Coventry University
School of Engineering

332MEC Thermodynamics
Prof. P. White

Combined Heat and Power

Author:

Mario Fritzsche
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Initials used

CHP	Combined Heat and Power
MW	Mega Watt
MWe	Mega Watt electric
MWth	Mega Watt thermal
TWh	Terra Watt hours
MPa	Mega Pascal
kWe	kilo Watt electric
SI	spark ignition
CI	compression ignition

Contents

1 Pattern of energy usage in UK

To understand this model the reader should know what primary and secondary energy means.

Primary energies are natural resources like fossil fuels, wind power, biomass, hydrogen fuel, tidal power, solar power, geothermal energy, hydroelectric energy or nuclear power. Transformed in energy conversion processes to more convenient forms of energy, such as electrical energy, heat energy or cleaner fuels this energy is called secondary energy.

1.1 Key indicators for Energy policy

Naturally occurring greenhouse gases maintain the earth's surface at a temperature 33°C warmer than it would be in their absence. At present greenhouse gas concentrations in the atmosphere are increasing as a result of human activities. Greenhouse gas emissions fell by 13% between 1990 and 2003, mainly due to a fall in carbon dioxide emissions. Carbon dioxide emissions contribute about 70% of the potential global warming effect of anthropogenic emissions of greenhouse gases and are created when fossil fuels are burned. Emissions of carbon dioxide fell by 5.6% between 1990 and 2003. Estimates based on energy production and consumption in 2004 indicate that emissions rose by 1.5% during 2004, thus the total change from 1990 is a fall of 4.2%.

Target is to ensure that the market provides sufficient capacity to meet maximum gas and electricity demand in each year. In response to NGT's forecasts last summer of lower levels of electricity capacity, prices rose and generators brought previously mothballed plant back into service. As a result, plant margins for England and Wales rose from around 16% to over 20% for the winter period.

In 2003, the UK ranks the highest out of all the EU and G7 countries in both electricity and gas markets, and therefore also has the most competitive energy market overall, as it has done in each of the two previous years.

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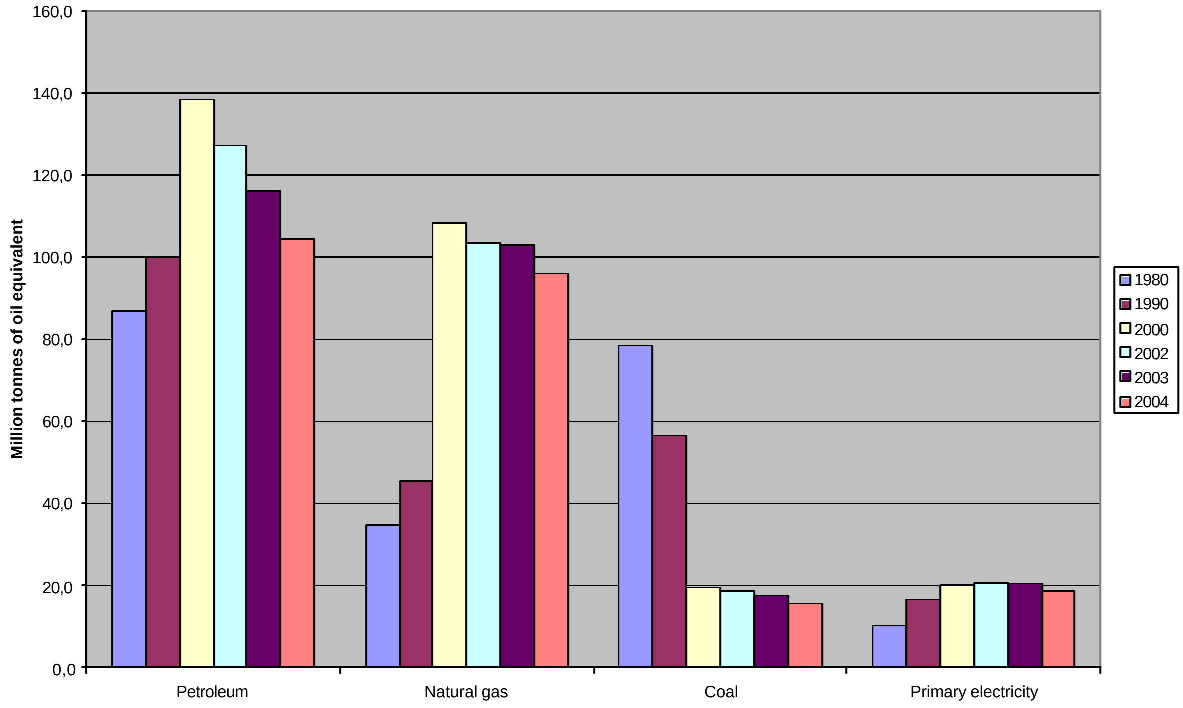
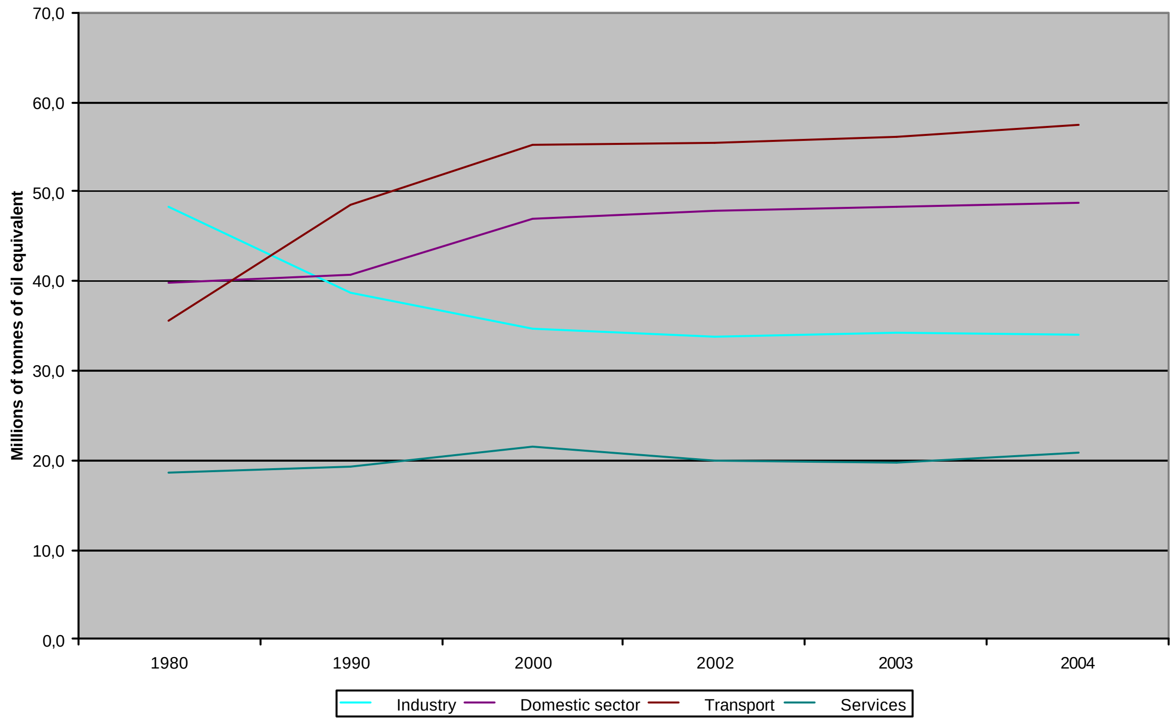
1.2 Overall Energy

Total production of primary fuels, when expressed in terms of their energy content, fell by 8.4% in 2004 compared to 2003.

Petroleum accounts for 44% of total production, natural gas 40%, coal 7% and primary electricity (nuclear and natural flow hydro) 8%. Renewables and waste account for the remaining 3.6 million tonnes of oil equivalent. Total production has risen by 13% since 1980, primarily due to the growth of oil and gas. Production in 2000 was at record levels for natural gas, whilst in 1999 it was at record levels for overall energy and petroleum.



Primary energy consumption was 1.0% higher in 2004 than 2003. Since 1980 consumption of natural gas and primary electricity has risen considerably, whilst consumption of oil has remained around the same and coal has fallen. Energy industry use, losses during conversion to secondary fuels and losses during distribution accounted for 31% of inland energy consumption in 2004.



