Optimal utilization of the work potential of fuels and renewable energy with combined cycle power plants

The title could just as easily be 'Use of non-renewable energy for optimizing the utilization of renewable energy'. Ambient heat is renewable energy without or with only a marginal temperature potential. It can be utilized for heating purposes with the help of work obtained, for example, entirely from non-renewable energy, ie, from fossil fuels or nuclear fission. Considered as a whole, such an indirect method is capable of contributing much more to reducing the environmental impact of emissions and waste heat than the direct utilization of solar, wind, geothermal and other kinds of renewable energy, all of which can still be used only on a modest scale. An exception is, of course, hydropower, which provides many countries with an abundance of environmentally compatible energy. Notwithstanding the subject matter, the direct utilization of every kind of renewable energy should obviously be preferred wherever it can be justified economically.

The 'work potential' that can be obtained from fossil fuels and nuclear fission is called exergy, which can also be defined as the work capability of heat. In accordance with the laws of physics it is always less than the thermal energy that is expended. When state of the art technologies are used, large power plants are capable of an exergy value which is equal to 50 to 58 percent of the energy (lower heating value) expended through the combustion of fossil fuels; when used directly for heating, 90 to 100 percent of the energy can be utilized.

However, since only a small amount of exergy is necessary in heat which is used directly for heating (this is because of the low temperature level, or more precisely the small temperature difference between the heating water and the surroundings that is required), a multiple of heat H can be realized with 100 percent fuel energy E when thermodynamic heating is employed.

According to Carnot's principle, the maximum *work* that is theoretically obtainable from the energy form *heat* is

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$$A = E \cdot \eta_C \tag{1}$$

where

$$\eta_C = \frac{T_{max} - T_{min}}{T_{max}} < 1 \tag{2}$$

corresponds to the Carnot efficiency and represents the exergetic yield. Taking the temperatures T_{max} = 1273 K (1000°C) and T_{min} = 273 K (0°C) as examples, the theoretical work (exergy) that can be obtained from 100 % heat energy is

$$A = \frac{1273 - 273}{1273} = 78.56\,\% \tag{3}$$

The remainder (21.44 %) is dissipated to the surroundings as waste heat (anergy) at 0°C. Thus,

$$U = E - A \tag{4}$$

In practice, however, the processes involved in the conversion of heat energy into work are not ideal, with the result that the thermal efficiency of power plants is approximately two thirds of the value theoretically possible. With the values given above, the figure would be about 50 percent. Modern large thermal power plants burning natural gas or oil in combined cycles operate with an even higher T_{max}, whereby efficiencies between 50 and 58 percent can be achieved.

The question could also be asked 'How much heat can be obtained from 100 percent work?' Lord Kelvin (1824–1907), after whom the absolute temperature scale is named, realized very early that a substantial amount of heat is yielded by a small amount of work when the prime mover's process is reversed. In addition to the applied work A, this process also takes heat U from the surroundings and raises it to the level of the required heat H. The total quantity of heat then available for heating purposes is

$$H = A + U \tag{5}$$

It is clear that this corresponds to the ideal heat pump process. In an example with T_{min} = 273 K (0°C) as the ambient temperature and T_{max} = 323 K (50°C) as the hot-water temperature, the efficiency, in accordance with Carnot's principle, will at first be low:

$$\eta_C = \frac{T_{max} - T_{min}}{T_{max}} = \frac{323 - 273}{323} = 0.155 \qquad (6)$$

