INNOVATION PROCESS IN THE ENERGY TRANSFORMATION SECTOR: A CASE STUDY FOR FLUIDIZED BED COMBUSTION (FBC)

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PREFACE

The case study by Wolfgang Oest is the result of cooperation between the Innovation Task Group at IIASA and the Institute of Prognosis and Applied Research in Hannover, Federal Republic of Germany. Dr. Oest worked here at IIASA with the Innovation group for two months, during which the conceptual framework and the first draft of his study were completed. The main idea of the study is to prove and elaborate the relative efficiency concept of the Innovation Task Group. We hope that the results of this study will stimulate the empirical studies about the relation of concrete Innovation and Efficiency. The IIASA Innovation Group is hoping that the results of this will not only extend our knowledge about key technologies but will also help us to develop a common technology to assess technologies from the efficiency point of view.

Harry Maier
Leader of Innovation Group
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1. BASIC DESCRIPTION OF FLUIDIZED BED COMBUSTION (FBC)

The conventional methods of burning coal for power and heat generation are the following two processes. The older process--especially used in small coal power plants--is characterized by a grate which is moved through the steam boiler carrying burning solid pieces of coal. In the second process, which is used in almost every new big coal power plant, the coal is ground to dust and then blown into the combustion chamber. In both cases the heat is transferred to water tubes by radiation and convection. These processes have reached a high level of technical performance and there is no longer a major potential for further development and new appliances.

Fluidized bed combustion (FBC) is a new technique of coal combustion, which is just leaving the level of pilot studies and experiments. The following is a short description of the process. When a material consisting of small pieces of sand, ashes and coal with a size less than 6 mm is run through by gas, for example air, with increasing speed, the material gets into a fluid whirling condition if the speed is high enough. This condition keeps stable also by further increase of the gas speed until the speed is high enough to carry more and more particles out of the layer. Reaching the whirling condition the material begins to behave in a similar way as liquids; it becomes fluidized. An observer gets the impression of a boiling suspension. Coal can be burnt very intensively within the fluidized material. Therefore, the fluidized condition is maintained and operated in a special combustion chamber, which is characterized by a jet bottom the combustion air is blowing through with a pressure of about 10 atm.

The boiler tubes are dipped into the fluidized bed which reaches a height of between 0,6 and 3 m depending on the furnace and the speed of the combustion air. So a very good heat transmission is provided. The burning material, which is normally coal but may also be household waste, oil shale, tar sand, or gas, is brought in the fluidized bed from below or sometimes put just on the surface. Other material such as limestone, dolomite, ashes and sand is added in the same way. The coal must be crushed into pieces of less size than say, 6 mm up to 10 mm. In comparison with the conventional technique of coal combustion, FBC has the following advantages:

1. The whirling movement of the particles in the fluid bed leads to a heat transmission, which is significantly higher than it is with conventional coal burning methods. This allows a reduction of size and number of boiler tubes (Locke speaks of 75% saving in tube requirement) and enables smaller, more compact boilers and furnaces to be built with the same heat output as bigger conventional ones. Therefore, the specific investment is lower when the standardization phase has begun and a sufficient high number of combustion chambers are built.

2. When limestone or inferior quality dolomite is added to the bed material a high desulphurization of up to more than 80% can be obtained. The reason for this is that the limestone is changed to gypsum when it comes into fast, continuing contact with the burning coal particles. In conventional furnaces the desulphurization can only be undertaken when the smoke has already left the furnace. This results in high investment expenditure and a percentage drop in efficiency

3. The combustion temperature is between 800°C and 950°C, which is considerably lower than in other processes. This leads, on the one hand, to a lower output of NO_x. On the other hand the ash particles, having not been melted, remain soft and non-abrasive and provide little chance of forming hot spots.

4. The fluidized bed normally contains only 1% or even less of carbon. This makes it possible to burn almost every kind of coal. Even colliery tailings which until now are taken as waste, can be burnt. Also household waste is considered to be burnt together with coal in fluidized beds.

5. Fluidized bed combustion is especially suitable for decentralized combined production of power and heat. Combustion furnaces can be built even in densley populated areas, because the emission of SO_x, NO_x and dust is lower than with single heat systems for each building.

Although these are very important advantages, there are also some disadvantages which have to be mentioned:

1. Scaling-up fluidized bed combustion is difficult. Until now all FBC plants which are in operation have a steam output of less than 140 t/h with an electricity power of

30 MW_e. Already at this size the fluidized bed must be divided into sections because the fluidization does not work very well on a greater area.

2. The operation of part load seems to be better in the conventional processes. This is important for usage in industrial firms, because the load factor often changes very quickly.

3. The combustion in fluidized beds is not as complete as in conventional processes. One possibility to increase the burn-out of coal is a feedback of the ashes from the cyclus to the fluidized bed.

In spite of these problems there are already a number of FBC plants in different countries in operation. The next section gives an overview of the technological development of FBC and the state of the art.

2. TECHNOLOGICAL DEVELOPMENT--STATE OF THE ART

To a smaller extent, FBC has already been used in Chemics 60 years previously (see Schytil, 1961) which has been documented by the patents of Winkler in the 1920s. Apart of some special appliances, FBC reached a more general interest within the last ten years. In this period, 30-40 very different plants with FBC have been constructed.

Most of the technological work and investigations has been done in the UK, which can be cited as the leading country in FBC technology. With some years delay the USA and the FRG turned their technological interest to FBC and undertook additional efforts to improve FBC and to make it more suitable for applications in industry and district heating. Also Sweden and Finland have to be mentioned because there are plants for district heating already working since 1978. In Enköping (Sweden) a plant for district heating with a 25 MW fluidized bed combustion part began operation in May 1978. The boiler was constructed by the firm Kymi Kymmene in Heinola, Finland. However, it is said that the plant is working normally with gas and oil residues, as well as wood wastes and that it is not optimal for the usage of coal (see Fogelklou, 1978; Lindberg, 1977).

In the development of FBC two main directions have been undertaken: first, atmospheric fluidized bed combustion, and second, FBC under higher pressure. FBC under atmospheric pressure is much further developed than under high pressure and is performed in far more constructions. Figure 1 shows the more important power plants with FBC in the UK, the USA, and the FRG the year the operation began and the thermal power. The main results of analysis of the existing FBC power plants are the following:

-- Operation of FBC plants began in 1970 in the UK, in 1976 in the USA, and in 1978 in the FRG,

