Comparison of combined heat and power generation plants

Combined heat and power (CHP) generation, or 'cogeneration', is possible with steam turbines, gas turbines or a combination of the two in a so-called combined cycle. Each of these options has specific advantages that depend on the fuel type, production costs for electricity and heat, type of cogeneration and output range. A comparison of their respective economics, power or heat efficiency and control characteristics, shows that, in the majority of cases, the combined cycle is the most economical option and offers most benefits. Of special interest are power plants with an electrical output of about 25 MW and above, since this is the size of plant that industry and public utilities generating electricity and heat require.

The chief advantage of CHP is that it allows an improvement in fuel utilization which translates into a major fuel saving in comparison with separate heat and power generation. The better fuel utilization comes mainly from use of the steam's condensation heat, which is lost in a conventional power plant.

The advantages of simultaneously generating electricity and heat or steam in a single plant have been recognized for a long time, and both industry and electric utilities have made use of cogeneration for decades.

There are two possible ways of cogenerating heat and electricity. In the first, known as the 'topping cycle', the steam at the highest temperature level is used to generate the power (electricity). 1 shows an example of a topping cycle with a backpressure steam turbine.

In the second, the so-called 'bottoming cycle', heat recovered from the high-temperature process is used to generate electrical power. Bottoming cycles are seldom economical, since the electricity is generated with a low efficiency from waste heat at a relatively low temperature. It is usually more favourable to use this waste heat as process heat.

Only cogeneration plants of the first type – ie, with a topping cycle – will be considered here, as only these are of real interest thermodynamically and allow a true saving in primary energy.

The advantage of cogeneration, in accordance with the laws of thermodynamics, lie mainly in the improved utilization of the condensation heat in the steam. Fairly large heating boilers achieve fuel efficiency ratings at least as high as those for district heating power plants. The latter have, however, the advantage that they produce electricity at high steam temperatures and heat at low temperatures. Thus, from the thermodynamic viewpoint, the heat is produced from a low-quality energy.

2 compares the fuel utilization ratio of CHP and separate heat and power generation for different heat-to-power ratios. Point (1) represents pure heat generation with a boiler at approximately 90 percent efficiency, point (2) a steam power plant generating just electricity at 45 percent efficiency. The straight line connecting these two points represents the relationship between the fuel utilization and the ratio $P/(P + H)$ for power plants for heat and power generation. The upper line shows the same relationship for CHP plants. Fuel utilization is seen to be significantly better for CHP plants than for separate heat and power generation, the fuel utilization benefit being given by the area between the two lines (1...2).

At the same time, however, CHP plants usually require higher capital investment than separate generation. The following types of power plant will be compared in the following:

A Steam power plant, gas- or oil-fired, with backpressure steam turbine 1

B Steam power plant, gas- or oil-fired, with extraction/condensing steam turbine 3

C Combined cycle power plant with natural gas- or oil-fired gas turbine, with heat-recovery boiler 4

D Combined cycle power plant, fired with natural gas or oil, with backpressure steam turbine 5

E Combined cycle power plant, fired with natural gas or oil, with extraction/condensing steam turbine 6

Coal-fired steam power plants are not considered, as the lower fuel costs for the smaller plants can hardly balance the increased capital and operating costs. Also, the economic operation threshold of coal-fired plants is rising due to stricter emissions legislation. Nevertheless, a fuel saving similar to that in 2 can be achieved for the coal-fired plant in 1.

Anton Rohrer
ABB Power Generation

Output and operating range

The operating ranges for heat and power generation are shown in 7 as a function of the fuel utilization for power plant types A to E. It is seen that only the extraction/condensing turbine is capable of satisfying the power and heat production requirements with the desired degree of accuracy in every case. All the other plants are capable of this only within limited ranges.

The backpressure turbine offers advantages in CHP plants when the demand for power is low compared with the demand for heat. However, when the power-to-heat ratio is high, it is the combined cycle plant with extraction turbines that offers most benefits. Gas turbines with heat-recovery boilers (type C) lie between these two types.

A steam bypass (SBP) can extend the operating range for heat production with backpressure or extraction/condensing steam turbines. Another option is additional firing for the heat-recovery boiler to extend the heat-to-power ratio in favour of more heat (for types C, D and E).

Controllability and part-load efficiency

The most important control task in cogeneration plants is to match the process steam production or heat output to demand. (7 shows the full-load operation of a boiler and a gas turbine.)