The exergy content of this heat is therefore only 15.5 percent. Now, for an ideal heat pump

$$H = \frac{1}{\eta_C} \cdot A = \varepsilon_C \cdot A \qquad (7)$$

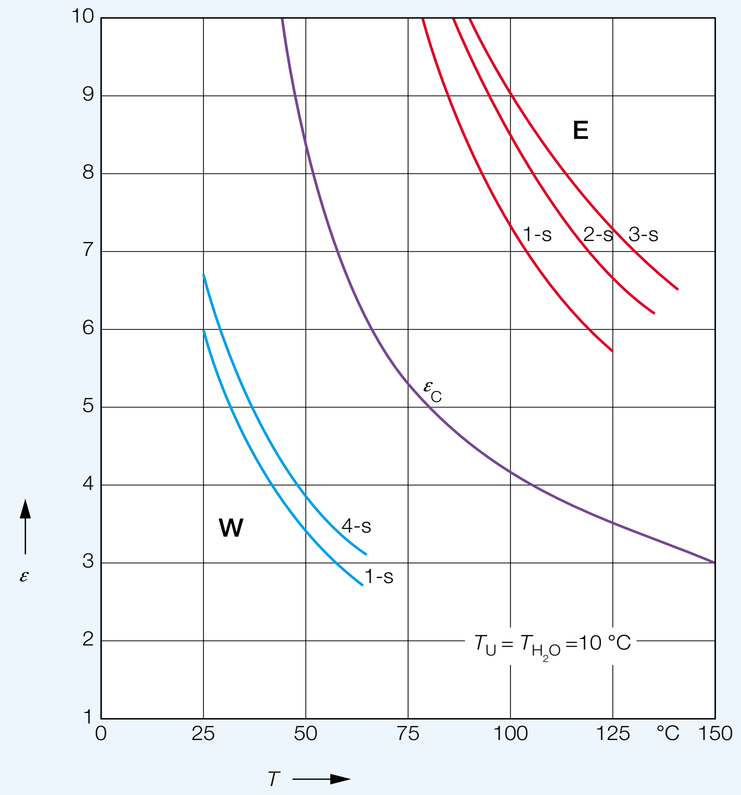
and

$$U = (\varepsilon_C - 1)\, A \qquad (8)$$

The theoretical performance coefficient of a heat pump (according to Carnot's principle) corresponds to the reciprocal of the Carnot efficiency, being

$$\varepsilon_C = \frac{T_{max}}{T_{max} - T_{min}} > 1 \qquad (9)$$

Non-conforming processes lower the performance coefficient ε of actual heat pumps to a value close to 50 percent of the Carnot value, resulting in a value of ε = 3 for the temperatures of 323 and 273 K given in the example.



Performance coefficients for heat pumps and steam extraction **1**

E *Steam extraction*
W *Heat pump*
1-s, 2-s *1-stage, 2-stage, etc*

T *Heating water temperature*
T_U *Ambient temperature*
T_{H_2O} *Water temperature*
ε *Performance coefficient*
ε_C *Performance coefficient, Carnot*

Efficient heating plant

High-efficiency heating plants can be obtained by combining power stations with heat pumps. In such cases, at least some of the electricity generated by the power station will be needed to drive the heat pumps. If it is assumed that a modern thermal power station – eg, a combined cycle plant with gas and steam turbines – generates electrical energy with an efficiency of 56 percent and the heat pumps driven with this energy exhibit a net performance coefficient of 3.5 (allowing for a 10 percent loss in power transmission), heat equivalent to H = $\varepsilon \cdot A$ = 3.5 · 56 % = 196 % is obtained from 100 % fuel energy. This is twice as much as a good boiler is capable of.

Table 1 shows the heat figures which are possible with different power plant efficiencies and net performance coefficients. The figures are based on the lower heat value H_u of the fuel. The values that can be achieved with modern plants are shown against a red background.

A look at the chief factors having a negative effect on efficacy, eg, the unit efficiencies of the turbine and generator in the power plant and also the drive motors of

Table 1:
Heat achievable with heat pumps supplied with electricity from a thermal power plant, as a percentage of the fuel energy

ε	η =	20	30	40	50	60 %
2	H =	40	60	80	100	120 %
2.5		50	75	100	125	150 %
3		60	90	120	150	180 %
4		80	120	160	200	240 %
5		100	150	200	250	300 %
6		120	180	240	300	360 %