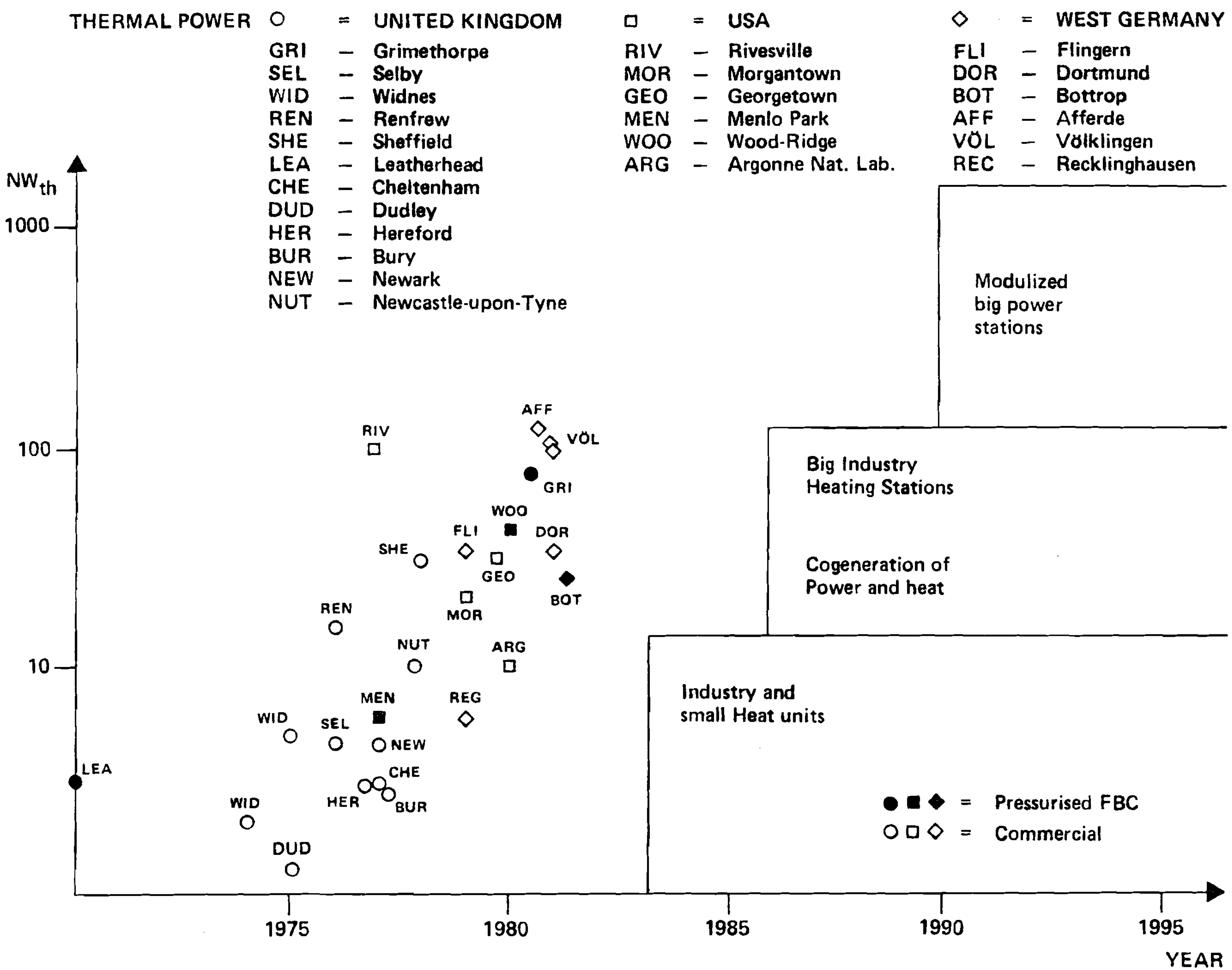


Figure 1 Important plants with fluidized bed combustion; beginning of operation; thermal power.

- There is a strong trend in scaling-up plant size;
- Commercialization is up until now, seldom and can only be found in the lowest power class;
- There are only very few plants with pressurized FBC.

The USA and the FRG could take advantages from the know-how, which the UK engineers had won in the lowest power class and so both could join the development process at a higher level. The FBC plants in Rivesville, Renfrew, and Flingern can be seen as the most important of those which are cited in Figure 1 and they are described in detail as follows.

The Rivesville Plant in West Virginia (USA) still ranks as one of the largest operating FBC plants all over the world. It is generating about 100 MW_{th} and produces electric power of 30 MW. The plant was financed by the Department of Energy (DOE), constructed by Pope, Evans and Robbins (PER) in cooperation with Foster Wheeler and is used as a demonstration unit. Operation began in December 1976. The boiler is said to be the first in which fluidized combustion technology has determine the design of the boiler (Gibson, 1977). The fluidized bed is separated into four sections, three of which are used for initial combustion, while the fourth is used for fly ashes which still contain 15% unburnt coal and are recycled and burnt up. A significant feature of the plant is the vertical arrangement of the four sections. The plant should give experience for the construction of a 200 MW plant after 1980. When the feasibility of vertically arranged fluidized bed calls is proved in a 200 MW plant, these modules shall be used to build a power station with an output of 600 MW or 800 MW. The Rivesville plant burns 14 tons/hour of coal to raise 136 tons/hour steam at a temperature of 496°C and pressure of 94 bar. Although there have been several shutdowns, most of which have been caused by problems not resulting from the fluidized bed, the results are said to be extremely encouraging. The shutdowns had been used to modify the fuel feeding system and to adjust the recycling section. The combustion efficiency is about 79% to 83% at multiple cell operation and 89% to 93% at single cell operation; this is somewhat low, but efforts are undertaken to improve the values. A desulphurization of more than 90% has been repeatedly obtained, while NO_x emissions have been a fraction of the allowable levels. In November 1978, the total hours of coal firing had already exceeded 2200 hours (see Pope, 1978).

The National Coal Board (NCB) of the UK had already constructed or supervised 16 FBC plants at the end of 1977, of which the Renfrew Plant in Scotland was the largest. The boiler produces thermal power of 16 MW. The construction was supervised by Babcock Combustion Systems Limited (BCSC) and the plant began operation in 1976. At the end of 1977 the plant had already clocked a working time of about 5000 hours. The boiler is divided into three sections, although there is no separation within the bed itself. The steam is produced with 28 bar and 300°C at a rate of 18 tons/hour. Total boiler efficiency is 80% but this value can be improved when new advanced boilers are constructed, because the existing boiler is a modification of an older one which had a wandering grate before. The efficiency had already been increased by some percentage with the modification to FBC. A desulphurization of up to 90% by adding limestone had been proved. There is no carbon burn up cell as there is at the Rivesville plant; however it is possible to recycle the fly ashes. The problem of getting sufficient part load results is solved by shutting down different sections and fields. By this, part load of 25 percent can be obtained. The plant was designed to get know-how for building larger plants of up to 160 tons/hour steam production.

The largest FBC plant in the FRG is adjusted to the heat station in <u>Flingern</u>, a suburb of Düsseldorf. Its thermal power is 35 MW. The plant is operated by Ruhrkohle AG (RAG) and Gesellschaft für Vergasung und Verflüssigung mbH (GVV), while it was constructed by Vereinigte Kesselwerke AG (VKW), which belongs to Deutsche Babcock AG. Operation began in the summer of 1979. Until the summer of 1980 different programs to get more knowledge about the behavior of the fluidized bed had been undertaken. Flue-gas desulphurization of up to 90% has been proved; however, a significant dependence from the sort of limestone has been found. The performance of the plant and the results have encouraged the building of three further FBC plants for similar appliances, i.e., combined heat and power generation. The Flingern plant produces 50 tons/hour steam at a pressure of 17 bar and a temperature of 460°C. The coal input is 6 tons/hour of high ash coal with about 35% ash. The fluidized bed is divided into four sections, each of which can be operated independently of the others, so that sufficient part load performance can be obtained. The fly ashes can be recycled to gain a better burn out of the coal. Figure 2 gives an overview of the technological design. The coal and limestone supplying system is very complicated and still a subject of further development. The whole project costs 18 million DM of which 60% had been sponsored by the German Ministry of Research and Technology.

The second main direction, the development of FBC under pressurized conditions, is not proceeded as far as FBC under atmospheric conditions. The heat transfer characteristics are much better under pressure than under atmospheric conditions. So the tube surface and volumina is in the boiler and as a consequence the total plant size can be reduced. The small plant size and tube volumina is the main advantage of pressurized FBC because it allows the saving of a significant amount of investment capital. In Figure 3, which is very often cited (see Schilling, 1977; Holighaus, 1977; Locke, 1974), a graphic estimation of the size relationship is shown.

In connection with pressurized FBC a gas turbine is necessary to relax the high pressure flue gas to atmospheric conditions. A result of implementing the gas turbine is an increase in efficiency of some percentage, because the better burn out of coal is reached and the temperature relations in the carnot process are better than in boilers with atmospheric combustion conditions.

