Leonardo ENERGY

Power Quality and Utilisation Guide

Distributed Generation and Renewables

8.3.5 Cogeneration

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Distribution Generation and Renewables

Cogeneration

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KEMA Nederland BV
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Cover, top picture: a biomass power plant in Malchin, Mecklenburg-Western Pomerania, Germany. Cover, bottom picture: a gas and steam combined heat and power station at Nossener Brücke in Dresden, Germany.

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Cogeneration

Introduction

This Application Note is an introduction to cogeneration; what it is and how it is used in Europe. First, a description of the basic principle is given. The different cogeneration technologies that are currently in use, and those that are likely to enter use in the near future, are discussed. Attention is given to the way cogeneration should be matched to the energy demand at the application site to guarantee best environmental performance. In the EU member states, about 10% of all electricity production involves cogeneration. The European Commission wants to see this percentage increased because of the environmental benefits (especially with regard to carbon dioxide emissions) and the potential security-of-supply benefits. The EU is therefore supporting increased use of cogeneration with various directives that are to be implemented by the EU member states over the next few years.

Basic principles and definition

Cogeneration is the simultaneous production of power and heat. This is not, however, a complete definition since all installations that produce power also produce heat. What distinguishes cogeneration is that the heat is used in a practical application i.e. both the power and heat outputs are fully utilised. For example, a car produces power (motion) and heat, but a car is not a cogeneration unit, because most of the heat produced is not put to any practical use. Cogeneration may therefore be defined as follows:

Cogeneration is the simultaneous production of power and heat, with a view to the practical application of both products.

Because of this combination of heat and power production, cogeneration is often also called Combined Heat and Power (CHP). In this Application Note both these synonyms will be used. The 'power' product from cogeneration is almost always electricity, although it may otherwise be compressed air or another form of power. Depending on the cogeneration technology used, the heat produced can be used at a relatively low temperature for spatial heating, or at a higher temperature for process heating (usually in the form of steam). This Application Note will focus on cogeneration with electricity as the power product.

A cogeneration unit always consists of the following basic components:

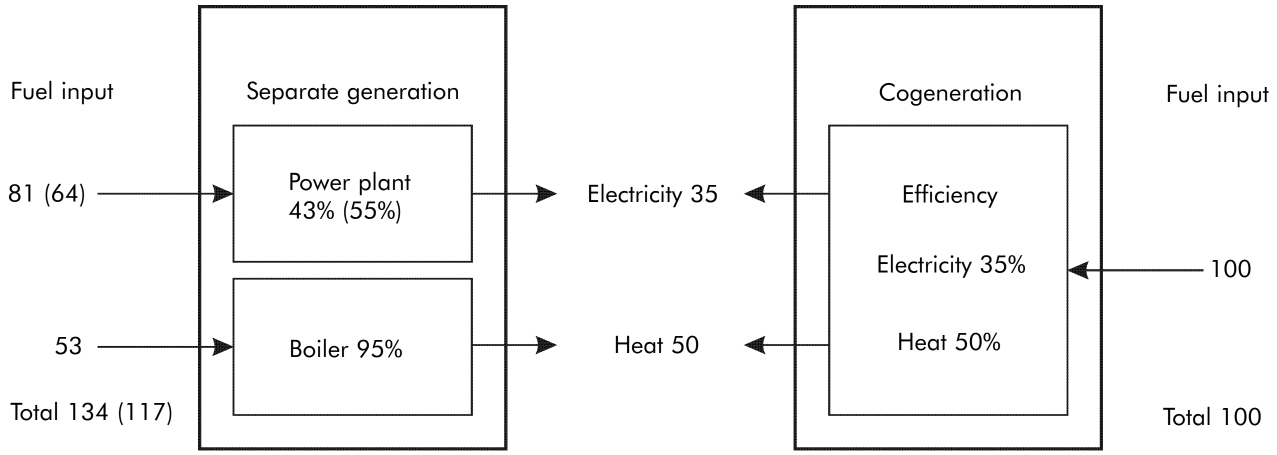
- A primary driver in which fuel is converted into motion and heat
- A generator to transform the motion into electricity
- A heat recovery system to collect the produced heat.

