorized* (see Table 12) according to these factors in the following order: type of project→fuel characterization (see Fig. 9)→application→region (see for categories Table 4). The relationship between globally gained experience (cumulative installed capacity in MWe net) and the specific investment price (in $/kWe net) is analysed.

The larger samples (typically larger than 5), derived from the constructed database, are used for regression analysis. This analysis was performed with the use of curve estimation in a statistical software system [72]. Dependent variable 'price' (in $/kWe net) and independent variable 'cumulative installed FBC technology' (in MWe net)[25] were used in the equation. The value for factor 'b' in the experience curve equation was estimated by the analysis and was used to calculate the PRs (2^b) for categories of plants. The PRs of the curve estimations are given in Table 12. Examples of estimated relationships are given in Figs. 16 and 17.

The results in Table 12 show that in general R^2 improves when accounting for more price influencing variables. This suggests that the defined price influencing variables have an effect on the investment price. An example of that can be seen in Fig. 16 where categories of installations with some fuel challenges seems to have a higher investment price than installations with a standard design.

Further the results show that PRs with acceptable R^2 lie in a range between 0.42 and 0.93. The PR for the project price of BFB plants is 0.90. This value corresponds with the PR for large plants found in the literature [5,6,8,73,74]. The same trend as in SFs is seen for the PRs: the PR declines (improves) when the boiler price represents a larger part of the price. An example is the very low PR found for the boiler price of new CFB plants with standard design (see Table 12). This suggests that a large part of the price reduction is due to price reduction in the boiler section.

This can be explained by assuming that scaling-up is the main factor for price decline and experience. This assumption is based on the theory that experience is needed to scale-up installations. PR and scale factor are thus interrelated. The prove for that is seen in the steady scale-up of CFB technology and the problems which had to be overcome and the tendency for technologies in general to increase scale over time [75].

The low PR for the boiler price can partially be explained by the scale effect (see Tables 11 and 12). The fast price reduction of the boiler is achieved in the period between 1990 and 2000. In that period the maximum boiler capacity scaled up from 100 to 300 MWe net (see Fig. 14). Another part can be explained by innovations in process or product. In

[25] Cumulative installed FBC capacity is the cumulative sum of installed capacity (in MWe net) of the BFB, CFB and hybrid variants.

Box 3
Experience curve concept.

Experience curve

Learning in terms of everyday experience and activities of engineers, sales representatives, and other employees can according to Lundvall [77] be summarised under three types of learning:

- *Learning by doing*: increasing the efficiency of production operations.
- *Learning by using*: increase the efficiency of operating complex systems.
- *Learning by interacting*: the interaction between users and producers for example can result in product innovations.

By analysing this trends, prospects of future energy cost, the potential and commercialization of a new energy technology can be made [73]. A well-established and documented method for quantifying technological change, with the use of economical factors as measuring tool, is the experience curve.

The general experience curve equation is often expressed as [73]

$$C_{\mathrm{cum}} = C_0 \times \mathrm{CUM}^{\mathrm{b}}, \tag{5.2}$$

where C_{cum} is the output of the equation which represents the cost of a unit after a number of cumulative units are produced. The element C_0 represents the cost of the first unit. CUM is the cumulative number of units produced. The most important element in this equation is the experience index called b; it defines the steepness of the curve and thus determines the reduction of cost. This can be calculated for each doubling of cumulative production with $(1-2^{\mathrm{b}})$. This value is called the learning rate (LR). The value 2^{b} is called the progress ratio (PR). A progress ratio of 0.9 means that the cost to produce a unit (C_{cum}) after one doubling of cumulative production is 90% of that of the first unit produced (C_0). Experience curves are mainly expressed in log–log diagrams. When plotting in a log–log diagram equal relative changes in X and Y parameters are expressed linear. The main advantage is that the line (experience curve) is then in the form of a linear equation, hence, the decline of cost can easily be seen and compared with other technologies.