The most progressive project of pressurized FBC is the <u>Grimethorpe Plant</u> in the UK, which was constructed by the

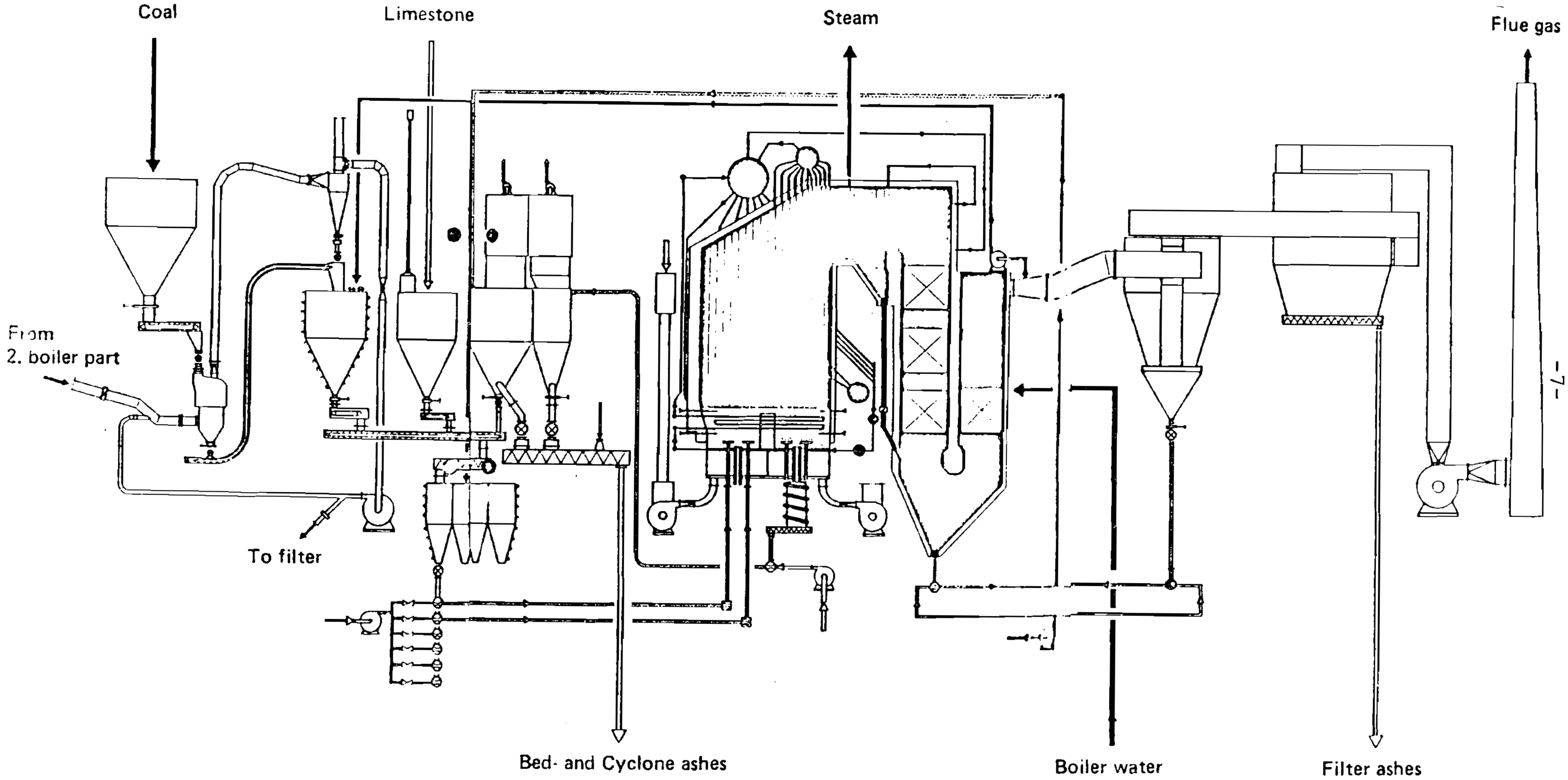


Figure 2   Flow chart of the fluidized bed combustion plant at Düsseldorf-Flingern.

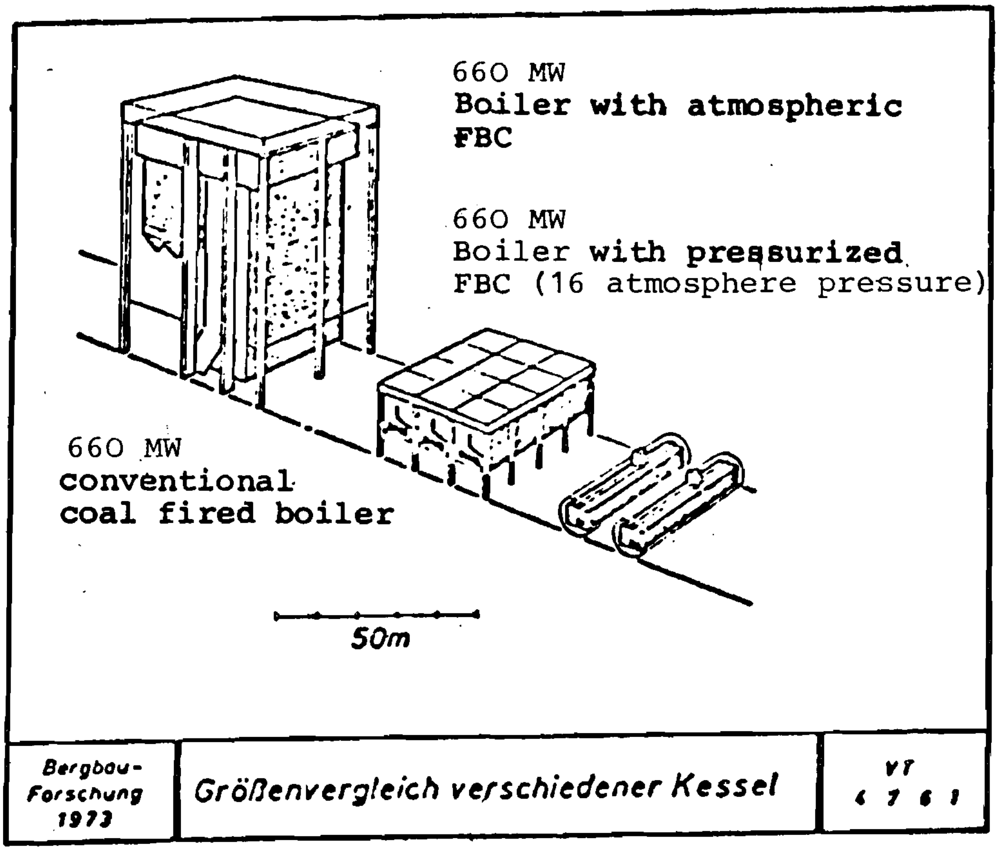


Figure 3 Comparison of different coal fired boilers

International Energy Agency (IEA) and financed by the National Coal Board (UK), the Department of Energy (USA) and the West German Ministry for Research and Technology. The plant will produce 80 MW_{th} under a pressure of 10 bar. It will be taken as a feasibility study for modules of future power stations with electric power of 600 MW.

For further investigations a smaller experimental plant is in construction in Bottrop at Haniel colliery (FRG). It will produce 25 MW thermal power at a pressure of 4,5 bar and is built by Arbeitsgemeinschaft Wirbelschichtfeuerung (AGW), which is a Co-Foundation of a boiler firm and the Ruhrkohle AG. The adjusted gas turbine will generate 3,5 MW electric power and will be used to investigate the turbine behavior over long running periods and produce values about the level of cleaning of the combustion gas, which is necessary to give a sufficient turbine performance.