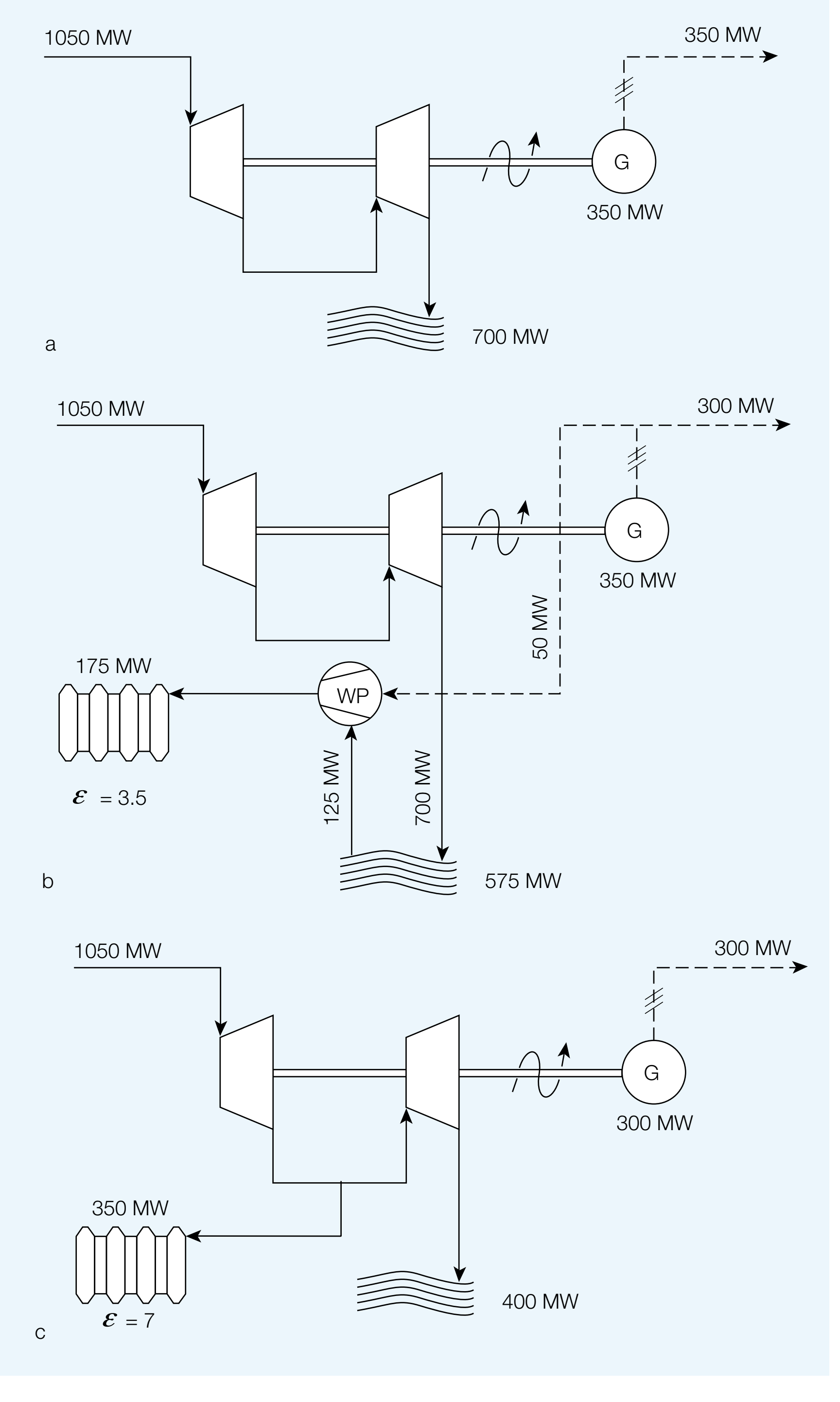
ε Performance coefficient of heat pump
η Power plant efficiency
H Heat energy gained