The estimation of the experience curve can be done with a regression analysis. The analysis yields estimations for the parameters. It also yields two valuable indicators for the 'quality' of the estimated relationship. First, the Coefficient of determination (R^2), which is used as an indicator for the goodness-of-fit measure for the (experience curve) model. It quantifies the portion of variation in the dependent variable explained by the regression model. Small values indicate that the curve estimation does not fit the data well. Second, the p-value represents the probability that a relationship as strong as the one observed in the data would be present by random chance and is an indicator for whether the suggested equation, as a whole, is valid [78].

that same period new product innovations were commercially introduced, for example the Compact CFB in 1992 built by Foster Wheeler and the IR-CFB by B&W in 1994. The manufacturers claim that the new boilers are less expensive and perform better than their predecessors. A third explanation can be that standardisation in building the boiler section has led to some kind of mass production. In the theory is already suggested that in the stages of development, where standardisation occurs, learning effects (cost decline) up to 40% can be found. The last explanation could be that in the period, due to heavy competition, a shake out phase occurred. The number of mergers, joint ventures and take-overs in that period (see Section 4.2) are an indication for such a phase. In a shake out phase the prices can decline much faster than the actual decline of production cost.

Table 12
Results of experience curve estimation for FBC technology

Categorization method		PR	R^2	p-value	Sample size
Project price	BFB	**0.90**	0.77	*	6
	CFB	1.02	0.00		15
	BFB, new plant (pilot plant excluded)	**0.91**	0.77	*	5
	CFB, new plant	0.91	0.06		11
	CFB, new plant, standard design	0.94	0.09		8
	CFB, new plant, standard design + no challenge	0.90	0.19		10
	CFB, new plant, standard design, power	***0.93***	0.61		7
EPC price	BFB	1.40	0.23	*	23
	CFB	0.93	0.09	*	56
	BFB, new plant	0.90	0.10	*	16
	CFB, Re-power	0.89	0.25		14
	CFB, add-on	0.90	0.31		9
	CFB, new plant	0.62	0.17	*	29
	BFB, new plant, some challenges	0.78	0.26		14
	BFB, new plant, some challenges, Scandinavia, Cogeneration	***0.79***	0.48		7
	CFB, new plant, standard design	0.78	0.13		16
	CFB, new plant, some challenges	***0.49***	0.67	**	11
	CFB, new plant, no challenges + standard design, North-America	**0.82**	0.96	**	5
	CFB, Re-power, standard design	0.93	0.29		11
	CFB, Re-power, no challenges + standard design, North-America	**0.90**	0.95	**	5
Boiler price	BFB	0.91	0.04		14
	CFB	0.86	0.07		29
	BFB, new plant	0.71	0.16		7
	CFB, new plant	0.98	0.01		16
	BFB, new plant, some challenges	0.71	0.16		7
	BFB, new plant, some challenges, Scandinavia	***0.52***	0.42		5
	CFB, new plant standard design	**0.42**	0.85	**	10

R^2 is used as an indicator for the goodness-of-fit measure for the used equation.
** p-values $\leqslant 0.01$, * p-values $\leqslant 0.05$ (see Box 3).
Good PR = R^2 ($\geqslant 0.70$) and p-values ($\leqslant 0.05$) [78] are highlighted bold.
Marginal PR = R^2 ($\geqslant 0.35$–0.70) and p-values (> 0.05) are highlighted bold and italic.

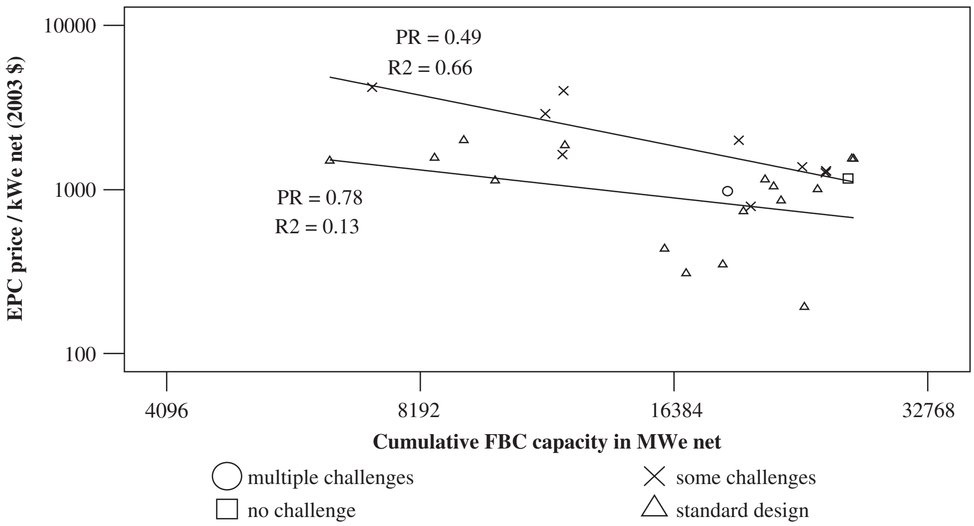

Fig. 16. Experience curve for new CFB plants and divided by fuel challenge with EPC price.