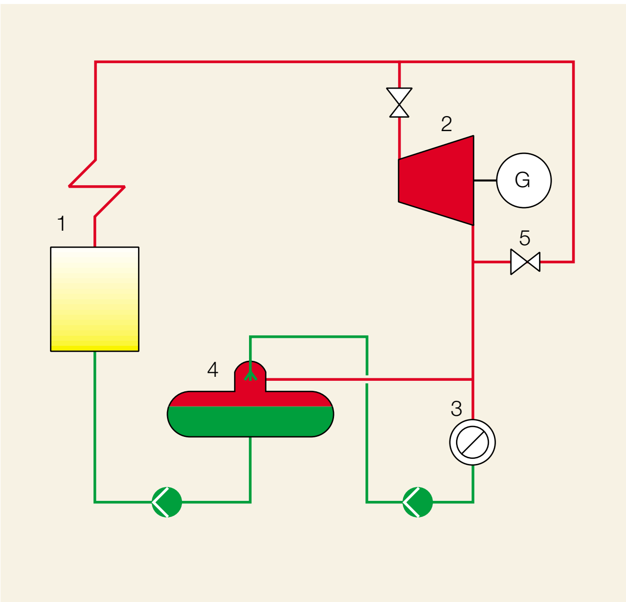
This type of control presents no problems for all the types of power plant considered (A to E). However, the control becomes complicated if it is necessary at the same time to regulate the electrical output, for example when the power plant is operating in 'island' mode (ie, isolated from the grid). The extraction/condensing steam turbine power plant is best suited for this, since it allows practically independent control of the two output variables (heat and power) without affecting the economics of the generation.

The backpressure turbine, by contrast, is least suited for this dual function, since in this case a valve is necessary to discharge the excess process steam. If the valve is operated frequently, the discharged steam should be led to an auxiliary condenser to enable the condensate to be recovered.

In terms of control and part-load operation, the combined cycle power plant and

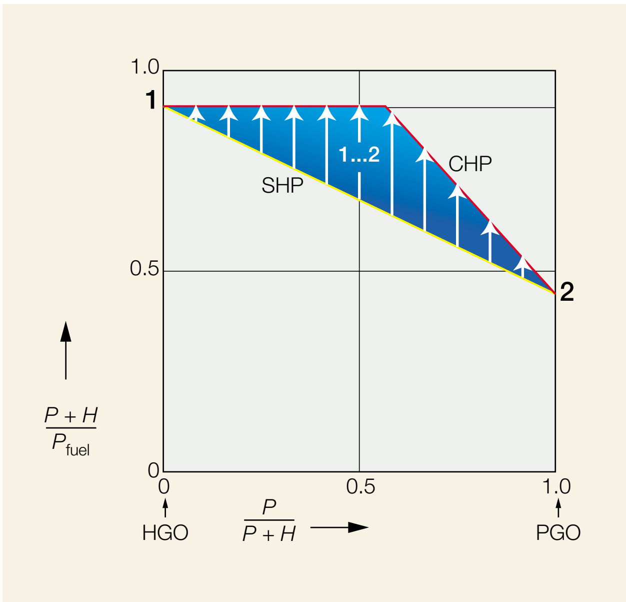
Power plant of type A: steam facility with backpressure turbine (basic diagram) 1

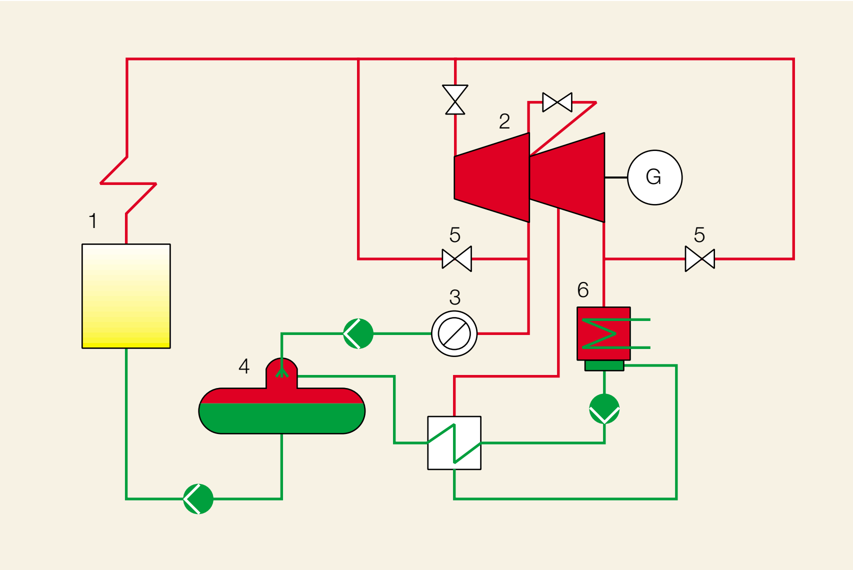
1 *Boiler*
2 *Backpressure steam turbine*
3 *Steam (heat) consumer*
4 *Feedwater tank/deaerator*
5 *Steam bypass*



Comparison of fuel utilization with cogeneration and with separate heat and power generation 2

CHP *Combined heat and power generation*
SHP *Separate heat and power generation*
HGO *Generated output, heat*
PGO *Generated output, power*
$\frac{P+H}{P_{fuel}}$ *Fuel conversion ratio (utilization)*
$\frac{P}{P+H}$ *CHP ratio*
P *Generated power (MW)*
H *Generated heat (MW)*
P_{fuel} *Heat supplied by fuel (MW)*
1…2 *Improved primary energy utilization with CHP*





Power plant of type B: steam facility with extraction/condensing turbine **3**

1 *Boiler*
2 *Extraction/condensing steam turbine*
3 *Steam (heat) consumer*
4 *Feedwater tank/deaerator*
5 *Steam bypass*
6 *Condenser*

the gas turbine with heat-recovery boiler lie between these two extremes. The combined cycle plant, especially when it features additional firing in the heat-recovery boiler, comes close to the performance of the extraction/condensing turbine. In each case, though, the economics depend to a large degree on the gas turbine load, since the fuel consumption is relatively high even under low-load conditions. Thanks to the efficient adjustment of the compressor vanes which is possible with modern gas turbines, even this problem has been solved.

