TECHNOLOGICAL CHANGE IN STEAM POWER GENERATION:

A research strategy for the study of certain innovations

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Purpose and basic outline

The purpose of this paper is to present a general conceptual framework for a study of technological change and the role of certain innovations in steam power generation.

The paper is divided into four parts. In part 1, some basic technological features of steam condensing an back pressure plants are discussed. The concept of thermal efficiency is presented along with the theoretical possibilities of improving it in the two types of plants.

The continuity of the development of the steam condensing process is one of its main features. Higher temperatures and pressures have been one of the main guide lines for engineers and and constructors. A synopsis over the development of the boiler is given in Appendix A. A description of the development of some major plant characteristics from the beginning of the 1960's referring to the United States but applicable also to other countries is presented in part 2.

After the descriptive part of the paper, the major concern is to make the necessary abstractions in order to present a research strategy. In part 3, therefore, the special conditions influencing the introduction of new technology in the power sector are discussed. It is found that new technology is introduced mainly in new plants because changes in old plants usually prove too expensive.

In part 3, an attempt is made to structure a model of technological change in steam power production. First, the special conditions influencing the introduction of new technology in the steam power sector are discussed.

Then attention is turned to the problem of the choice of technology and the considerations entering into this choice. Thirdly, some measures of technological change are proposed, namely certain technical parameters, and an example is presented to show how technological change can be analyzed through a study of such technical parameters. Fourthly, a two-step research strategy is proposed in shich the first step is an analysi of the development of the steam generating process during the 1960's and 1970's and the second step analyzes the role and determinants of certain innovations in this process. The basic data requirements are also indicated. The strategy implies that emphasis should be laid on studying the developmen of the process of steam-power generation, thus considering the effects of th total stream of innovations during the studied period. In the second step, some innovations are picked out for more detailed investigation of the innovation process. Fifthly, data on steam power installations in Sweden in the last 10 years are presented.

Finally, in part 4,a basic description of six important innovations within burner, boiler, turbine, and generator technologies is presented.

1. Basic Concepts of Steam Power Generation

1.1. The steam condensing cycle

The steam condensing cycle is the physical base around which a steam power plant is built. There exist mainly two types of steam power plants:

1. Steam condensing plants (see figure 1).
2. Back-pressure plants (see figure 2).

Figure 1. Simplified description of water and steam flow in a steam condensing plant

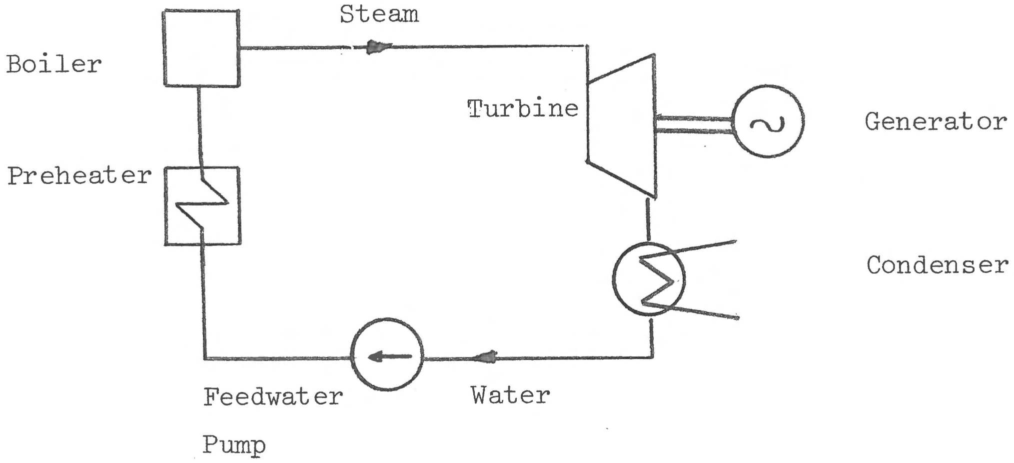
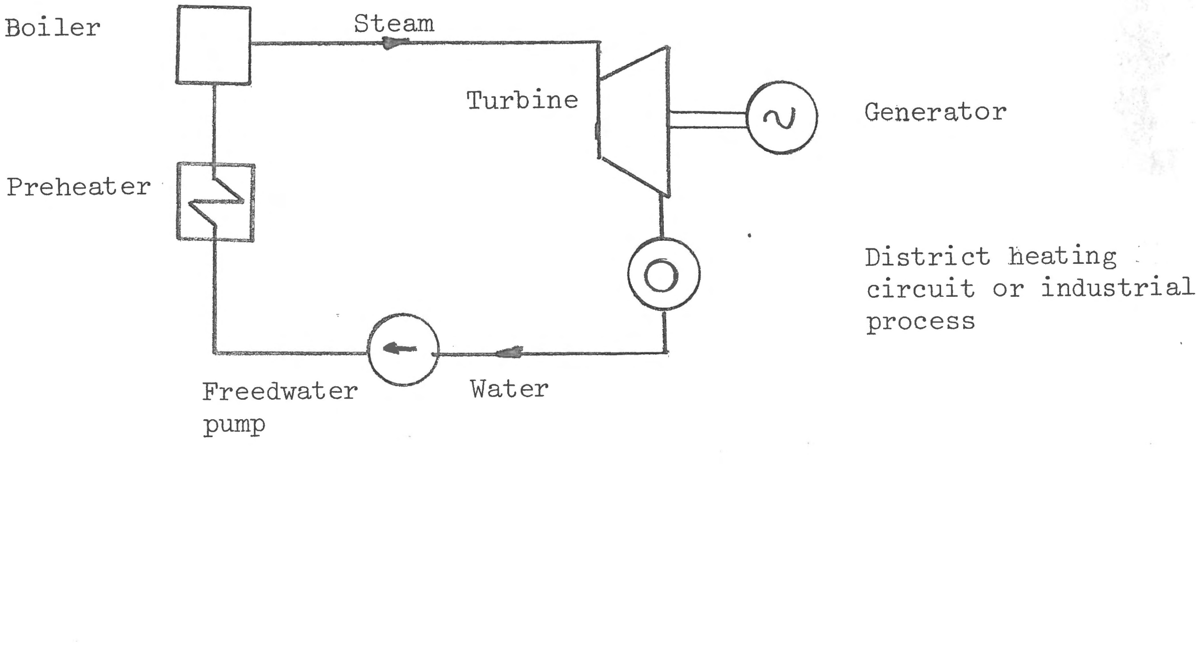


Figure 2. Simplified description of water and steam flow in a back-pressure plant



The two types work principally in the same way but differ in the manner in which cooling heat is used. Energy bound in the fuel is converted into thermal energy through combustion. Heat is transited in the combustion chamber through radiation to the side wall tubes and through convection[1)] to the overheater. The overheaters are usually placed on top of the boiler. In the overheater the steam is " dried" which means that its temperature is raised above the condensing point. The steam which now has a high temperature and is under high pressure is forced to pass through a turbine before it reaches the condenser. The condenser is a heat-exchanger which in a concenser plant usually is cooled by a nearby river. Steam now condenses to water. This water returns to the boiler. The power which is possible to receive out of the turbine depends to a large extent upon the capacity of the condenser unit. In a back pressure unit, pressure is applied after the last turbine unit to permit steam to be distributed for district heating or industrial purposes without condensing in the distribution system. This means that pressure and temperature must be increased before the first turbine in order to compensate for the higher pressure in the back end of the turbine. The higher technical requirements on the back pressure units due to the higher thermal load are compensated by the higher efficiency in the use of total delivered energy.

1.2. Thermal efficiency

One of the central concepts in thermodynamics is thermal efficiency. It is a measure of the degree to which energy put into a process is converted into useful energy (i.e. in a form which can be utilized). In modern condensing power units the thermal efficiency lies around 40 %. In back-pressure units the equivalent measure stays around 80-90 %. The maximum theoretical thermal efficiency (MTTE) is 100 % in a back-pressure unit while in a condensing unit MTTE asymptotically reaches 100 % with higher

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[1)] Energy transportation due to transition of thermal movements of atoms from hotter to colder media.

pressure and temperature. With present normal pressures and temperatures, the theoretical maximum lies at around 60 % in condensing units due to the fact that steam must be cooled to make the process work at all.

1.3. Raising thermal efficiency

Naturally, a unit with maximum theoretical efficiency would not be profitabl to build today, since the required capital investment would be enormous. The present level of 40 % for the largest units in Sweden doesn't necessarily need to be final in any manner, but it seems to reflect an optimal level with respect to the capital prices and the cost increased thermal efficiency with present technology.

Steam condensing processes permit an increment in thermal efficiency basically in two ways, namely through:

1. Higher temperature and pressure in the process
2. Diminishing the amount of thermal losses through boiler walls, turbines, tubing etc.

By increasing temperature and pressure (type 1 measures), it is possible to increase that part of the fuel inputs which is converted to steam while reducing cooling looses.

Type 1 measures involve difficult technological problems since modern plants work in a pressure range close to the so called "critical pressure". The critical pressure is the pressure (~ 221 bar) where water only exists as steam. This means that no boiling takes place in the usual sense by the addition of energy.

Technological development or a change in energy prices in relation to capital could, however, push forward a development towards more frequent use of "overcritical" boilers with higher thermal efficiency.

Water in overcritical boilers exists only as steam. This means that at all temperatures no density differences exist. There is no need for stea separation and the dome is therefore superfloucus but pumps have to be installed to garantee circulation. The boilers are constructed as pass-through boilers (see innovation list) with forced circulation.

Engineers and experts in power generation with an outlook over the development during the sixties consider it a period of working for "thermal efficiency at any price". A main subject of interest must therefore be to study whether this has been the goal in all three countries in this project an whether there are any major differences in the actual development which can be explained by differences in the economical, technological and social surroundings.