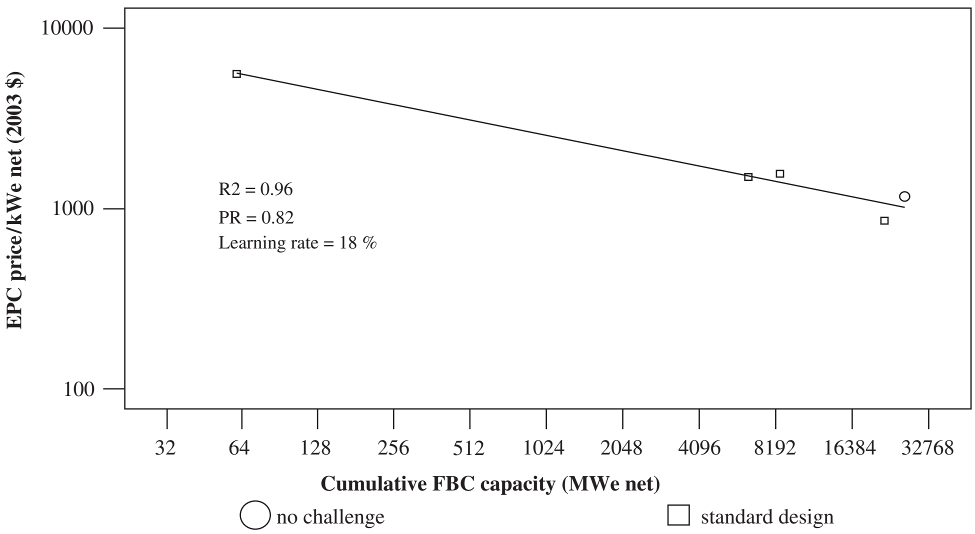

Fig. 17. Experience curve for EPC prices new CFB plant in North America (region) and no fuel challenge and standard design (fuel types).

5.3. Discussion of the methodology

The data used for constructing the database is an important factor in determining if the experience curve theory can be applied to FBC technology. All data about economic performance of the technology is price data derived from mainly secondary sources in the form of contract values, thus no cost data is derived from the manufacturers or databases with cost data. The quality of the data thereby differs highly from case to case. This adds up to the inherent heterogeneity of the installations and with it the breakdown of cost, which makes it very difficult to categorize and compare installations.

Attempting to categorize the data in the sample to eliminate the variation in cost and installations brings another problem: data availability. The result is that the selected data samples were often too small to analyse the experience curve effect or scale factor. Even for the data samples, which were relative large, the poor data availability (especially of old plants) had a large and undesired effect. An example of this can be seen in Fig. 17, where one data point has large influence on the estimated experience curve and thus the PR and R^2. In Fig. 17 the price of the oldest plant determines the slope of the curve very strongly.

Data preparation can also have influence on the PR. Junginger [7] found that the PR can vary with the chosen deflator[26], geographical boundary and time frame. However, no sensitivity analysis for these factors has been performed in this study.

The experience index[27] 'cumulative installed FBC capacity worldwide in MWe net since introduction' is used, because the main manufacturers operate worldwide and thus makes it likely that learning is not bounded to a region. Conferences on FBC, which are held since the 1970s, and cooperation between institutions are an example of worldwide knowledge transfer (which implicates learning).

6. General conclusion and recommendations

The results show that the technology variants diffused differently over time. Drivers, which influenced the diffusion and technological developments were different for the selected regions. These drivers were market regulation, environmental legislation and RD&D programs. Specific drivers, which can be added for FBC technology are fuel availability (quantity and quality), required applica-

[26]The chosen GDP-deflator (averaged for the OECD countries) should be appropriate, as in this article the technology is installed

(*footnote continued*)
in various regions. The chosen currency converter may even have a larger effect on the results.