Final energy consumption (excluding non-energy use) was 1.6% higher in 2004 than in 2003. Since 1980 energy consumption by individual sectors has changed substantially: there have been rises of 62% for transport, 22% for the domestic sector and 11% for the service sector, whilst consumption by industry has fallen by 29%. The rate of increase in transport has slowed in recent years.

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1.3 Oil and Gas production

Oil production in 2004 was 30% lower than the record level in 1999 and 10% lower than in 2003. Six new fields started production in 2004, but production from these fields was insufficient to make up the general decline in production from older established fields. Gas production in 2004 was 7% lower than in 2003. As with oil, UK gas production is also declining as UK Continental Shelf reserves deplete.

In earlier years estimates of remaining reserves in present discoveries stayed at broadly similar levels despite the large increase in oil and gas extracted. This was due to newfound discoveries and new technology allowing exploitation of discoveries being made and new technology allowing exploitation of discoveries that were previously regarded as not viable.

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1.4 Petroleum

Since the first ‘surplus’ on oil trade (£0.3 billion) in 1980, oil trade has contributed £98 billion to the UK balance of payments. The largest ‘surplus’ (£8 billion) in 1985 reflected high crude oil production and prices. The ‘surplus’ fell from this peak due to lower prices but, with recent higher prices, has increased from £1.6 billion in 1990 to £2.0 billion in 2004, despite a decline in crude oil production.

In 2004 transport fuels increased their share of overall oil demand which was due to increases in consumption for air and road transport. Deliveries of motor spirit decreased but this was offset by an increase in DERV fuel. The move to natural gas by electricity generators and industry as the preferred energy source explains the fall in demand for fuel oil. However, compared with 2003, oil products used for electricity generation in 2004 bucked this downward trend and increased which was probably due to high gas prices. There has been a small increase in Non-energy use since 2003.

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1.5 Natural Gas

In the early 1970s, following the advent of natural gas, gas consumption grew rapidly. Industrial consumption peaked 2000 and has fallen since then by around 20%. Over the last 20 years domestic consumption has grown by 30% and services consumption by 42%. However, since 1991 the growth in gas consumption has been dominated by its increasing use in electricity generation, which now accounts for 30% of all natural gas consumption.

The UK began exporting natural gas in 1993 but did not become a net exporter of as until 1997. Exports grew rapidly with the opening of the Bacton-Zeebrugge interconnector in 1998 and net exports reached their peak in 2003. In 2004, with the decline in UK natural gas production, exports of gas fell by 35 per cent compared with 2003 and imports increased by 54 per cent and the UK became a net importer of gas once again.

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1.6 Coal

Coal production was 11% lower in 2004 than in 2003; deep mined production fell by 20%, while opencast production fell by 1%. Coal production in 2004 was less than a fifth of the level in 1980 and around a quarter of the level in 1990. Imports, initially of coal types in short supply in this country, started in 1970 and then grew steadily to reach the 20 million tonnes a year mark by the late 1990s. The very rapid expansion of imports in 2001 meant that imports exceeded the level of UK production for the first time. Although there was a decrease in imports in 2002, the level imports went above the level of production again in 2003 and in 2004 imports reached a new record of 36 million tonnes.

The proportion of coal consumed by power stations has increased steadily since the 1970s, reaching a level of 84% in 2003 but in 2004 it fell marginally to 83%. The decline in coal consumption at power stations has halted in recent years, and remained above 50 million tonnes in 2004. Coal consumption as a whole declined sharply during the 1990s, at an average annual rate of 7% compared with just a 2% annual decline over the previous 20 years. Following a small increase in coal consumption between 1999 and 2001, 2002 saw a 9% decrease from the previous year. There was a partial recovery in 2003 as consumption rose again by 6%. However, in 2004 consumption fell slightly by 2.5%.

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1.7 Electricity

The mix of fuels used to generate electricity continues to evolve. Since 1990, the use of all fuels in electricity generation has fallen, except for gas, which has risen markedly over this period from 1.6 to 153 TWh. Net import levels averaged over 16 TWh in the mid 1990s. In 2004 imports recovered from an unusually low level in 2003. This was mainly because in 2003 lower prices made the UK less attractive to French exporters while higher prices in Continental Europe fostered growth in UK exports. Since 2000 coal has been called upon to make up for unavailable nuclear and gas fired stations and then as a substitute for high gas priced gas. However, gas continues to retain the largest share of the market (40%) while coal's share of the market has fallen from two thirds in 1980 to a third in 2004. Nuclear's share peaked at 26% in 1997 but in 2004 it was only 19%.

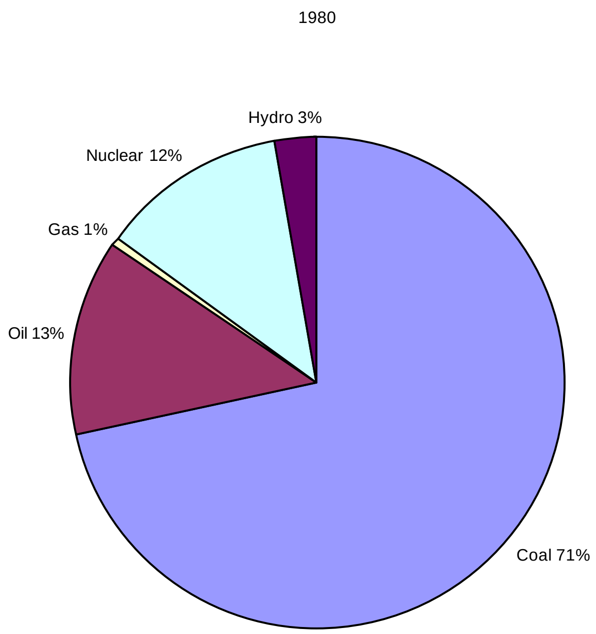

Diagram 1: Available electricity in 1989

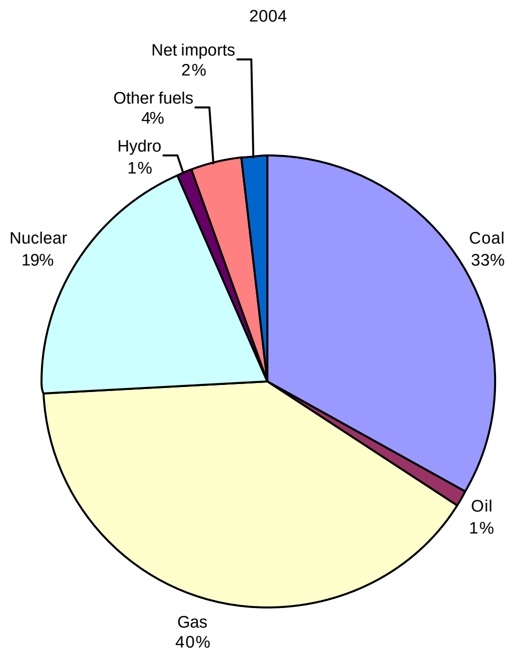

Diagram 2: Available electricity, 2004

Over the last 5 years electricity consumption in the domestic and services sectors has grown by 3% and 4% respectively. Industrial consumption varies with business activity: it rose every year between 1994 and 2000, fell back by 2.5% in 2001 but in 2003 it climbed back to the 2000 level and continue to grow in 2004.

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1.8 Combined heat and power

Electrical capacity and electrical generation increased in 2004 by 17% and 10% respectively. 40% of the CHP installations in the UK are small schemes with an electrical capacity of less than 100 kWe, however schemes larger than 10 MWe account for over 83% of the total CHP installed electrical capacity.