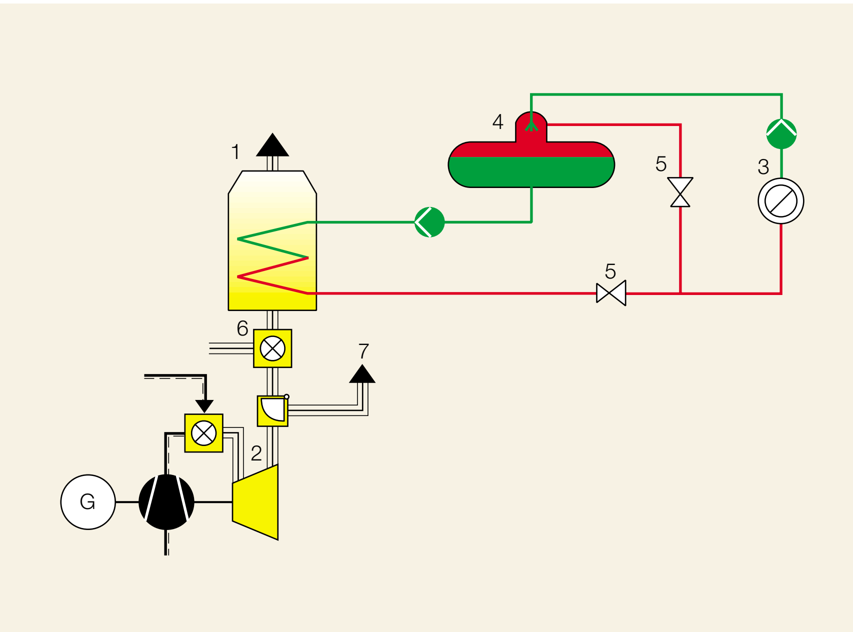
If the heat-recovery boiler operates without additional firing, the control range for the process steam will have an upper limit. This is because the maximum steam that can be produced by the heat-recovery boiler is dependent upon the gas turbine load.

Comparison of the economics of different industrial power plants

Comparable economic assessments are generally difficult to find in the field of cogeneration, since almost every plant is complex and built to meet specific needs. The majority of industrial power plants, however, have one thing in common: their main product is heat or steam. Electrical energy can almost always be obtained from a power utility, but steam cannot. Therefore, in an industrial plant at least as much fuel is required as is consumed by a simple steam boiler for generating process steam. The additional fuel that is necessary corresponds to the difference between the fuel consumption of the cogeneration plant and that of the steam boiler. The efficiency of the power generation can therefore be defined as follows:

$$\eta_P = \frac{P}{P_{fuel} - \frac{H}{\eta_{HP}}} \qquad (1)$$

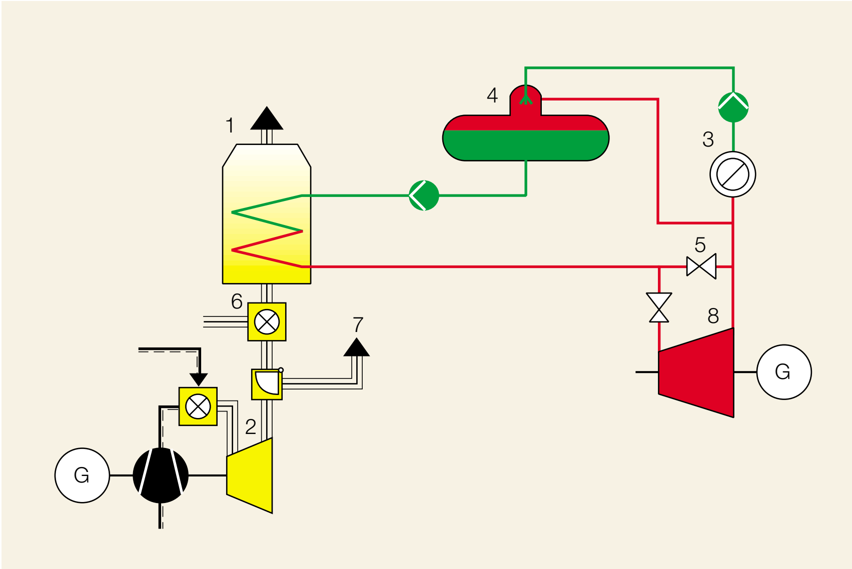
η_p Efficiency of power generation
P Generated power output (MW)
P_{fuel} Heat provided by fuel (MW, MJ/s)
H Generated process heat (MW, MJ/s)
η_{HP} Efficiency of steam boiler



Power plant of type C: combined cycle with gas turbine and heat-recovery boiler **4**