[27]When using for example regional installed capacity of a technology as experience index, this would lead to the exaggeration of the PR. The PR < 1 would decline and PR > 1 would incline. This is due to the fact that the same price development occurs with less increase in capacity. The results derived from the constructed database should be considered the same, while the cumulative capacity of this database does not cover the whole installed FBC technology worldwide. This means that the PR's presented here are somewhat exaggerated.

tion in market, innovation spill over and competing technologies.

The drivers together resulted in the development of BFB towards a technology, which is primarily used for cogeneration with the use of an increasing variety of low-grade fuels with high moisture content. Biomass is the dominant fuel for BFB and seems to be the dominant choice in expected market growth in Scandinavia, Asia and North America. The availability of the fuels and capacity requirement in the niche market of industrial application are limited. These markets set limitations as well as technological limitations made scaling-up of BFB towards utility size capacity undesirable.

Innovation spill-over from the materials industry and IT market made it possible to reach higher steam parameters and improve the O&M of the installation. Consistent scaling-up of boilers as well as total plant capacity made it possible for CFB to reach utility size installations. This trend of changing application from cogeneration to power generation set a different market niche for CFB technology, namely burning low-grade fuels, primarily low-grade coals with high ash contents, in the industrial and utility size range. Potential growth markets for CFB technology are Asia (especially India and China), Eastern Europe and North America where bituminous coal, anthracite coal and lignite are the dominant fuel choices.

The results presented in this article show economies of scale have a significant influence on the investment price. Applying the experience curve on FBC technology is difficult due to data limitations and the variety of other price influencing variables. The used method seems a viable option for dealing with those variables. More in general, as the experience curve method is up to now primarily applied on modular energy technologies (photo voltaic solar cells and wind turbines), the method used in this article seems to be an option for applying the experience curve on complex and large power plants. However, data quality and availability are expected to remain a limitation for this application.

Although the experience effect on investment price was statistically proven for some categories of installations, the results should be handled with care, especially regarding the possible application of the results. Using the results in modelling or other form of forecasting exercises, specific attention is recommended on the method and results. When using the results of this article, for example, the scale factor and PRs, they should not be used without paying attention to the method used. That is to say that the results may only be valid for groups of installations.

In general, the recommendation is that more attention should be given to the drivers, which influence and explain cost/price variations. The method of reducing variations by averaging cost/price can result in neglecting these drivers and with it reducing the accuracy of the forecast. The method of categorizing data can give a better explanation for the development in a niche of the technology, but it is more difficult to generalise the results to the whole technology. The recommendation becomes thus to set an uncertainty interval for the PR when using the PR in forecast exercises. Based on the results, a PR between 0.90 and 0.93 for new FBC plants is suggested with an uncertainty interval between 0.80 and 0.95.

Further research is suggested by repeating the applied method with use of a larger dataset with more detailed cost/price data. Such a research can yield a better estimation of the PR in order to narrow the uncertainty interval for the PRs. Also determining the PR for the generating cost/price for FBC technology per unit output (e.g. $/kWh) would be desirable. The advantage of such a study is that technological development and learning is better incorporated in the PR. Such a PR would incorporate and quantify increasing efficiencies, better availability, emission cost and change in fuel cost in the form of declining or increasing generating cost/price.

Acknowledgements

The authors would like to thank H. Spliethoff, K. Haasnoot, H.P. Calis and J. Hämäläinen for their valuable contributions to this work. In addition, the reviewers are greatly acknowledged for their constructive comments.

Appendix

For a more detailed overview of design, operating and economical variables of FBC installations see Fig. 18.

Fig. 18. Overview of variables influencing economical and technological performance.

References

[1] Spliethoff, H. Verbrennung und Vergasung in Wirbelschichtanlagen—Stand, Entwicklung und Forschungsbedarf. In: Proceedings of the VDI, Tagung, Cottbus, 2000.

[2] Watson WJ. Success in the electric power industry: combined cycle gas turbines and fluidised beds. In: Science policy research unit. Sussex: University of Sussex; 1997.

[3] Minchener A, Cross P, Smith T, Fisher AM. Fluidised bed combustion systems for power generation and other industrial applications. CRE Group Limited; 2000.

[4] Claeson Colpier U, Cornland D. The economics of the combined cycle gas turbines—an experience curve analysis. Energy Policy 2002;30:309–16.

[5] Junginger M, Faaij A, Turkenburg WC. Global experience curves for wind farms. Energy Policy 2003;33(2):133–50.