Furthermore, the 13 MW_{el} unit incorporating a gas turbine, which is being built by Curtis Wright Corporation in the USA has to be mentioned as well as some smaller plants with about 3 MW thermal power. Among those the experimental unit at Leatherhead Laboratories of the NCB was already in operation in 1970.

Summing up, one can conclude that atmospheric FBC has left the experimental and pilot study level. As there are demonstration units with commercial background working a broader commercialization will start within the next few years. Pressurized FBC has not proceeded that far but when the Grimethorpe plant will produce good results, pressurized FBC will also come to the level of commericalization.

3. REASONS FOR THE INNOVATIONAL PROCESS OF FBC

If we want to analyze fluidized combustion as an example for innovations in the energy sector it is interesting to ask for the reasons which started the innovation process. It is obvious that these reasons had been different in the UK, the USA, and the Federal Republic of Germany.

In the UK where development had already begun in the early 60s, the search for new methods of using coal in power raising was the starting point. Investigative work began under the leadership of the National Coal Board (NCB), the British Coal Utilization Research Association (BCURA) and the Central Electricity Generating Board (CEGB). FBC soon emerged as the most promising new technology because of its simplicity, flexibility and potential economic advantages (see Gibson, 1977). It seemed most important to develop the new technique first for those applications which would show the most advantage over alternative systems. So development was directed on burning low grade and 'difficult' fuels, as:

-- high ash coals, where the ash content makes pulverized fuel firing difficult, if not impractical,

-- fuels with high alkali or other contents, where FBC offers a way of avoiding extensive boiler fouling or deposit formation,

-- waste fuels, sludges or slurries which are impossible to burn successfully in existing units.

Sulphur retention was a good side effect but not a driving power.

In the USA the first efforts to develop atmospheric FBC was widely sponsored by government. The reasons for the development of FBC are not as obvious as in the UK but it can be said that:

-- fundamentory research, and

-- the possibility to reduce investment costs in big power stations,

were the driving forces. So development work started at the laboratory scale studying NO_x and SO_2 emission and suppression, the life of materials in fluidized beds, etc., followed by highly valuable design studies and cost comparisons. On the other hand, the Rivesville prototype boiler with 100 MW thermal power was constructed to demonstrate the feasibility of building a module of multiple fluidized bed cells to produce about 200 MW. The future was seen in 600 MW or 800 MW power stations consisting of several modules for which the Rivesville plant was a pilot study.

In the FRG not very much had been done in the field of FBC before the first oil price crisis. After 1973, however, coal as an energy resource got a higher level of importance especially influenced by the first government energy demand prognosis. Furthermore, the situation had become better in the FRG for new activities promoting the usage of coal because almost all coal mining companies had transmitted their capital into one new firm, the Ruhrkohle AG (RAG), which was in the government's favor.

RAG developed a program for the market introduction of FBC in the FRG (see Schilling, 1978). The managers of RAG saw the following main advantages of FBC:

- After the first oil price crisis the difference between oil and coal prices had decreased and the OPEC-cartell seemed to allow further price liftings which would be much higher than those for coal. This situation allowed the way for a comeback of coal as an energy resource.
- Possibility of burning high ash coal, and colliery waste, such as flotation residues (see Asche, 1978).
- High desulphurization without expensive new components.
- Possibility to get back market shares in heat-generation especially district heating within the last quarter of this century, when oil will run short.

A comparison of the reasons for developing FBC in the UK and the FRG shows that in the UK desulphurization did not play an important role and that in the FRG it did. This difference must be dedicated to environmental laws in the FRG. These laws postulated for all coal fired power plants stronger than 400 MW a desulphurization unit. Desulphurization at big plants, however, seemed only possible by flue gas treatment which is expensive and causes a decline of efficiency. So the way which had been started in the USA with the Rivesville 100 MW_{th} plant showed the possibility of building big coal fired power plants without flue gas desulphurization. Seen in this way, it can be said that environmental laws contributed to the introduction of FBC in the FRG. Until now, there are no strong laws for desulphurization in coal fired power plants in the UK, so that the interest in FBC under this special aspect is still very low.

4. FLUIDIZED BED COMBUSTION IN THE CONTEXT OF INNOVATION THEORY

Schumpeter and others already stated in 1950 that technological progress and innovation are promoted predominantly by large firms and trusts (Schumpeter, 1950; Galbraith, 1952; Duesenberry, 1958). This theory is verified by the innovational process of fluidized bed combustion as far as it has developed until the present, because the process has the following features which, in general, support Schumpeter's theory:

- The development of FBC required a lot of research input and specialized scientists (for example, for the solution of problems of streaming dynamics), which can merely be provided by small firms.

- The danger that the research input will have no results is high. The risks can be borne when many different research projects are undertaken. This, however, is typical for large firms and not for small ones.

- The costs of research and development are high and need current profits from other parts of the firm. So, financial requirements have to be fulfilled which are bearable only by large firms.

- For large firms it is much easier to get governmental subsidies and support as well as credits from banks and other institutions than for small firms.

All these arguments are proved completely right in each of the three main FBC developing countries. The facts of the few FBC stations described in section 2 also support this theory.

A counter-argument is that the predominance of large firms with a monopoly-like strength do not need innovations and so such firms do not spend much activity in promoting innovations. This argument, however, does not hold true when new market areas and appliances are opened by the innovations. For FBC technology, this is indeed the fact. In the FRG and in the UK, Ruhrkohle AG and the National Coal Board have approximately the monopoly of the national coal market and FBC technology offers further market areas in the energy market as, for example, district heating and heat supply of firms (see section 5) and special applications (in the UK, see section 2).

Another point of interest within innovation theories is the question of defining and classification of innovation. Müller and Schienstock (1978) are orienting their typology of innovation on the social unit of an organization which is defined as a purposeful, open, socio-technical system. Thus, innovative changes may have the following organizational items:

- Organizational Purposes and Goals, i.e., innovative changes may concern an object reduction or enlargement, a change of priorities in a given object system, as well as specifying intermediate aims.

- Relationship Between Organization and Environment. Innovation can be done autonomously, in agreement with the environment, and induced by the environment (the case against the environment is included in autonomous innovation).

- Organizational Structure. Innovations mean the change of the elements of the organization system or a change of the interdependences of the elements of which the organization exists.

In this context the case of FBC concerns all three items. The organizational purposes and goals are changed because of the innovation of FBC--and here one has to determine strictly between innovation and invention--enlarges the object area of the promoting organizations (Ruhrkohle AG, National Coal Board, etc., boiler firms) from very large scale power plants belonging overwhelmingly to public electricity corporations to small and medium scale power plants belonging to firms, communities and public electricity corporations. Furtheron a change in the priorities in the object system of the coal mining corporations is, or will, be evolved by the innovation of FBC. The object system until the present time is characterized by the electricity generating sector and for special coal sorts as, for example, cooking coal by the steel production sector as well as a lot of less important applications. FBC offers the way into almost all heat consuming applications beginning at a minimum size of approximately 3 MW_{th} which are, until now, less important because most of the heat in this field is produced with oil. Zintl (1970) postulates a necessary condition for an innovation: innovation has the task to improve the situation of the innovating organization, and to enlarge its autonomy. Considering the described aspects of FBC, this postulate is obviously fulfilled by FBC.