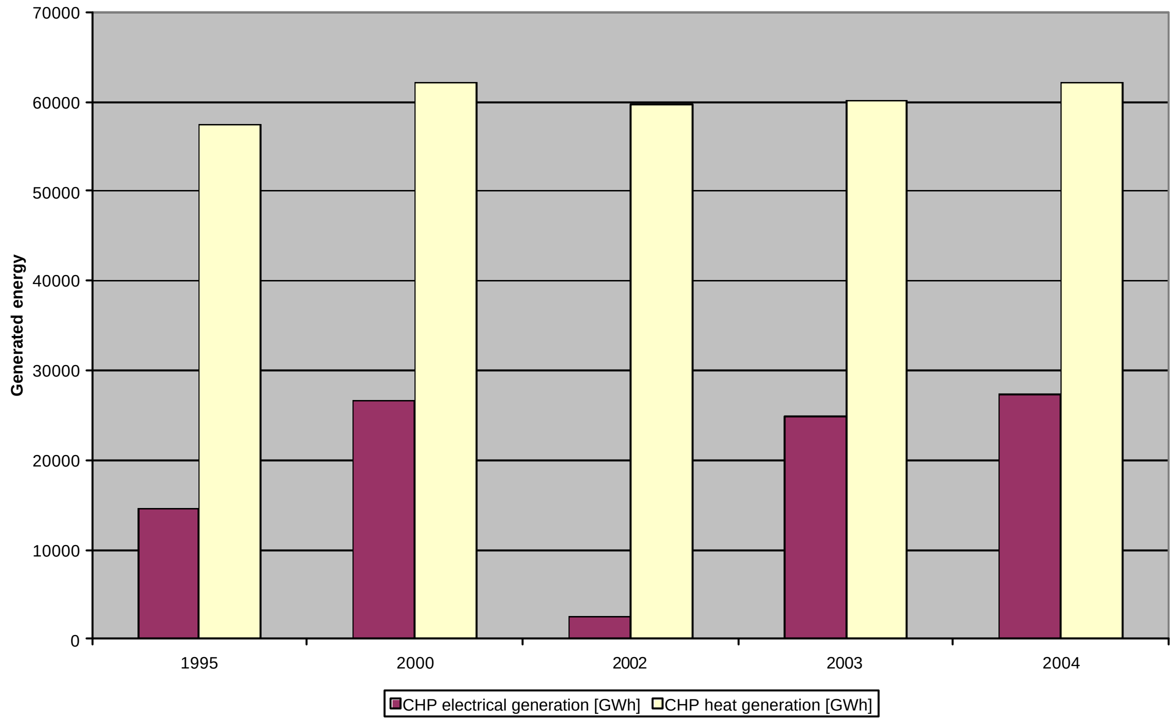

Diagram 3: Generated energy by CHP schemes

In 2004, 7% of the total electricity generated in the UK came from CHP plants. The Government has a target of reaching at least 10,000 MWe of CHP electrical capacity by 2010, as part of its Climate Change Programme.

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1.9 Nuclear power

During 2004 nuclear generators experienced unplanned outages due to emergency maintenance and safety concerns so electricity output was down 10% from the previous year. It represented just under a fifth of the total volume of electricity generated in the UK in 2004. Nuclear electricity output was 25% higher in 2004 than in 1990.

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1.10 Renewables

In 2004, biofuels accounted for 84% of renewable energy sources with most of the remainder coming from large-scale hydro, wind and other electricity production. Hydro accounted for 11% and wind power contributed 4.5%. Of the 3.81 million tonnes of oil equivalent of primary energy use accounted for by renewables, 3.14 million tonnes was used to generate electricity and 0.67 million tonnes to generate heat. Renewable energy use grew by 18% in 2004 and has more than tripled since 1990.

Renewables accounted for 3.58% of electricity generated in the UK in 2004, up from 2.67 in 2003. Hydro recovered from unusually low levels in 2003, which were caused by decreased water flow from low rainfall. Renewables accounted for 3.08% of UK electricity sales on a Renewables Obligation basis, up from 2.21% in 2003.

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1.11 Energy efficiency

Energy consumption per unit of output, known as energy intensity, gives a broad indication of how efficiently energy is being used over time. Changes in energy intensity can occur for a number of reasons: process change, technological change and structural change (in the case of industry and the service sector) as well as efficiency change. The largest fall in energy intensity over the last thirty years has occurred in the industrial sector and is mainly due to structural change. The largest increase has occurred in the road freight transport sector where the move towards heavier vehicles has resulted in higher levels of energy consumption, although the trend has been relatively stable over the last decade.

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2 Concept of combined heat and power

Combined Heat and Power is, at present, the most significant type of generation embedded in distribution systems. CHP, sometimes known as cogeneration, is the simultaneous production of electrical power and useful heat.

Generally the electrical power is consumed inside the host premises or plant of the CHP facility, although any surplus or deficit is exchanged with the utility distribution system. The heat generated is either used for industrial processes and/or for space heating inside the host premises or alternatively is transported to the local area for district heating.

Steam is raised using the exhaust gases of the gas turbine passed through a waste heat boiler which is fed to either a back-pressure or pass-out condensing steam turbine. Useful heat is then recovered from the steam turbine. In a CHP scheme using a combined cycle some 80- 90% of the energy in the fuel is transformed into electrical power or useful heat, with a lower heat/power ratio than that of single-cycle gas turbines. Combined cycle CHP plants, because of their complexity and capital cost, tend to be suitable for large electric and heating loads such as the integrated energy supply to a town or a large industrial plant [5].

For larger engines (i.e. approaching 500 kW) it becomes economic to pass the exhaust gas, which may be at up to 350- 400 °C, to a steam producing waste heat boiler. The heat available from the cooling jacket and the lubrication oil is typically at 70- 80 °C. The fuel used is usually natural gas, sometimes with a small addition of fuel oil to aid combustion, or, in some cases, digester gas from sewage treatment plants. Typical applications include leisure centres, hotels, hospitals, academic establishments and industrial processes. Landfill gas sites tend to be too far away from a suitable heat load and so the engines, fuelled by the landfill gas, are operated as electrical generating sets only, and not in CHP mode.

The economic case for a CHP scheme depends both on the heat and electrical power load of the host site and critically on the costs of alternative energy supplies and also the rate received for exporting electrical power to the utility.

This is a list of the principal economic attractions of small-scale CHP in the UK in 1991 as being due to savings from: (1) the high cost of electrical energy from the utility, (2) high electrical maximum demand charges and (3) reduction in inefficient boiler operation.

CHP units are typically controlled, or despatched, to meet the energy needs of the host site and not to export electrical power to the utility distribution system [7]. It is common for CHP units to be controlled to meet a heat load and, in district heating schemes, the heat output is often controlled as a function of ambient temperature. Alternatively, the units can be controlled to meet the electrical load of the host site and any deficit in the heat requirement is met from an auxiliary source. Finally, the units may be run to both heat and electricity to the site in an optimal manner, but this is likely to require a more sophisticated control system.

Although CHP schemes are conventionally designed and operated to meet the energy needs of the host site, or a district heating load, this is a commercial/economic choice rather then being due to any fundamental limitation of the technology. As commercial and administrative conditions change, […] it may be that CHP plants will start to play a more active role in supplying electrical energy and other ancillary services to the electricity distribution system.

For example, the main objective of the Danish dispersed CHP plants described in Reference 3 is to provide 95% of the annual requirement for district heating within their area of operation. The direct relationship between heat and electrical power production from these mainly reciprocating engine units was a major concern as it would have imposed significant additional load variations on the larger electrical power generating units when the dispersed CHP units responded to the varying demand for district heating. Therefore, large heat stores were constructed for each district heating scheme to accommodate approximately 10h of maximum heat production. One benefit of the heat stores is that they allow the CHP units to be run for reduce periods but at rated output, and hence maximum efficiency. Also, the periods of operation can be chosen to be at periods of maximum demand on the electrical power network. A three-rate tariff was introduced for the electrical power generated by the CHP units. The high kWh tariff corresponds to the demand for electricity on the utility system and, together with the facility to store heat, ensure that the CHP units generate electrical power when it is most needed by, and hence is most valuable to, the electricity system.

Embedded Generation 2000 Jenkins / Allan / Crossley / Kirschen / Strbac: *Embedded Generation,* London: The Institution of Electrical Engineers, 2000

3 Main components of CHP plant

CHP plants usually consist of:

- Turbine
- Reciprocating engine
- Generator
- Heat exchanger
- Combustor

3.1 Turbine

Gas turbines

In Gas turbine operation the air is admitted continuously to a compressor which, in modern turbines, is generally axial flow. Pressure is raised through two or three compressors each driven independently from its own turbine disc on coaxial shafts to allow each to turn at different speeds. […] Most of the compression is carried out in the intermediate and high pressure compressors which themselves each have large numbers of rows of blades. Pressure ratios of the order of 20:1 to 30:1 are typical of modern engines.

In modern gas turbines, the turbo machinery nearly always consists of an axial flow compressor and an axial flow turbine. Very early engines used centrifugal compressors and occasionally these still have some application but they are not suited for the multistaging necessary for the very high pressure ratios used on modern engines. The power for the compressor is taken from a turbine in the first stage of expansion and, as the compressor can consist of several stages, there maybe two or even three turbine stages each driving a compressor stage via coaxial shafts. The remainder of the expansion is used for power in […] further turbine sections to drive a power shaft.