2 ***Cogeneration with steam extraction, compared with heating systems based on heat pumps. Steam extraction yields, at the cost of a certain reduction in electrical output, twice as much heat as heat pumps.***

a *Electricity generation only*
350 MW, electrical power
700 MW, waste heat

b *Heat pump*
300 MW, electrical power
175 MW, heat
575 MW, waste heat

c *Cogeneration*
300 MW, electrical power
350 MW, heat
400 MW, waste heat

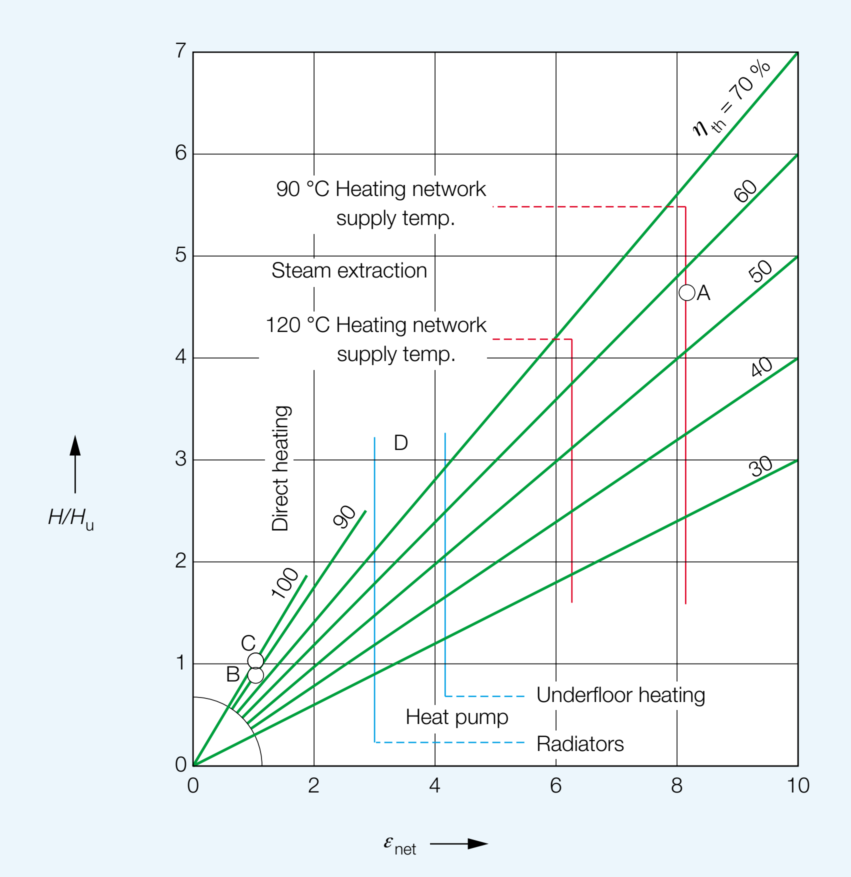


the heat pumps and their compressors, raises the question of whether the required heat should not be taken directly from a point at a suitable temperature on the steam turbine. The losses referred to above would then cease to be a factor. This is exactly what happens when steam is extracted and fed into a district heating network. Instead of the power transmission losses of about 10 percent which are taken into account in the net performance coefficients of the heat pumps, heat losses equivalent to approximately 10 percent of the total occur in the district heating pipeline. In addition, the temperature in the district heating network is considerably higher than the hot-water temperature of the heat pumps. Despite this, the advantages of steam extraction still greatly outweigh those of heat pump operation.

1 shows, besides the theoretical Carnot performance coefficient ε_C, the performance coefficient ε for steam extraction, in each case as a function of the upper hot-water temperature. Also shown are the performance coefficients obtainable with heat pumps. It can be seen that, although a much higher hot-water temperature is required for district heating purposes, the performance coefficients are about twice those with heat pumps.

This is illustrated in **2** for the case of a steam power plant with 33 percent thermal efficiency (an older steam power facility or nuclear power plant). The configuration in Fig 2a is for generation of electrical energy only. 350 MW of electrical power is obtained from 1050 MW of thermal power, while 700 MW is dissipated as heat into the cooling water or escapes via the cooling tower.