As far as the relationship between organization and environment is concerned the case of FBC is an example for an innovation which is induced by the environment of the innovating organization because:

-- the oil prices have risen to such a high level that the inventions in the field of FBC offered a cheaper way to heat production,

-- the ecological and environmental movement caused the first laws for retention of SO_x, dust and other emissions. If this trend continues, then the main market areas for coal are threatened. Thus, innovating FBC is a strategy to avoid emerging problems,

-- the supply situation has become unreliable and more and more dependent on political circumstances. Coal, the input energy for FBC, however, is sufficiently available in all of the FBC innovating countries (except Sweden) and also available on the world market. A physical shortage as can be foreseen for oil, is not evident for the next 200 years. Thus, a situation similar to that which marks the oil supply cannot be expected, although short-time supply problems may occur as a result of too slowly extended mining capacities.

The organizational structure of the FBC innovating organizations is concerned because FBC corresponds to other market areas, i.e., the coal selling organization will have a lot of small and medium size customers in the case of FBC instead of a few large sized customers such as public electricity corporations and steel production corporations in the conventional case.

The discussed items are similar to Schumpeter's (1961) description of innovation: innovation includes the case of a new commodity as well as opening up new markets or a new type of organization as well as a fusion. From this viewpoint two items have to be distinguished in the case of FBC. First of all for the coal mining corporations FBC offers new market areas for the sale of coal especially high ash coal and sulphuric coal (the fact that parts of this market belonged to the coal companies in the 50s is no longer important because they had been definitely lost to oil in the 60s). Secondly, for the boiler producing industry FBC offers a new market area because FBC gives the possibility to supply many urban districts with heat in cogeneration with electricity; districts which are up until now provided with single furnaces using oil or gas or direct electricity. How can FBC be classified in the context of innovation theory?

The most used classification of innovation is the distinction in basic, improvement and perhaps pseudo-innovation (Mensch, 1975; Haustein, Maier, 1979). The terms basic innovation (sometimes also called revolutionary innovation), however, is not defined uniformly. Haustein and Maier (1979) propose to call basic innovations such major technological changes which:

-- are based on fundamental and applied research,

-- have a well defined high range of application,

-- are connected with new scientific-technological principles of a different order.

Thus, Haustein and Maier restrain basic innovations (BI) to technological changes.

Uhlmann (1978) proposed to call such technological changes BI when new scientific knowledge is incorporated or applied in the technology concerned. Last but not least, Mensch (1977) defines BI more narrowly: BI are innovations, which lead into new industrial areas. The term improvement innovation (sometimes also called routine innovation (Uhlmann, 1978), or evolutionary innovation) needs no further explanation because it is clear from the context in each of the three cases. Pseudo innovation is first discussed from Haustein and Maier: "In reality we have some innovations, seemingly appropriate to meet the goals of the socio-economic system or subsystem, but having a negative influence on it over a longer time. Its primary or secondary consequences damage the efficiency of the system".

In this classification system it is difficult to decide if FBC is a basic or improvement innovation. If one takes the Mensch definition it is obviously an improvement innovation because it does not lead to new industrial areas as, for example, the innovations of television or nylon. From the Uhlmann viewpoint, however, FBC is a BI, as scientific progress is incorporated (desulphurization in the burning process, completely new combustion chamber, etc.). In the sense of the first definition FBC is a BI if one looks on the set of technologies concerning the combustion of coal, but it is an improvement innovation if the whole field of coal usage as an energy resources is concerned. Thus, it turns out that the classification system is up until now not sufficiently based because different definitions are broadly used and the standpoint of view may decide the question whether an innovation is basic or improving.

Another field of investigation in the theory of innovations is the analysis of the process leading to an innovation. This process is divided in four steps:

-- Research (basic, fundamental, non-product directed);

-- Invention (laboratory proof, test results or test groups);

-- Pilot Projects (dissemination of results, <u>proof of efficiency</u>);

-- Market Diffusion.

A high sensitive point in the queue of steps leading to an innovation is the question of efficiency. Following the efficiency model of Maier (1979,1980) an invention will not become an innovation if the efficiency of the new process is not higher than the average efficiency of the production system as a whole. This predominantly mental model needs, however, mathematical interpretation. So we define efficiency as an n-dimensional vector e with the following groups of components:

-- efficiency of material flows

-- energetic process efficiency (energy necessary for the process itself)

-- informational efficiency

-- economic efficiency

-- social efficiency.

Efficiency is measured by the proportion of total output to input, i.e., for example:

$$e^i = \frac{\text{total output}}{\text{i input}} \quad . \qquad (1)$$

Where e^i is the i-th component of the vector e.

The average efficiency of an economic sector is defined in the same way. In this case the vector e is similar to the reciprocal of the vertical coefficients of an input output matrix. A problem is the embedding of environmental and ecological relationships in this theory. Of course, higher efficiency cannot mean higher emissions of, for example, SO_x. But innovation has to be seen in the context of economy and operations research, and in this context environment is embedded by laws. This means that if there is a law which forbids an emission of SO_x, then those technologies will be the most efficient, which fulfil the law with the lowest amount of costs or efficiency losses.

A new technology or an invention can be compared with the average efficiency of the sector concerned by comparing the different components of efficiency. It may happen that in one component the new technology has a better efficiency while it is worse in another component. In this case we can come to a decision whether the new technology is better or not by weighting the n components with weights:

$$\{g^i | i = 1, \ldots n\} \quad \text{with} \quad \sum_{i=1}^{n} g^i = 1 \qquad (2)$$

and defining for the new technology $e_j = \{e_j^1, \ldots e_j^n\}$ and the average or sectoral technology $\tilde{e} = \{\tilde{e}^1, \ldots \tilde{e}^n\}$ the ratio

$$\frac{e_j}{\tilde{e}} = \sum_{i=1}^{n} g_i \cdot \frac{e_j^i}{\tilde{e}^i} \qquad (3)$$

which we call dynamic efficiency. We can now say:

- -- the efficiency of e_j is equal to the average efficiency when $\frac{e_j}{\tilde{e}} = 1$
- -- it is better than the average efficiency when $\frac{e_j}{\tilde{e}} > 1$ and
- -- it is worse than the average efficiency when $\frac{e_j}{\tilde{e}} < 1$.

Thus the innovation process will have the graph as shown in Figure 4 with the five different stages well known from the mental model of Maier (see Maier, 1980; Haustein and Maier, 1979). Phase I is determined by the invention for which the laboratory proofs are fulfilled. At the end of Phase I pilot projects show the possibilities to reach higher efficiency. At the beginning of Phase II demonstration plants or units show the higher efficiency and organizations begin to apply the innovation. In Phase III improvement changes supersede the foundation phase. In Phase IV only improvement changes take place, while the technology concerned becomes standard, i.e., $\frac{e_i}{\tilde{e}}$ tends to decrease to 1.