1 *Heat-recovery boiler*
2 *Gas turbine*
3 *Steam (heat) consumer*
4 *Feedwater tank/deaerator*
5 *Steam let down device*
6 *Additional firing (optional)*
7 *Bypass stack (optional)*

Power plant of type D: Combined cycle with back-pressure steam turbine **5**



1 *Heat-recovery boiler*
2 *Gas turbine*
3 *Steam (heat) consumer*
4 *Feedwater tank/deaerator*
5 *Steam bypass*
6 *Additional firing (optional)*
7 *Bypass stack (optional)*
8 *Backpressure steam turbine*

The following formula can be used to calculate the power production costs, thereby permitting a comparison with the capital and operating costs of cogeneration:

$$Y_P = \frac{(I_{CHPP} - I_{HP})\,\Psi}{EN \cdot P} + \frac{Y_{fuel}}{\eta_P} + \frac{U_{CHPP} - U_{HP}}{EN \cdot P} + u'_{CHPP} - u'_{HP} \qquad (2)$$

Y_p Cost of electricity generation (currency unit/kWh)
Y_{fuel} Fuel costs (currency unit/kWh)
I Capital costs, including taxes and insurance (currency unit)
EN Equivalent utilization period (h/a)
u' Variable operating costs (currency unit/kWh)
U Fixed operating costs, including personnel costs (currency unit/a)
Ψ Annual amortization
η_p Efficiency of power generation

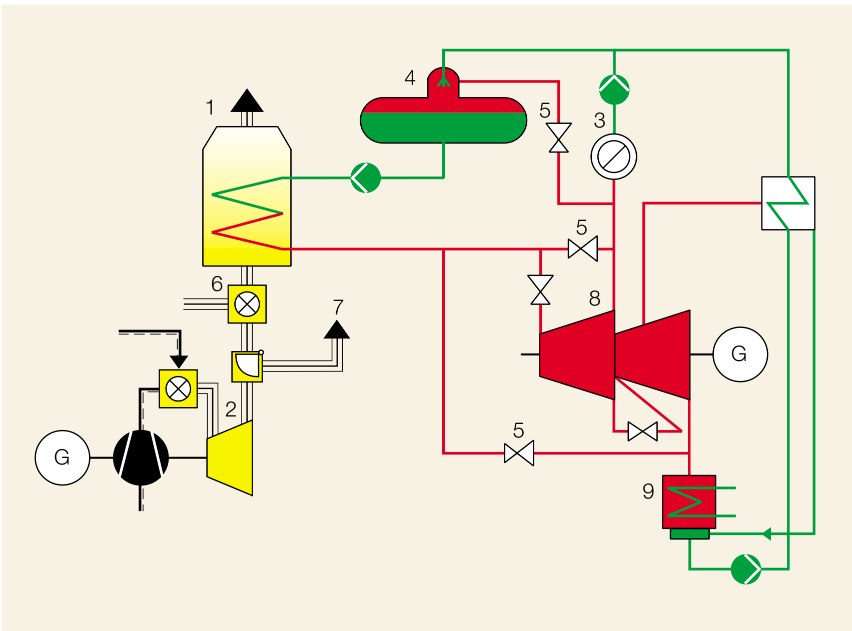
Indices:
CHPP Combined heat and power plant
HP Heat or steam boiler plant

Formula (2) can be used to investigate whether it is more economical to generate power in the industrial operator's own plant or to meet the full power demand with energy purchased from the utility (ie, whether the plant should produce steam only or electrical power as well).

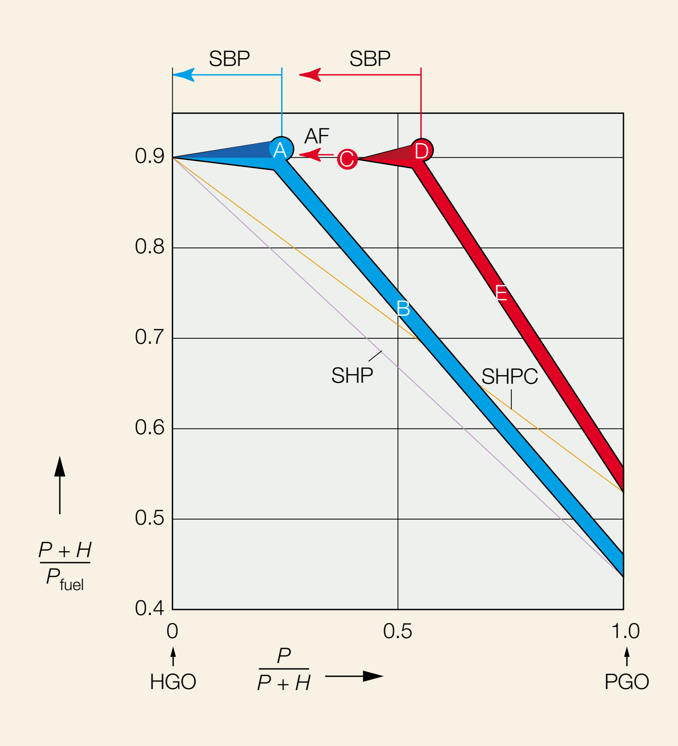
The economy of power plant types A to E is best compared by referring to an example: *Table 1* shows the respective costs for a paper mill with an electrical power demand of approximately 45 MW.