[6] IEA. Experience curves for energy technology policy. Paris, France: OECD; 2000.

[7] Junginger M. Learning in renewable energy technology development. Department of Science, Technology and Society, Copernicus Institute, Utrecht University: Utrecht; 2005. p. 206.

[8] McDonald A, Schrattenholzer L. Learning rates for energy technologies. Energy Policy 2001;29(4):255.

[9] Visser ED. Technological learning on biofuelled combined heat and power plants in Sweden. Copernicus institute, department of science, technology and society, University of Utrecht: Utrecht; 2004. p. 107.

[10] Scherr F, Fuller J. Cost of atmospheric fluidized-bed combustors for electric power generation. Energy J 2002;23(1).

[11] DOE, Marked-based advanced coal power systems, 1998.

[12] SFA Pacific, Commercial FBC projects/FBC database. The SFA quarterly report, 1999 (Fourth Quarter 1999).

[13] SFA Pacific, Commercial FBC projects update. The SFA quarterly report, 2002 (Fourth Quarter 2002).

[14] SFA Pacific, Commercial FBC projects and status of technology/FBC database. The SFA Quarterly Report, 1998 (Second Quarter 1998).

[15] EPI. EPI technology, June 28, 2004 [cited 2004; available from: 〈http://www.energyproducts.com/EPITechnology.htm〉].

[16] Lurgi-Lentjes. Circulating fluidised bed, 2004 [cited; available from: 〈http://www.lurgi-lentjes.de/english/nbsp/index.html〉].

[17] Basu P, editor. Fluidized bed boiler design and operations. Toronto: Pergamon Press; 1984.

[18] Basu P, Fraser SA. Circulating fluidized bed boilers—design and operations. Stoneham, USA: Butterworth-Heinemann; 1991.

[19] Tennessee Valley Authority. Fluidized bed combustion and gasification: a guide for biomass waste generators. Chattanooga: Southeastern regional biomass energy program; 1994.

[20] Karppanen E. Advanced control of an industrial circulating fluidized bed boiler using fuzzy logic. Department of Process Engineering, OULU University; 2000.

[21] Grubler A, Nakicenovic N, Victor DG. Dynamics of energy technologies and global change. Energy Policy 1999;27(5):247.

[22] Rogers EM. Diffusion of innovations, fourth ed. New York: The Free Press; 1995 (p. 501).

[23] Banales-Lopez S, Norberg-Bohm V. Public policy for energy technology innovation—a historical analysis of fluidized bed combustion development in the USA. Energy policy 2002;30:1173–80.

[24] Norberg-Bohm V. Creating incentives for environmentally enhancing technological change: lessons from 30 years of US energy technology policy. Technol Forecast Soc Change 2000;65:125–48.

[25] IEA. IEA R&D database. Series IEA R&D database, 2004. Last Update Date; available from: 〈http://library.iea.org/rdd/eng/ReportFolders/Rfview/Explorerp.asp〉.

[26] EPRI. The current state of atmospheric fluidized-bed combustion technology. Electric Power Research Institute, 1989

[27] Kostama J, Alakangas E. Evaluation of the policy and legal frameworks and barriers of biomass CHP/DHP in Finland. OPET CHP/DH task 3: biomass CHP and district heating. OPET country survey, Finland. 2004.

[28] Engstrom F, Pai D. Fluidised bed combustion technology—the past, the present, the future. Modern Power Systems, 1999. p. 21–26.

[29] Watson J. Selection environments, flexibility and the success of the gas turbine. Res Policy 2004;33(8):1065.

[30] Fuller JA. Combustion technology research and development issues. In: The US Department of Energy Combustion Technology University Alliance Workshop. Department of Management West Virginia University, 2003.

[31] Hupa M, editor. M.Z., Fluidised bed conversion—year report 2003. IEA, 2004.

[32] Hupa M. Fluidised bed combustion. In: Politecnico di milano lecture series—options for energy recovery from municipal solid waste, 2005.

[33] Scott L, Darling SL. Foster wheeler experience with clean coal technology in China. Technical paper by Foster Wheeler.

[34] IEA, World Energy Outlook, 2004.

[35] NETL. Tracking new coal-fired power plants: coal's resurgence in electric power generation. Department Of Energy (USA), 2004. p. 17.