Analyzing FBC in this context one can distinguish the following market regions:

1. Combustion of residues and waste in industry, especially in collieries.

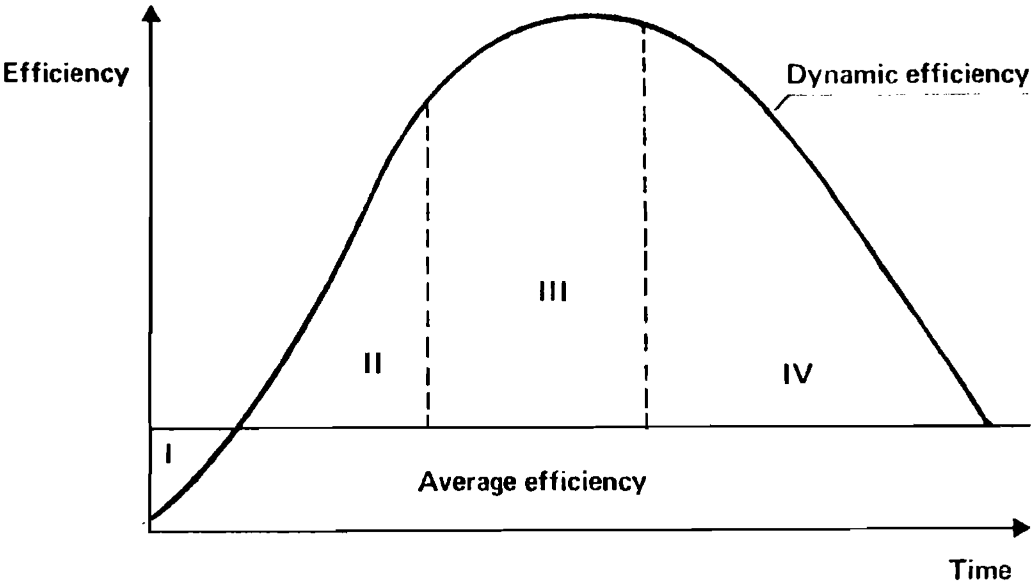


Figure 4 Relationship between efficiency of an innovation process (technology e_j) and efficiency of the production system as a whole over time t.

2. Block heating units for groups of connected households and small scale users.
3. District heating, combined heat and power generation.
4. Big power plants with several pressurized FBC models.

5. EFFICIENCY COMPARISON BETWEEN FBC AND COMPETING TECHNOLOGIES

5.1 Replacement of Oil-fired Boilers by FBC Boilers in the Energy Station of an Automobile Plant

In industry, a great number of combined power and heat producing energy stations are actually heated with oil and gas or sometimes with coal. As FBC is only a boiler technology, it is possible to change the heat station in an existing power plant to an FBC heated system and use the other parts of the system (turbines, building, heat distribution, etc.) without further change.

This operation was planned for the power station of an automobile plant in Hannover, FRG. This plant covers an area of approximately 1 km^2, where a working area of 0.3 km is under cover and 18,000 persons are working at this plant.

The heat consumption is fully covered by a plant owned energy station (some production data of this station are shown in Table 1). Electricity consumption in relation to heat is too high, so that nearly half of it must be bought from external public power plants. The energy station consists of seven independent oil heated boilers with an output of 58 metric tons of steam/h. These boilers serve eight independent turbines with a maximum electricity load of 48 MW. In 1978 the energy station burned 67,700 metric tons of fuel oil. The internal status quo price of one unit of heat and electricity is calculated from partial costs, as shown in Table 2.

Table 1 Energy production within the automobile plant in GWh

Energy Type	1977	1978	Maximum 1970-1978/ Minimum 1970-1978
Electricity	136	154	185/130
Heat below 130°C	154	182	220/150
Heat over 130°C but below 160°C	200	210	290/198

Table 2 Status quo costs of the energy station in 1978

		10^6 US dollars
Gas oil costs (114 US$ per metric ton)		7,73
Repair and spare parts		0,57
Manpower cost, capital costs and other general costs		6,41
Total costs:		14,71
Cost of one unit of electricity (MWh)	US$	71,19
Cost of one unit of heat 130°C (MWh)	US$	8.503
Cost of one unit of heat 160°C (MWh)	US$	10.492

It must be analyzed if the replacement of the present boiler-system by FBC-boilers can lower the costs shown above. To simplify this calculation it is assumed that manpower costs and other general costs of the power station hold their level after the replacement. This assumption is very conservative, as the 75 technical employees in the present power station are mainly occupied with repair and maintenance of the 20 year old machines. So it seems to be sure that manpower costs of the new FBC boiler system can be lower.

The technical construction and the investment volume of the FBC boiler system was done by "Vereinigte Kesselwerke AG" in Düsseldorf, FRG. The former six boilers are replaced by only three boilers with an output of 140 metric tons of steam per hour each. Table 3 gives an overview of some technical data.

Table 3 Technical data of a 140t steam/h FBC boiler

1. Primary Energy	Hard coal
1.1 calorific value	20.930 KJ/kg
1.2 water content	4.6%
1.3 ash content	35-45%
1.4 sulphur content	0.8%
1.5 size of coal pieces	10 mm
2. Preparation of the Fuel	
2.1 size of ground coal dust	0-6 mm
2.2 residual water content	3%
2.3 ground limestone added	8%
3. FBC Combustion Unit	
3.1 fuel quantity	5.6 kg/sec
3.2 temperature of combustion air	210°C
3.3 air speed	2.0 m/sec
3.4 fluidized bed temperature	850°C
3.5 height of the fluidized layer	1.2 m
3.6 surface of the fluidized bed	72 m^2
3.7 number of sections in the fluidized bed	6
3.8 flue gas temperature	160°C
3.9 flue gas quantity	56.5 kg/sec
4. Boiler Unit	
4.1 steam quantity	140 t/h
4.2 steam pressure	95 bar
4.3 steam temperature	530°C

Figure 2 gives an overview of one FBC boiler and the fuel transportation construction. The value of the total investment of three new FBC boilers, including transportation of all the parts and the costs of the coal depot is (in 1980 prices) US\$37.29 x 10^6. (All government subsidies which are granted in the FRG are not considered.)

The following cost comparison of the existing plant with a hypothetic FBC driven plant is made under the assumption that the new FBC boilers have already been installed in 1980. For this comparison the capital costs of the FBC boilers and capital costs for the existing boilers have to be accounted for. The existing boilers have been constructed in 1960 (average) at a price of 5.7 x 10^6 US\$. The average lifetime is 25 years. Taking an average inflation rate of 5% per year into account the value of the old boilers in 1980 is 3 x 10^6 US\$. So investment volume of US\$ 3 x 10^6 for the old boilers and US\$ 37,29 x 10^6 for the FBC boilers have to be compared. They are calculated with a fixed interest rate of 3% and a further interest rate of 4.5% to compensate inflation, which is assumed to be on an average rate of 4.5% over a long period of time and which is specific for the situation in the FRG. Depreciation is linear over a lifetime of 25 years with 4% per year. So capital costs for the old boilers are 0,35 x 10^6 US\$/a and 4,34 x 10^6 US\$/a for FBC boilers.

Fuel costs are based on an energy input of 98,000 TCE corresponding to 70,000 metric tons of gas oil and 165,000 metric tons of high ash coal (45% ash). The 1980 price of gas oil is 169.5 US\$/t so that the fuel cost for the oil boiler amounts to 11,86 x 10^6 US\$. The 1980 price of high ash coal is 59,82 US\$/t including freight rates from colliery to the automobile plant. High ash coal is subsidised by government with 24,3 US\$/t.[1] Thus, fuel costs for FBC boilers amounts to 5.86 x 10^6 US\$. It was already mentioned that all the other costs (manpower and general costs) are assumed to be equal for the two systems. Table 4 shows the direct comparison of the two different technologies in 1980.

Table 4 Cost comparison of the oil-fired boilers and FBC boilers in 1980 in 10^6 US\$

	Oil boiler	FBC boiler
fuel costs	11.86	5.86
capital costs	0.35	4.34
Total costs	12.21	10.20

[1] There are further subsidies in the FRG (handling support for coal combustion, investment support for coal fired power plants) which are not taken into account in this paper. Thus, a comparison to the situation in other countries can be done in an easier way.

The cost advantage of 2×10^6 US$ is fully induced by the lower fuel costs of the coal technology and not by the FBC system itself. Hence, capital costs of FBC are higher than the normal coal combustion so there must be other advantages to strengthen the total efficiency gain of FBC.

