Part III:

Primary Energy Savings by District Heating Compared to Local Heating Systems

By

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Table of Contents

Abbreviations:

AHP	Absorption Heat Pump
BHPP	Block Heat and Power Plant
CHP	Combined Heat and Power
COP	Coefficient of Performance
DC	District Cooling
DH	District Heating
DIN	Deutsche Institut für Normung (DIN Standards)
EFLH	Equivalent Full Load Hours
elHP	Electrical Heat Pump
f	Factor of energy mix
FC	Fuel Cells
GTC	Gas Turbine Cycle
GTCC	Gas Turbine Combined Cycle
HP	Heat Pump
HPP	Heat Pump Plant
HRSG	Heat Recovery Steam Generator
MCFC	Molten Carbonate Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
PE	Primary Energy
PEMFC	Polymeric Electrolyte Membrane Fuel Cell
σ	Electricity losses of a CHP plant [kW_{el}/kW_{th}]
SNG	Substitute Natural Gas
SOFC	Solid Oxide Fuel Cell
STC	Steam Turbine CHP
W,Q	Energy [kJ]

Indices:

a	absorber
AHP	Absorption Heat Pump
b	boiler
c	condenser
CHP	Combined Heat and Power
com	combustion
cr	Convection & Radiation
d	distribution
el	electrical
elHP	electrical Heat Pump
f	fuel
fl	flow line
fr	firing residue
h	heat
HP	heat Pump
ib	incomplete burning
nda	no data available
pe	primary energy
pp	power plant
rl	return line
th	thermal
thm	total heat method
tot	total
wg	waste gas
η	efficiency
ξ	heat ratio

1. **Introduction (Part III)**

This report is one part of the IEA research project "District Heating and Cooling in Future Buildings". The main objective of this project is to perform joined research to sort out the new conditions for the future expansion of DH and DC regarding forthcoming developments in building stock. District heating with CHP-plants and district cooling are considered as those energy supply systems with the largest primary energy saving potential for industrial nations and the biggest reduction of environmental damage. The following points, which have an essential influence on the design of future energy supply systems, are discussed in the frame of the main project:

- Development of heating and cooling load and energy consumption patterns
- Potential for increased energy efficiency and energy savings by fitting new and older local heating and cooling plants into parts of DH and DC systems
- Environmental benefits of the increased energy efficiency by DH and DC compared to local heating and cooling plants

The following part examines the possibilities for primary energy savings by the use of district heating systems in contrast to local heating systems.

The report is divided into five chapters. In chapter two the system components for district heating generation and distribution are described. The combined heat and power generation (CHP) and a brief description of fuel cells are presented. Furthermore, the possibilities for heat pump plants are considered.

In chapter three the different types of local heating systems are described. Apart from the typical systems fired by fossil fuels, absorption and electrical heat pumps are also considered.

In chapter four the different systems are compared primarily from an energetic point of view. The energetic evaluation of heat generation with CHP is problematic and different valuation methods are therefore described briefly.

In chapter five a short summary and evaluation of the results of the report will be given. However, a favourable evaluation of primary energy savings can only be made under a specific energy requirement situation and available primary energy sources.

For a primary energy evaluation of the different processes the following details are needed:

For the CHP process:
electrical and thermal efficiency, power and heat ratio and the influence of the temperature

For DH:
thermal efficiency of the DH distribution and ratio between base and peak load

For local heating:
boiler and total boiler efficiency / COP and COP_{tot}

All data in this report are given for the net calorific value.

1.1. Situation of Heat Supply World-wide

The heat supply of buildings worldwide is still mainly guaranteed by fossil fuels. In Europe however district heating supply has increased in the last decades to reduce the primary energy need by using combined heat and power plants (CHP).

Fig. 1 shows the heating systems for space heat in selected European countries. The missing amount in each country is provided by other sources.

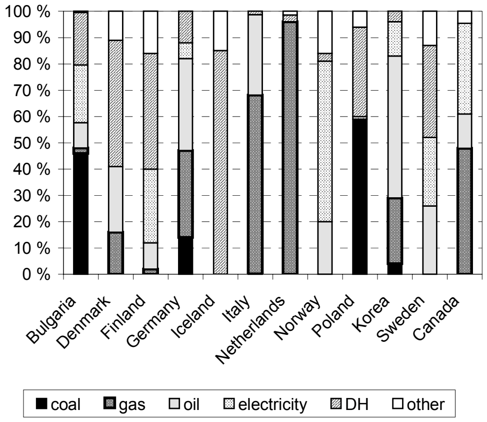

Figure 1 Type of residential heating in selected countries /1/

District heating is used primarily in Eastern Europe, Germany and several Scandinavian countries. Electrical heating systems are spread particularly in those countries in which the electricity is mostly produced by hydropower or nuclear energy.

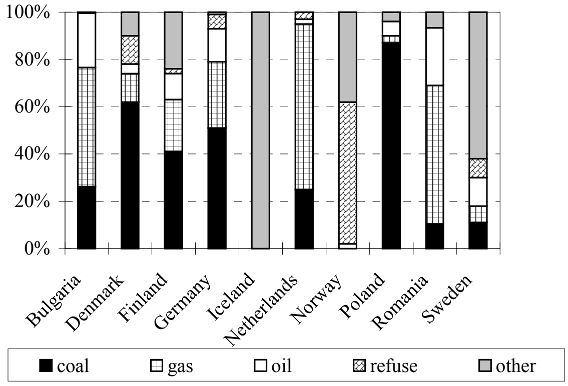

Figure 2 Primary energy to produce district heating /1/

Fig. 2 shows the input primary energy sources for district heating generation. In Iceland district heating produced by geothermal energy is predominantly used. In Finland the share of the other primary energy consists mostly of heat generation from peat. In Norway district heating is produced partly electrically. Sweden has a particularly interesting composition of DH. Besides the classic primary energy sources (coal, oil, gas, refuse), there is DH from regenerative power generation, too (biomass, peat). In addition, heat pumps and industrial waste heat are used in large-scale units (see Fig. 3).

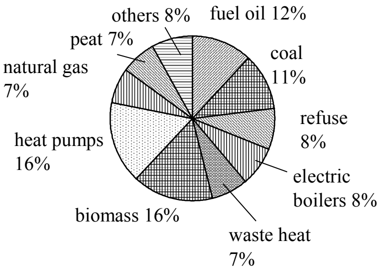

Figure 3 Primary energy used for district heating in Sweden /1/

Fig. 4 shows the district heating produced 1995 in different countries. The heat produced with CHP is marked black. Large networks in Europe were set up in many East European countries and in Germany, Sweden, Finland and Denmark.

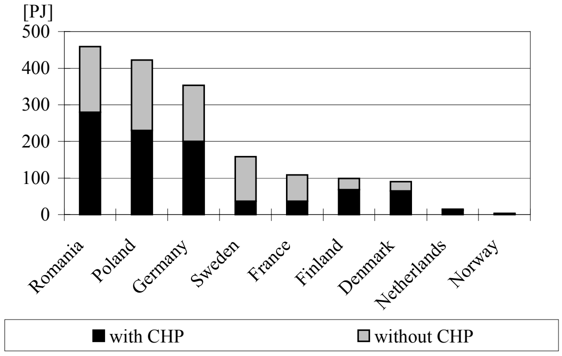

Figure 4 Heat production for district heating /2/

Fig. 5 shows the primary energy source for the electricity production. In Sweden and France electricity is predominantly produced by the nuclear energy, while Norway and Brazil use their geographical advantage to produce electricity mostly by hydropower. How electricity is generated is a main criterion to calculate the primary energy savings of CHP-processes.

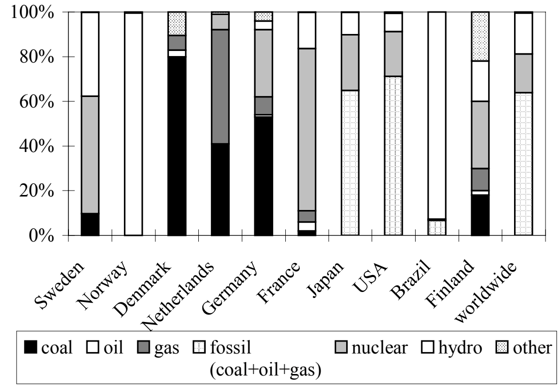

Figure 5 Primary Energy for electricity production /3/

1.2. Situation of Heat Supply in Germany

The final energy consumption of private households in Germany is to more as 75% by space heating (Fig. 6 /4/). It is still about 30% of the total energy consumption /5/, and is produced by the energy sources shown in Fig. 7 /6/.

Since reunification, the share of district heating has increased clearly because the district heating has a much larger market share in East Germany. District heating now provides about 12% of the total heat distribution.

Apart from the district heating the share of coal has also increased after reunification. The reason is that many local heating systems in East Germany are still fired by brown coal. This share is declining as expected and will diminish further.

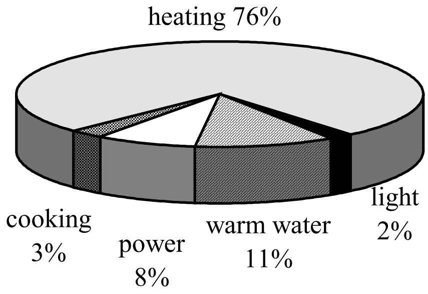

Figure 6 Proportions of the energy consumption of residential buildings (Germany)

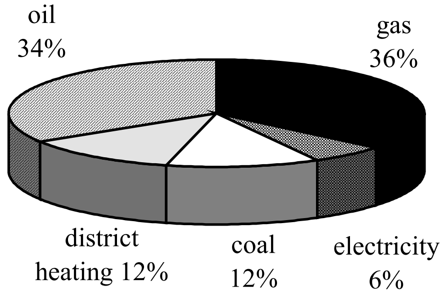

Figure 7 Different energy sources for heating of residential buildings (Germany)

Unlike district heating with CHP plants, which stagnates in Germany at the moment, the share of the CHP with block heat and power plants (BHPP) for single units increases. Especially those units with large heat base loads (e.g. hospitals, swimming pools, shopping malls and also smaller neighbourhoods and industry) are interesting for the use of CHP-processes.