Type 1 measures have somewhat different effects in condenser units than in back pressure units. In a condense plant, no use is made of cooling heat, and it is therefore desirable to keep cooling looses to a minimum. In a back pressure unit where excess heat is utilized it does not matter _in principle_ whether the energy bound in the fuel is converted to steam for electricity generation or steam for district heating or some similar purpose However, the prices on these two outputs are normally such that a premium is put on electricity generation rather than on steam generation for distric heating purposes. This tradeoff will be discussed in more detail later in this paper.

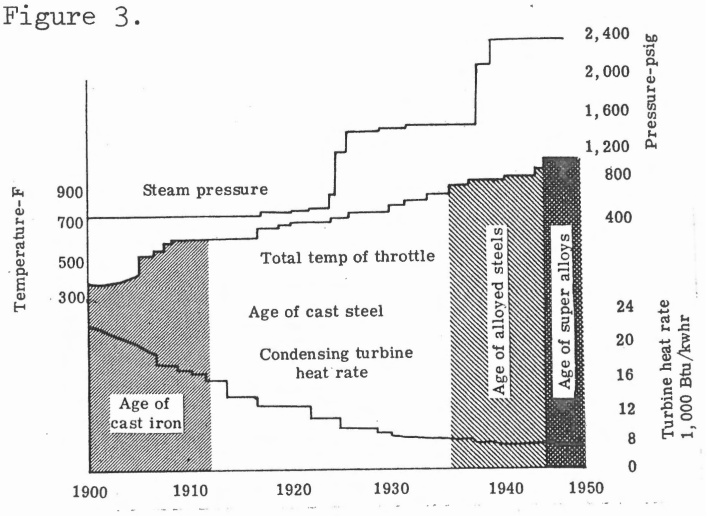
Type 2 measures include the installation of better insulating materials, better design of equipment, etc., in order to improve thermal efficiency. These measures are equally important in condenser and back pressure units. They can be regarded primarily as a means to substitute capital for energy.

2. Brief Survey of the Technological Development in Steam Power Plants[1]

2.1. The historical development up to 1960

Since the invention of the steam engine in 1705, steam has been used as an intermediate medium to transform chemically bound energy into mechanical energy. Despite the fact that they are over 200 years apart, there is a traceable continueity between the most modern steam power plants and the oldest coal fired bilge-pumps. The physical properties of steam have been known for a long time and engineering efforts have been directed at making use of these to make the process as efficient as possible. The relation between higher temperature and pressure on the one hand and better thermal efficiency on the other has provided strong incentives to improve materials, construction methods, welding techniques,etc. Figure 3 illustrates the steady increase in operating pressures and temperatures in turbines (and boilers) between 1900 and 1950. In addition, it illustrates developments in metallurgy. Finally it presents an indication of the improved thermal efficiency of steam plants due to countless improvements in boilers, turbines generators and auxiliary equipment.

Figure 3.



Source: Electrical World Editorial Staff, The Electric Power Industry (New York: McGraw-Hill, 1949), p.28.

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[1] For a more detailed survey of the historical development of steam power generation, see Appendix 1.

Figures 4 and 5 show two quite different units. Figure 4 shows the steam engine invented by Thomas Newcomens 1705 and figure 5 shows the boiler of a middle sized plant for oil combustion made in 1962. However superficially different these two units may seem, they have the steam-condensing cycle in common which makes them very much alike from a technical point of view. The difference between them represents the summed up result of a development influenced by a large number of factors. Due to the fact that the steam-condensing cycle has stayed unchanged and that the "inner" conditions of the process are therefore fixed we have a unique opportunity to study the influence of "outer" factors such as changes in prices etc. on the technological development of the process.

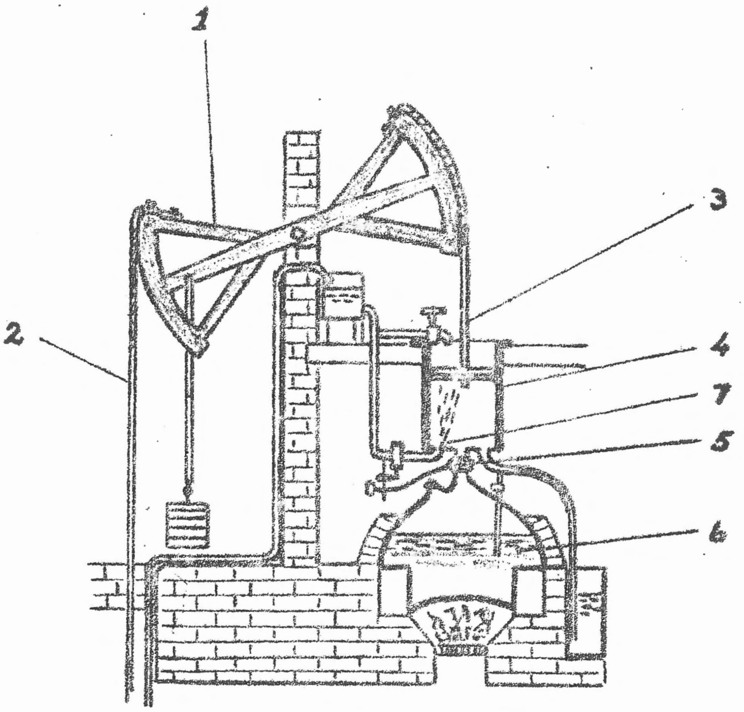


Figure 4. Newcomens steam engine 1705

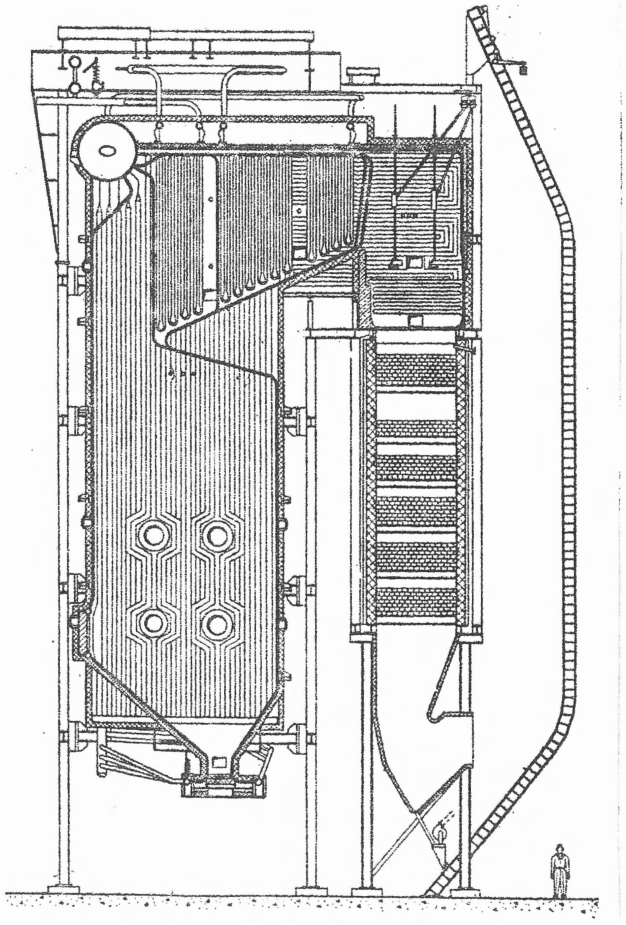


Figure 5. Modern boiler 1962

2.2. Main features in the development of boiler design in the 1960's and 1970's with special application to USA

2.2.1. General development

In order to describe the development of boiler design during the latest 14-15 years we use statistical data referring to the USA. The reason for this is twofold. Firstly, data of the kind presented have not been obtainabl for other countries. Secondly, the United States is in many ways, according to experts in the field, a pioneer in steam power generation, but the develo ment during the mentioned period shows similar trends in Europe, according to the same experts.

In figure 6 it can be seen that installed capacity (including nuclear power) has followed an increasing trend. The nuclear power share has varied between 8 % in 1963 and 65 % in 1972. Between 1968 and 1970 a decrease in the share of nuclear power (around 24 %) is noted. An explanation for this decrease is that the operation experiences made in earlier nuclear plants indicated constructional weaknesses.

The distribution of coal, gas and oil fired capacity has presented considerable fluctuations. The oil share increased strongly towards the end of the sixties at the cost of coal firing. During the beginning of the 70'ie coal firing has regained its previous position (see figure 7).

2.2.2. Development of pressure

According to figure 8 a drastic increase in the pressures is noted until 1969 when the share of overcritical boilers started to decline. Middle range pressure (124-165 bar) units then increased their share. The reason for this was the fact that high pressure units, which were designed for long running times with high thermal efficiency competed mainly against nuclear reactors as base load producers. Nuclear reactors took over the market for high pressure units and the more adjustable(in terms of utilized capacity)

Figure 6. Generating capacity ordered by U.S. utilities 1963-1973 (in MW)