In section 1, it has already been mentioned that by using the FBC technology in a very simple way a higher degree of desulphurization can be obtained. In normal coal boilers the flue gas desulphurization method is used. This method needs a special unit, is cost intensive and lowers the plant efficiency by approximately 2%. If compared, the investment costs of the FBC technology are at the same level or a little lower than those of this second way. However, a desulphurization is normally not prescribed, although there is a trend to stronger environmental laws. For example, in the FRG a desulphurization is prescribed for plants producing more than 400 MW_{th}. Table 5 shows the main components in the emitted flue gas induced by the combustion of 1,000 TCE.

According to the higher share of ash, the emitted dust quantitites are higher when using the coal technologies. On the other hand, the emission of SO_2 is much lower using the FBC technology. The amount of SO_2 emission is more than 100 times higher than the dust emission so that only this advantage of FBC may allow the change to a coal technology in areas where the environmental laws prevent higher rates of air pollution.

Finally it is possible to use for FBC high ash coal of which the availability is higher than for most of the other types of primary energy. This type of fuel may have also the lowest rate of price increase especially compared to oil and gas.

5.2 Efficiency Comparison Between an FBC Heated Combined Power Plant and Individual House Heating

The efficiency of a combined power and heat station together with a district heating net and individual house and room heating of an urban district in Hannover (FRG) are compared in a second case study (Möller, Oest, Ströbele). The difference to the first case study is the much higher investment volume of a totally new power plant and a heating net, compared with only the change of the boiler system as described in section 5.1.

Table 5 Flue gas components depending on different boiler technologies for combustion of 1,000 TCE

	gas oil fired	normal coal fired	high ash FBC fired
SO_2	14,65 t	16,22 t	7,91 t*
dust	0,106 t	0,1796 t	0,186 t

* according to a value of 0.85g sulphur/m^3 flue gas ≙ 70% desulphurization; 90% desulphurization (= 258 t) are already reached in smaller demonstration plants.

The status quo costs of the used individual energy supply system are shown in Table 6.

The energy demand for heating of the housing district and the industrial area is 700 TJ per year. This demand, actually covered by the enery types shown, should be settled by a new combined heat and power FBC station together with a new district heating net. The produced electricity is going to the public electricity net.

Construction and investment calculations of the new FBC station was done by Kraftwerk Union AG, Erlangen, FRG. Figure 5 shows the externals of the station and Figure 6 gives an overview of the energy flow. Table 7 shows the parts and the investment volume of the whole station and the district heating net. Capital costs are calculated with 4% depreciation and 7.63% total interest (3% real interest and 4.5% compensation of inflation). Depreciation and interest together gives an amount of 6.57 x 10^6US$ per year.

To produce 700 TJ heat for the private and industrial customers, the FBC station needs a primary energy input of 92,300 metric tons of high ash coal (45% ash). Including the same government subsidies and transportation costs as in the first case this primary energy input induces yearly fuel costs of 4,29 x 10^6US$.

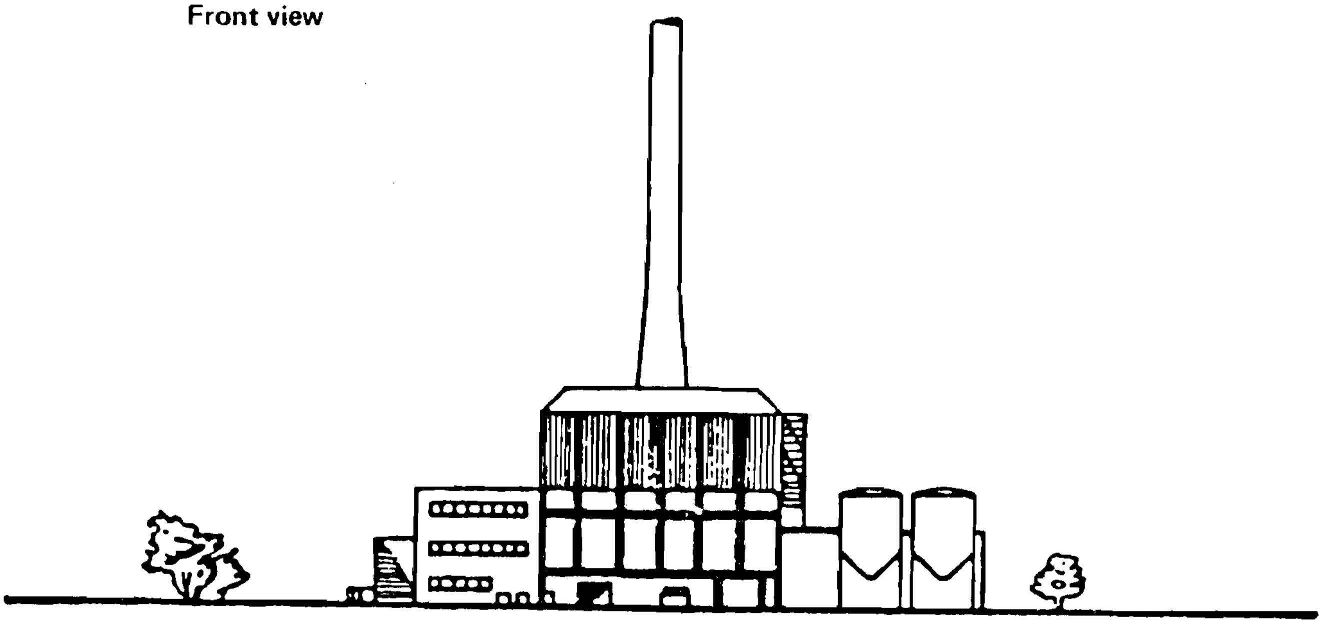
Manpower costs are induced by 45 people. Forty people are necessary to run the FBC station, five people are necessary for the general organization. Assume that each person has a gross salary of 33,900.- US$ per year (including all social costs) overall yearly manpower costs are 1,53 x 10^6 US$.

Other general costs like taxes, insurance, etc., are according to other combined heat and power plants, US$50 per year and installed KW_{el}. This gives a total of 1.13 x 10^6 US$. Table 8 shows the total costs of the whole FBC station.

Table 6 Energy supply costs of an urban district in Hannover (FRG) with 15,000 people and an industrial area with 1,000 working people in 10^6 US$

Gas 200 GWh	3.84
Oil 31 GWh	0.90
Coal 685 metric tons	0.06
Capital costs, depreciation and maintenance	0.56
	5.36