In Fig 2b, 50 MW of electrical power is tapped off to drive distributed heating systems based on heat pumps with a mean value for ε of 3.5, adding up to a heat output of 175 MW. 125 MW of this total is taken by the heat pumps from the surroundings (eg, rivers or lakes). Only 575 MW (700 MW – 125 MW) is therefore lost in the form of waste heat.



Heat potential of gas and oil **3**

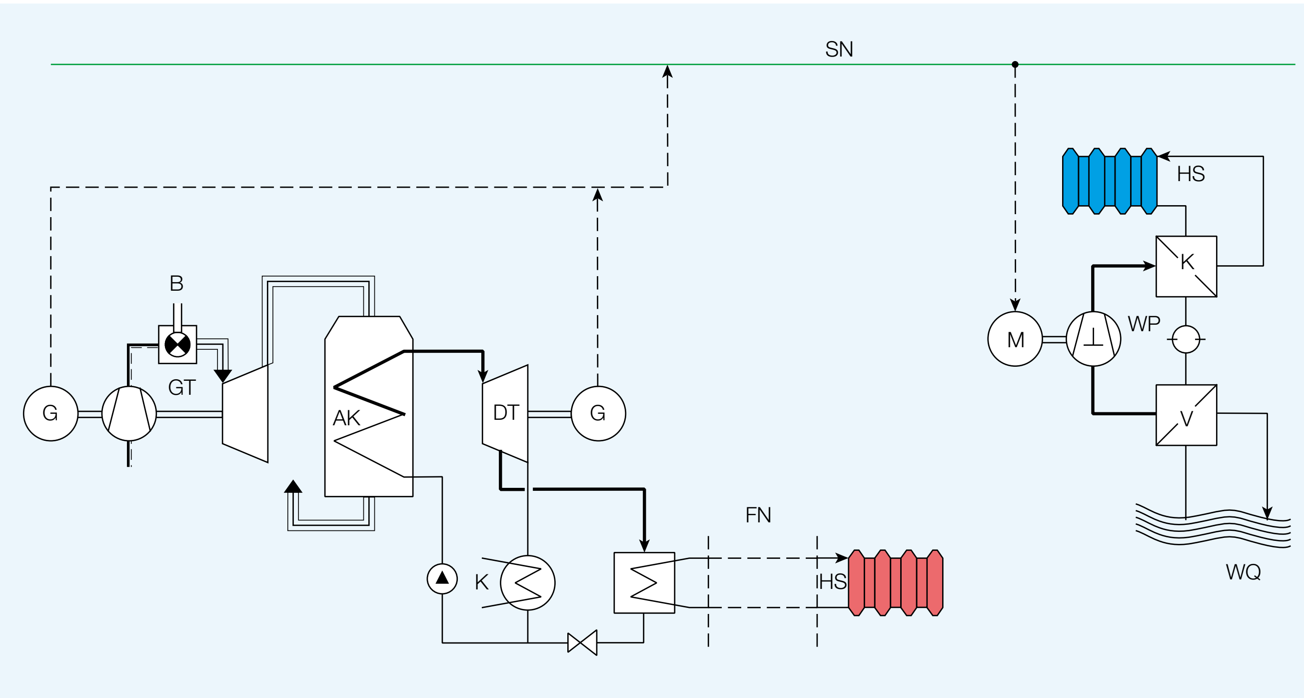
H *Heat*
H_u *Lower heat value*
ε_{net} *Net performance coefficient*
η_{th} *Thermal efficiency*

A *Combined cycle facility (heating network supply temp 90 °C)*
B *Conventional boiler*
C *HHV boiler*
D *Heating system with heat pumps*

In Fig 2c, on the other hand, some of the steam is taken from the turbine. Its temperature is just high enough for it to condense on the hot water used in the district heating network. The amount of steam taken is such that just 300 MW of electrical power can be generated, ie, as much as remains in the configuration in 2b. However, since the value of ε for the heat extraction is 7, the heat output is doubled to 350 MW. Only 400 MW therefore passes to the river or cooling tower. This is

Combined cycle power plant with steam extraction and electrical power supplied to heating systems based on heat pumps **4**

SN *Power grid*
G *Generator*
B *Fuel*
GT *Gas turbine*
AK *Heat recovery boiler*
DT *Steam turbine*
K *Condenser*
FN *District heating network*
HS *Heating system*
M *Motor*
WP *Heat pump*
V *Evaporator*
WQ *Heat source*



the environmentally compatible principle that is applied, for example, in Switzerland's REFUNA district heating network, which provides customers in the northeastern Aare valley with heat from Beznau nuclear power plant. (Transmission losses have been neglected in this comparison to keep it simple and transparent.)