Milton 1995 Brian E. Milton: *Thermodynamics, Combustion and Engines,*
London: Chapman & Hall, 1995

Steam Turbine

The works exactly in the same way as a gas turbine

In the steam turbine, the processes are essentially the same except that the fuel is transformed into heat which produces steam to run a steam turbine.

3.2 Reciprocating engine

Four-stoke engines

The basic principal of the operation of a four-stoke engine depends on the kind of the engine. There are two main groups, the spark ignition (SI) engine and the compression ignition (CI) engine, diesel type.

In the spark ignition engine, fuel and air are mixed at constant pressure by a spray basically controlled by pressure drop in a venture with some means of compensation for different conditions such as fully power or acceleration. The mixture may then be heated (using heat transfer from the exhaust manifold or engine coolant) to promote vaporisation and passed to the cylinders. In the first stoke, the inlet value is opened and the mixed gas flows into the cylinder as the piston moves down. The inlet value then closes and the mixture is compressed when the piston moves up. The compression ratio, i.e. the volume ratio between the lowest and the highest position of the piston, cannot be too great as the resulting temperature rise would then cause a spontaneous uncontrolled ignition of the fuel/air mixture. Just before the piston reaches the top of the stoke, ignition occurs at a controlled point by use of a high voltage spark. A flame front moves rapidly across the combustion chamber in a few degrees of crank angle movement causing a considerable increase in pressure and temperature. The expansion stoke follows and as the piston moves down work is extracted from the hot, high pressure gases. Towards the end of this stoke, the exhaust valve opens and the piston moves up expelling the burnt gases. Now the engine is back to its original state and the cycle can be repeated.

In the compression ignition engine, the processes are essentially the same except that air only is drawn into the cylinder during the intake stoke. Compression can now be much greater as no spontaneous combustion can occur. Indeed, the compression ratio has to be very high to provide the necessary temperatures for ignition. The fuel is now sprayed directly into the combustion chamber by a high pressure injector. Injector timing provides the controlled point to start combustion.

Combustion occurs by means of a diffusion flame over a somewhat longer period than with the spark-ignition engine. The pressure and temperature rises are thus somewhat more limited than with the SI engine. The remainder of the cycle is then identical to that of the SI engine.

Milton 1995 Brian E. Milton: *Thermodynamics, Combustion and Engines,* London: Chapman & Hall, 1995

3.3 Generator

Synchronous generators are very common and they are called so because they operate at constant speeds and constant frequencies under steady-state conditions.

The operation of a synchronous generator is based on Faraday's law of electromagnetic induction. Therefore the Stator of the generator and the rotor of the generator have to turn in against direction. Usually the stator is fixed and the rotor is flexible. When the rotor is turned by the mechanical power of the turbine electrical energy will be produced because of the electromagnetic induction.

3.4 Heat exchanger

Heat transfer is a process of energy transport. It is the result of temperature differences. The medium is the flow of heat and the driving force of heat flow is the nonequilibrium in temperatures. Since all heat transfers processes involve the transfer and conversion of energy, they must obey the first and second laws of thermodynamics.

There are three basic heat transfer mechanism: conduction, convection and radiation. In a real process, heat transfer is usually a combination of all three modes.

Conduction is the transmission of heat trough media (solid, liquid or gases) in direct contact. In solid media, thermal conduction is the dominant process. In liquids and gases, conduction heat transfer is usually insignificant when compared with convection and radiation.

Convection heat transfer is conduction combined with the physical movement of fluids, and is the dominant mechanism of heat transfer from solid surfaces to fluids. The hot solid surface transfers heat, by conduction, to the nearby fluid. The hot fluid will then mix with adjacent colder fluid, attempting to establish a temperature equilibrium. Thus, in convection heat transfer, the energy is transferred by both temperature difference and fluid movement. When the fluid movement is caused by its internal temperature difference only, the process is defined as free or natural convection. If external energy is applied, to move the fluid, the process is called forced convection.

Radiation is a heat transfer process in either visible (light) or invisible form. Radiation heat transfer is usually a straight line heat transport process which may pass through vacuums, some gases, some liquids and few solids.

Types of heat exchangers are double pipes, trombone and air cooler, shell and tube heat exchanger, spiral heat exchangers, plate exchanger and heat storage exchanger.

Kiang 1981 Kiang, Yen-Hsiung: *Waste energy utilization technology,* New York: Marcel Dekker, Inc., 1981

3.5 Combustor

Combustion in a normal […] gas turbine is a continuous process in which fuel is burned in the air supplied by the compressor; an electric spark is required only for initiating the combustion process, and thereafter the flame must be self-sustaining.

Separate combustion cans are still widely used in industrial engines, but recent designs make use of cannular (or turbo-annular) system, where individual flame tubes are uniformly spaced around an annular casing.

Large industrial gas turbines, where the space required by the combustion system is less critical, have used one or two large cylindrical combustion chambers; these were mounted vertically and were often referred to as silo type combustors because of their size and physical resemblance to silos.

Gas Turbine Theory 1996 Cohen / Rogers / Saravanamuttoo: *Gas Turbine Theory,* Essex: Longman Group Limited, 1996

4 Types of combined heat and power

There are five common types of CHP power plants:

- Back-pressure power plant
- Extraction condensing power plant
- Gas turbine heat recovery boiler power plants
- Reciprocating engine power plant
- Combined cycle power plants

4.1 Backpressure power plant

The simplest cogeneration power plant is the so-called backpressure power plant, where CHP electricity and heat is generated in a steam turbine. Another main component of the backpressure power plant is the steam boiler, which can be designed to fire solid, liquid or gaseous fuels.

Conventional steam power plants generating both electricity and heat are called backpressure power plants as a distinction to condensing power plants, which are generating only electricity. In a conventional condensing power plant, high-pressure steam generated in a steam boiler, the so-called live steam, is lead through a steam turbine, where the steam expands and is taken out of the turbine to a condenser at a low pressure. The remaining heat energy in the steam is wasted into the cooling water or cooling air.

In a backpressure turbine the steam is taken out of the turbine at a higher pressure than in a condensing power plant and the steam is used for heating purposes as shown in the following figure.

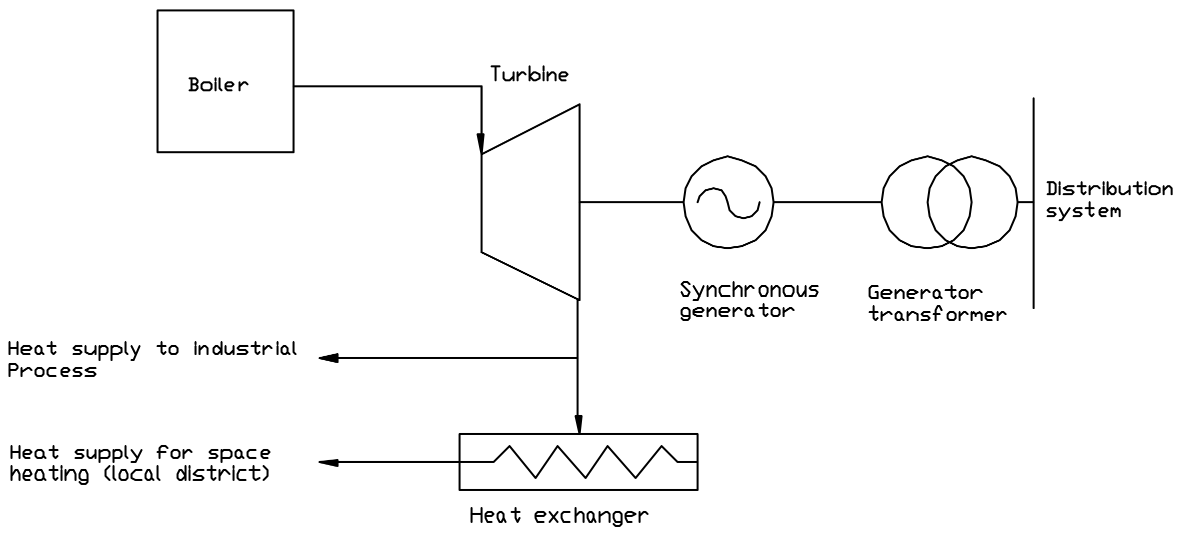


Figure 1: CHP scheme using a back-pressure steam turbine

Backpressure steam can be used directly as process steam in industrial applications such as paper machines or the steam can be condensed in heat exchangers, whereby the heat is transferred to the heating media such as district heating water.