Front view



Side view

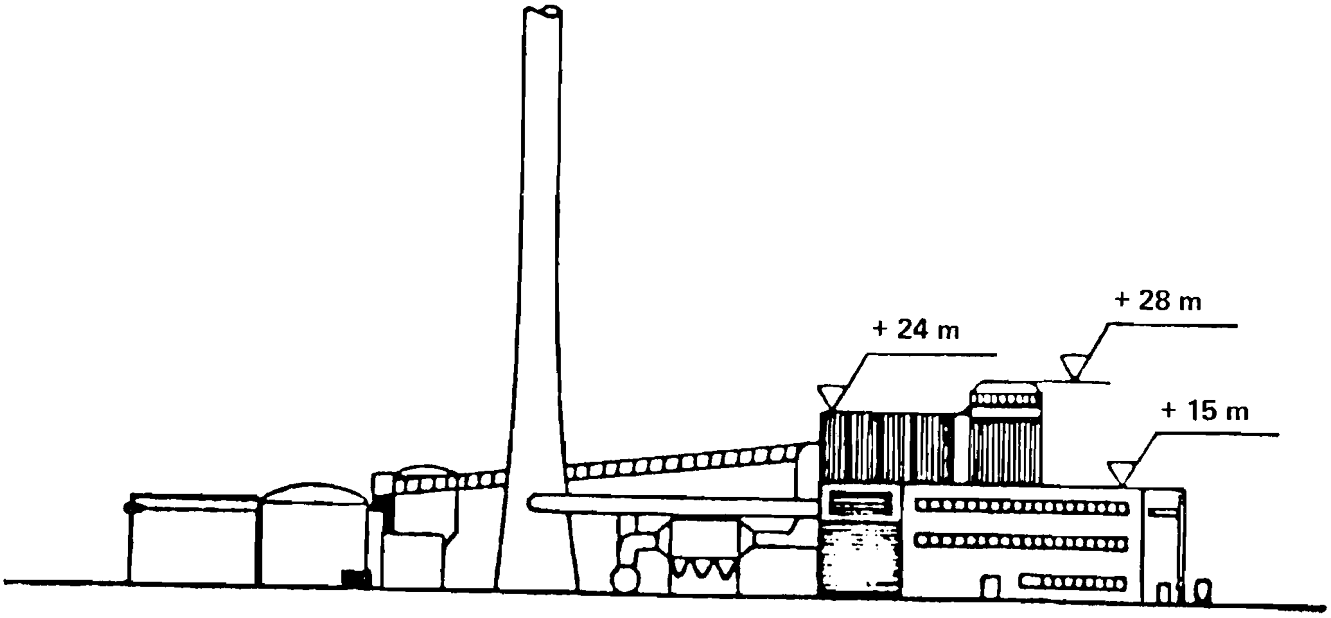


Figure 5 External view of the new FBC station in FRG

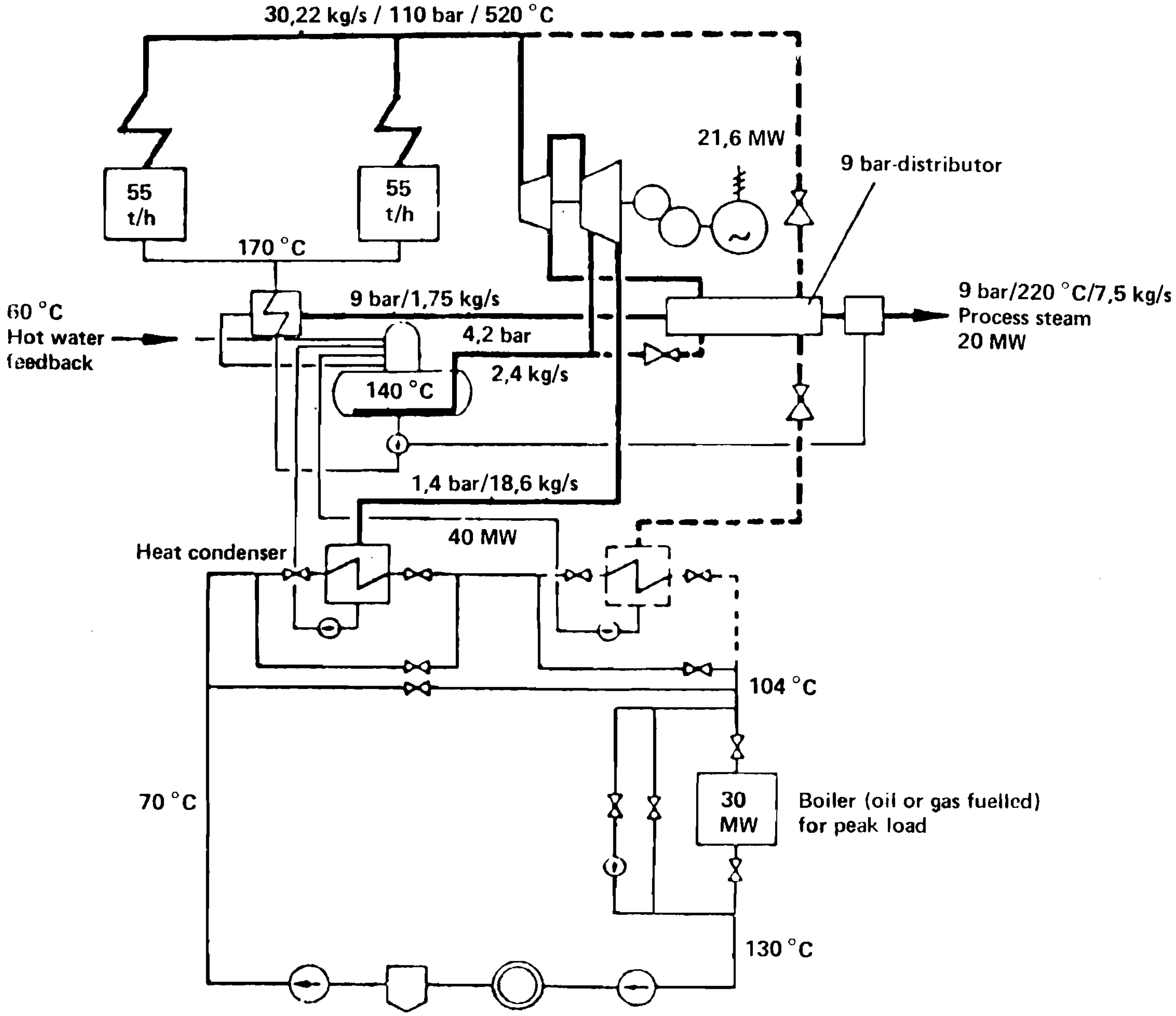


Figure 6 Overview of energy flow of FBC station in FRG

Table 7 Investment volume of a 60 MW_{th} and 22 MW_{el} FBC heat and power station together with the district heating net

Part of the investment	Financial volume in 10^6 US$
Planning fees	1.98
Building	11.69
FBC boiler	10.79
Turbine and other machines	11.53
Electric installation	3.39
District heating net	14.12
Other small parts	2.99
Total investment	56.49

Table 8 Total costs of the FBC in 10^6 US$

Fuel	4.29
Capital costs and depreciation	6.57
Manpower costs	1.53
Other general costs	1.13
	13.52

The costs shown above are induced by the production of 700 TJ heat (at the customers side) and 52.5 GWh electricity (according to 2,400 h full load of the turbine per year). The heat is delivered for the same price to the customers as already shown in Table 6. Additional revenue comes from the production of 52,5 GWh electricity, which can be sold at a price of 0.05 US$ per KWh. Total revenues (at the 1980 price level) are shown in Table 9.

The deficit of the FBC technology compared with the cost of the individual heating is 5,53 x 10^6 US$. This deficit is mainly induced by the high capital cost of the new technology. Fuel cost of FBC is already 0.51 x 10^6 US$ lower. So a much higher cost advantage of coal against gas oil is necessary to equalize the overall deficit. This is possible when imported coal, which is much cheaper than those produced in the FRG, is taken.

Finally it must be proved, if the environmental situation would be at least the same when the new FBC station will replace the individual heating of the district. The situation becomes more complicated, as emissions of the production of 52.5 GWh electricity must be calculated from the coproduction on the FBC side and not on the individual heating side. To get a fair comparison the emission coming from the production of 52.5 GWh electricity in a normal coal heated power plan must be added to those coming from the individual heating. The comparison is shown in Table 10. All emission values are better using the FBC station, so that in this case FBC seems to be the best coal combusting technology to serve districts with high population density.

Table 9 Revenue from the production of heat and electricity produced in the FBC station in 10^6 US$

Heat (700 TJ)	5.36
Electricity (52.5 GW)	2.63
Total Revenue	7.99

Table 10 Parts of total emission of individual heating and an FBC station producing 700 TJ heat and 52.5 GWh electricity in metric tons per year

Emission parts	Individual heating	FBC station
Dust	16.5	9.5
CO	12.0	< 0.1
NO_x	166.0	39.1
SO_2	406.5	335.0*

* According to a grade of desulphurization of 72%.

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