At the end of 1996 about 3.000 BHPPs were installed with a performance of approximately 1600 MW_{el} and about 300 gas turbines with a performance of 4000 MW_{el}. This corresponds to a share of approximately 5% of the German electricity generation. With the actual growth an increase up to 10% is expected in future.

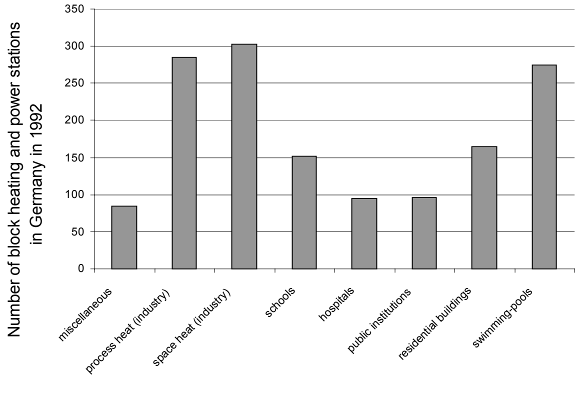

Figure 8 Area of the use of BHPPs /7/

2. District Heating Systems

The term "District Heating" is used for the central generation and distribution of heat by hot water or steam to provide heat and warm water for residential housing and industry.
The advantage of district heat for the customer is the simple availability and the good supply guarantee; the customer needs no own heating system. In addition district heating supply results in a reduced energy demand by efficient use of energy, and therefore in a reduced consumption of primary energy by waste heat utilisation of industrial processes or CHP-Systems.

2.1. Combined Heat and Power Plants

The simultaneous generation of mechanical or electrical energy and useful heat in one plant is called Combined Heat and Power process (CHP). All heat and power engines and combustion engines are suitable for the CHP-system. By using the CHP-system the demand of primary energy can be reduced clearly compared to the separate generation of electricity and heat.

The disadvantage of CHP-systems is that the demand of heat and electricity of the customer can deviate strongly from each other, whereas heat and electricity is always generated at the same time. To use CHP in the most efficient way, the heat demand is divided into base and peak load. Only the base load is generated by CHP plants, while the peak load demand is provided by peak boilers. Additional heat storage systems are sometimes integrated into the DH networks to guarantee longer utilisation periods and higher efficiencies.

Typical CHP systems are steam turbine and gas turbine heat and power plants. However in the future an increased use of fuel cells can be expected.

Heat pump plants are also used to provide heat. They are especially interesting, if electricity and waste heat are available under good primary energetic conditions and additional heat sources with a high temperature level can be acquired with moderate costs (e.g. from rivers or wastewater from industrial processes).

2.1.1. Steam Turbine CHP (STC)

Independent steam turbine power plants (i.e., steam turbines which are not just a component of a larger plant) are available in sizes ranging from 5 MW_{el} to over 1000 MW_{el}, and are the most common type of power plant in use world-wide. As a component in a larger plant, steam turbines are available in sizes of less than 1 MW_{el}. One of the advantages of this technology is the ability to use a wide variety of fuels, including solid fuels and waste materials. The basic elements of steam turbine CHP are illustrated in Fig. 9, and can be briefly described as follows.

Fuel and air are combusted in a boiler generating steam. To increase the efficiency of the steam turbine cycle, the steam is normally superheated. The steam exits the boiler and is directed to the steam turbine, where the steam expands through the turbine, turning the turbine blades, which are connected to the electric generator shaft. In a backpressure turbine, the steam is fed into a heat exchanger where thermal energy is transferred at a relatively low pressure to the district heating loop. If higher pressure steam is required, some steam is extracted through ports in the turbine prior to full expansion at the turbine exhaust. In a condensing turbine, the steam is condensed using a cooling tower, ground water or surface water, exiting at less than atmospheric pressure. Since turbine efficiency is directly related to the difference between inlet and exhaust steam pressures, condensing (non-CHP) turbine plants provide the highest electric efficiency.

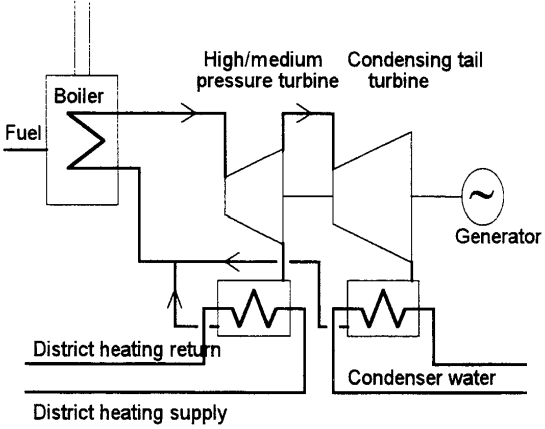

Figure 9 Schematic for CHP with steam turbine, including a condensing tail turbine

As illustrated in Fig. 9, some CHP steam turbine plants include a condensing tail turbine (the low pressure turbine in the figure) to increase the electric output regardless of district heating demand. In some steam turbine plants a reheat cycle is used, in which steam is extracted from the turbine and reheated during the expansion process. Reheat cycles, with one or two reheat points, improve the overall thermal efficiency because the average temperature of the heat supply is increased. Steam turbine plants usually also include a regenerative cycle in which steam is extracted from the turbine and used to preheat boiler feed water /8/.

Table 1 Technical data for steam turbine heat and power plants

types	back pressure HPP extraction condensing HPP uncontrolled extraction condensing HPP
performance	5 - 1000 MW_{el}
fuels	all fuel types (coal, oil, biomass, ...)
elec. efficiency (net)	up to 45 % (total condension) 15 - 35 % (with heat extraction)
total efficiency	85 - 88 %
temperature level of heat extraction influence of heat extraction	60 - 200 °C n_{tot} = const, n_{el} = 0,35 at T_c = 60 °C n_{el} = 0,2 at T_c = 200 °C
operating method	total condensing operation total CHP operation (back pressure HPP) variable operation
power to heat ratio σ	0,3 - 0,7

2.1.2. Gas Turbine Combined Cycle / Gas Turbine Cycle

The gas turbine combined cycle (GTCC) as well as the simple gas turbine cycle (GTC) are increasingly common configurations. Fig. 10 illustrates an example of a combined cycle, showing components for both condensing and CHP options. Temperatures and pressures vary depending on the particular combined cycle configuration. This figure shows one example for illustrative purposes.

Natural gas is combusted in the gas turbine, producing electricity and hot flue gases. The hot flue gases enter the Heat Recovery Steam Generator (HRSG), where heat is recovered to produce steam (and, in some CHP operations, hot water). Output can be increased through supplemental firing, in which additional fuel is combusted using the high oxygen content in the exhaust gas. Supplementary firing can improve the overall efficiency and electric efficiency at part-load conditions.

Steam is used to produce additional electricity in a steam turbine; in the example shown, 32 MW_{el} in condensing mode. The steam cycle usually has 2-3 pressure levels; the higher steam pressure to enhance the electric efficiency and the lower pressure to enhance the heat recovery efficiency. To increase the overall efficiency a district heating economiser can be installed in the HRSG.

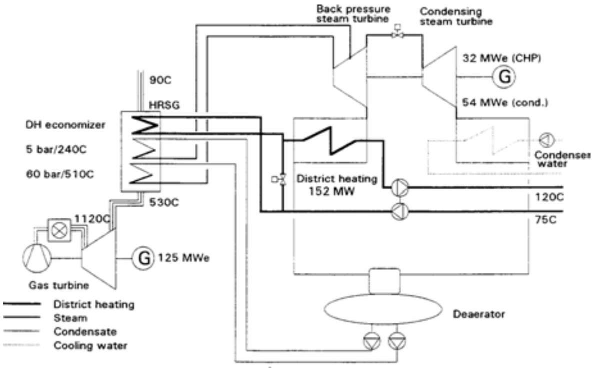

Figure 10 Schematic of a gasfired combined cycle CHP plant

The GTCC in condensing mode can reach an electric efficiency around 50%, with an efficiency above 55% possible in larger facilities with multiple steam pressure levels. The design of particular facility is based on an optimisation relative to a higher overall efficiency and the additional cost and complexity of more steam pressure levels.

Table 2 Technical data for GTCC and GTC

types	GTC	GTCC
performance	1 - 150 MW_{el}	20 - 300 MW_{el}
fuels	gas, oil, gasified fossil fuels	gas, oil, gasified fossil fuels
elec. efficiency (net)	25 - 35%	43 - 56 %
total efficiency	85 - 90 %	82 - 90 %
temperature level of heat extraction influence of heat extraction	80 - 400 °C n_{tot} = 0,9, T_c = 80 °C n_{tot} = 0,8, T_c= 250 °C n_{el} = constant	40 - 180 °C n_{tot} = 0,9, T_c = 80 °C n_{tot} = 0,82, T_c = 180 °C n_{el} = 0,5 , T_c = 40 °C n_{el} = 0,38 , T_c = 180 °C
operation method	operated according to the heat / power demand	operated according to the heat / power demand
power and heat ratio σ	0,4 - 0,65	0,8 - 1,2

2.1.3. Block Heat and Power Plant

Block heat and power plants are CHP plants with combustion engines. In general they are fired by diesel or natural gas but also allow the possibility to use waste and biogas and gasified wood. Their main advantage is that they can be installed very close to the customer and the produced heat can easily be distributed to local heating stations.