Heat potential of fuels

The ratio of available heat to the lower heat value (LHV) can be referred to as the 'heat potential' of fossil fuels **3**. Thus,

$$H_{pot} = H/H_u \tag{10}$$

Applying the earlier definition of the net performance coefficient,

$$H/H_u = \eta \cdot \varepsilon_{net} \tag{11}$$

3 shows clearly the respective ranges for heat pumps and steam extraction for district heating. Although extraction is twice as efficient as heat-pump operation, there is no justification for playing one system off against the other. Both allow a huge increase in the fuel efficiency of heating systems. When employing these methods, the logical approach is to use district heating within the area being served by the power plant – this can have a radius of 20 to 30 km and more – and install heating systems with heat pumps at convenient locations to extend the network's reach as required. Suitable locations for heat pumps are rivers, lakes, wastewater treatment plants, groundwater sources, to mention just the more important ones. The cycle shown in **4** illustrates this method in connection with a combined-cycle power plant.

Such combined-cycle facilities today achieve efficiencies of 50 to 58 percent, depending on their size and the type of fuel burnt. The best figures are obtained with large plants fired with natural gas. When the value of the heat potential of such facilities is included in the equation, their importance for the environmentally compatible combustion of fossil fuels soon becomes apparent.

GT24 gas turbine being installed in the Gilbert power plant, New Jersey, USA **5**

Highest energy efficiency with the new GT24 and GT26 gas turbines

In the case of combined cycle power plants employing new ABB gas turbines with sequential combustion **5**, the result for a mean annual heating water supply temperature of 90°C is given by point A in **3**. In other words, almost five times the heat value of the fuel can be utilized. This corresponds to an improvement over a good boiler (point B) of half an order of magnitude. Compared with it, the improvement to be gained by upgrading a boiler to a so-called HHV boiler is infinitely small.

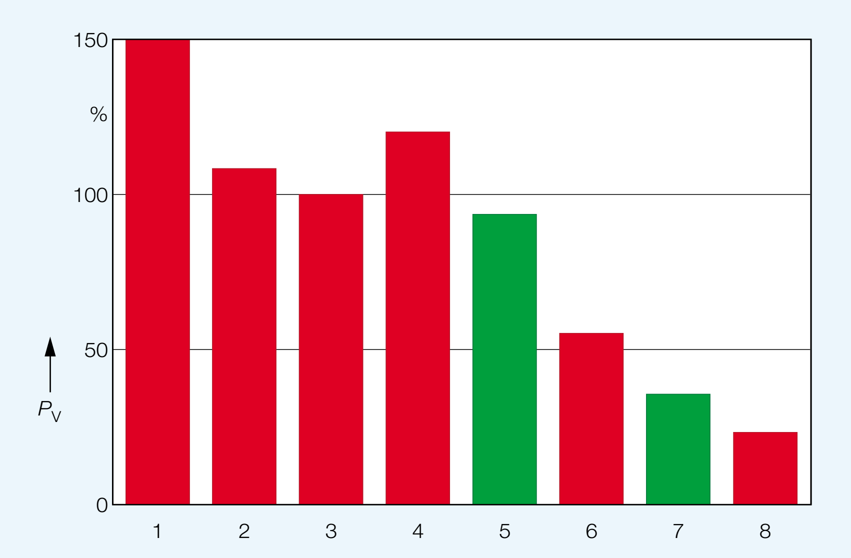
What is more, heating systems based on heat pumps driven by electricity from such power plants also manage to realize about twice the fuel's heat value for heating purposes (range D).