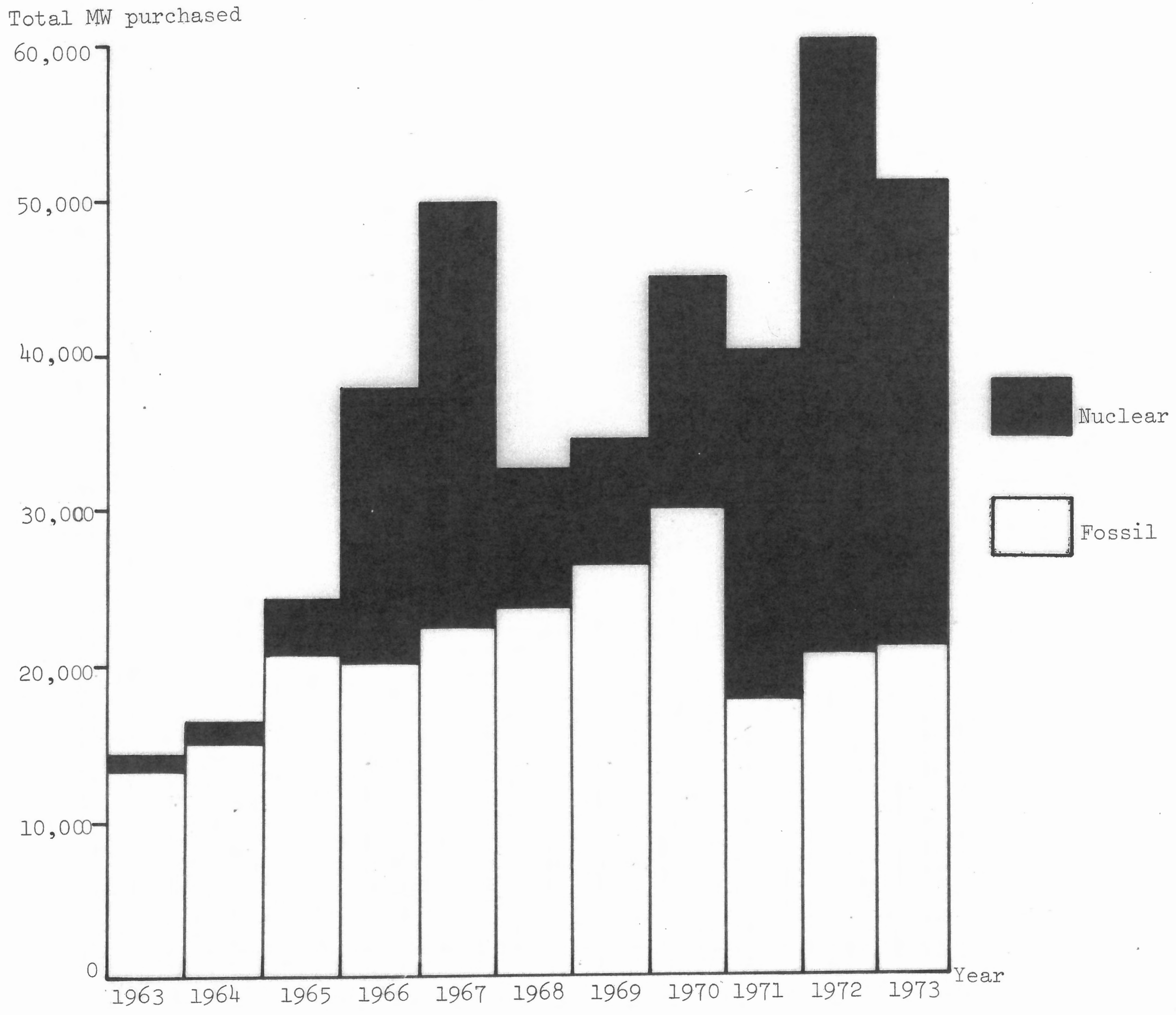


Figure 7. Installed capacity by U.S. utilities 1963-1973, distributed on kinds of fuels

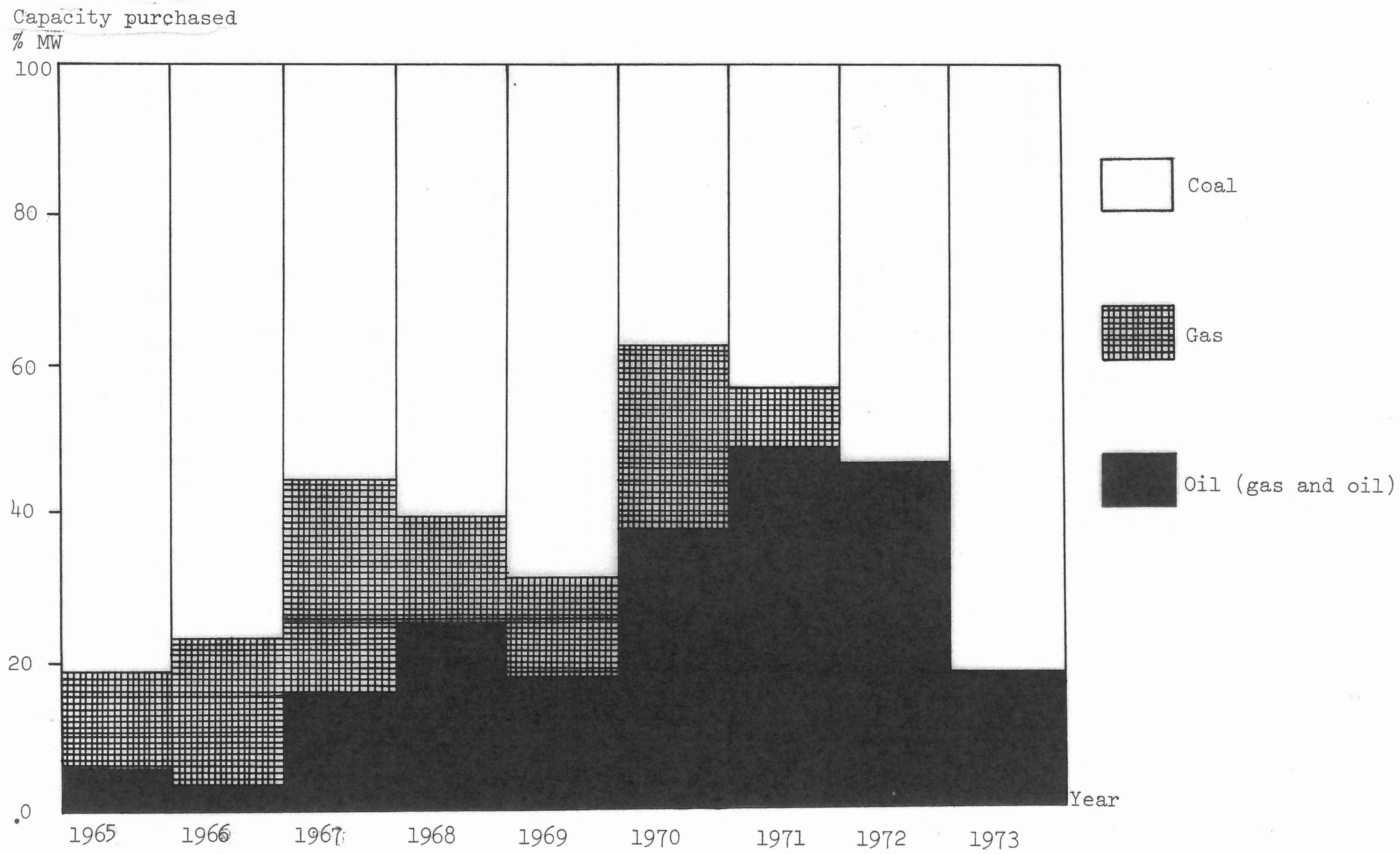


Figure 8. Steam pressures in installed steam electric generating plants in the U.S.,1961-1973