Depending on the above mentioned application, the backpressure power plants are divided into the following two main groups:

- Industrial back-pressure power plants
- District heating power plants

The level of backpressure depends on the required heating temperature and is generally higher in industrial applications than in district heating power plants. The differences of the two backpressure power plant groups are described in the following.

In **industrial backpressure power plants** backpressure in normally kept constant in full and partial loads due to process requirements. Steam can also be extracted from the turbine at higher pressure levels and used either in industrial processes or for the power plant itself such as heating of feed water in a feed water tank. However, internal steam consumption of the power plant cannot be considered as CHP Heat. The higher the backpressure or the higher the pressure of extractions, the less electricity can be generated in the steam turbine. In other words, the expansion of steam is shorter in a backpressure turbine than in a condensing turbine, and therefore the heat energy contained in backpressure steam could still be used in a condensing turbine to generate more electricity. Depending on the industry, one part or in some cases almost all of the process steam can be recovered back to the power plant process as a form of condensate. This also has an effect on the heat consumption, since the temperature of the condensate is normally almost 100 °C and the recovery of condensate also means the recovery of remaining heat.

In a conventional **district heating power plant**, district-heating water is circulated through one or two heat exchangers […]. The temperature of district heating water varies in relation to ambient temperature. For example, typical average values for incoming water temperatures can be 50-55 °C and for outgoing temperatures 80-85 °C. Depending on the design of the network, the maximum outgoing temperatures can during cold winter days reach 120-150 °C. However, the increase of water temperature is often accomplished by using hot water boilers connected in series with the power plant. It has to be noted that the heat generation in hot water boilers is not considered as CHP Heat. The higher the temperature of the district heating water after the turbine heat exchangers, the less electricity can be generated in relation to heat. This relation of electricity generation to heat generation in cogeneration power plants is called the *Power to Heat Ratio*

CHP Combined Heat and Power. 28 Nov. 2005. CHP Combined Heat and Power Association. < http://www.chp-info.org/ >.

4.2 Extraction condensing power plant

A condensing power plant is generating only electricity. However, in an extraction condensing power plant some part of the steam is extracted from the turbine to generate also heat.

CHP Heat can be generated even in condensing power plants, when part of the steam passing through the turbine is extracted from the turbine before it reaches the last turbine stages and the condenser. District heat can be generated with the extracted steam in the same way as in district heating power plants, or the steam can be supplied to industrial purposes as shown in the following figure.

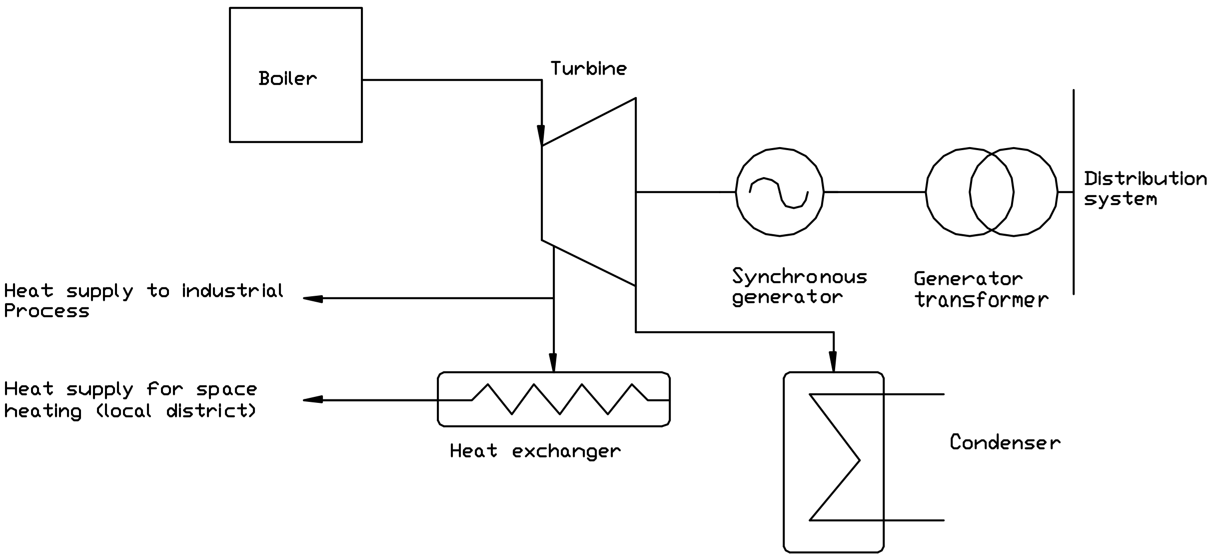


Figure 2: CHP scheme using a pass-out condensing steam turbine

[…] a steam reduction station can be used, when the steam turbine is not available in order to secure process heat to the factory. Naturally, the process heat supplied through the steam reduction station is not CHP Heat according to the definition. Correspondingly, there is no electricity generation connected to the process steam going past the turbine through the steam reduction station and thus there is no corresponding CHP Electricity.

It is possible to operate the steam turbine and the steam reduction station simultaneously. In this case, a distinction has to be made concerning the part of steam going through the turbine and the part of steam going through the reduction station.

It is a common practice to construct steam reduction stations in all cogeneration power plants, where steam is used for CHP Heat supply.

CHP Combined Heat and Power. 28 Nov. 2005. CHP Combined Heat and Power Association. < http://www.chp-info.org/ >.

4.3 Gas turbine heat recovery boiler power plants

In gas turbine heat recovery boiler power plants heat is generated with hot flue gases of the turbine. The fuel used in most cases is natural gas, oil, or a combination of these. Gas turbines can even be fired with gas fuel, solid or liquid fuels.

A simple and low-cost cogeneration power plant can be constructed by combining a gas turbine and a heat recovery boiler as shown in the following figure.

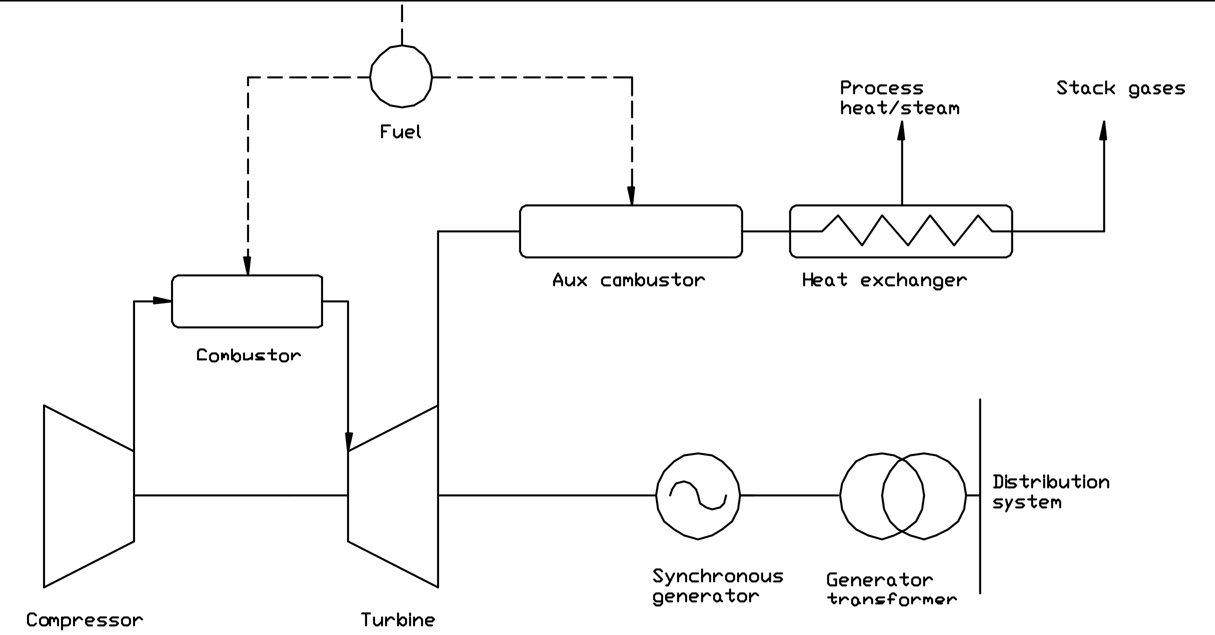


Figure 3: CHP scheme using a gas turbine with waste heat recovery

Heat is generated by the hot exhaust gases from the gas turbine. Heat can be taken out of the heat recovery boiler either in form of district heat or process steam.