The objection could be raised here that older thermal power plants do not work with such good efficiencies. While this is true, to realize thermodynamic heating with steam extraction and heat pumps on a large scale, additional power plants would have to be built to compensate for the power consumption. Since these new plants will be state of the art and replace, through their higher efficiency, the electricity 'lost' to heating, this objection becomes irrelevant in practice.

Primary energy consumption of different heating systems

6 shows the percentage primary energy consumption, based on the established heat potential, that corresponds to 100 percent heat energy availability. A comparison is also made with direct heating methods.

Column 1 shows the primary energy consumption of an older, hugely oversized boiler with a mean efficiency of 67 percent. Column 2 gives the consumption for a boiler with 90 percent efficiency, and column 3 for an HHV boiler, which makes use of some of the condensing heat in the combustion vapour in the flue gas. An in-



Primary energy consumption P_V for different heating methods **6**

Red *Referred to lower heat value of fuel*
Green *Referred to thermal output of reactor*

Column	Heating method	Efficiency %	Transmission losses El. energy %	Transmission losses Heat %
1	Old boiler	67		
2	Modern boiler	90		
3	HHV boiler (partial condensation)	100		
4	District heat from large boiler	90		10
5	Heat pumps with el power from nuclear facility (ε_{net} = 3.5)	33	10	
6	Heat pumps with el power from combined cycle facility (ε_{net} = 3.5)	56	10	
7	District heat from nuclear power facilities (ε_{net} = 8.1)	33		10
8	District heat from combined cycle facility (ε = 8.1)	56		10

teresting result is shown by column 4. Here, heat for district heating is taken from a boiler; the efficiency is 90 percent and 10 percent of the heat is lost in the pipeline. In terms of fuel economy and CO_2 emissions, this is not a good method.

Column 5 shows the consumption of thermal reactor heat when heat pumps are driven by electricity from a nuclear power plant. This result may not, however, simply be compared or equated with that in column 3, as there are no CO_2 emissions from the nuclear facility. If the heat pumps are driven by electricity from a fossil-fired power plant with 56 percent efficiency, the primary energy consumption is as given in column 6. An even better result is obtained with district heating based on steam extraction from a nuclear power plant (column 7). Finally, column 8 shows the result for district heating with steam extraction from a combined cycle power plant of the type currently being built by ABB (and how it could also be built in order to replace the electrical energy utilized for the proposed heating methods). About four times as much heat as with a very good boiler, or five times more than a district heating network fed by boilers, is possible when district heating is based on steam extraction from a modern combined cycle facility. It can be seen that heat for district heating is not simply heat. What counts is where it comes from!

Summing up

The term ‘renewable energy’ also covers the waste heat from electrical power generation which is not dissipated to the surroundings and the ambient energy that is absorbed by heat pumps. The higher the thermal efficiency of the power generation, the more renewable energy there will be which can be utilized with increasingly smaller amounts of non-renewable energy (fuel) for heating purposes. The heat gained in this way is several times the fuel energy that is employed.

ABB’s new family of gas turbines with sequential combustion are outstanding for the results they allow in just this area.

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[3] **H. U. Frutschi:** Advanced cycle system with new GT24 and GT26 gas turbines – historical background. ABB Review 1/94, 20–25.

[4] **H. Neuhoff, K. Thorén:** GT24 and GT26 gas turbines – sequential combustion the key to high efficiencies. ABB Review 2/94, 4–7.

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Two GT26 gas turbines for a 720-MW combined cycle facility in the UK

ABB has won an order for two 240-MW type GT26 advanced gas turbines and other equipment and services for the 720-MW Rocksavage combined-cycle power plant at Runcorn, near Liverpool, in the UK. The order, valued at approximately US$ 250 million, was placed by the power project developer *International Generating Company* (InterGen) of the UK. InterGen is co-owned by Pacific Gas & Electric Enterprises and Bechtel Enterprises, both of the US.