It is seen from *Table 1* that the CCPP with gas turbine and heat-recovery boiler (type C) generates the cheapest power. However, it does not meet the full power demand, so that the difference has to be purchased from the utility. The second cheapest power is generated by the CCPP with backpressure steam turbine. In this case, however, more power is generated than is needed, and the surplus can be exported to the grid, thereby providing revenue, which reduces the operating costs. The power plant with extraction/condens-

Power plant of type E: Combined cycle with extraction/condensing steam turbine **6**



1 *Heat-recovery boiler*
2 *Gas turbine*
3 *Steam (heat) consumer*
4 *Feedwater tank/deaerator*
5 *Steam bypass*
6 *Additional firing (optional)*
7 *Bypass stack (optional)*
8 *Extraction/condensing steam turbine*
9 *Condenser*



Operating ranges of power plant types A to E **7**

- A *Steam power plant with backpressure steam turbine*
- B *Steam power plant with extraction/condensing steam turbine*
- C *CCPP with gas turbine and heat-recovery steam boiler*
- D *CCPP with backpressure steam turbine*
- E *CCPP with extraction/condensing steam turbine*

- SHP *Separate heat and power generation in steam plants*
- SHPC *Separate heat and power generation in combined cycle plants*
- HGO *Generated output, heat*
- PGO *Generated output, power*
- SBP *Steam bypass operation*
- AF *Additional firing in heat-recovery boiler (optional)*

$\frac{P+H}{P_{fuel}}$ *Fuel conversion ratio (utilization)*

$\frac{P}{P+H}$ *CHP ratio*

- P *Generated power (MW)*
- H *Generated heat (MW)*
- P_{fuel} *Heat supplied by fuel (MW)*

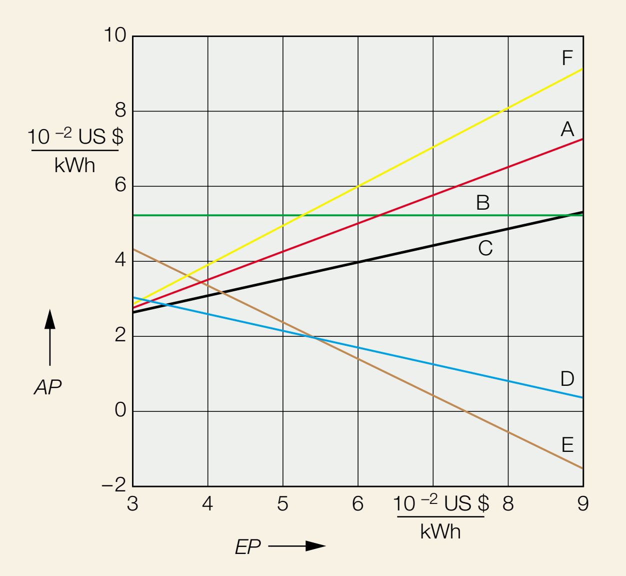
Table 1:
Comparison of industrial power plants for a paper mill with an electrical power demand of 45 MW_{el}

Type of plant		A Backpressure steam turbine	B Extraction/ condensing steam turbine	C CCPP with gas turbine and heat-recovery boiler	D CCPP with backpressure steam turbine	E CCPP with extraction/ condensing steam turbine
Net power output	MW	15	45	26	65	90
Power generation efficiency η_P (eqn 1)	%	81.3	43.1	95	76	75
Additional investment (versus steam boiler)	10^6 US$	11.5	34.6	13.8	38.5	69.2
Capital costs*	10^{-2} US$/kWh	1.54	1.54	1.06	1.18	1.54
Fuel costs*	10^{-2} US$/kWh	1.55	2.92	1.32	1.66	1.68
Operating costs*	10^{-2} US$/kWh	0.3	0.7	0.23	0.38	0.46
Electricity production costs	10^{-2} US$/kWh	3.39	5.16	2.61	3.22	3.68

Boundary conditions:

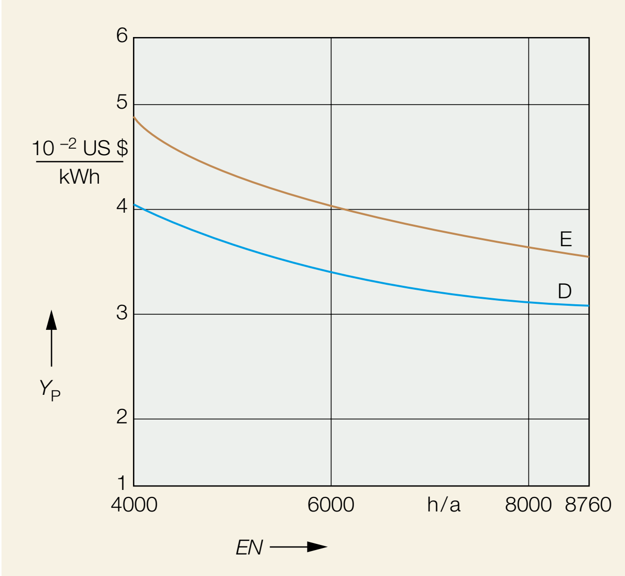
– Process heat flow	25 kg/s (90 t/h)
– Process steam conditions	3.5 bar/190 °C
– Power demand	45 MW
– Equivalent utilization period	7000 h/a
– Annual amortization	14.0% (10 years, 8% interest)
– Fuel price (assumed)	3.5 US$/GJ (natural gas)