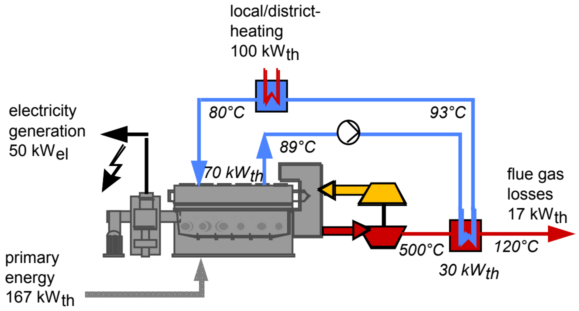

Figure 11 Schematic of BHPP with Gas engine

BHPPs can be divided into the following groups:

- Normal and hot cooled BHPP - engine
- Otto engine / diesel engine
- Differentiation by fuel (substitute natural gas (SNG), diesel, oil or natural gas)

At a BHPP the temperature level for heat generation from waste gas is about 600 °C and from cooling water around 90 °C (cylinder or oil cooling). With the separation of the heat sources (waste heat and cooling water) it is possible to generate steam with BHPP.

The electric efficiency of BHPPs can reach more than 40% especially for larger diesel BHPPs. With a combined generation of thermal energy total efficiencies up to 90% are possible. Since BHPPs only offer poor part load efficiencies, especially gas Otto engines, the total performance is often split into several modules. Depending on the required heat, the number of working modules can easily be adjusted.

Hot cooled engines have lower thermal efficiencies (about 50 - 55%) than normal cooled engines, because the temperature level of the cooling oil is higher and the oil is cooled external.

The maximum cooling water outlet temperature of hot cooled engines is about 120 °C. Further heating can be realised with waste gas heat exchanger. The cooling water of normal cooled gas engine is heated up to 85-90 °C.

Table 3 Technical data to BHPPs with combustion engines

types	hot cooled engines (up to 120 °C waste heat) normal cooled engines (up to 85 °C waste heat) Otto engines, diesel engines
performance	0,05 - 50 MW_{el} (Otto engines up to 2 MW_{el})
fuels	natural gas, SNG, gasified fuels, oil
elec. efficiency (net)	24 - 44 %
total efficiency	85 - 88 %
temperature of heat extraction influence of heat extraction	60 - 200 °C n_{tot} = const, n_{el} = 0,35 at T_c = 60 °C n_{el} = 0,2 at T_c = 200 °C
operation method	operated according to power demand (with emergency cooling) operated according to heat demand
heat to power ratio σ	0,45 - 2,6

2.1.4. Fuel Cells

Fuel Cells (FC) convert chemical energy directly into power and heat. This kind of CHP technology represents a new development. Only some systems of FCs are available at the moment. Because of their advantages compared to standard CHP-technologies and their potentials to extend the field of application of CHP, they are discussed here.

Because of the direct conversion there is no limitation by the Carnot efficiency and therefore electric efficiencies above 60% can be reached. Today, most available cells have an electric efficiency of about 40%, which can decrease to 30% due to ageing.

The total efficiencies of FC are comparable to BHPPs with low performances, only the electric efficiency is higher. Apart from the low emissions of harmful substances and noise, fuel cells have the advantage of good part load conditions. Therefore FC-CHP plants can be designed for much higher base loads than conventional BHPPs and modular-type design is not necessary.

The development of the Phosphoric Acid Fuel Cell (PAFC) has progressed lately and the company ONSI Cop. can offer modules with performances of 200 kW_{el} since 1995. 69 units of this type were in use in 1997 and the total working time of all units exceeds 500.000 h /9/. Phosphoric acid is taken as an electrolyte. The working temperature of those units is about 170 - 200 °C. PAFC are running with natural gas, which needs to be reformed with steam at a temperature of 700 - 900 °C. After the following shift reaction at 400 °C the gas of CO_2 and H_2 can operate the fuel cell.

Flow temperatures up to 75 °C are possible with PAFCs (high temperature extraction is also offered with 120 °C/70 °C). The return line temperature should be between 30 and 50 °C. In the near future PEMFC (polymeric electrolyte membrane fuel cells) are expected to supply decentralised district heating networks. The Canadian Company Ballard is testing a prototype with a performance of 250 kW at the moment. By the end of 1999 a unit with 250 kW will be installed in Switzerland. It is considered that in the future PEMFCs can be very interesting for decentralised CHP plants without complex district heating networks (concept from Sulzer-Hexis).

MCFC (Molten Carbonate Fuel Cell) have been tested by the companies MC Power and ERC with 2 MW and 250 kW prototypes.
A pilot project from MTU Friedrichshafen with a 300 kW prototype has just started in Germany with MCFC. They are normally chosen for base load operation because of the high energy demand to heat up these FC in the starting period. They need a continuous CO_2 supply. Therefore gases, with a high content of CO_2 (SNG, biogas, gasified fuels) are particularly suitable.

SOFC (Solid oxide fuel cells) are still in its initial test stage. They are expected to realise high electric efficiencies with a simultaneous process steam generation (the electric efficiency is higher due to its internal gas reforming).

Table 4 Technical data for fuel cells

type	PAFC	PEMFC	MCFC	SOFC
performance (aspired)	50 kW_{el} - 10 MW_{el}	5 - 1000 kW_{el}	10 - 100 MW_{el}.	5 kW_{el} - 100 MW_{el}
fuels	natural gas (hydrogen)	natural gas, SNG, (hydrogen)	hydrogen, methanol, CO_2, natural gas	natural gas, methanol, gasified coal, hydrogen
elec. efficiency (total, incl. reforming)	40%	up to 45%	50 - 55%	50 - 60 %
thermal efficiency	45%	up to 40%	> 40 %	up to 40 %
temp. level of heat extraction	80 °C / 120 °C	80 °C	n.d.a.	n.d.a.
working temp.	200 °C	120 °C	650 °C	800 - 1000 °C
influence of heat extraction	n_{el} = constant n_{th}=0,42 (T=50 °C) n_{th}=0,13 (T=80 °C)			
operation methods	according to power demand according to heat demand	according to power demand according to heat demand	according to power demand according to heat demand	according to power demand according to heat demand
power to heat ratio	about 1	about 1	up to 1,5	up to 2
stage of development	available on market	demonstration, begin of commercial use	begin of demonstration	begin of demonstration
applications	BHPP	BHPP, local unit	larger plant	BHPP, local unit, larger plant

2.2. Heat Pump Plants

Heat Pump Plants (HPP) are used instead of or combined with conventional heat and power plants. In combination with BHPPs they are often called total energy plant or tandem plant. Compared to standard BHPPs with constant heat to power ratio σ , heat pump plants offer a variable ratio between heat and power.

The following heat sources can be used for heat pump plants:

- Industrial waste heat
- Sea or river water
- Ground water
- District heating supply or return line

If district heating is used as a heat source, the heat pump only transforms the district heating to the desired temperature level. It is interesting for customers with a need of high temperature heat or to extract heat at a low district heating temperature. Especially thermal-driven absorption heat pumps offer a good opportunity from a primary energetic point of view. Electrical heat pumps as well as absorption heat pumps are suitable for heat pump plants (see /10/). The data for heat pumps is given in chapter 3. Because of the larger design and the more favourable working conditions, (especially higher temperature level of the heat sources) heat pump plants may offer higher COPs. The following table 5 shows the figures of heat pump plants.

Electrical-driven HPPs are an interesting option for countries with electricity produced by hydro or nuclear power. Thermal HPPs are best used, when waste heat on a temperature level of 120 - 200 °C is available.
Another interesting alternative is the installation of cold district heating networks. The supply line temperatures are dropped to 30 – 40 °C and electrical heat pumps at the customers’ site raise the temperature individually to the desired level.

Table 5 Technical data for heat pump plants

type	electrical /mechanical HPP	thermal HPP
performance	0,5 - 30 MW_{th}	0,5 - 10 MW_{th}
driving energy	electricity	thermal energy (temperatures between 120 - 200 °C)
refrigerant	ammonia (R 717), R 124a, R 134a (R 114)	water - ammonia, water - LiBr
coefficient of performance (COP)	3 – 5	1,3 - 1,7 (excl. efficiency of burner), 1,2 - 1,4 (incl. efficiency of burner
temperature level of heat source	3 - 40 °C	4 - 40 °C
temperature level of useful heat	50 - 85 °C (120 °C with R114)	40 - 100 °C

2.3. Heat Plant / Heat Distribution

In district heating systems peak load heat plants are used besides CHP-plants for economic and operational reasons and to guarantee uninterrupted service.

Because of seasonal and daily variation, the heat demand is divided into base and peak load. While the base load is often provided by CHP, the peak load is mostly generated by peak boilers. Alternatively, conventional heating systems (electricity, natural gas) at the customers' site can cover peak load. This system is popular in the Netherlands. Another possibility is the use of long- or short-term heat storage systems. Depending on the type and size of the storage additional heat losses has to be accepted.

A classification of the heat demand into base and peak load is necessary for economic reasons, because only during base load the equivalent full load hours (EFLH) are large enough for capital intensive CHP-plants. A CHP-plant designed for 50% of the maximum heat demand can supply more than 90% of heat, depending on the demand characteristics.

To cover the peak load, oil-fired peak boilers are often used. Although higher variable costs have to be considered, they cause lower fixed costs. Other fuels can also be taken into account; those boilers are described in chapter 3.1.

Heat plants fired by natural gas reach total efficiencies about 88 - 90% including heat losses of the boiler by operation stop.

Table 6 Technical data for peak load boilers and heat distribution

boiler:	
range of performance	0,5 - 30 MW_{th}
driving energy	electricity, oil, natural gas, coal , biomass
design	50 - 80% of maximum DH performance 5 - 20% of heat supply
total efficiency	80 - 90%
district heating distribution:	
distribution efficiency	0,85 - 0,95
temperatures (supply line /return line)	55 - 130 °C
electricity demand	0,018 - 0,03 kWh_{el}/kWh_{th}

3. Local Heating Systems

Local heating systems are systems with decentralised heating. The fuel or electricity is transported to the customer and transformed into heat at the customer's place. Local heating systems are:

- Heating systems with fossil fuels (heating with gas, oil, wood)
- Electrical driven heating systems (electrical storage heating, direct heating)
- Heat pumps (gas fired absorption heat pumps, electrical heat pumps)

3.1. Heating Systems with Fossil Fuels

For the energetic assessment of heat generating units efficiency is defined as follows:

eq.1 $$\eta_b = \frac{\dot{Q}_b}{\dot{Q}_f} = 1 - (q_{wg} - q_{ib} - q_{cr} - q_{fr})$$

The efficiency of the boiler η_b is the ratio of the boiler performance and the primary energy input (enthalpy flow of the fuel). It includes the losses from waste gas (q_{wg}), incomplete burning (q_{ib}), convection and radiation (q_{cr}) and unburned material in the firing residue (q_{fr}).