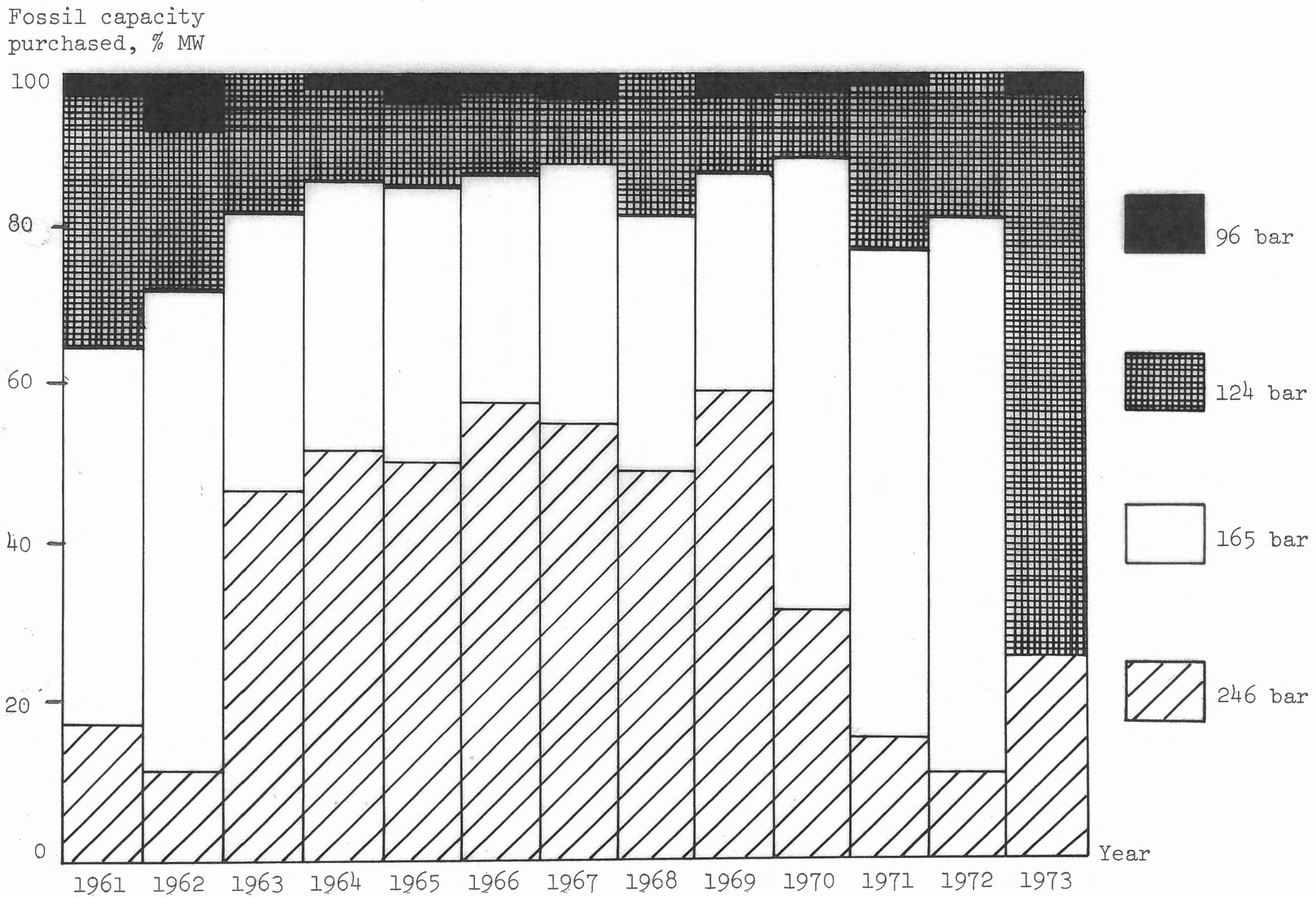
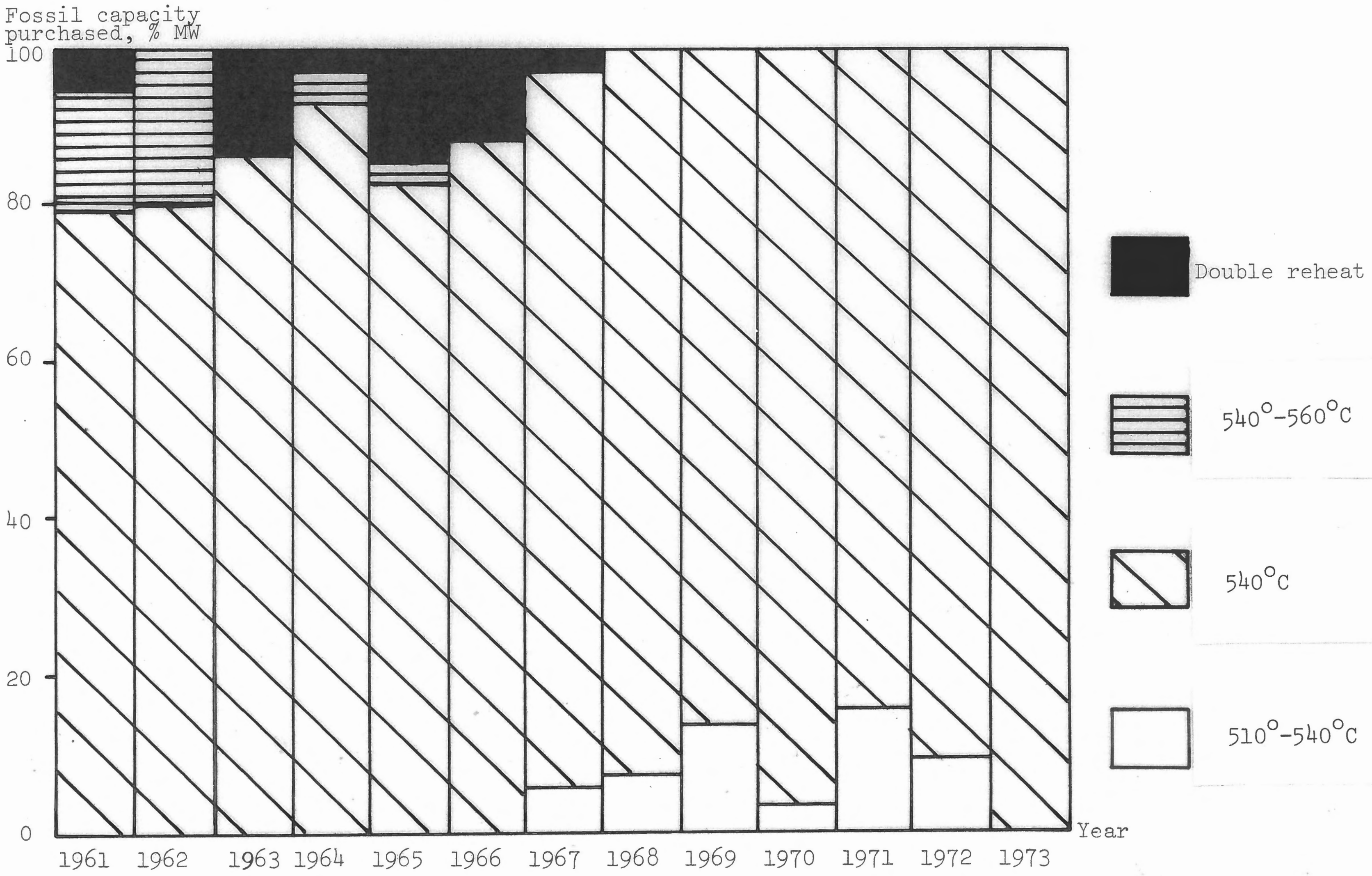


Figure 9. Steam temperatures in newly installed steam power plants in the U.S., 1961-1973



medium pressure units increased their share. Another reason why high pressur units didn't manage to compete was their lower availability. Availability is a measure of dependability Over critical (supercritical) technology is considered to be in an early stage of development.

The development towards over critical pressures can be explained by efforts to reduce fuel costs. In Sweden there are no overcritical boilers installed. A move from subcritical boilers means a great technological leap. For this reason it is reasonable to predict that in the countries where the latest boilers operate close to the critical pressure, efforts will be made to increase the operations reliability and reduce capital costs per produced kWh rather than to increase thermal efficiency.

2.2.3. Development of temperature

Figure 9 shows that steam temperatures in most installed power generating units lie around 540°C. (This temperature is common also in Sweden in newly built units.)

It may be seen in figure 9 that in the beginning of the 1960's there were investments made in boilers with higher temperatures. A certain number of units with so called double reheating were built, but after 1967 this activity ended. Double reheating implies briefly that steam is taken back to the boiler not only after the first turbine as in common units but also after the second turbine before the steam enters into the third turbine. The construction was considered too complicated to justify its continued production.

During the same period (beginning of the 1960's) a couple of units were built with temperatures around 560°C. These units required chiefly austenitic materials (rust-proof steel with high content of alloys) and were relatively expensive (capital requiring). Another reason for their limited success was the fact that (according to a main Swedish producer of boilers) turbine engine producers standardized their units for lower temperatures. This meant that turbines for "differing" temperatures had to be "tailor made" and were considerably more expensive to produce in relation to the standardized units. (A factor 0.5 times more expensive for units of same capacity is normal).

During a five-year period beginning in 1967, a small number of "peaking units" were built. These units were inexpensive (low capital costs) to construct, but had low thermal efficiency. But since they were built for a running time of only about 800 hours per year it was thought that the lower capital costs would more than make up for higher fuel costs than in conventional plants. However delays in construction of nuclear capacity led to running times for these plants of around 5-6000 hours per year. The nuclear plants were designed for a longer lead time than fossil fuel equipmen which in combination with the inefficient use of fuel in the peaking units led to the emergence of units which were designed for longer running times. Environmental considerations also greatly contributed to the noted descent in installation of "peaking units".

2.2.4. Development of size

In figure 10 it may be seen that the size of the overage installed plant in the United States was around 200 MW in 1960 and roughly three times as large ten years later. This trend towards larger units has been made possible mainly in two ways (see also figure 11).

1) The demand for electric energy has increased to such a level and at such a rate (an average rate of around 7-8 % per year) that it is possible for the largest plants to keep growing bigger without increasing their relative shares of total system production. A rule of thumb says that no single power generating units is permitted to produce more than 10 % of tota system production. The reason is the requirement for net stability and security of delivery during temporary breakdowns.

Figure 10. Size distribution of fossil capacity purchased by U.S. utilities,1961-1973