* Difference with respect to simple steam boiler



Average cost of electricity for combination of self-production and bought-in or sold power **8**

A–E *Types of power plant*
F *Plant generating heat only; no self-generated power*
AP *Average cost of electricity with combination of self-production and bought-in/sold power*
EP *Price of bought-in or sold electricity*



Production cost of electrical power for annual equivalent utilization periods **9**

D, E *Types of power plant*
Y_P *Power production costs*
EN *Equivalent utilization period*

ing turbine meets the power demand exactly, but the power it produces has the highest kWh price.

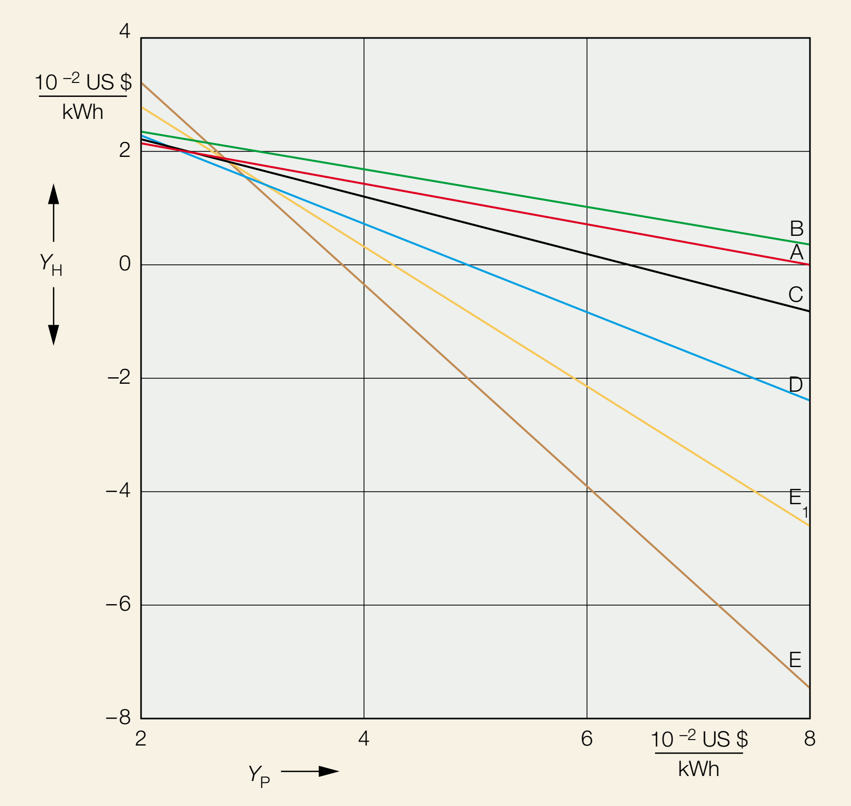
The average cost of electricity with the different power plant types is shown in **8** for combinations of self-production and bought-in or sold power.

When the current power price is right, it is more economical in almost all cases to operate a CHP plant than it is to purchase the electrical power from the grid. The export of power to the public grid is also a

Table 2:
Comparison of different district heating power plants with a heating output of 60 MW

		A Backpressure steam turbine	B Extraction/ condensing steam turbine	C CCPP with gas turbine and heat-recovery boiler	D CCPP with backpressure steam turbine	E CCPP with extraction/ condensing steam turbine	E1 CCPP with extraction/ condensing steam turbine
Heat output	MW	60.9	60.9	76.0	60.9	60.5	60.5
Power output	MW	22.0	21.4	34.9	48.1	107.6	74
Heat supplied by fuel	MW	94.0	95.5	129.6	125.3	211	156
Fuel utilization	%	88.2	86.2	85.5	87	79.7	86
Capital costs	10^{-2} US$/kWh*)	0.56	0.69	0.57	0.81	1.84	1.6
Fuel costs	10^{-2} US$/kWh*)	1.95	1.96	2.15	2.6	4.4	3.25
Operating costs	10^{-2} US$/kWh*)	0.28	0.28	0.28	0.37	0.38	0.38
Revenue from exported power	10^{-2} US$/kWh*)	−1.70	−1.65	−2.15	−3.71	−8.36	−5.75
Cost of heat production	10^{-2} US$/kWh*)	1.09	1.28	0.9	−0.07	−1.74	−0.52

Boundary conditions:	– Heat output	approx. 60 MW
	– Outward line temperature of district heating mains	95 °C
	– Return line temperature of district heating mains	60 °C
	– Annual amortization	10.2% (20 years, 8% interest)
	– Fuel price (assumed)	3.5 US$/GJ (natural gas)
	– Electricity price (revenue)	4.7 × 10^{-2} US$/kWh
*) kWh of heat	– Equivalent utilization period	5000 h/a



Influence of the price of electricity on the production cost of heat in different heating power plants **10**

A–E *Types of power plant*
Y_H *Cost of heat production*
Y_P *Revenue from exported power*

good solution when purchasing prices and utility operating policies are favourable.