For conventional gas and oil heating systems waste gas losses and convection and radiation losses are the fundamental losses. Incomplete burning and unburned material have to be considered when firing with wood.

Waste gas losses are determined by the waste gas temperature, heat losses from convection and radiation by the quality of insulation, boiler temperature and downtimes.

Modern boilers have reduced waste gas losses to about 8% (waste gas temperatures of 160 °C) condensing boiler to 3%. Convection and radiation losses have diminished to 1-2%.

The total efficiency of boilers η_{tot} is the ratio between the generated useful heat Q_η and the fuel input heat Q_F in a defined period. Modern boilers have to be compared with the standardised efficiency $\eta_{tot,st}$ as described in DIN 4702 [1]. It is useful for the energetic assessment, because part load conditions and downtimes of the burner are already considered.

For the evaluation of local heating systems it is better to use standardised efficiencies as to use total boiler efficiencies. We have to take into account that the value of total boiler efficiencies are

- only exactly, if we measure this value,
- this value of course depends on the weather (cold year/warm year)
- we can only get an approximation of η_{tot} by calculation

The standardised boiler efficiency $\eta_{tot,st}$ is basis of the planning of heating systems in Germany at first. It does not take into account the dimensioning of the boiler, habits of heating and the kind of the building. As experience shows, η_{tot} is 1 to 2 % lower than the standardised total boiler efficiency ($\eta_{tot,st}$).

Table 7 shows the efficiency and the total efficiency of local heating stations:

Table 7 Efficiency and total efficiency of local heating stations [2]

type of boiler	Efficiency η_b	total efficiency $\eta_{tot,st}$ (excl.warm water generation)
oil	0,88 - 0,92	0,83 - 0,86
gas boiler	0,91 - 0,94	0,84 - 0,88
condensing boiler (gas/oil)	1,04 - 1,09	0,98 - 1,06
wood fired single stoves	0,4 - 0,6	0,4 - 0,6
boilers (fired by wood pieces)	0,65 - 0,8	0,7 - 0,8
boilers (fired by wood chips)	0,75 - 0,85	0,7 - 0,9
large boilers	0,7 - 0,9	n.d.a.

In the following chapters the different heating technologies and their advantages and disadvantages are described.

3.1.1. Gas Heating

Advantages:

- Waste gas with a high percentage of water and therefore low CO_2-emissions, clean burning
- Little cleaning and service necessary
- No fuel storage necessary

Disadvantages:

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[1] The standardised boiler efficiency is calculated for five different daily average boiler efficiencies for five different part load situations.

[2] Values refer to the lower heating value of the fuel.

- Fuel distribution by installed tube systems (much lower costs compared to district heating)
- Price changes take effect immediately because of missing storage capacity

Gas heating systems can be divided into burners with and without ventilation. Burners without ventilation need specific design and are mostly used for smaller units (up to 1000 kW_{th}) with the advantage of very quiet working process, while burners with ventilation are similar in design compared to oil heating systems. They are built in all sizes up to large industrial plants.

3.1.2. Oil Heating

Advantages:

- Price changes effect slower because of storage capacity
- No distribution from a network (gas/ district heating) is required, and therefore ideal for remote houses

Disadvantages:

- More cleaning compared to gas is necessary
- Storage tanks are necessary and therefore more space is required

Over the years the oil heating has been under permanent development. Especially it is possible today to work with low water temperatures without corrosive condensation of the waste gas. This is achieved by a special design of the boiler walls or the increased temperature of the walls above dew point. Especially the convection and radiation losses can be decreased fundamentally. Therefore the over all efficiency can be increased.

3.1.3. Heating with Wood Boilers

Wood-fired heating systems are especially popular in countries with large forests and wood industry. Fuels are wood pieces and residues from the forest and waste products from the wood industry. In 1991 4,5 mill. m^3 of wood residues were collected from the forests in Germany, which is equal to 1,2 mill. l of oil. In addition, other renewable fuels like straw and peat can be used.

Wood contains hardly any sulphur. Only nitrogen oxide, tar condensates have to be controlled in the waste gas (and require controlled combustion). The calorific value of wood depends strongly on the moisture of the wood, which should be lower than 20%. Wood with moisture of 15% has a calorific value of about 14-16 MJ/kg.

Wood-fired heating systems are designed as single units (single stoves, tiled stoves, open fireplaces) and as central heating systems. Single units are only used to heat single rooms and have very low efficiencies. A controlled combustion is not possible. Wood fired central heating systems use water as heat carrier and require a more complicated design to reach a better combustion and to be able to compete with oil and gas heating systems.

The following constructions are possible:

1. Burn-out-furnace, furnace for wood pallets with burning from upside/downside. They have low efficiencies and difficult control responses and are used for warm water generation
2. Furnaces fired by wood chips (with automatic wood supply)
   They have better efficiencies but more complicated design.
3. Underfeed or stoker furnace
   Also better efficiencies. Higher investment costs
4. Wood injection combustion (for chips or wood dust)
5. Change-over furnace
   Bivalent firing with wood (main heating period) and oil/gas (for interseasonal period)

3.1.4. Condensing Boiler (Gas / Oil)

The application of the condensing boiler technology presupposes that the fuel contains hydrogen. The higher the hydrogen ratio, the larger is the energy profit achieved by steam condensation, which is theoretically around 11% for natural gas and 6% for oil /11/. Today, even gas heating systems with small performances and a low temperature level already reach total efficiencies on the calorific value (net) of around 91-93%. Heat generators of larger performance with double effect or modular burners obtain approximately 94 to 95%.

A considerable increase of the total efficiency can be reached if the enthalpy of vaporisation of the steam in the waste gas is used. In conventional heating systems this enthalpy leaves the system unused through the chimney. By lowering the waste gas temperature the steam in the waste gas condenses and even the sensible heat is gained more effectively. Depending on construction, performance and operating mode total efficiencies of 100 to 109% for available condensing boilers can be reached today.

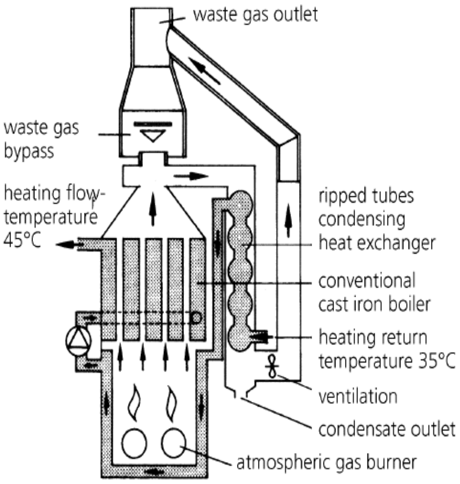

Figure 12 Typical construction of a condensing boiler with atmospheric gas burner

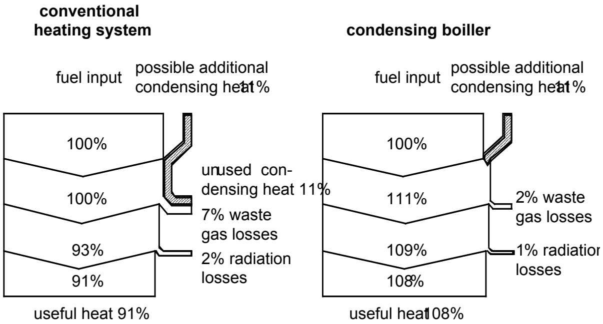

Figure 13 Energy balance of conventional and of condensing boiler systems with warm water temperatures of 40/30 °C

Fig. 14 shows the dependence of the efficiency on the return temperature. It demonstrates that low return line (or back flow) temperatures are an important prerequisite for an effective use of the condensing boiler.

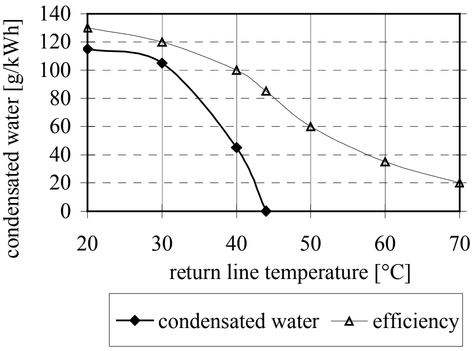

Figure 14 Efficiency and amount of condensed water of condensing boilers depending on the back flow temperatures

To use the condensing effect, the waste gas temperature has to be lower than the dewpoint temperature of the natural gas, which is 56 °C. A total condensation of the steam is obtained at a return line temperature lower than 40 °C. In this case the waste gas temperatures are only 46 °C.

It is obvious that a complete use of the condensing advantage is only possible with low temperature heating systems (underfloor central heating). But also with design temperatures of 50/70 °C a total condensation can be reached for most of the year.

Per one m^3 of natural gas, about 1.7l condensate (-> 1.07 kWh) have to be disposed. Apart from steam the waste gas also contains carbon dioxide, nitrogen oxides, and with the use of fuel oil, also sulphur oxides. These are gaseous in the waste gas but are absorbed however by the condensing water at the heat exchanger surface and in the waste gas unit. These generated acids can lead to damages, if they are disposed into the waste water system in undiluted form.
Therefore in Germany a neutralisation of the waste gas must be provided for condensates with a pH value under 6.5.

3.2. Electric Resistance Heating and Electrical Storage Heating

The electric resistance heating provides space heating the simplest manner. The efficiency is almost 100% since no transformation losses occur during generation heat. Electric resistance heating is used in the form of direct or storage heating systems:

- The direct heating immediately converts the electric energy into useful heat. In Germany it is normally only used as an additional or interseasonal heating system because of high electricity tariffs.