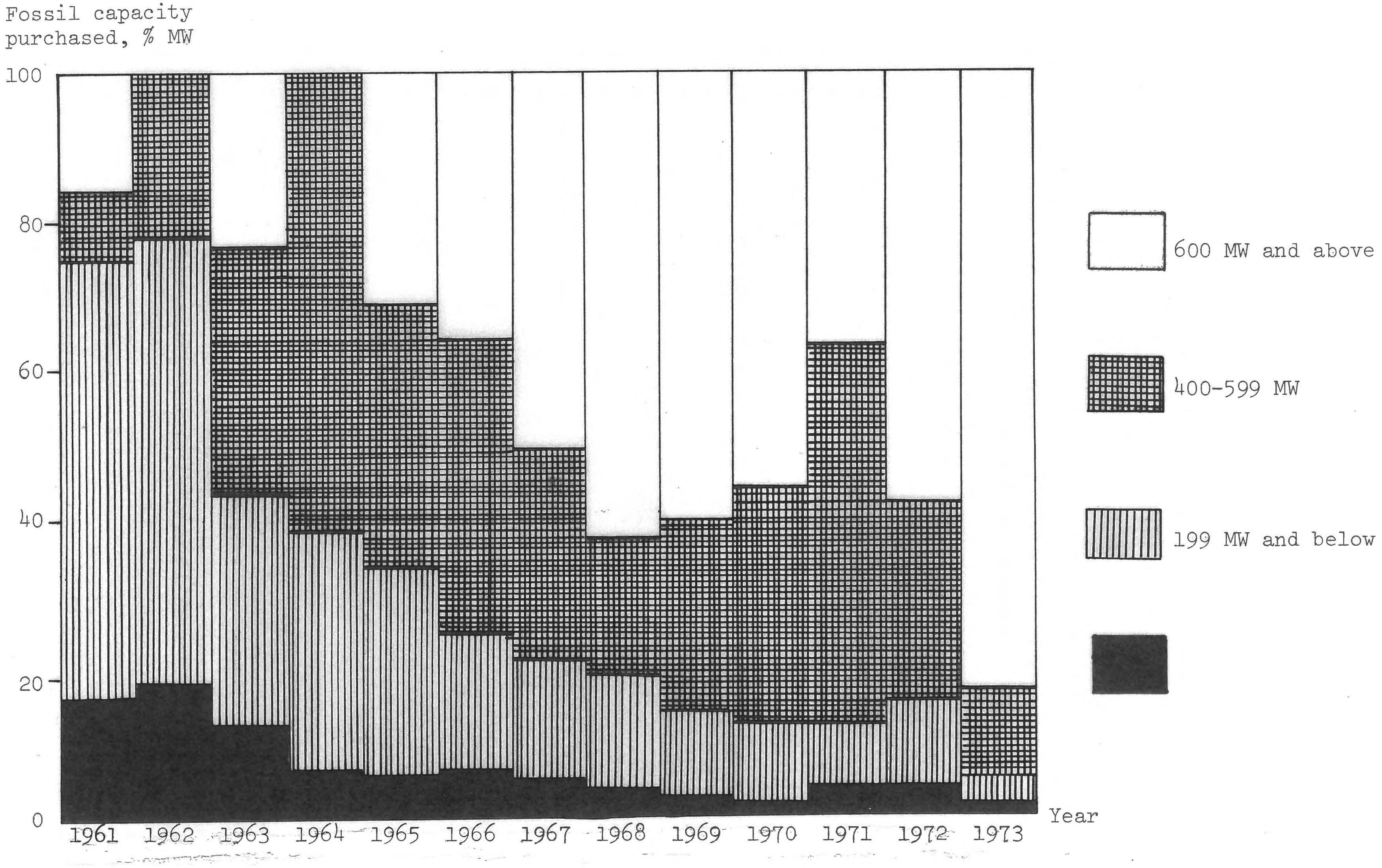
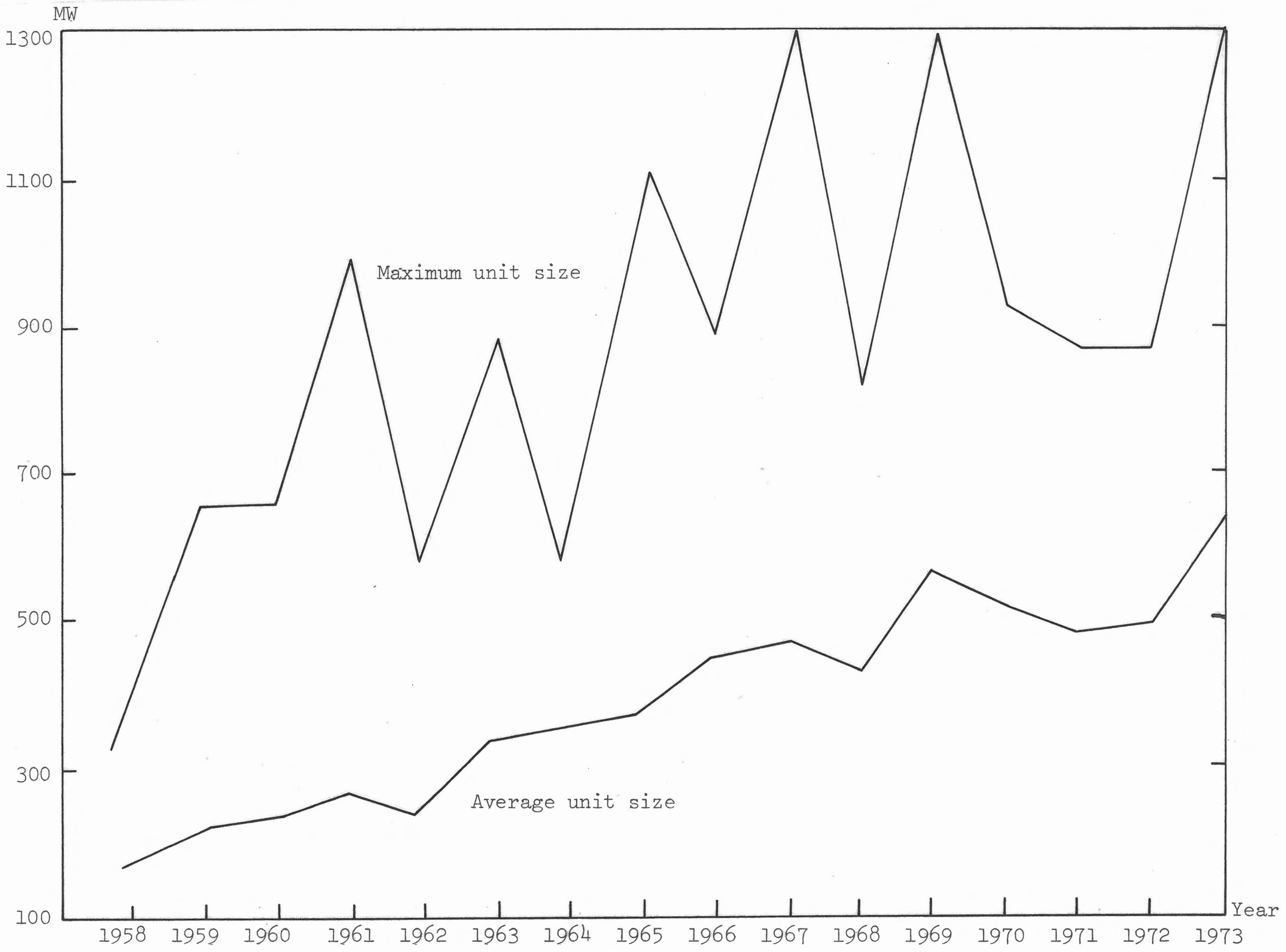


Figure 11. Fossil unit size developement by US. utilities 1958-1973.



2) Economies of scale. Without discussing these economies in detail it can be state on physical grounds that an "upscaling" of equipment leads to better thermal efficiency due to the fact that production is proportional to volume whereas cooling losses are proportional to the area of the equipment. Some labour saving equipment such as automatic steering and controlling devices will be profitable to install only in larger plants.

There are, however, some major draw-backs to the development towards larger units of equipment (diseconomies of scale). Some components are very difficult to construct and transport if their dimensions increase beyond a certain size. Technology to stress-release large domes is not developed which makes constructors hesitate when designing domes above certain diameters. (This is an example of the fact that size increments demands new technology.) Partly because of such problems with the domes, some larger plants install pass-through boilers (see innovations list). These boilers demand higher feedwater quality than dome boilers. Corresponding, there has been a marked development towards cleaner feed waters in the 1960's.

The development towards larger components has been compared by certain diseconomics of scale, namely the increasing problems of reliability and the sharply increasing development costs of larger units of equipment. In spite of increasing plant size the increase in plant capacity has often been achieved through a larger number of units rather than through larger units. The state of technology can therefore be said to have hindered the exploitation of potential economies of scale. We would then expect that a comparison between two large plants, one from the beginning of the 1960's and one from the 1970's will show that the latter is less space demanding (and therefore probably also less capital consuming).

2.2.5. Other trends

Back-pressure plants have continuously increased the share of electricity in total delivered energy. A normal plant built 15 years ago was dimensioned fo for 120 MW heat and 50 MW electricity, that is with a relation electricity/ heat of 2.5/1. A modern plant gives around 300 MW heat and 200 MW electric power, i.e. a relation of 1.5/1. The technical conditions for this trend lie to a large extent in the possibilities of working at higher pressures and temperatures. According to the association of district heating power **producers**, the reason why efforts have been made to increase the electricity share is that electricity yields a higher return per energy unit and that therefore further use of capital is justified.

A chiefly capital saving trend in Sweden has been noted in connection with decreased flexibility of the plants with regard to fuel. This has meant to that expensive coal handling equipment hasn't been needed. Also, burner technology and boiler construction will be better adapted if only one fuel is used. Less flexible plants also have better thermal efficiency than flexible ones. The basic reason is that e.g. a burner designed for comcombustion of coal, has different specifications from a burner designed for oil. The design of other equipment is similarly affected.

Increased automation of plants has also led to a decreased dependency upon operations personnel.However, the main benefit of automation (according to experts) is not its personnel saving effect but rather its positive effects on thermal efficiency and availability of the plant.

3. Rough Outline of a Model of Technological Change in Steam Electric Power Generation

3.1. The special conditions for adaption of new technology in a power system

Steam power generation differs from most other types of production (e.g. steel manufacturing) in that its main components are storngly integrated both technologically and as a construction. The degree of integration is almost total. Burners, boiler, heat-exchangers build up a closed unit. Technology for the whole plant is therefore fixed at the time of constructio Only smaller reparations, changes and additions usually come in question. An example of built-on equipment from recent years is the installation of dust precipitators to prevent pollution. In all cases it is the prohibitively high capital costs connected with installation of new components in an already built power plant which prevent the introduction of new technology in old plants. It is simply more profitable to build new plants. In the iron and steel industry the different process units are more loosely connecte to each other and permit greater flexibility in the installation of new process units. Nevertheless, the electricity production technology is considered a technology in the midst of a "dynamic development process". The question is, how does this development take place and where?

In newly constructed power plants usually the latest solutions to technological problems are used. Considerations pertaining to the use of new technology (i.e. innovations) have to be acted upon at the drawing board before the final blueprint of a power plant is made.

Considering the great need of engineering data and operational experience during such a planning process, one can expect that the amount of information exchange between power producers is relatively large. Many signs confirm this assumption.

A relatively swift international diffusion of new technology is therefore to be expected. Due to the fact that the introduction of new ethnology takes place in connection with the construction of new plants the technological development can be traced as vintages in the steam power system. The rate of diffusion of a certain technology into the power system therefore depends on

a) the rate of growth of demand for electricity

b) the vintage structure of existing plants which determines the rate at which old plants are scrapped

c) the cost advantages of the new technology over its competitions.

3.2. The choice of technology

The engineer constructing a boiler, a generator, etc. is confronted with the task of giving equipment all the features required by the final customer This means that he has to balance different features against each other. The level of existing technology gives him only a limited choice of possibilitie The perfect engineer, i.e., an engineer with perfect information about the demands of his customers,on his construction, knows what effect every component has on the cost and operation of the plant. Such an engineer is fictitious but will serve our purposes for a while. If, e.g., he adds a superheater to the construction, he knows that his choice will influence the availability, capital costs, operational costs and flexibility of the plant. His choice reflects the values he puts (and therefore those of his customers, since he is a perfect engineer) on all mentioned characteristics with given technology. He will add all components together and the final construction represents the plant with the optimum characteristics.

In contrast to the perfect engineer, the engineer in the real world works under constraints concerning both his knowledge about the needs of the customers and the knowledge of the effect of introducing different components upon the above mentioned characteristics of the plant.