[36] North American electric reliability council. Electronic GADS publications for Windows 1998–2002 generating availability report, October 2003.

[37] Sanden BA, Azar C. Near-term technology policies for long-term climate targets–economy wide versus technology specific approaches. Energy Policy 2005;33(12):1557.

[38] IEA. Energy policies of IEA Countries: Germany 2002 review. USA: OECD/IEA; 2002 (p.145).

[39] Sapy G. CFB: scaling up to 600 MWE. Mod Power Syst 1998;18(8).

[40] Hämäläinen, J. Fluidized bed combustion in praxis. In: IV international Slovak biomass forum. Bratislava, 2004.

[41] Joskow PL, Rozanski GA. The effects of learning by doing on nuclear plant operating reliability. Rev Econ Stat 1979;61(2):161–8.

[42] Lichtendonk K. Practical experiences in the use of forest fuels for large-scale CHP. In: Wood energy conference. Johnstown Castle, Wexford: Siemens; 2003.

[43] Babcock, Wilcox. Design, Start-up and initial operating experience of B&W's IR-CFB coal-fired boilers. In: Power Gen Asia, Singapore, 1997.

[44] Järvinen T, Alakangas E. Cofiring of biomass—evaluation of fuel procurement and handling in selected existing plants and exchange of information (COFIRING), V. Energy, Editor. 2001, ALTENER.

[45] Bush SA, Buck JW, Friedman MA, Divillo RJ, Rekos NF. Operating cost for the Nucla CFB. In: 1993 international conference on fluidized bed combustion. San Diego, CA, USA: ASME; 1993.

[46] Permchart W, Kouprianov VI. Emission performance and combustion efficiency of a conical fluidized-bed combustor firing various biomass fuels. Bioresour Technol 2004;92:83–91.

[47] US DOE and NETL, JEA large-scale CFB combustion demonstration project—a DOE assessment, 2005.

[48] Bessette R. Energy efficiency and industrial boiler efficiency: an industry perspective. In: Steam digest 2002. CIBO; 2002.

[49] Foster Wheeler. Advanced circulating fluidized bed (CFB) boilers. sa [cited 2004; available from: 〈http://www.power-technology.com/contractors/boilers/foster_wheeler/index.html#foster_wheeler1〉].

[50] Marion J. Near and future coal combustion system developments and products. In: Evolution of combustion technology to support national energy needs. Orlando, USA: Alstom power; 2002.

[51] PowerClean. CO2NET, and CAME-GTEC thematic R&D networks. Strategy for sustainable power generation from fossil fuels 2004:20.

[52] NRME. Electricity generation using steam turbine. Energy generation 2004, 30 April 2004 [cited; Department of Natural Resources, Mines and Energy; available from: 〈http://www.nrme.qld.gov.au/energy/infosite/eg_using_-steam_turbines.html〉].

[53] Rajaram S. Next generation CFBC. Chem Eng Sci 1999;54:5565–71.

[54] CRE Group Ltd, Opportunities and markets for co-utilisation of biomass and waste with fossil fuels for power generation, European Union—Energy.

[55] EPA. AP 42 (fifth ed.), Stationary point and area sources, chapter 1: external combustion sources. In: Compilation of air pollutant emission factors, vol. I, 1998.

[56] World Bank. Selective Non-Catalytic Reduction (SNCR), 2004 [cited; available from: 〈http://www.worldbank.org/html/fpd/em/power/EA/mitigatn/aqnosncr.stm〉].

[57] Armesto L, Boerrigter H, Bahillo A, Otero J. N_2O emissions from fluidised bed combustion. The effect of fuel characteristics and operating conditions*. Fuel 2003;82(15–17):1845.

[58] Mann MD, Collings ME, Botros PE. Nitrous oxide emissions in fluidized-bed combustion: Fundamental chemistry and combustion testing. Prog Energy Combust Sci 1992;18(5):447.

[59] Spliethoff H. Personal communication. J.M. Koornneef: Delft; 2004.

[60] Weinstein RE, Goldstein HN, Buchanan TL, Freier MD. Merchant cost of repowering with APFBC. In: Advanced coal-based power and environmental systems '98 conference, Morgantown, West Virginia, USA, 1998.

[61] NEA, IEA, and OECD. Projected costs of generating electricity—2005 update. 2005.