- The storage heating a storage mass is heated by cheap off-peak electricity. The stored heat is released slowly again depending on demand. Cheap off-peak electricity is offered by the electricity suppliers, since it increases the load at night without additional charges. This heating system is suitable for flats and houses but is limited in its distribution. The suppliers will only allow these heating systems until base load conditions are reached at nighttime.

Advantages of electric heating are

- Clean working conditions, no air pollution at the customers site
- Easy handling
- No fuel storage
- Easy supply of light, power and heating (no gas or DH supply line)

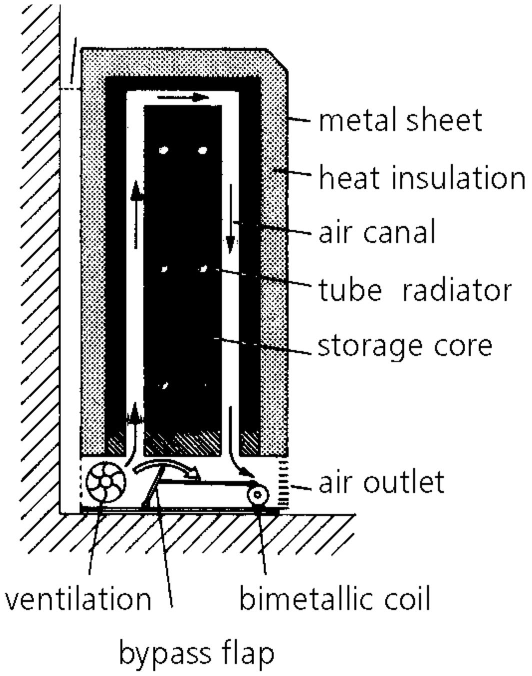

Figure 15 Electrical storage heating

3.3. Heat Pumps

With the heat pump it is possible to extract heat from the surroundings with input work in a circle process and release it on a higher temperature level for heating. The output heat quantity is a multiple of the heat equivalent of the used work.
Groundwater, soil, outside air/released air and waste heat sources are suitable for heat pump operation. To ensure an efficient heat pump operation, the temperature level of the heat source should be as high as possible. For conventional heat sources heat pumps are only favourable with low supply line temperatures (max. 55 °C).

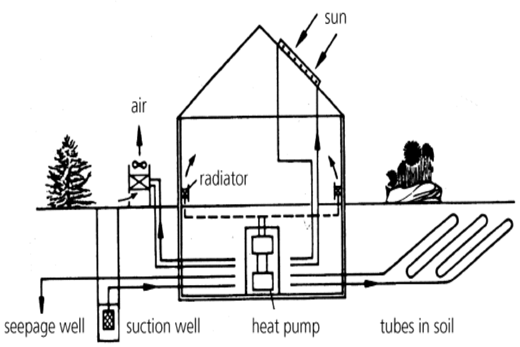

Figure 16 Heat sources for heat pumps

Electrically driven compression heat pumps and heat driven absorption heat pumps are used to heat dwellings. A heat source with temperatures of at least 100 °C is required for thermal heat pumps. Often absorption heat pumps are heated with natural gas or other fossil combustibles.

The useful heat is released on a temperature level of maximum 55 °C. Higher temperatures are possible. In this case, however, the use of heat pumps is energetically and economically not interesting. The best conditions are given for low temperature heating/underfloor central heating with flow temperatures of 35 - 40 °C.

For the description of the performance of heat pumps the coefficient of performance (COP) and the average annual COP_m (also called total COP) is used. The COP is the ratio between the useful heat and the input energy. The COP_m is decisive for an energetic comparison with other heating systems where the input energy and useful heat are balanced over a whole year. COP_m depends very strongly on the chosen operation moduls.

Since at maximum load (coldest days) the performance of heat pumps is poor, an additional, conventional heating is favourable for these conditions. This heating type is called bivalent. An extended heat pump, which can also cover these peaks, is called monovalent. However it is inferior though to the bivalent heating because of the bigger components. The following cases can be distinguished:

Bivalent operation (heating system with at least two heating systems):

1. Bivalent alternative: By temperature below a minimal outside temperature the HP is switched off and only the additional heating is operated.

2. Bivalent parallel: By temperature below a minimal outside temperature the heat demand is covered by HP and additional heating together.

(only possible for low temperature heating systems)

3. Bivalent part parallel: By temperature below a minimal lower outside temperature the HP is supported by the additional heating system. The HP is used within its operation range.

Monovalent operation: the heat demand is only supplied by the HP.

3.3.1. Electrical driven Heat Pumps

Compression heat pumps consist of a compressor, a throttle valve, a vaporiser and a condenser. A refrigerant is vaporised in the vaporiser at low pressure and the cold vapour is compressed to the condenser pressure. The condensing heat is passed on to the heating system in the condenser. The condensate is expanded with a controlled throttle valve to the lower pressure level (see Fig. 17).
R22, R134a, ammonia and for small heat pump units also propane/butane gas are used as refrigerants. Today „new“ refrigerants are examined, too, e.g. CO_2 or water.

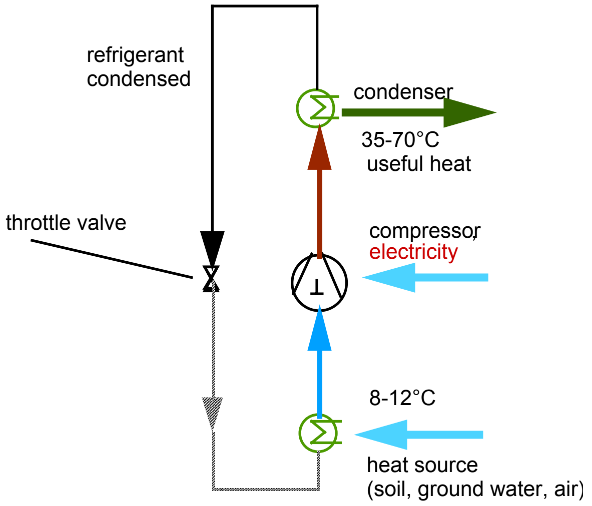

Figure 17 Scheme of an electrical driven heat pump

The COP depends on the evaporation temperature T_c as well as the condensation temperature T_0 (see eq. 2).

eq. 2 $$COP_{HP} = \eta_{c,HP} \cdot \varepsilon_{c,HP} = \eta_{c,HP} \cdot \frac{T_c}{T_c - T_o}$$

With the Carnot coefficient of performance $\varepsilon_{c,HP}$ and the Carnot efficiency $\eta_{c,HP}$ of about 0.5 to 0.6.

Fig. 18 shows flow temperature and the COP depending on the outside temperature.

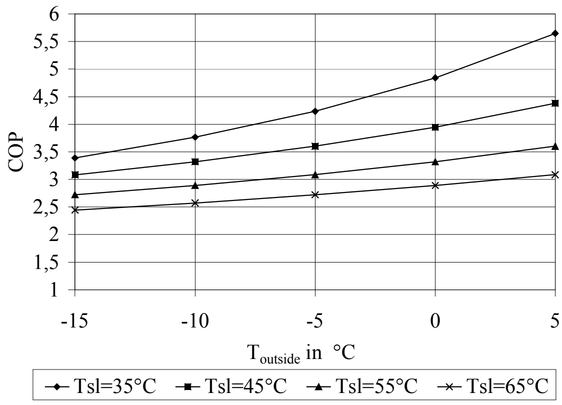

Figure 18 COP of an electrical driven heat pump

3.3.2. Absorption Heat Pumps

Absorption heat pumps (AHP) can also be used for the heating of detached and multiple dwellings. For the driving heat natural gas, oil (fossil fuels) or waste heat is chosen. The AHP is comparable to a compression chiller. The compressor is replaced by a „thermal compressor“. It consists of four components: the absorber, solution pump, desorber and expansion valve (see Fig. 19).

The refrigerant (ammonia/water) is released by heat on high pressure level from a hygroscopic solution and falls out in the condenser. The compressor is replaced by a solution pump, which has an electric performance of less than 2% of heat performance.

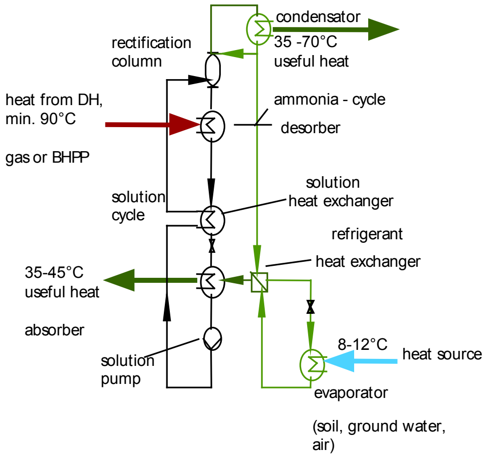

Figure 19 Scheme of a thermal driven absorption heat pump (water-ammonia)

The useful heat Q_U from AHP is the sum of the condensing heat Q_C and the absorbing heat Q_A.

Fig. 20 shows the COP depending on the operating conditions. The internal process temperatures have been used in this illustration. To calculate the external temperatures, the driving temperature difference of the heat exchangers have to be taken into account. To calculate the heat ratio ξ, the efficiency of the burner has to be multiplied with the COP.