In general, the CCPP generates a high power-to-heat ratio, allowing the excess power to be exported to the public grid. The combined cycle option with extraction/condensing steam turbine is highly flexible in terms of heat generation and, due to its size, offers considerable potential for exporting power. Besides offering high operational flexibility, this configuration is therefore also usually the most economical solution; the revenue obtained from exporting power will depend on actual market conditions.

9 shows how the equivalent utilization period influences the electricity production costs for power plant types D and E.

Comparison of the economics of different district heating power plants

The conditions in district heating power plants are usually different from those in industrial power facilities. The most economical solution here is the plant that offers the lowest heat production costs.

In the calculation of these costs, the

Table 3:
Advantages and disadvantages of power plant types A to E

Type of plant	Advantages	Disadvantages
A Backpressure steam turbine	– High fuel utilization – Simple plant – Suitable for low-grade fuel	– Limited flexibility as regards design and operation
B Extraction/condensing steam turbine	– Highly flexible as regards design and operation – Suitable for low-grade fuel	– Expensive plant – High cooling-water demand
C CCPP with gas turbine and heat-recovery boiler	– Good fuel efficiency – Simple plant – Short delivery period	– Moderate part-load efficiency – Less suitable for low-grade fuel
D Combined cycle power plant with backpressure steam turbine	– Good fuel utilization – Relatively low capital costs	– Average to moderate part-load efficiency – Less suitable for low-grade fuel
E Combined cycle power plant with extraction/condensing steam turbine	– Good flexibility as regards design and operation – Moderate investment costs	– Less suitable for low-grade fuel – Moderate cooling-water demand

electricity is considered as a by-product that brings in a certain revenue. This income can be deducted from the operating costs. The heat production costs can be calculated from the difference using the following formula:

$$Y_H = \frac{I \cdot \Psi}{H \cdot EN} + \frac{Q_{fuel} \cdot Y_{fuel}}{H} + \\ + \frac{U}{H \cdot EN} - \frac{P \cdot Y_P}{H} \quad (3)$$

Y_H Heat production costs (currency unit/kWh, thermal)
Y_P Selling price of electrical power (currency unit/kWh)
Y_{fuel} Fuel price (currency unit/kWh)
I Capital costs, including taxes and insurance (currency unit)
EN Equivalent utilization period (h/a)
Ψ Annual amortization
H Generated heat (kW)
Q_{fuel} Heat provided by fuel (kWh)
U Operating costs (currency unit/a)
P Generated power output (kW)

Diemen 33 combined cycle power plant in the Netherlands. This plant corresponds to a type E facility. **11**

Table 2 shows a comparison of different district heating power plants with a heat output of approximately 60 MW and an equivalent utilization period set at 5,000 h/year. As a rule, a heating power plant meets only the base-load demand in a district heating network.

An extraction/condensing steam turbine in a CCPP or a conventional steam turbine power plant, on the other hand, runs according to the heat demand, operating more than 5,000 h/year. At the same time, it will generate power as a by-product – an important source of revenue. Due to the power-to-heat ratio being higher than for other types of power plant, the revenue from the exported power is highest for the combined cycle plants. Their economic performance is therefore more dependent upon changes in the price of power. If the price is high the CCPP is most economical, if it is low the other types of power plant will be more economical.

The influence of the price of electrical power on the heat production costs is shown in **10**. If the electricity price is above US$ 0.03 per kWh, combined cycle plants are the more economical option for the example considered, combined cycle plants with an extraction/condensing steam turbine topping the list. Due to its operational flexibility in terms of heat production, this type of plant can generate power as a by-product over the entire year.