This means that the perfectly informed engineer will have to be substituted by a screening process, in which the customer solicits offers from various producers of plants and he himself puts values on various characteristics. If he is rational, the customer will then choose the plant with the best set of features for his needs. The decision he makes is an a priori decision that is, he makes his decision with the best available information about the characteristics of the plant before it is built.

The role of the innovations with regard to this process may now appear somewhat more clear. The innovations will alter the main characteristics of the process and therefore present a new combination of characteristi to the customer. Depending upon the valuation of these characteristics, the plant containing the innovation will be accepted or rejected. Most new plants introduce many innovations which can make it difficult to isolate the impact of a single innovation. Whether a certain innovation (or set of innovations) will be introduced in a given case depends on the economic, social, and technical surroundings, e.g. relative prices on capital and fuels, shadow prices on availability, etc.

3.3. Measures of technological change

3.3.1. The use of technical parameters to trace technological change

As was printed out in the previous section, the performance of a steam power plant can be evaluated in terms of a set of characteristics such as thermal efficiency, availability, flexibility in both choice of fuels and utilization of plant, capital costs, and operational costs. These characteristics are determined in part by a number of parameters associated with each piece of equipment or with the system as a whole, e.g., maximum thermal load, maximum pressure, maximum temperature, etc.

Since technological change in the system affects primarily these parameters, we now propose, that in order to trace technological charge we should study the changes in these technical parameters over time.

There is, of course, a multitude of parameters, and some systematic screening in accordance with our needs will have to be performed. A study of parameter development should bring forth the information required for an integrated study of the development of the steam power generating process and the role of certain innovations.

From a technical point of view one could say that technical development means that the properties of a component (physical or functional) go through an evolution (improvement). Strain resistance, heat resistance, etc. are examples of such properties. These (in the following named parameters) are of interest to the engineer, but far from all play a strategic or "dimensioning" role in the construction of a piece of equipment.

Improving strain resistance in a piece of equipment is uninteresting if only the thermal expansion characteristics of the material are important. We can think of an immense linear programming system where all physical features of the components are described. One or more of the restrictions will have a high shadow price. A certain technological improvement will be introduced only if its shadow-price is high enough to pay for the cost of attaining this change.

3.3.2. An example of the analysis of technological change through a study of technical parameters

How can the study of certain parameters help us to find out if technological change has taken place or not? In order to illustrate the kind of analysis we have in mind, the following example is given.

Let us compare two plants, one old and one new. They are identical in all respects except one: the boiler of the new plant is cheaper to run than that of the old one due higher thermal efficiency. The boiler in the new plant has a material in the superheater which can withstand a greater thermal load. This thermal load can be attained with the old burners through a change in the air/fuel mix. Both the old and the new plants represent optimal plants of the respective vintage and with prevailing prices

Technological change can now be said to make the new plant more effective than the old one. The value of the new superheater is the capitalized value of the fuel savings. (We assume that both plants produce at full capacity.)

Technically, the parameters of the new plant have changed in comparison with the old one, so that thermal efficiency was raised thanks to the fact that the super-heater material was able to resist the higher demands on a strategic parameter. One measure of the technological change between the old and the new plants would thus be the change in the parameter thermal load. We can therefore say that the maximum thermal load was a significant restriction for the old plant and that it had a "shadow price" higher than zero. The change in the parameter in each time period is a measure of the speed with which technological change takes place.

When the new material is introduced, another "bottleneck" arises which eventually reaches its solution, etc. We can see that technical development will change its aim and direction from one field to another and from one time period to another. Some non-strategic parameters are transformed into strategic ones, and so on.

3.3.3. Conclusions with respect to the strategy of the study

1) Changes in technical parameters provide quantified measures of technological change.
2) We can study the time lag between the emergence of a "strategic" paramete and the time it begins to "move". (This kind of analysis is suited specially for comparisons between countries with different operating conditions.)
3) We obtain a measure of the relative importance of an innovation if, for example, the parameter values show great changes when an innovation is introduced.

Having presented a general structure for our study, we now proceed to proposing an outline of a research strategy. As stated above there will be certain difficulties in studying the introduction of innovations in steam power generation without first charting the development of the process as a whole. For this reason a two-step approach is suggested, in which the first step analyzes technological change in aggregate terms and the second step focuses on the role of specific innovations.

3.4. Outline of a research strategy

3.4.1. Step I: an analysis of the development of the process

The previous discussion has suggested that information on two kinds of variables is necessary to enable us to describe technological change in steam power production, namely technical parameters and performance characteristics. Accordingly, we propose the following two kinds of data collection:

a) the gathering of data concerning certain strategic technical parameters related to the sub-processes in steam power generation, as for example,

- a1) maximum pressure
- a2) maximum temperature
- a3) maximum heat load
- a4) measure on degree of contamination of feed water
- a5) content of nitric oxides (NO_x), sulphuric oxides (SO_2,SO_3) in flue gases.

The parameters should be selected to cover as wide a range of the development as possible. We will, however, be able to manage with a rather small number due to the fact that we have the possibility of selecting adequate parameters in cooperation with technical experts in the field.

b) the gathering of data concerning main performance characteristics of the process. The main characteristics suggested for study are following:

b1) thermal efficiency

b2) availability. We have mentioned availability in the previous section without defining it. Availability is a measure of the reliability of process (and therefore the quality of the product, the reliability of supply being an important aspect of product quality). It can be expressed in several ways. The most common is the so called energy-availability, which expresses the relation between actual production and potential capacity. Potential capacity is a measure of output during a given period if no breakdowns occur and if no time is needed to start up the plant to full capacity. Availability is an important characteristic of a plant. One major power producer (Karlshamn, 320 MW capacity) has stated that a one percent increase in availability would be worth a 10 percent increase in capital costs. The shadow price of availability depends mainly upon the size of the plant and the costs of alternative sources of power

b3) flexibility in the use of fuels, e.g. ability to use alternatively oil or coal

b4) capital cost depending upon the interest rate, size of investment and expected lifespan of the plant

b5) other operating costs. These consist mainly of labour and maintenance costs (e.g. cleaning of boiler tubes).

Innovations make possible new combinations of the above listed characteristics, that is, new possibilities of substituting one characteristic for another. The study of such changes in relation to different "environmental" factors ("Umweltfaktoren") must be seen as one of the main objectives of the study.

3.4.2. Step II: an analysis of the role and determinants of certain innovations

The second step concentrates more on the study of certain innovations. Great care has to be taken to make the selection properly. The innovations should preferably be easy to define in terms of both their impact on the choisen parameters and their physical characteristics. The analysis of the impact of the selected innovations on the development of the process (technically and economically) constitutes the connection with step one. One aspect in this analysis is the study of the effects of differences in the information available to decision makers, managerial methods, attitudes, and other non-economic parameters on the diffusion of the selected innovations.

3.4.3. Information requirements

The previous argumentation is based upon the presumption that the introduction process of new technology takes place in connection with the construction of new plants. Therefore, information relevant to the date of the final investment decision is needed. Data on actual operating costs thermal efficiency and availability refer to actual operation of the plant, i.e. after investment.

The information required refers to two main levels of aggregation:

1) The entire plant.
2) The various sub-processes (e.g. burners, boilers, turbines, generators and other).

The costs of the sub-processes sum up to the costs of the whole plant. Availability and thermal efficiency of the whole plant consists of the product of the corresponding data for the sub-processes.

To sum up, we will need information concerning

1) The chosen technical parameters.
2) The previously listed performance characteristics.
3) Other, non-technical/economic information.

The first type of information is needed only for sub-processes, whereas the second type of information is needed for both sub-processes and entire plants. The third type of information will probably only be needed at the plant level. After consultations with representatives for the Swedish Association of District Power Producers and for the main power producing plant in Stockholm there seems good reason to believe that this kind of information can be delivered without greater problems from the plants. The sources of information in these plants will be:

1) Experts at the plants.
2) Operations statistics.
3) Investment information.

If complete information of the latter kind cannot be obtained from individual plants, it may be supplemented through major equipment deliverers/manufacturers.

3.5. Steam power installations in Sweden 1963-1972

The number of steam power plants installed in Sweden in the period 1963-1972 is around 40. That makes an average of 4 plants per year. The last five years of the period the growth rate was above the average (around 6 plants per year) of the ten year period. The reason for this is the strong expansion of the thermal power sector due to both an increase in electricity demand and lack of exploitable water ways for increased hydro-power generation.

As we see in table 1 condensing power generation has been installed mainly during the last five year period while back pressure units have

Table 1. Steam power installations in Sweden 1963-1972

Year	Number of plants	Total capacity. MW	Condenser plants		Back pressure plants		Combined condenser and back pressure plants		Industrial back pressure plants	
			Number of boilers	Capacity. MW	Number of boiler	Capacity. MW	Number of boilers	Capacity. MW	Number of boiler	Capa city MW
1963	3	101	-	-	≥3	101	-	-	-	-
1964	3	197	1	160	2	17	2	20	-	-
1965	1	45	1	23	1	22	-	-	-	-
1966	2	77	2	34	1	43	-	-	-	-
1967	3	303	1	275	2	8	-	-	2	20
1968	2	206	-	-	-	-	1	160	1	46
1969	4	494	≥ 8	494	-	-	-	-	-	-
1970	4	350	1	320	-	-	-	-	2	30
1971	10	447	1	40	≥3	82	1	250	≥ 8	75
1972	8	598	1	65	1	4	2	432	≥ 5	97
Totalt	40	2 818	≥16	1 411	≥13	277	6	862	≥18	268

installed mainly during the first five year period. The distribution over the ten year period is,however, relatively even for both types of power generation. Out of the total of 40 plants 18 represent industrial back-pressure which differs from other back pressure plants with respect to the use of fuels (they can use lyes, back-wastes from pulp industries and for example coke-oven gas from the iron and steel industry).

4. Innovations in Steam Power Generation

4.1. Boiler technologies:

4.1.1. Dome boilers vs pass-through boilers

There are two main types of boilers - dome boilers and pass-through boilers.