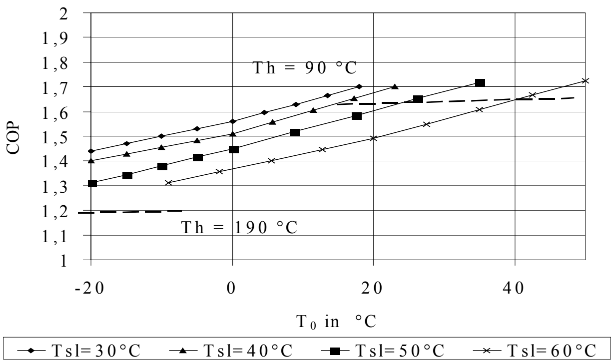

Figure 20 COP of an absorption heat pump /12/

The essential characteristics of heat pump processes are listed in the following table:

Table 8 Technical data for heat pumps

type	absorption heat pump	compression heat pump
range of performance	10 - 50 kW$_{th}$	10 - 100 kW$_{th}$
refrigerant	water-ammonia, water-LiBr	R22; R 134a; Propane/Butane, R717
driving energy	thermal energy; fossil combustibles, waste heat	elec. energy
COP (T_{sl}=40 °C)	1,45 1,65	3 (low outside temperatures) 4,5 (interseasonal period)
COP$_m$ (T_{sl}=40 °C) soil heat source air ground water, sea water	 1,55 1,45 1,65	 3 2,5 4
heat ratio ξ_m	1,32 - 1,51	η_{el} =0,38 0,95 - 1,5 η_{el} =0,53 1,3 - 2,1
useful heat	35 - 55 °C	35 - 55 °C (80 °C)

4. Comparison of District Heating and Local Heating Systems

4.1. Remarks on the Energetic Comparison of Different Heating Systems

A comparison between district heating generated by CHP and local heating is very difficult, since the different qualities of electricity and heat can not be ignored.

For an assessment of the electricity and heat generation three methods are introduced; the method using credits for the substituted electricity (chap. 4.2), the total heat method, where the generated electricity is transformed into heat (chap. 4.3), and the total energy method (chap. 4.4) The second method is used by Spurr et al. /8/ for the assessment of chilled water from CHP processes (chap. 4.2).

With the first method the problem of the allocation of the primary energy demand for the coupled products electricity and heat is solved with a credit for electricity.
This strategy derived from economics; electricity produced by the CHP substitutes the electricity produced alternatively in a condensing power plant. This is the common method to assess the heat generation from CHP plants.

The first method is problematic however, because of the quantitative specification of the credit for electricity. This credit depends on a reference object, whose electricity is substituted. There are different possibilities for the specification of the electricity credit:

1. Determination of the electricity credit with the electric efficiency for the complete electricity production of a country (mean value for PE savings)
2. Determination of the electricity credit with a concrete reference object, which is substituted (difficult to determine)
3. Determination of the electricity credit with the most inferior reference object, since these are substituted most likely (largest possible PE savings)
4. Determination of the electricity credit with the newest plants, since these reflect the actual competition with other techniques (minimal PE savings)

These points represent different borderline cases. The actual primary energetic savings, however, should always be in this range.

The second method does not need any reference power station either. Exact results for comparison are obtained, which are depending on the assessment of electricity. Depending on the quality of the transformation of electricity into heat, various conclusions arise (heat pump, electrical heating, etc.).

With the total energetic method no reference object is needed. It is unfortunate that electricity and heat must always be observed simultaneously. It is not possible to assign a specific value to one coupled product. This method will only be introduced briefly as an alternative procedure in this context.

A further problem with the assessment of CHP plants occurs, if electricity and heat are produced predominantly from regenerative primary energy sources. In this case it should be distinguished between regenerative and not regenerative energy sources.

4.2. Method with credit for the substituted electricity produced by CHP

With this method, a heat ratio ξ is introduced. It is defined by the generated heat $W_{th,tot}$ and the needed input fuel W_f (see for example /13/).

eq. 3 $$\xi = \frac{W_{th,tot}}{W_f}$$

This definition is adapted for the CHP processes with the credit for electricity. The fuel balance is calculated therefore with the difference between input fuel quantity $W_{f,CHP}$ and the substituted fuel quantity for the power plant $W_{f,PP}$.

eq. 4 $$\xi = \frac{W_{th,tot}}{\Delta W_f}$$

eq. 5 $$\Delta W_f = W_{f,CHP} - W_{f,pp}$$

eq. 6 $$W_{f,CHP} = \frac{W_{th,CHP}}{\eta_{th,CHP}} = \frac{W_{th,tot}}{\eta_{th,CHP} \cdot \eta_{d,th}}$$

The distribution efficiency $\eta_{d,th}$ and $\eta_{d,el}$ take the transportation losses into account. Typical values are $\eta_{d,th}$ = 0,90 for heat losses and $\eta_{d,el}$ = 0,965 for electricity.

eq. 7

$$W_{f,pp} = \frac{W_{el}}{\eta_{el,pp}\cdot\eta_{d,el}} = \frac{\sigma\cdot W_{th,CHP}}{\eta_{el,pp}\cdot\eta_{d,el}} = \frac{\sigma\cdot W_{th,tot}}{\eta_{el,pp}\cdot\eta_{d,el}\cdot\eta_{d,th}}$$

The power ratio is defined by the quotient of electricity generation and heat generation. The heat ratio is therefore defined as follows:

eq. 8
$$\xi = \frac{\eta_{d,th}}{\left(\frac{1}{\eta_{th,CHP}} - \frac{\sigma}{\eta_{el,pp}\cdot\eta_{d,el}}\right)}$$

It has to be taken into account, though, that the calculated heat ratios of the CHP processes considerably depend on the efficiencies of the replaced electricity generation.

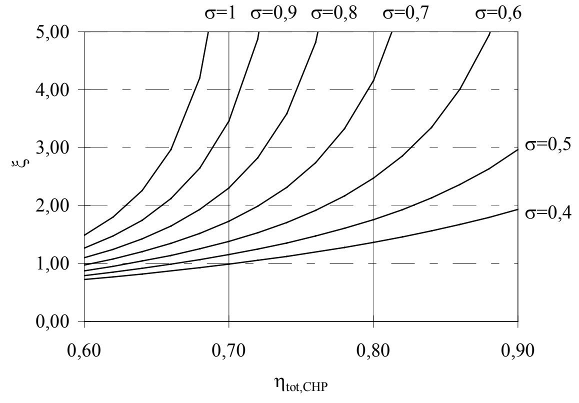

Figure 21 Heat ratio with a reference power plant with an efficiency η_{el}=0.38

Fig. 21 shows the heat ratios depending on the total efficiency and the power ratio of a coal fired power plant (η_{el}=0.38) as a reference object. It indicates that with higher power ratios the heat ratios increase significantly. It happens, when the electrical efficiency of the CHP process gets close to the one of the reference power plant. In the case, that $\eta_{el,CHP} > \eta_{el;PP}$ the heat ratio becomes negative. Just by looking at the electrical efficiency, the CHP plant is then economic.

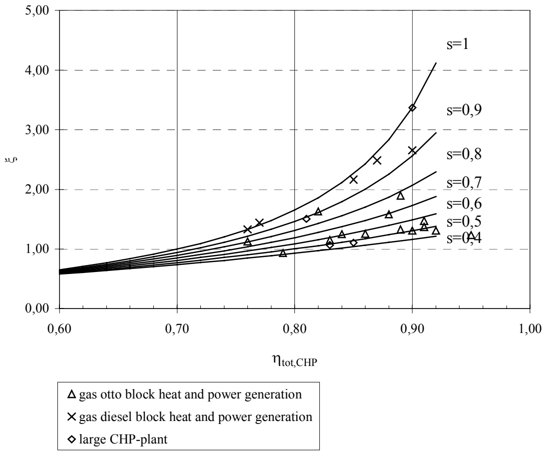

Figure 22 Heat ratio with a reference power plant with an efficiency η_{el}=0.53

In Fig. 22 and in Tab. 9 a modern GTCC power station was the reference object with an electric efficiency of 0.53. Fig. 22 shows the heat ratio depending on the total efficiency and the power ratio. Selected plants are furthermore indicated as datapoints. It can be seen, that large gas diesel BHPPs (1-7 MW_{el}) can reach much higher heat ratios than gas otto BHPPs (0,01-2,2 MW_{el}).

The calorific values calculated for the CHP processes can be compared with the calorific values of single heating plants. For these the calorific value corresponds exactly to the thermal efficiency of the plant.
To determine the heat ratio (ξ_{HP}) of electrical heat pumps, the COP of the heat pump has to be considered as well as the efficiency of the electricity generation ($\eta_{el,pp}$ + $\eta_{d,el}$). For the absorption heat pump (ξ_{AHP}) the efficiency of the combustion (η_{com}) has to be taken into account additionally (see chap. 3.3).

q. 9
$$\xi_{elHP} = \eta_{el,pp}\cdot\eta_{d,el}\cdot COP_{HP}$$
$$\xi_{AHP} = \eta_{com}\cdot COP_{AHP}$$

The following heat ratios (unit: kWh useful heat/kWh primary energy) are calculated with the data shown in chap. 2 and 3 for the different energy supply systems. For the CHP processes a range is indicated, which results from the choice of reference power stations mentioned in the previous chapter (η_{el} = 0.38 - 0.55).

Table 9 Overview on heat ratio of different heat generation

	fuel	power and heat ratio σ	electrical efficiency η_{el}	thermal efficiency η_{th}	COP_m	heat ratio ξ kWh heat / kWh PE $^{II)}$
GTCC – CHP $^{I) IV)}$	natural gas	1.00	0.45	0.45		-1.28/2.25
STC – CHP $^{I) IV)}$	coal	0.46	0.27	0.58		1.67/0.97
heat plant $^{I) IV)}$	oil, coal			0.88		0.72
BHPP – otto engine	natural gas	0.70	0.35	0.50		8/1.2
BHPP – diesel engine	natural gas	0.98	0.42	0.43		-1.93/1.64
Fuel Cell (PAFC)	natural gas	1	0.4	0.4		-3.02/1.31
electrical heat pump $^{III)}$	electricity				2.5/4	0.95/1. 5
absorption heat pump	natural gas				1.4/1.6	1.32 - 1.51
natural gas boiler	natural gas			0.91/0.94		0.91 - 0.94
fuel oil boiler	oil			0.88/0.92		0.88 - 0.92
gas condensing boiler	natural gas			1.04/1.09		1.04 - 1.09
electrical heating $^{III)}$	electricity			1		0.38
heating by biomass	*wood, ..*			*0.7/0.9*		*0.7/0.9*

I) The distribution efficiency for district heating and electricity has to be taken into account ($\eta_{V,th} = 0.90$, $\eta_{V,el} = 0.965$)

II) The heat ratio for the CHP-plants is calculated with a substituted electricity with $\eta_{el} = 0.38$ (first column) and 0.53 (second column)

III) electricity supply generated with $\eta_{el} \sim 0.38$

IV) 20% of the heat supply by peak load boilers (total efficiency 80%)

With the given details the highest heat ratios are reached with GTCC-CHP. The heat ratio of the chosen STC-CHP is only insignificantly more favourably than a condensing boiler. However it has to be taken into account that fuel used is coal, which could otherwise fired only much poorer for heat production.