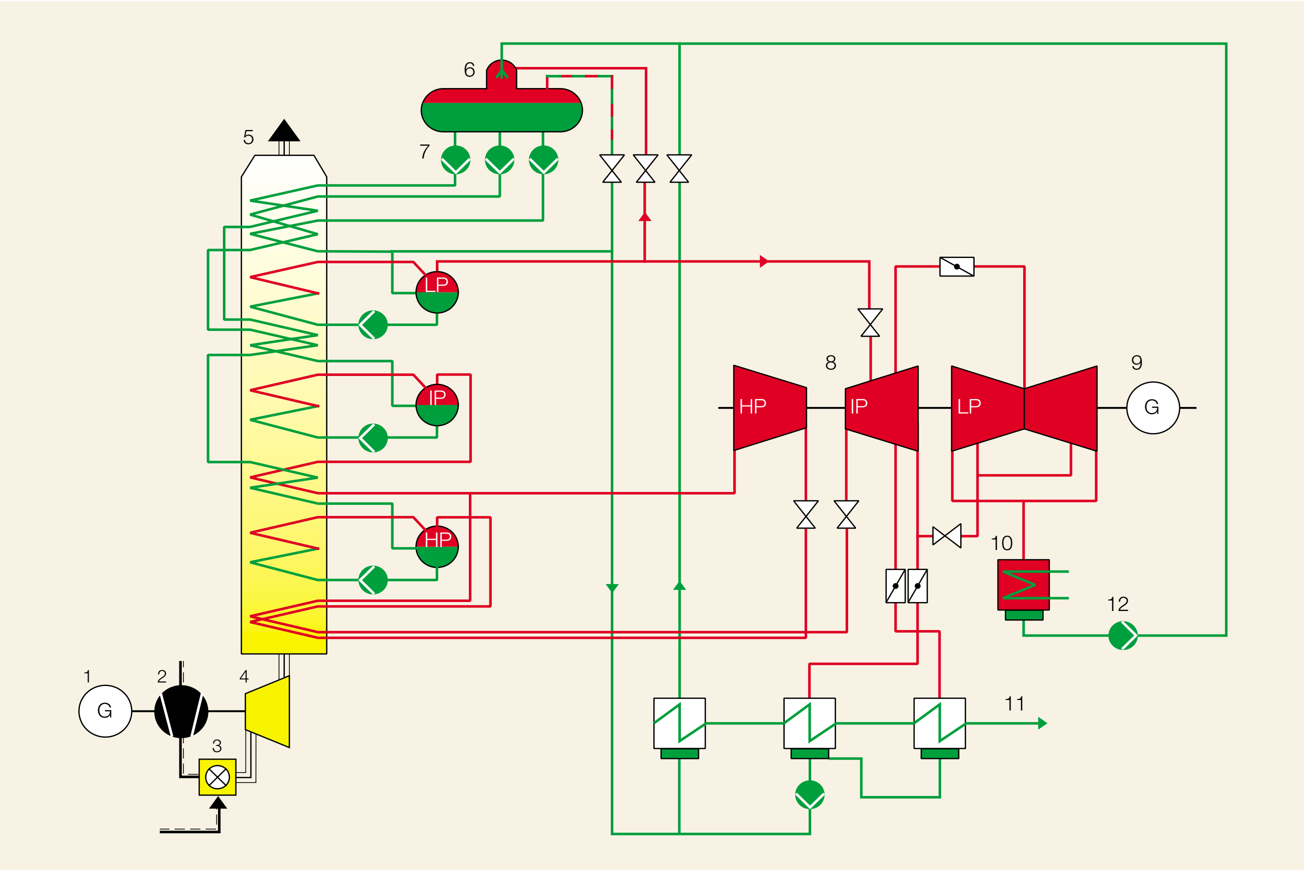
CCPPs are usually the best option

Table 3 gives an overview of the advantages and disadvantages of the different CHP concepts. It can be seen that the combined cycle power plant represents the best option in most cases. This plant is also the one with the best fuel utilization, is least complex, and is most economical to run.

An example of such a plant is the Diemen 33 CCPP in the Netherlands **11**. The plant owner is replacing two conventional gas/oil-fired units (Diemen 31 and 32) to secure district heating for the south-eastern area of Amsterdam. The main benefit of the new plant will be its net efficiency of 54.7 percent, one of the highest

Table 4:
Performance data of the Diemen 33 combined cycle plant in the Netherlands

Owner:	Energieproduktiebedrijf UNA	
Type of plant:	Combined cycle cogeneration (type E)	
Commissioned:	1995	
Performance data based on firing with natural gas		
	Electricity production in summer	District heating in winter
CCPP series (GT type)	1 × KA13E2-1 (GT13E2)	
Total power output (gross)	253 MW	228 MW
Power output of gas turbine (gross)	162 MW	176 MW
of steam turbine (gross)	91 MW	52 MW
Heat production	0 MW	193 MW
Power efficiency (gross)	55.5 %	48.4 %
Fuel utilization (net)	54.7 %	88 %
Frequency	50 Hz	
NO_x emissions	45 g/GJ of heat input	



Simplified flow diagram for the Diemen 33 combined cycle power plant **12**

1 *Gas turbine generator*
2 *Compressor*
3 *Combustor*
4 *Gas turbine*
5 *Heat-recovery steam generator*
6 *Feedwater tank/deaerator*
7 *Feedwater pumps*
8 *Steam turbine*
9 *Steam turbine generator*
10 *Condenser*
11 *City heaters*
12 *Condensate pumps*

HP *High pressure*
IP *Intermediate pressure*
LP *Low pressure*

figures anywhere in the world. *Table 4* gives the most important technical data, with **12** showing the heat chart for the plant.

The proven technology of the gas turbines' EV dry low-NO_x burner will ensure compliance with the Netherlands' very strict emission legislation, while at the same time maintaining high efficiency rates.

Steam power plants are preferred to combined cycle plants only when lower-grade fuels have to be fired and these are suitable to only a limited extent for gas turbines. Since clean air legislation often means that only high-quality fuels can be used, the combined cycle power plant is, in many cases, the preferred option here, too.

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