[62] Semedard J, Skowyra R, Seeber J. Scale-up of CFB technology to the utility class: evolution of clean, efficient power generation. Alstom, After 2002.

[63] Sheahan Rt. Section IX-4 summary of operating experiences. In: Proceedings of the 5th national conference: evaluating the fluidized bed combustion option. sa. Rockville, Maryland: Government Institutes Inc.
[64] Semedard J, Skowyra R, Seeber J. Scale-up of CFB technology to the utility class: evolution of clean, efficient power generation, Alstom.
[65] Armistead TF, Schwieger R, Reina P. Boiler technology pursues goals of efficiency and lower emissions-circulating fluidized-bed equipment pushes size limits. In: Power & industrial-POWERPLANTS, 2002.
[66] Yin C. Circulating fluidized bed combustion boilers. sa. Denmark: Aalborg University.
[67] Thomas F, Armistead RS, Peter Reina. Boiler technology pursues goals of efficiency and lower emissions-circulating fluidized-bed equipment pushes size limits. In: Power & Industrial-POWERPLANTS. 2002.
[68] Lundqvist R, Schrief A, Kinnunen P, Myöhänen K, Seshamani M. A major step forward—the supercritical CFB boiler. In: PowerGen international 2003. Foster Wheeler, Siemens; 2003.
[69] Hämäläinen J, Tourunen A. VTT Processes—research and development on fluidized bed combustion, VTT.
[70] Evald A, Jakobsen HH. Experiences from 30 wood chip fired district heating systems in Denmark. In: Biomass for energy, environment, agriculture and industry-proceedings of the 8th European biomass conference. Vienna, Austria: Pergamon; 1994.
[71] Joskow Pl, Rose NL. The effects of technological change, experience, and environmental regulations on the construction cost of coal-burning generating units. RAND J Econ 1985;16(1):1–27.
[72] SPSS Inc. SPSS 12.0.1 for Windows, 2003
[73] Neij L. Dynamics of energy systems—methods of analysing technology change. In: Department environmental and energy studies. Lund: Lund University; 1999.
[74] Kouvaritakis N, Soria D, Isoard S. Modelling energy technology dynamics: methodology for adaptive expectations models with learning by doing and learning by searching. Int J Global Energy Issues 2000;14(1–4):104–15.
[75] Grubler A. Technology and global change. IIASA Laxenburg, Austria: Cambridge university press; 1998.
[76] Tassey G. Standardization in technology-based markets. Res Policy 2000;29(4–5):587–602.
[77] Lundvall BA. National systems of innovation: towards a of innovation and interactive learning. London: Pinter; 1992.
[78] Department of Defense U. Joint industry/government—parametric estimating handbook, 2nd ed. ISPA: NORAD; 1999.
[79] Oka S. How to use data about coal combustion in bubbling fluidized beds for design of the circulating fluidized bed boilers? In: 41st IEA FBC technical meeting. Salerno: Institute for nuclear Sciences VINA Laboratory for thermal Engineering and Energy Research; 2000.
[80] Lurgi Lentjes. ROWITEC® fluidised bed firing. 2004 [cited 2004; Available from: 〈http://www.lurgi-lentjes.de/lentjes_headoffice/english/nbsp/menu/technologies/waste_to_energy/fluidised_bed_incineration/rowitec_fluidised_bed/〉].
[81] Kevin Toupin. Modern wood fired boiler designs—history and technology changes. Worcester, MA, USA: DB Riley, Inc.; 1996.
[82] Alliston MG, Luomaharju T, Kokko A. Improved water-cooled cyclone constructions in CFB's. In: Proceedings of the 15th international conference on fluidized bed combustion. Savannah, GA, USA: ASME; 1999.
[83] Modern Power Systems. Power from biomass—wood plant aims high. Mod Power Syst 2003;2003(3):27–9.
[84] IEA. Electric technologies—bridge to the 21st century and a sustainable future. In: Report of an IEA workshop, IEA, 1997.
[85] Zeevalking JA, Ree RV. Conversietechnologieen voor de produktie van eletriciteit en warmte uit biomassa en afval-deel 3. TNO-MEP, ECN, Novem, 2000 (in Dutch).
[86] Pfleger D. Clean coal technologies—development status. In: World coal institute workshop. Alstom: Essen; 2002.
[87] Weitzel PS, McDonald DK, Whitney SA, Oda N. Directions and trends for commercial PFBC and hot gas clean up. In: Pittsburgh coal conference. Pittsburgh, PA, USA: Babcock & Wilcox; 1996.
[88] Alakangas E, Hillring B, Nikolaisen LS. Trade of solid biofuels, and fuel prices in Europe, sa.
[89] EnergieNed and CBS. Brandstofprijzen voor grootverbruikers, 2005 [cited; available from: 〈http://www.energie.nl/〉].
[90] Eurostat. Natural gas prices for large industrial standard consumers. Series natural gas prices for large industrial standard consumers, 2005 [last update date; available from: 〈http://epp.eurostat.cec.eu.int/portal/page?_pageid=1073,1135280&_dad=portal&_schema=PORTAL&p_product_code=EBC25872〉].
[91] McGowin CR, Tavoulareas S, Howe WC. Design, performance and cost of atmospheric fluidized bed combustion power plants. In: 1987 international conference on fluidized bed combustion. Boston, USA: ASME; 1987.
[92] Sheahan RT. Cost analysis for an FBC system including cogeneration. In: Evaluating the fluidized bed combustion option. Rockville, MD, USA: Government Institutes Inc.; 1986.
[93] Granatstein DL. Technoeconomic assessment of fluidized bed combustors as municipal solid waste incinerators: a summary of six case studies. CANMET Energy Technology Centre (CETC), IEA bioenergy task 36, 2004.
[94] Kavidass S, et al. Why build a circulating fluidized bed boiler to generate steam and electric power. In: PowerGen Asia 2000. Bangkok, Thailand: Babcock & Wilcox Company; 2000.
[95] Broek RV, Faaij A, Wijk AV. Biomass combustion power generation technologies. Department of Science, Technology and Society, Utrecht University: Utrecht; 1995.
[96] Jokiniemi E. In: Koornneef, JM, editor. Personal communication on automation and controls. Director, Plant Performance Solutions, Metso Automation Inc., 2004.
[97] Modern Power Systems. Recent power industry contracts. Mod Power Syst 2003;2003(7):8.
[98] Blankinship S. Coal-fired power generation: the need to be nimble. In: Power engineering, 2003.
[99] EPRI. ESP power supplies for reduced cost operation. Program 76 2004 [cited; available from: 〈http://www.epri.com/destinations/product.aspx?id=122&solution=4&issue=6〉].
[100] World Bank. Wet flue gas desulfurization (FGD). 2004 [cited; available from: 〈http://www.worldbank.org/html/fpd/em/power/EA/mitigatn/aqsowet.stm〉].