The amount of heat that can be recovered depends on the required temperature level of the heat recovery and on the fuel used. Due to sulphur corrosion risk, the exhaust gas temperature must not go below 120- 170 °C with oil firing depending on the sulphur content of the oil. When natural gas is used, the temperature can be reduced to 60-100 °C depending on the returning district heating water temperature and thereby more heat can be recovered from the flue gases.

In some applications the power plant is equipped with a supplementary burner, which utilises the exhaust gases of the gas turbine as combustion air, since the gases still contain about 15 % of oxygen. Naturally, the heat generated with the supplementary burner is not CHP Heat by definition. The same applies to fresh air burners, which are not dependent on the gas turbine, because they have separate combustion air fans.

In some cases, the power plant contains a by-pass stack past the heat recovery boiler, so that the gas turbine can be operated without the boiler, if necessary. In this case, the electricity generated without the heat recovery boiler is not CHP Electricity. The same applies, when the capacity of the heat recovery boiler is much less than what would be economically feasible, in which case only part of electricity generation can be regarded as CHP Electricity.

CHP Combined Heat and Power. 28 Nov. 2005. CHP Combined Heat and Power Association. < http://www.chp-info.org/ >.

4.4 Combined cycle power plants

Recently, natural gas fired combined cycle power plants consisting of one or more gas turbines, heat recovery boilers, and a steam turbine have become quite common.

A combined cycle power plant consists of one or more gas turbines and one or more steam turbines, which are connected in one single power plant process. Based on the steam turbine type, the power plant can be either a condensing or a cogeneration power plant. […] a cogeneration combined cycle power plant generates both, electricity and district heat. […]

All electricity generated in the power plant […] can be considered CHP Electricity, since there is no auxiliary cooler or condensing tail in the steam turbine.

A characteristic feature to all *combined cycle power plants* is that the heat contained in the gas turbine flue gases is recovered into the steam-water cycle of the power plant in a heat recovery boiler. The heat recovery boiler can be equipped with supplementary firing using the gas turbine flue gases as combustion air. The fuel used in the burners of the supplementary firing system can be different from the gas turbine fuel. In a combined cycle condensing power plant the total efficiency lies in the range of 50 %.

A *combined cycle process* can be applied, for example, when repowering existing power plants. For example, it is possible to utilise the flue gases as combustion air in a normal power boiler, which may use coal or some other solid fuel as main fuel. Another solution could be to replace existing high pressure feed water heaters with heat exchangers, where gas turbine flue gases are used as heating medium. These and similar solutions do not necessarily mean, that the complete power plant would be converted into a combined cycle power plant. In this case, it would be possible to speak about *combined cycle power generation* covering only one part of the power plant electricity production. This part of the generation may have the same efficiency as that of the combined cycle power plant, namely about 50 %.

In case, that the combined cycle power plant includes a condensing turbine with steam extraction for heat generation, it has to be agreed, among other things, which part of the gas turbine electricity generation can be regarded as CHP Electricity.

CHP Combined Heat and Power. 28 Nov. 2005. CHP Combined Heat and Power Association. < http://www.chp-info.org/ >.

4.5 Reciprocating engine power plant

Instead of a gas turbine, a reciprocating engine, such as a diesel engine, can be combined with a heat recovery boiler, which in some applications supplies steam to a steam turbine to generate both electricity and heat.

In a reciprocating engine power plant heat can be recovered from lubrication oil and engine cooling water as well as from exhaust gases as shown in the following figure.

The electricity generating efficiencies of reciprocating engines vary from 35 to 42 %. In cases, where low nitrogen oxide (NO_x) emissions are required by legal standards, the efficiencies that can be reached are about one percentage lower.

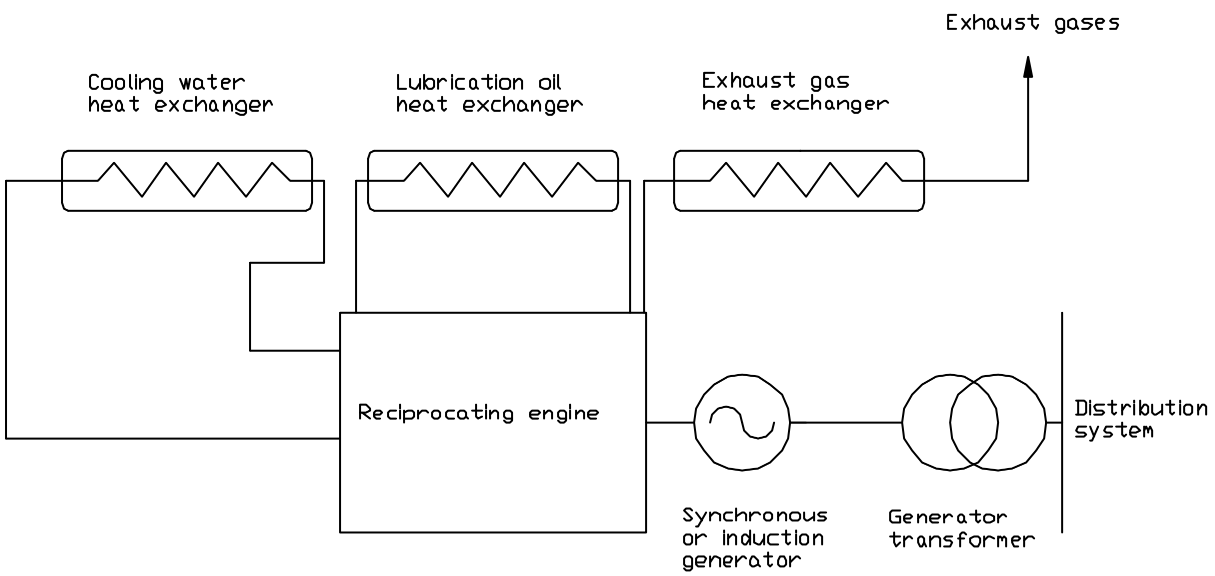


Figure 4: CHP scheme using a reciprocating engine with heat recovery

Some of the waste heat from the engine, such as waste heat from generator cooler, can normally not be used for useful heat generation due to low temperature level.

Because modern engines have rather cool exhaust gases (approximately 400 °C), only part of the heat can be recovered in the form of steam. For example, a diesel engine generating 4,2 MW of electricity can generate about 1,5 MW of steam and about 3,1 MW of warm and hot water. Since the fuel consumption is about 10, 0 MW, the total efficiency of the plant in this example is 88 %.

When using supplementary firing, about 9,5 MW of steam or district heat can additionally be generated with the remaining oxygen in flue gases. This steam or district heat, however, cannot be considered as CHP steam.

CHP Combined Heat and Power. 28 Nov. 2005. CHP Combined Heat and Power Association. < http://www.chp-info.org/ >.

5 Potential of CHP

Industrial CHP schemes typically achieve a 35% reduction in primary energy use compared with electrical generation from central power stations and heat-only boilers.

In the UK power system, this leads to a reduction in CO_2 emissions of over 30% in comparison with large coal fired stations and over 10% in comparison with central combined-cycle gas turbine plant [1].

The use of CHP for district heating is limited in the UK, although small schemes exist in some cities. However, in northern Europe, e.g. Denmark, Sweden and Finland, district heating is common in many large towns and cities, with the heat supplied at water temperatures in the range of 80-150 °C, either from CHP plant or heat-only boilers [2].

A recent development in Denmark has been to extend the use of CHP into rural areas with the installation of smaller CHP schemes in villages and small towns using either back-pressure steam turbines, fed from biomass in some cases, or reciprocating engines powered by gas [3].

In 1998, the total capacity was 3929 MWe, which may be compared with the government policy target of 5000 MWe by the year 2000 10000 MWe by 2010.

The high overall efficiency of nearly 70% confirms the potential of CHP in reducing in environmental impact as well as for financial savings: 321 industrial sites make up 88% of the CHP capacity, while the remaining 1055 sites are in the commercial, public and residential sectors.

Table 2 shows that the installed capacity is dominated by a small number of large installations while the largest number of sites has an electrical capacity of less than 100 kWe. Some of the very large CHP installations, e.g. on chemical works and oil refineries, are connected electrically to the transmission network, and so this generation cannot be considered to be embedded.

In contrast, many of the CHP schemes installed in buildings in the leisure, hotel and health sectors have installed electrical capacities below 1 MWe and are connected to the 11kV distribution network.