Electric heat pumps have heat ratios up to 1.5, which is about the same range as for heat driven absorption heat pumps. In any case heat pumps used as single heating systems are a good solution if CHPs incl. district heating distribution systems cannot be used. The heat ratios are clearly larger than the one of condensing boilers and other heating boilers provided that HPs are designed for favourable operating conditions.

Electric heating and the heating with biomass have the poorest heat ratios. For biomass it is acceptable though because of its regenerative character.

The calculation with the credit for electricity is only valid, if the electricity from CHP substitutes the electricity generation with fossil fuels. If the CHP share reaches a certain limit, it is possible that it replaces the electricity from CHP itself or from regenerative sources. In this case heat and power can be considered equal and the primary energy efficiency corresponds to the total efficiency.

For the assessment of electricity generated with regenerative carriers, the factor f is introduced. It characterises the share of non-regenerative energy sources to the total primary energy consumption (unit: kWh $PE_{n.r.}$/ kWh PE_{tot}). Fig 1 shows the dependence of the heat ratio on the composition of electricity generation. Only the factor f is used for the calculation of the electricity credit.

The factor f for selected countries is:

Norway	0.01	Germany	0.62
Sweden	0.10	Japan	0.65
France	0.11	Brazil	0.07
USA	0.71	Denmark	0.90
Netherlands	0.92	world	0.64

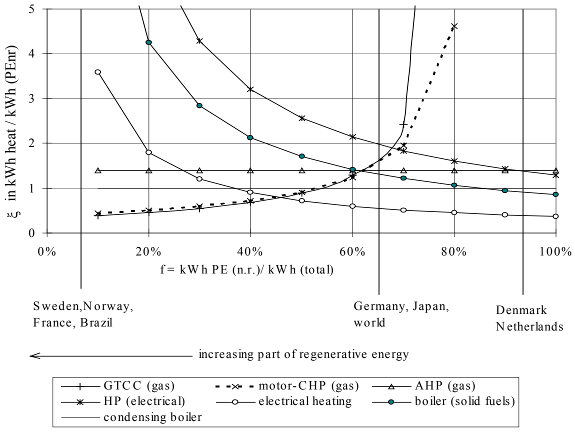

Figure 23 Heat ratio corresponding to different mix of electricity

If f reaches zero, the heat value ξ (kWh heat / kWh $PE_{n.r}$) for CHP plants approaches the thermal efficiency η_{th}, with the use of electricity the total efficiency $\eta_{\tau o \tau}$. The heat ratios for the CHP plants shown in Fig. 23 are calculated with the efficiencies from Tab. 9.

These considerations are probably too pessimistic, because countries with a high percentage of regenerative energy sources will probably replace the few conventional power plants first. In this case the factor f can be set to 1. Furthermore, we also have to take into account that the transport of electricity from one country with surplus of electricity from regenerative sources to another country with electricity generation by non-regenerative energy sources could be possible (e.g. from Norway to Germany). In this case, the factor f can be set to 1, too. For countries like Norway, Sweden or Brazil, a CHP-system with fossil fuels will only save primary energy from non-regenerative sources if electricity exports to other countries are possible or in individual cases. In this case, district heating is only favourable with the use of waste heat or large heat pumps (driven by electricity produced from renewable sources). In Germany, Japan and the Netherlands however, CHP plants result in major primary energy savings compared to local supply with boilers.

4.3. Total Heat Method

This method uses almost the same ideas as the method described in the chapter before. The only difference is the avoidance of a defined reference object. The idea is to transform the electricity produced by the CHP plant into heat. To take account of the different quality of electricity and heat, this transforming process is realised with a heat pump. The heat ratio ξ_{thm} is then calculated as follows:

eq. 10 $$\xi_{thm} = \eta_{th} \cdot \eta_{d,th} + \eta_{el} \cdot \eta_{d,el} \cdot COP_m$$

The results of the total heat method are slightly different to the method with the credit for electricity. The ranking of the processes remains the same. Only the difference to the local heating systems is reduced. Tab. 10 shows the calculated heat ratios for different CHP systems.

Table 10 Overview on heat ratio of CHP plants calculated with the total heat method

	fuel	power and heat ratio σ	electrical efficiency η_{el}	Thermal efficiency η_{th}	heat ratio (total heat method) ξ_{thm} kWh heat / kWh PE $^{III)}$
GTCC - CHP $^{I) II)}$	natural	1.00	0.45	0.45	1.34 / 1.86

	gas				
STC - CHP I) II)	coal	0.46	0.27	0.58	1.08 / 1.4
BHPP- otto engine	natural gas	0.70	0.35	0.50	1.18 / 1.58
BHPP- diesel engine	natural gas	0.98	0.42	0.43	1.26 / 1.75
Fuel Cell (PAFC)	natural gas	1	0.4	0.4	1.2 / 1.67

I) The distribution efficiency for district heating and electricity has to be taken into account ($\eta_{V,th} = 0.90$, $\eta_{V,el} = 0.965$)

II) 20% of the heat supply by peak load boilers (total efficiency 80%)

III) assessment of the electricity with HP process, $COP_m = 2.5$ (first column), 4 (second column)

4.4. Total Energy Consideration of CHP

This method for the assessment of CHP described by Alefeld /14/ is a causal orientated method. Based on thermodynamic laws, system efficiencies are calculated for the combined generation of heat and power. A comparison between local heating stations and different CHP systems is possible. With the causal orientated method no reference plants need to be defined.
An energy balance is devised with the first thermodynamic law and the quantities primary energy Q_{pe}, electrical performance P_{el}, heat performance Q_h, and waste heat Q_{rh}:

eq. 11 $$Q_{pe} = Q_h + P_{el} + Q_{rh}$$

The second thermodynamic law determines that

eq. 12 $$P_{el} = P_{el}\left(Q_{pe}, Q_h, Q_{rh}\right)$$

and therefore a connection exists between the generated electrical performance P_{el} and the generated heat performance Q_h. With the elimination of the variable Q_{rh} there is the following linearized relation:

eq. 13 $$Q_{pe} = aP_{el} + bQ_h$$

The coefficients a and b are described by the efficiencies and distribution losses. With this relation a division of the energy input is made and a subjective contradiction to the second thermodynamic law is avoided.

With eq. 13, differential system efficiencies for heat and electricity generation can be derived.

eq. 14 $$\eta_{el,Sys} = \left.\frac{\partial P_{el}}{\partial Q_{pe}}\right|_{Q_h}$$

and

$$\eta_{th,Sys} = \left.\frac{\partial Q_h}{\partial Q_{pe}}\right|_{P_{el}}$$

With these efficiencies different local heating systems, CHP systems and combinations of CHP plants are comparable. The derivatives of different system efficiencies can be found in /15/.

In Fig. 24 the specific primary energy demand is described depending on the specific heat demand for different energy supply systems. The primary energy and heat both refer to the electrical performance. Depending on the given ratio Q_h/P_{el}, predefined by a concrete object to be supplied (single object, town, country), the maximum possible primary energy savings can be determined directly. With this solution it is also possible, to determine the primary energy savings over a longer period with varying ratio Q_h/P_{el}. Therefore the figure shows, that there are ranges where the alternative with GTCC and condensing boiler can be more favourable than with district heating provided by a gas turbine (for a low ratio Q_h/P_{el}).

To consider electricity generation with renewable sources, only the part of P_{el} is taken into account, which is produced with fossil fuels ($P_{el,tot}$ (1-f)). The result of such consideration is comparable to those in Fig. 24. If the factor f is zero and the energy is generated with condensing boilers, there would be a straight line with a gradient of one.

For an explanation a comparison will be carried out with a single object in table 11 (office building). The ratio of Q_h/P_{el} is calculated for summer time ($Q_h \approx 0$), interseasonal and wintertime. The interseasonal time is weighted by the factor 2 in order to get annual average.

For this example an electricity and district heat supply with GTCC-CHP is the most favourable option, followed by a GTCC and a heat pump. The worst alternative is the conventional power plant process with gas boiler.

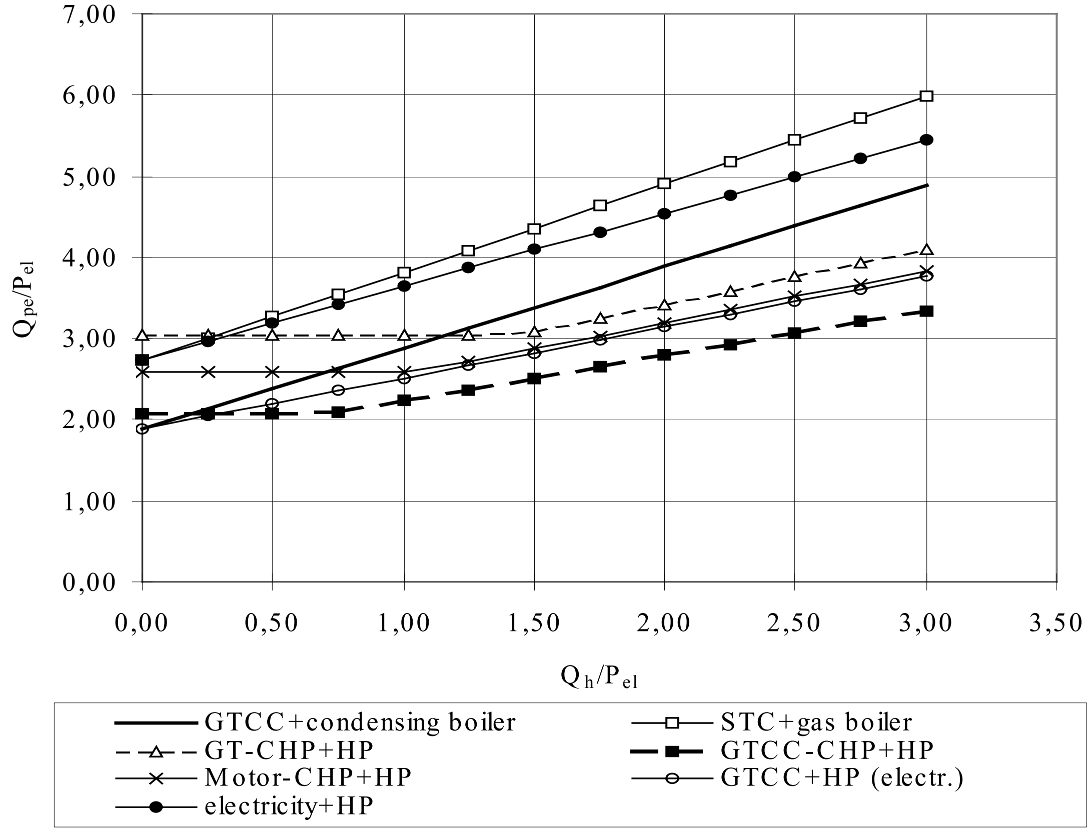

Figure 24 Spec. primary energy demand for different spec. heat demand

The following options are chosen for the illustration:

1. GTCC + condensing boiler: η_{el} =0,55, $\eta_{d,el}$ =0,965, η_b =1
2. GTC-CHP + elHP: η_{el} =0,34, $\eta_{d,el}$ =0,965, η_{th} =0,55, COP_m = 3, $\eta_{d,DH}$ =0,9
3. motor-CHP + elHP: η_{el} =0, 4, $\eta_{d,el}$ =0,965, η_{th} =0,47, COP_m = 3, $\eta_{d,DH}$ =0,9
4. STC + gas boiler: η_{el} =0,38, $\eta_{d,el}$ =0,965, η_b =0,92
5. GTCC-CHP + elHP: η_{el} =0,5, $\eta_{d,el}$ =0,965, $\eta_{d,DH}$ =0,9, σ =1,38, η_{th} =0,4
6. GTCC + elHP: η_{el} =0,55, $\eta_{d,el}$ =0,965, COP_m =3
7. Electricity mix + HP: η_{el} =0,38, $\eta_{d,el}$ =0,965, COP_m =3

Table 11 Specific PE-Demand of a single building (office building)

Pos.	Variant	$Q_h/P_{el}=0$	$Q_h/P_{el}=1{,}25$	$Q_h/P_{el}=2{,}5$	Q_{pe}/P_{el} (annual average)
1	GTCC + Condensing boiler	2	3,1	4,3	2,73
2	GTC-CHP + elHP	3	3	3,55	3,08
3	BHPP-CHP + elHP	2,7	2,75	3,6	2,85
4	STC + gas boiler	2,8	3,85	5,4	3,56
5	GTCC-CHP + DH (incl. peak boiler)	2	2,4	3,6	2,38
6	GTCC+ elHP	2	2,6	3,4	2,42
7	Electricity + HP	2,8	3,9	5	3,52

4.5 Evaluation of relative Primary Energy Reduction

Subsequent the relative savings of primary energy are calculated by the methods 2 (chap. 4.3) and 3 (chap. 4.4). Method 1 we renounce since with it also negative primary energy savings are possible. As reference supply case the power and heat supply from steam power plants and heat from gas or oil boilers, as this is the typical supply case in Germany, are assumed. The values indicate the savings of primary compared to this supply case.

For the two methods a little divergent values are got. With the method 2 smaller primary energy savings are determined in any case. This can be explained by the fact that different operating conditions are taken into account for method 3. No primary energy can be saved for example in summer since there is no need for heating. For method two, however, we presuppose an always sufficient demand of power and heat. The primary energy savings with method 3 go up to 33 % compared to the reference case. The most favourable result is obtained with a GTCC and district heating. GTCC and electrical HP achieve an almost equal result. Full-coverage use of electric heat pumps (including the heat source installations) and corresponding low temperature heating systems is surely sensible only for new buildings and at detached houses or two family houses. At a larger density of heat demand the concept of district heating supply should be the more suitable strategy, however.

GTCC and condensing boiler only obtain a reduction of the primary energy consumption of 23 %. At this strategy the most modern and at the moment available technology for a separate supply with power and heat is used. But also with this procedure, the reduction of the primary energy consumption or the CO_2 output demanded by the international community should be realised.

In the context of the calculation of the primary energy reduction by method 2 we get a bandwidth, which arises on the assessment of the required heat pump process. The larger values are calculated for a COP of 4, the smaller value for a COP of 2. The highest savings will be obtained by use of GTCC and district heating systems, followed by BHPP and local heating systems. The electric power for electric heat pumps supply is presupposed according to the mix of electricity in Germany. Because of that assumption the values for electric heat pumps are lower than the results shown in table 12.

Table 12 PE-Reduction calculated by Total Energy Consideration of CHP (method 3, chap. 4.4)

Variant	Q_{pe}/P_{el} (annual verage)	PE-Reduction
GTCC-CHP + DH (incl. peak boiler)	2,38	33%
GTCC+ elHP	2,42	32%
GTCC + Condensing boiler	2,73	23%
BHPP-CHP + elHP	2,85	20%
GTC-CHP + elHP	3,08	13%
Electricity + HP	3,52	1%
STC + gas boiler	**3,56**	**0%**

Table 13 PE-Reduction calculated by Total Heat Method (method 2, chap. 4.3)

	PE-Reduction	
	Minimum	Maximum
GTCC – CHP	32%	49%
BHPP – diesel engine	28%	46%
Fuel Cell (PAFC)	24%	44%
BHPP – otto engine	23%	41%
absorption heat pump	31%	38%
electrical heat pump III)	4%	37%
STC – CHP	16%	33%
gas condensing boiler	13%	14%
natural gas boiler	**0%**	**0%**
fuel oil boiler	-3%	-2%
heating by biomass	-30%	-4%
heat plant	-26%	-31%
electrical heating	-139%	-147%

5. Summary / Evaluation

In this report different local and district heating concepts are presented and the primary energy demand for the heat supply is calculated. The comparison of these systems takes into account the essential primary energy sources (fossil fuels like coal, gas, oil, or regenerative fuels like biomass, water, nuclear power). The share of those carriers varies strongly between each country and influences the assessment of the different systems.

The following generation systems for district heating supply are described in this report:

1. District heating from CHP - plants (GTC-CHP, GTCC-CHP, STC-CHP, BHPP)
2. District heating from heat pump plants
3. District heating from heat plants, waste incinerators

   or industrial waste heat

The described local heating systems are:

1. Gas and oil boiler, condensing boiler
2. Wood combustion
3. Electrical resistance heating and with and without storage
4. Heat pumps (electrical and thermal)

The problem of all energetic comparison of the different heat supply systems is the cogeneration of heat and electricity of CHP plants. The total primary input energy for those systems cannot easily be divided into the energy needed for heat and into energy needed for electricity. To take into account the electricity produced by CHP plants, three methods are introduced in this report with the following advantages (+) and disadvantages (-):

- Credits for the substituted electricity:

  + Defined value (heat ratio) for the energy needed for district heating
  + Direct comparison between local heating and CHP plants is possible
  - The heat ratio depends on the electrical efficiency of the substituted power plant
  - Negative heat ratios are possible (credit for electricity larger than primary energy demand for the CHP process)

- Transformation of electricity into heat with a heat pump:

  + Defined value (heat ratio) for the energy needed for district heating
  + Direct comparison between local heating and CHP plants is possible
  + Only positive heat ratios
  - Theoretical concept, since heat pumps are not often used for heat generation

- Total energetic assessment:

  + Examination of the total energetic assessment
  + Taking into account of different annual supply situations
  - No primary energetic value (heat ratio) for the heat generation alone

The following assessments refer to the second method although the results of the first and third methods are not fundamentally different:

District heating from GTCC-CHP plants offers heat ratios between 1.2 and 1.8. Therefore CHP plants should be preferred over fossil-fired local heating systems. Only thermal and electrical heat pumps with reasonable operation conditions (low temperature heating, good heat source) can also be a possible alternative.

The heat ratios of central heat pump plants are between 1.3 and 1.5 and are therefore more efficient than local heating systems. Compared to local heat pumps the central generation of heat is only favourable, if a heat source with a high temperature level can be used. Otherwise local HPs should be preferred because of smaller distribution losses.

An interesting solution is the combination of CHP plants and heat pumps with a possible flexible operation (no fixed ratio between heat and electricity).

Since heat plants only generate heat, an increase of the heat ratio above 1 is not possible. Because of distribution losses the efficiency is lower than local heating systems. From a primary energetic point of view, heat plants should be avoided. The only favourable use is to cover the peak load demand. An exclusively thermic use of the energy from biomass or refuse can be preferable but it should be questioned why an additional generation of high quality electricity is not possible.

In conclusion a short ranking of the different processes for the heat supply is given as follows (in order of an increasing use of fossil primary energy):

1. Use of industrial waste heat and waste incineration, CHP and DH driven with biomass, heat pump driven by biomass
2. Electrical heat pumps, electrical heating systems, electricity from **regenerative** energy sources, provided that electricity cannot be used sensibly at other locations to substitute fossil energy sources [3]
3. CHP + DH
4. Heat pump processes (local or in combination with DH)
5. Condensing boiler
6. Gas boiler, oil boiler
7. Electrical heating systems (electricity from fossil energy sources)

Depending on the composition of the generated electricity (ratio between renewable and fossil electricity generation) a detailed assessment with exact prevailing circumstances is necessary. An energetic assessment of heat supply systems is only possible and correct if the electricity supply is taken into account, too.

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[3] The emphasis lays on the phrase "**electricity from regenerative energy sources**". Only in this case the use of electricity is desirable. In reality we should expect better possibilities to use electricity for heating applications (for example by electricity export to other countries).

6. List of Figures / List of Tables

List of Figures

List of Tables

7. Literature

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