The dome boilers contain a dome with feed water from which water is circulated. The boiling water streams up to the high-placed dome from the side-walls of the combustion chamber. Steam is separated from water in the dome and is led to the superheater. The density differences within the tubing system are large enough to guarantee self-circulation. However, dome boilers have some major disadvantages:

1) The dome is difficult to construct in larger boilers
2) Dome boilers are difficult to adapt to changes in production due to the large volumes of water in the system
3) When the pressure approaches the so-called critical pressure, self-circulation gets more difficult to obtain due to lack of density differences.

The pass through -boilers eliminate the dome and overheat steam directly after it is produced in the side-walls. (A small dome is installed however, to refill the system after water-leakages, etc.). This direct meth puts high requirements on circulation systems because if it is disturbed at one point of the tubesystem water will boil away, the tube will run dry, and disastrous thermal tensions will be the consequence. The pass-through boilers reduce the mentioned disadvantages of the dome-boilers. The pass through boiler is, however, no modern invention. The basic idea was pursued in the 1930's but the construction has not come into frequent use until the demand for higher pressures and temperatures and larger plants became sufficient. It could be said that the technology belonged to a "stock" of innovations and was possible to introduce only when the economic conditions permitted.

4.1.2. Welded tube panels

Furnance-wall systems constitute one of the most important components of modern utility steam generators in terms of sheer size and complexity. Because furnace-wall systems provide the enclosure walls around the major part of a steam generator, they participate in all essential characteristics of the unit. Enclosing the furnace proper, they become a part of the firing system; being a link in the steam generating cycle, they are a component of the pressure-parts system. The support of furnace-wall system is linked to that of all other components1).

The development of the construction of the furnace-wall has shown a marked trend. The oldest boilers (cf. the historical survey in Appendix A) consisted of water containers which were heated from below. A major step was taken when heat-reception was made by tubes in direct contact with the combustion chamber. The chamber was hereby enclosed by brick walls. However, heat losses were too large and the walls were substituted for insulating walls covered with tampring clay. This clay didn't cope very well with the temperature fluctuations. This latter technology, called "skin casing" was replaced during the 1950's and 1960's by a new technology which was an entirely welded construction of tube panels. This later technology is easily definable and has been diffused widely.

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1) W.W. Schroedter, Furnace Walls in C-E Controlled Circulation Units, 1972.

4.2 Combustion technologies

4.2.1. Sequence-governing

In the middle of the 1950's and the beginning of the 1960's a great degree of automation within combustion technology was introduced. The basic combustion process did not change, but new methods for ignition, control and extinction were introduced. This technology was made possible by mainly two circumstances:

a) larger production units

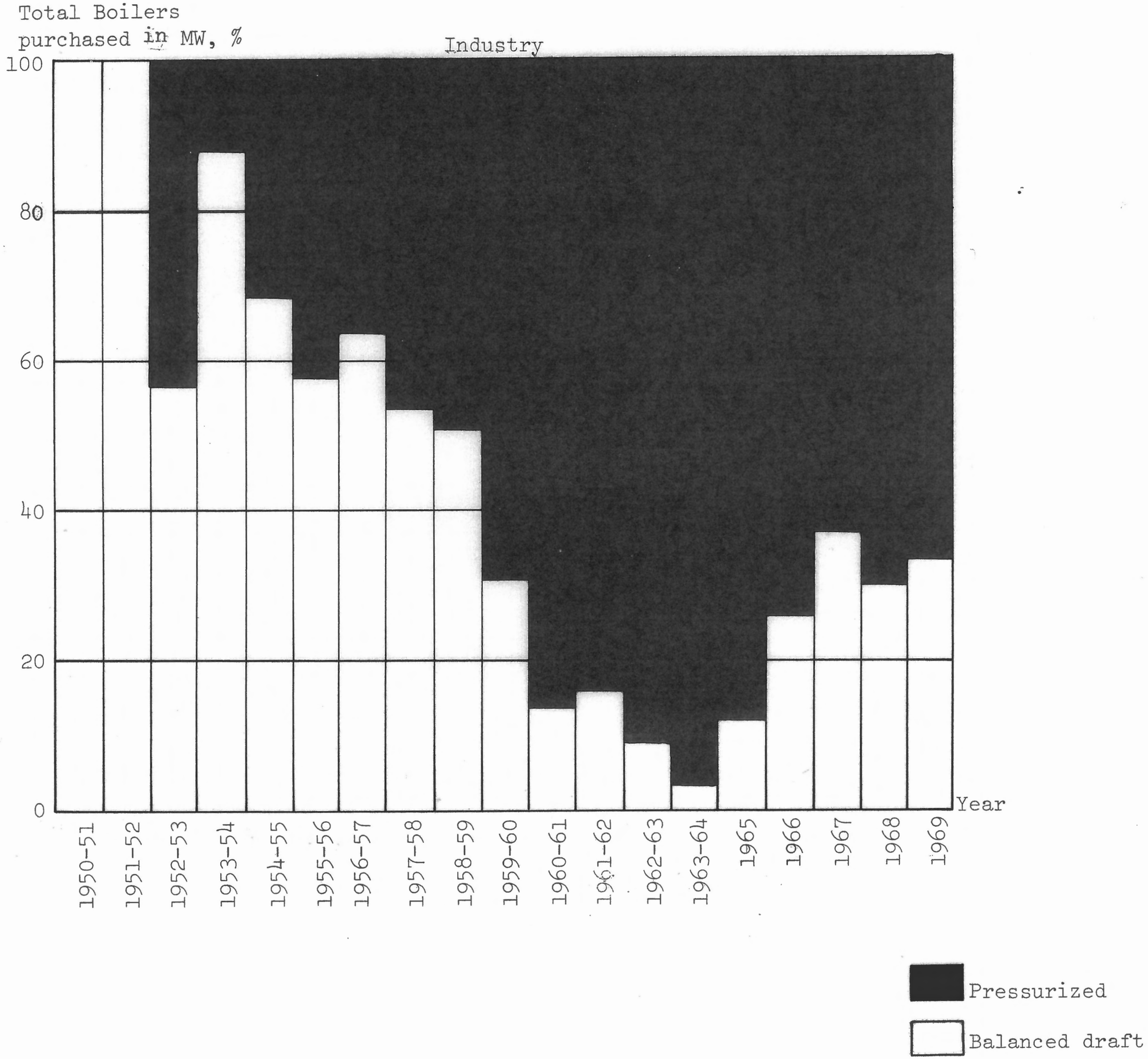
b) greater availability of electronic equipment during the 1950's and 1960's.

Technology is abstract in the sense that it can be performed through many techniques. In addition the degree of automation may vary among plants.

4.2.2. Balanced versus pressurized draft

An example of an innovation which has competed against older technology which ha maintained its position is the pressurized draft technology. Briefly it implies that the combustion chamber is set under pressure thus pressing flue gases through the stack instead of foreign them out of the chamber through suction as in the balanced draft case. A draft fan constructed to withstand the high temperatures is thus eliminated. The advantages of pressure firing are quite well known in terms of reduced power costs, equipment costs and the elimination of induced draft fan maintenance. Diagram 12 illustrates the experiences in the United States with regard to this technology. Economics dictated the adoption of pressure firing in the U.S. market up to 1964 increasing to about 95 per cent of the total capacity purchased in that year. Since that time much has been learned about the problems of pressurized casings, particularly in coal fired and indoor units where escaping gases were injurious to personnel and created a very dirty power plant. The problems have largely been associated with expansion joints and penetrations through the furnace enclosure. There have been particular difficulties with the superheater and reheater tubes passing through the furnace roof. All the required seals and expansion joints have presented a continuing maintenance problem.

Fig. 12. Balance draft vs pressurized draft purchase by U.S. utilities 1950-1969



This has led a number of companies to reverse their policies and go back to balanced draft operation as is shown on this chart. For example, in 1969 the industry was using balanced draft for 30 per cent of their new purchases.

4.3. Turbine technologies

4.3.1. Electronic governing

When generating electricity the effect is somewhat governable in the turbine stage (short governing cycles). This is made possible through the regulation of the steam flow through the turbine. In older plants this was done with mechanical equipment. During the 1960's electronic regulation systems have been introduced. The change has meant better regulation characteristics with resulting thermal efficiency increases.

4.4. Generator technologies

4.4.1. Water cooling of rotor and stator

When generation of electricity takes place, heat is produced in both rotor and stator ("primary"). These heat losses come from currents and magnetic fields passing through circuits and the iron material. The cooling problems are considerable and the dimensioning of the generators is to a great extent dependent upon cooling possibilities. Until now, the most common cooling method has been hydrogen gas cooling of both stator and rotor. An essentially more compact construction can be attained if the windings are cooled with water. A compact construction of the generators will to a large extent reduce investment costs.

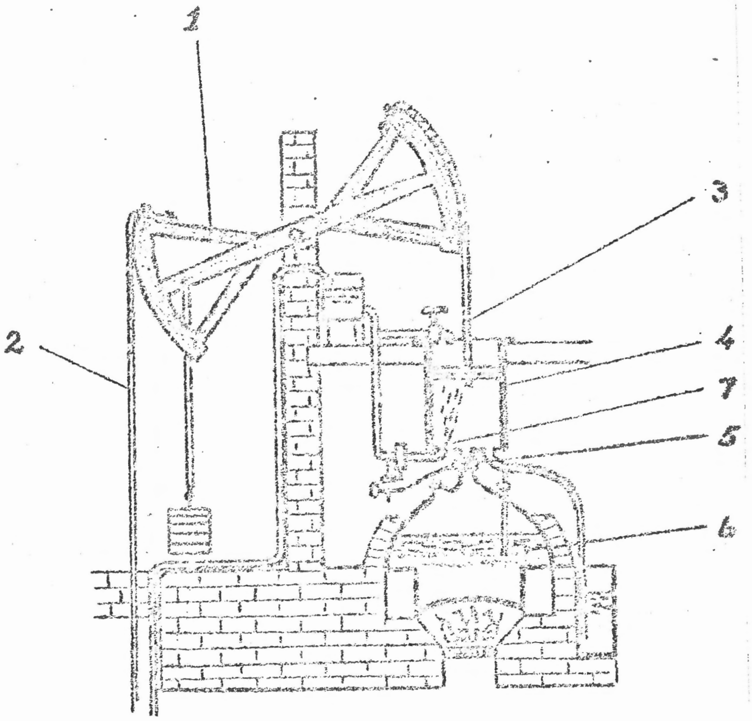
APPENDIX A

Brief Synopsis of the Development of the Boiler

Looking back to the distory of the boiler there is a good reason to study the development of the steam engine which in a way influences the boiler. The atmospherical steam engine built in 1705 by Thomas Newcomens is considered the first practically usable steam engine. Its purpose was to run pumps for mines, mainly coal mines, where its great need for fuel (around 20 kg coal/kWh) could be attained from near by sources.