Embedded Generation 2000 Jenkins / Allan / Crossley / Kirschen / Strbac: *Embedded Generation,* London: The Institution of Electrical Engineers, 2000

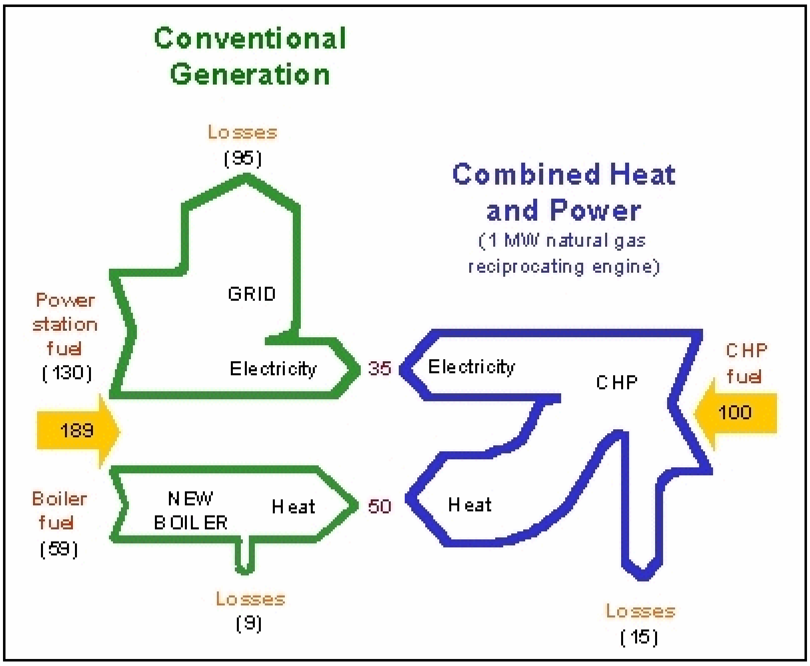


Diagram 4: Compared fuel input for the same energy output

This diagram compares the typical fuel input needed to produce 35 units of electricity and 50 units of heat using conventional separate heat and power. For typical electric and thermal efficiencies, CHP is nearly twice as efficient.

United States Combined Heat and Power Association. 28 Nov. 2005. *United States Combined Heat and Power Association*. < http://uschpa.admgt.com/CHPbasics.htm >.

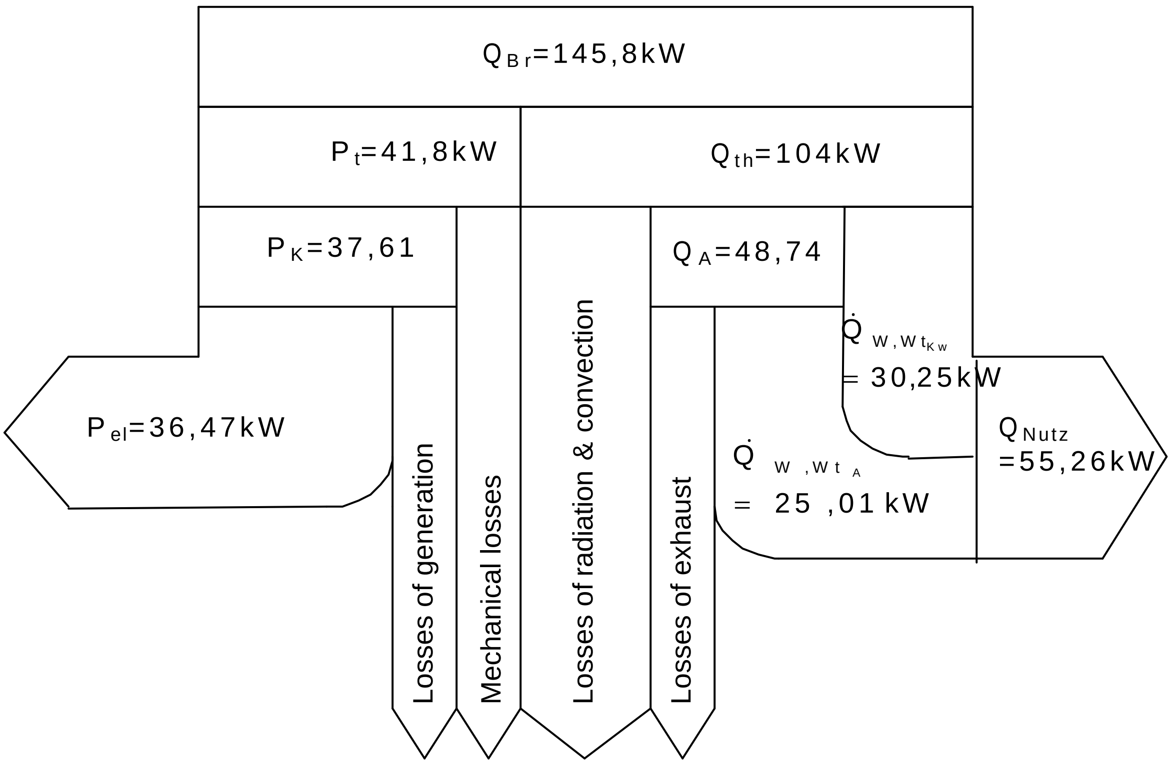
6 Application

In my last chapter I will give an example of a CHP scheme.

In my fourth semester at the University of Applied Sciences, Berlin I have had a labour about CHP technology.

We analysed a CHP scheme, which includes a car engine, for producing energy to drive a generator and heat. The explanation of all the equations for the power and efficiency will take to long time and hence I will only discuss the output.

The CHP scheme provides heat energy of about 55 kWth. The output of electrical energy is about 36 kWe. The efficiency of the engine is 26 %.



In the sankey-diagram all the flow of energy is shown. The energetic efficiency of the hole CHP scheme is 63 % by a power to heat ratio of about 0,66.

In order to get the highest efficiency, the CHP scheme should work full loaded. This is the case when the fuel flow is in the range of 17-22 kg/h. Otherwise the efficiency is not the best as the system can do. In compare to other energy converter, this scheme has a high efficiency.

The most important by using such an application is that the provided heat must be used by anyone. Otherwise the sense of the system is misunderstood.

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United States Combined Heat and Power Association. 28 Nov. 2005. *United States Combined Heat and Power Association*. < http://uschpa.admgt.com/CHPbasics.htm >.

Appendix

Low carbon - greenhouse gas and carbon dioxide emissions, 1990 to 2003
Million tonnes of carbon

	1990	**1995**	**2000**	**2002**	**2003**
Carbon dioxide	165,4	154,7	152,8	152,7	156,1
Methane	21,1	18,0	13,6	12,3	11,1
Nitrous oxide	18,5	15,6	12,2	11,2	11,0
HFC	3,1	4,2	2,5	2,8	2,9
PFC	0,4	0,1	0,1	0,1	0,1
SF	0,3	0,4	0,5	0,4	0,4
Basket' of greenhouse gases	**208,8**	**192,9**	**181,8**	**179,5**	**181,6**

Production of primary fuels, 1980 to 2004
Million tonnes of oil equivalent

	1980	**1990**	**2000**	**2002**	**2003**	**2004**
Petroleum	86,9	100,1	138,3	127,0	116,2	104,5
Natural gas	34,8	45,5	108,4	103,6	102,9	96,0
Coal	78,5	56,4	19,6	18,8	17,6	15,7
Primary electricity	10,2	16,7	20,2	20,6	20,4	18,9
Total	**210,5**	**219,4**	**288,7**	**272,9**	**260,3**	**238,5**

Inland energy consumption, 1980 to 2004
Million tonnes of oil equivalent

	1980	1990	2000	2002	2003	2004
Conversion losses	62,1	66,4	53,9	52,5	53,7	53,5
Distribution losses and energy industry use			20,8	20,7	20,2	20,2
Final consumption						
Industry	48,3	38,7	34,6	33,7	34,2	34,1
Domestic sector	39,8	40,8	46,9	47,9	48,3	48,7
Transport	35,5	48,6	55,3	55,4	56,0	57,4
Services	18,7	19,2	21,5	19,9	19,8	20,8
Total final energy consuption	**142,4**	**147,3**	**158,3**	**156,9**	**158,4**	**161,0**
Total inland primary energy consumption	**204,5**	**213,7**	**233,0**	**230,3**	**232,5**	**234,9**
Temperature corrected total	206.2	221,6	237,9	236,0	236,3	238,2