ABB will supply the two sequential combustion gas turbosets, heat-recovery steam generators, one steam turboset and auxiliary equipment as well as maintenance services. The plant will supply electricity to a nearby chemical manufacturer and to the public grid. The plant is scheduled to go into commercial service by the beginning of 1998.

The new GT26 gas turbines, a report on which appeared in ABB Review 2/94, will make Rocksavage the most efficient combined cycle power station in the UK. To date, a total of 13 advanced gas turbines of type GT24 (60 Hz) and GT26 (50 Hz) have been ordered worldwide.

ABB wins US$ 230 million PFBC plant order in Germany

ABB has won the contract to build a combined heat and power plant fired with brown coal at Cottbus in Brandenburg, Germany. The order was placed jointly by the local utility *Stadtwerke Cottbus* and the *Hamburger Kommunalfinanz-Gruppe*. In addition to planning, construction and commissioning of the turnkey plant, the order also includes a long-term service agreement. The plant is scheduled to begin operating in the autumn of 1999.

By utilizing ABB advanced pressurized fluidized bed combustion (PFBC) technology, the power plant – the first of its kind in Germany – will be able to burn locally mined low-quality brown coal more efficiently and with lower emissions than conventional coal-fired plants. ABB has built similar PFBC power plants in Japan, Spain, Sweden and the USA.

ABB will supply the boilers, the gas and steam turbosets and the complete electrical infrastructure, including the power plant control system. The plant will generate 74 MW of electricity for the local power grid and an additional 220 MW of steam and hot water for district heating and local industry, thus combining high efficiency with environmental compatibility.

Russian utility orders 110-kV gas-insulated switchgear

Mosenergo, a Russian electric utility based in Moscow, has awarded ABB Calor Emag Schaltanlagen AG an order for 110-kV gas-insulated switchgear of type ELK-0. The order, for nine double-busbar switchbays, also includes the high-voltage cable, service and test equipment, etc.

The switchgear will be installed in the 220/110-kV transformer substation Nowozentralnaja in the center of Moscow. Gas-insulated switchgear was chosen because of

its compact design, which is important due to the confined space available in the substation. The switchgear has to be ready for operation just six months after signing of the contract to meet schedules connected with the celebration of the city's founding, 850 years ago.

Electrical equipment for a cement works in Thailand

Siam Cement Public Co. Ltd. has signed contracts with ABB Industry Ltd, Thailand, for the supply of the complete electrical equipment for its new number 6 cement production line at Thung Song. The Thung Song plant is located in Thailand's Nakornsrithammarat Province, approximately 500 km south of Bangkok. Line number 6 is designed to produce 7,500 t/day cement and is scheduled to begin operating in late 1997.

Whereas ABB acted as subcontractor to KHD Humboldt Wedag GmbH, Germany, for line number 5, which is due to start up this year with a production capacity of 5,500 t/day, it will act as general contractor for the electrical installation for line number 6.

The electrical equipment includes high- and low-voltage switchgear, transformers, drives and the overall plant control system. The Advant® Cement System was chosen to provide the process control and information management for the new line.

ABB Industry Ltd, Thailand, is working closely together with ABB Industrie AG of Switzerland on this project.

Automation of six cement production lines in Indonesia

Indonesia's largest cement manufacturer, *P. T. Indocement Tunggal Prakarsa*, Jakarta, has ordered ABB automation systems for six cement lines at two of its production sites. It is one of the largest orders for cement automation ever placed in Asia, and represents another success for the Advant® Cement System (a report on Advant appeared in ABB Review 6/7-95.

The automation systems are for the Cirebon and Citeurop-Bogor plants, being for four existing and two new cement lines.

The new number 10 line at the Cirebon site is scheduled to begin production in the fourth quarter of 1996 with a capacity of 1.5 million t/year. Retrofitting of the existing number 9 line is due to be completed in mid-1997.

At Citeurop-Bogor, lines 6, 7 and 8 will be retrofitted and go on-line in 1996 and 1997, while the new line number 11, designed for a capacity of 2.5 million t/year cement, is due to go on stream in early 1998.