[101] World Bank. Electrostatic precipitator (ESP), 2004 [cited; available from: ⟨http://www.worldbank.org/html/fpd/em/power/EA/mitigatn/aqpcesp.stm⟩].

[102] Carnot program, case study: co-firing Stora Enso Fors mill. In: CARNOT Online, 1998.

[103] Impola R, Alakangas E. The analysis report of plant no. 17—Forssa CHP Plant, Finland. In: Cofiring of biomass—evaluation of fuel procurement and handling in selected existing plants and exchange of information (COFIRING)—part 2, VTT Energy, ALTENER, 2000.

[104] Modern Power Systems. Power plants go to waste in Sweden. Mod Power Syst 2003 [cited; available from: ⟨http://www.modernpowersystems.com/story.asp?storyCode=2021930⟩].

[105] Kvaerner, A. Aker Kvaerner supplies energy-from-waste boiler plant to Borås in Sweden. 2003 [cited; available from: ⟨http://www.akerkvaerner.com/Internet/MediaCentre/PressReleases/All/2003/AKPressRelease_890875.htm⟩].

[106] Libal A, Phalen J, Shepard T. Manitowoc public utilities' choice for a circulating fluidized bed boiler. In: Clean energy for the world: proceedings of the 1991 international conference on fluidized bed combustion. Montreal, Canada, New York: ASME; 1991.

[107] Business Wire. Fitch IBCA expects to rate AES-PR's $736M Proj Debt 'BBB', 2000 [cited; available from: ⟨http://www.findarticles.com/p/articles/mi_m0EIN/is_2000_May_8/ai_61938407#continue⟩].

[108] Modern Power Systems. Recent power plant contract awards. Mod Power Syst 2000 [cited; Available from: ⟨http://www.modernpowersystems.com/story.asp?storyCode=5817⟩.