Final energy consumption, 2004
Million tonnes of oil equivalent

	Industry	Domestic	Transport	Services	Total
Coal & manufactured fuels	1,7	1,3	-	0,1	3,1
Gas	12,5	34,1	-	9,5	56,1
Oil	8,3	3,1	56,8	1,6	69,8
Electricity	10,1	9,9	0,7	8,5	29,2
Renewables & heat	1,5	0,3	-	1,1	2,9
Total	**34,1**	**48,7**	**57,4**	**20,8**	**161,1**

UK continental shelf production, 1980 to 2004
Million tonnes of oil equivalent

	1980	1990	2000	2002	2003	2004
Oil	86,9	100,1	138,3	127	116,2	104,6
Gas	34,8	45,5	108,4	103,6	102,9	96
Total	**121,7**	**145,6**	**246,7**	**230,6**	**219,1**	**200,6**

Remaining oil and gas reserves, 1980 to 2003

	1980	1990	2000	2002	2003
Oil			**Million tonnes**		
Cumulative production	263	1374	2570	2799	2910
Estimat of remaining reserves in present discoveries	2300	1815	1490	1345	1267
Total reserves in present discoveries	**2565**	**3190**	**4060**	**4145**	**4175**
Gas			**Billion cubic metres**		
Cumulative production	382	752	1518	1726	1828
Estimat of remaining reserves in present discoveries	1560	1785	1630	1330	1241
Total reserves in present discoveries	**1940**	**2535**	**3150**	**3055**	**3070**

Foreign trade in crude oil and petroleum products, 1980 to 2004
£ billion

	1980	1990	2000	2002	2003	2004
Export	6,5	8,1	15,6	14,3	14,6	16,3
Import	6,2	6,4	9,0	8,6	10,5	14,4
Net export	**0,3**	**1,6**	**6,5**	**5,7**	**4,1**	**2,0**

Demand by product
Million tonnes

	1980	1990	2000	2002	2003	2004
Energy uses						
Petrol	19,2	24,3	21,6	20,8	19,9	19,5
DERV fuel	5,9	10,7	15,6	16,9	17,7	18,5
Aviation turbine fuel	4,7	6,6	10,7	10,5	10,8	11,8
Burning oil	2,1	2,1	3,8	3,5	3,5	4,0
Gas oil	11,6	8,0	6,6	6,0	6,4	6,1
Fuel oils	22,7	14,0	3,4	4,1	4,4	4,7
Other	4,3	4,9	5,5	4,9	4,6	5,0
Total energy uses	**70,5**	**70,6**	**67,2**	**66,7**	**67,3**	**69,6**
Of which:						
Transport fuels	31,9	43,5	49,8	49,3	50,0	51,3
Non-energy uses	**7,0**	**9,2**	**10,1**	**9,6**	**10,5**	**10,6**
Total deliveries	**77,5**	**79,8**	**77,3**	**76,2**	**77,8**	**80,2**

Natural gas consumption, 1980 to 2004
TWh

	1980	1990	2000	2002	2003	2004
Electricity generators	4	6,5	324,6	329,8	324,6	338,7
Energy industries	19,1	39,2	102,1	113	108,6	118,6
Industry	177,5	164,6	198,5	176,2	177,1	156
Domestic	246,8	300,4	369,9	376,4	386,5	396,4
Services	60,4	86,4	110,5	100,8	106	110,1
Total	**507,8**	**597**	**1105,5**	**1096,3**	**1102,7**	**1119,8**

UK trade in natural gas, 1980 to 2004
TWh

	1980	1990	2000	2002	2003	2004
Natural gas production	404,8	528843	1231263	1204505	1197,1	1116,6
Imports	116291	79833	30464	60493	86298	133035
Exports	-	-	138330	150731	177039	114111
Net imports (+) or exports (-)	-116291	-79833	107866	90238	90741	-18924

Coal production and Imports, 1980 to 2004
Million tonnes

	1980	1990	2000	2002	2003	2004
Deep mined	112,4	72,9	17,2	16,4	12,5	12,5
Opencast	15,8	18,1	13,4	13,1	12,0	12,0
Total (including slurry)	**130,1**	**92,8**	**31,2**	**30,0**	**25,1**	**25,1**
Coal imports	7,3	14,8	23,4	28,7	36,2	36,2

Coal consumption, 1980 to 2004
Million tonnes

	1980	1990	2000	2002	2003	2004
Power stations	89,6	84	46,2	47,7	52,5	50,5
Domestic	8,9	4,2	1,9	1,8	1,2	1,4
Industry	7,9	6,3	0,7	1,1	0,9	1,5
Services	1,8	1,2	0,1	< 0,1	< 0,1	< 0,1
Other energy industries	15,3	12,5	10	8	7,6	7,3
Total consumption	**123,5**	**108,3**	**58,9**	**58,7**	**62,3**	**60,8**

Electricity available by fuel type, 1980 to 2004
TWh

	1980	1990	2000	2002	2003	2004
Coal	190	208	114,7	118,5	131,7	126,6
Oil	33,9	21,1	5,9	4,2	4,1	4,3
Gas	1,6	1,6	145	148,9	145,1	152,8
Nuclear	32,3	58,7	78,3	81,1	81,9	73,7
Hydro	7,3	7,9	4,2	3,9	2,3	4,2
Other fuels	-	-	9,2	10,2	11,5	13,6
Net imports	-	11,9	14,2	8,4	2,2	7,5
Total	**2651**	**309,4**	**371,5**	**375,1**	**378,9**	**382,7**

Electricity consumption, 1980 to 2004
TWh

	1980	1990	2000	2002	2003	2004
Industrial	88,6	100,6	115,3	113,3	115	117,8
Domestic	86,1	93,8	111,8	114,5	115,8	115,5
Services	58,4	80	103,5	106,2	107,4	107,4
Energy industrie	8,5	10	9,7	10,1	9,9	9,7
Total	**241,6**	**284,4**	**340,3**	**344,1**	**348**	**350,4**

Combined heat and power, 1993 to 2004

	1995	2000	2002	2003	2004
CHP electrical capacity [MWe]	3094	4730	4848	4777	5606
CHP electrical generation [GWh]	14468	26539	2442	24916	27354
CHP heat generation [GWh]	57401	62121	59721	60052	62065
Number of CHP sites					
Less than 100 kWe	686	667	641	622	618
100 kWe to 999 kWe	411	593	637	648	665
1 MWe to 9,9 MWe	147	192	184	190	194
10 MWe and greater	64	70	72	74	75
Total	**1308**	**1522**	**1534**	**1534**	**1552**

Gross electricity supplied by nuclear generation, 1990 to 2004
Terrrawatt hours [TWh]

	1990	2000	2002	2003	2004
Electricity supplied (gross)	59	78	81	82	74
% of electricity generation	21	22	22	22	19

Renewable energy sources, 1990 to 2004
Thousand tonnes of oil equivalent

	1990	2000	2002	2003	2004
Geothermal and active solar heating	7,2	12	17,1	20,8	24,9
Wind and wave	0,8	81,3	108	110,5	166,4
Hydro (small- and large scale)	447,7	437,3	411,7	277,5	423,9
Landfill gas	79,8	731,1	892,1	1088,1	1326,7
Sewage gas	138,2	168,7	174	165	176,7
Wood (domestic and industrial)	174,1	502,8	469,8	469,8	469,8
Waste combustion	100,8	375,6	453,8	479,5	463,1
Other biofuels	71,9	216,1	439,8	614,1	762
Total	**1020,5**	**2524,9**	**2966,3**	**3225,4**	**3814,3**

Percentage of UK generation from renewable sources, 1990 to 2004
Per cent

	1990	2000	2002	2003	2004
Wind, wave, solar and biofuels	0,19	1,27	1,64	1,86	2,33
Hydro	1,63	1,35	1,24	0,81	1,25
Total	**1,82**	**2,62**	**2,87**	**2,67**	**3,58**
Obligation (% of UK electricity sales)	-	1,32	1,8	2,21	3,08

Energy efficiency, 1980 to 2004
Tonnes of oil equivalent

	1980	1990	2000	2002	2003	2004
Industrial energy consumption per million units of GVA	362,8	236,6	186,1	188,9	192,4	191
Domestic energy consumption per household	2	1,8	1,9	1,9	1,9	2
Service sector energy consumption per million units of GVA	81,8	64,1	53,9	46,5	45,8	46,4
Road passenger energy consumption per million passenger-kilometres	45,7	41,6	38,9	37,1	36,3	-
Road freight energy consumption per million freight-kilometres	76,4	88	88,9	93,7	95,1	-