The construction and function can with help from figure A1 be described in the following way.

Figure A1. Newcomens' steam engine



To one end of a rocker (1) is attached a pumprod (2) and to the other end a piston (3) with a rod attached to it. The piston works in a cylinder (4). The cylinder is connected with a waterfilled vessel (6) via a steam valve (5). Heat is transmitted to the vessel by firing.

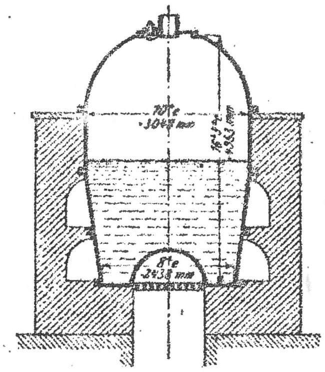
While the overweight of the pump rod pulls the piston upwards in the cylinder the valve is open and the cylinder is filled with steam. When the piston has reached its end-point the valve is closed and cold water (7) is forced into the cylinder where the steam condenses. In the cylinder arises a vacuum and the atmospheric pressure presses the piston down with such power that the rocker turns and the pumprod is pulled upwards. Due to the fact that the work-cylinder has to be cooled down during every cycle, the thermal losses are great.

The next larger step was taken by James Watt around the years 1960-1770. He introduced not only several mechanical improvements which made the steam engine usable to drive machines of different kinds; he also changed the process in such a way that the condensation process was moved from the cylinder to a separate condensing unit. This measure permitted the workcylinder to be kept hot continously, whereby the use of fuel was reduced by 75 %. After that he separated the steam generating unit from the work cylinder and thus emerged the true steam boiler. The demands on this were not great, as his constructions worked with steam close to atmospheric pressure. On the other hand, the imperfect materials and production methods of those days could not meet higher requirements. During the 19th century material production and work-shop technology were improved so the pressures that could be used successively increased. In the middle of the 19th century 5-6 bar had been reached and 25 years later 7-8 bar.

Some further attempts to increase pressures were made. Steam used in these processes was saturated. By the turn of the century it was possible to make use of overheated steam with pressures up to 11-12 bar. These changes had increased the efficiency of the machines to a consumtion of around 1 kg coal/kWh. By this time the steam turbine began to appear on the market and was soon the main steam consumer. Since then the development of the boiler plants has been attached to the increasing demands of steam quantity and characteristics from turbines.

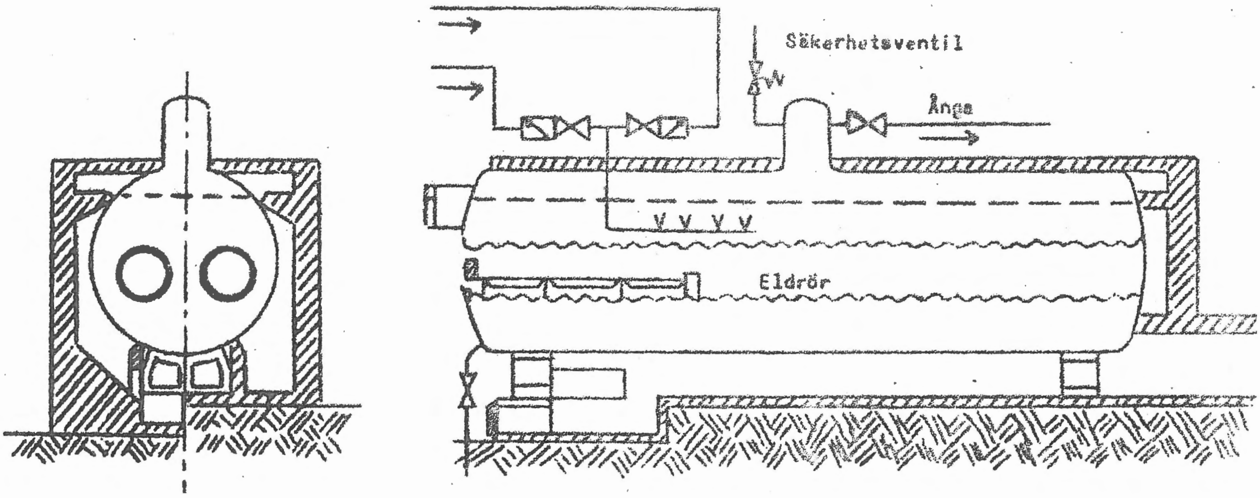
In Newcomens' boiler, steam was of atmospheric pressure and the vessel was round and made of copper. The same construction existed between 1700 and 1770, whereafter the copper was substituted by cast iron and later forged iron. At the same time certain modifications in form an construction were introduced, figure A2. Boilers of this type were used into the 1850's to run Watts' steam engine with pressures up to 1.2-1.5 bar.

Figure A2. Atmospherical boiler of cast-iron, 1773



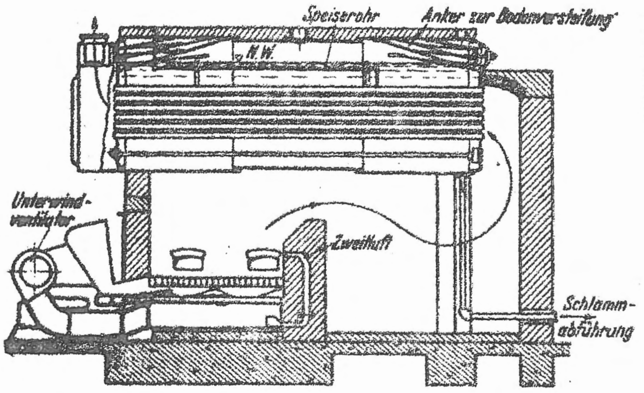
During the first half of the 19th century several other types of boilers were taken into operation. One of these consisted of a horizontal,closed cylindrical vessel with one or two wide tubes, fire-tubes, installed between the ends so that the tubes lay under the water level in the vessel. As the name fire-tubes indicates firing was performed in the wide tubes which also were the main heat-receiving surfaces (see figure A3).

Figure A3. Fire-tube boiler, 1815



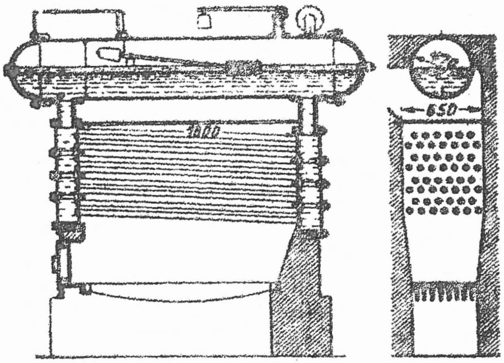
Another type which was similar to the last one was still fired from the outside of the water containing vessel but instead of fire tubes it had thinner tubes fitted between the ends. Through these tubes the flue gases passed several times, fig.A4. These two types, mostly in a combination, have been established and are still in operation in smaller plants.

Figure A4. Tube boiler



Both types had large water-rooms and at least the first type could easily be cleaned mechanically from the layers which arose from the poor waters of those days. The joining together was originally made through riveting but gave great problems because of leakages. Even if the methods after some time got better and made possible higher temperatures there were limitations in the possibilities to make them grow above certain pressures and dimensions. The great cylinder diameter, around 2.5 - 3 meters, demanded thicker sheets of steel and therefore greater riveting problems. Even the problem of thermal tension would increase in the material if either pressure or diameter would increase.

Figure A5. Two-chamber, water tube boiler



Around 1850 a new type of boiler, the so called water tube boiler, had reached some way in its development, figure A5. Due to the better thermal transmittance with the gas passing on the outside of the tubes such boilers could be made more compact than previous types. Still the constructions were riveted and had to be made with straight tubes for the sake of inner cleaning. The fire-tube was replaced by a walled fireplace which unfortunately required great maintenance costs.

It showed that the water tube boilers very well coped with the demands for higher pressures, larger units, cheaper boilers. A long period was necessary for development, detail for detail, a development which often was attached to the outcome of new materials and production methods.

To increase the efficiency of the steam cycle new heat receiving surfaces were added to the boiler. Thus thermal efficiency was raised by heating the feed water with hot flue gases by means of a heat-exchanger a capital cost increasing measure. economizer. One of the more important steps in the development was taken in the middle of the 1920's. Then methdos had been invented for chemical treatment of water to the boiler so that the risk for covering was markedly reduced even with high thermal loads. Through the introduction of welded constructions in the middle of the 1930's, through refined water chemistry, through cleaning methods using acids which removed both chemical and metal-covers, through increased understanding for the dimensioning of water circulation systems and better overall knowledge, the development has been able to move towards more and more advanced boiler types which can produce larger steam quantities with higher pressure and temperature.

Figure A6 shows a middle sized boiler for oil combustion at Linköpings Stads Tekniska Verks AB. It was delivered in 1962.

Many of the differences between the old steam engine and the modern boiler can not be seen in the picture. (Better feed water, reliability, etc.) However, one realizes that technology from 1705 was rather fuel consuming. Newcomens steam engine consumed around 155 kWh/kWh of energy output. This is to be compared with modern power plants requirements of 2.5 kWh/kWh energy output.

Figure A6. Modern boiler, 1962