Cogeneration can be applied on different scales, using different technologies and in different fields of application. In the context of cogeneration, distinction is often made between large-scale and small-scale cogeneration. Applications that use an internal combustion (IC) engine (also called a gas engine) as the primary driver are mostly classified as small-scale, while most large-scale cogeneration involves a gas turbine as the prime mover. However, it is more important to distinguish on the basis of the technology used than on the basis of scale.

Comparison with conventional electricity and heat production

Cogeneration is presently the most important available means of improving energy efficiency. An average cogeneration unit has an efficiency of 85% so only 15% of the energy initially used (fuel) is lost. By comparison, a modern electricity plant with a combined cycle of steam and gas turbine has an efficiency of 55%, meaning that 45% of the energy is lost.

In Figure 1, cogeneration is compared with the separate, conventional production of electricity and heat. It shows that the separate production of heat and electricity requires more primary energy (fuel) than the cogeneration of similar amounts of heat and electricity. The diagram assumes a realistic electrical efficiency of 35% and a thermal efficiency of 50% for a cogeneration unit based on an IC engine. The amount of energy saved (the efficiency improvement) depends on the separate forms of electricity and heat generation against which a comparison is made. The diagram assumes the average energy efficiency for a typical electricity production infrastructure (43%), and a boiler with an efficiency of 95%. Comparison against a modern combined-cycle electricity plant with an energy efficiency of 55% yields the energy conservation figures given in brackets.



$$\text{Energy conservation} = \frac{(134-100)}{134} = 25\% \ (15\%)$$

Figure 1 - Theoretical energy conservation of cogeneration compared to separate generation of electricity and heat

As indicated in Figure 1, the use of cogeneration leads to an energy efficiency improvement of 15 to 25%. The scope for improving efficiency is one of the main drivers behind the success of cogeneration.

Benefits of cogeneration

In addition to the scope for improving efficiency, cogeneration offers various other potential benefits. The most important are:

- If all the heat produced can be used on the production site, cogeneration is the cheapest way to produce electricity
- The use of cogeneration leads to lower emissions to the environment, especially of CO_2
- Local production of electricity can improve the local security of the electricity supply
- Process by-products (e.g. organic waste) can be used as fuel for cogeneration installations.

The application of cogeneration

Types of cogeneration

Cogeneration can be applied in many different fields. Combined generation is readily employed in buildings such as offices, hospitals, homes and swimming pools, as well as in glasshouse horticulture, industry and as a heat source for district heating.

The use of cogeneration has a long history of use in many types of industry, particularly in the paper and bulk chemicals industries, in which there is a high concurrent demand for heat and power. In recent years, the greater availability and wider choice of suitable technologies has meant that cogeneration has become an attractive and practical proposition for a wide range of applications. These include the process industries, commercial and public sector buildings and district heating schemes, all of which generate considerable demand for heat.

The possible applications can be classified on the basis of various parameters:

Scale of applications:	Large-scale or small-scale
Nature of heat usage:	Spatial heating or process heating
Type of technology:	Gas turbine or gas engine
User:	One or more users
Ownership:	Owned by user alone or in partnership with, for example, energy company.

Although classification on the basis of application scale is commonplace, 'small-scale' and 'large-scale' are subjective definitions. In the context of gas turbine industrial cogeneration, a unit with a capacity of 5 MWe (megawatts electric) is small. Where an internal combustion engine is concerned, however, a 5 MWe unit is large.

It is more helpful to classify on the basis of the technology used, possibly in combination with the nature of the heat usage. IC engines are normally used in situations where the heat is used for spatial heating. When higher-temperature heat is needed, e.g. for process heating, gas turbines tend to be more appropriate.

Traditionally, IC engines have been used for small-scale applications (200 kWe – 5 MWe), while gas turbines have been used for large-scale applications (> 5 MWe). In recent years, however, the micro turbine (30 kWe – 500 kWe) has become available for small-scale applications.

Cogeneration in Europe

Cogeneration plays an important role in the EU's energy supply, accounting for 10% of electricity generated. Across the EU there has been considerable diversity in both the scale and nature of the development of cogeneration. This diversity reflects differences in history, policy priorities, natural resources, culture and

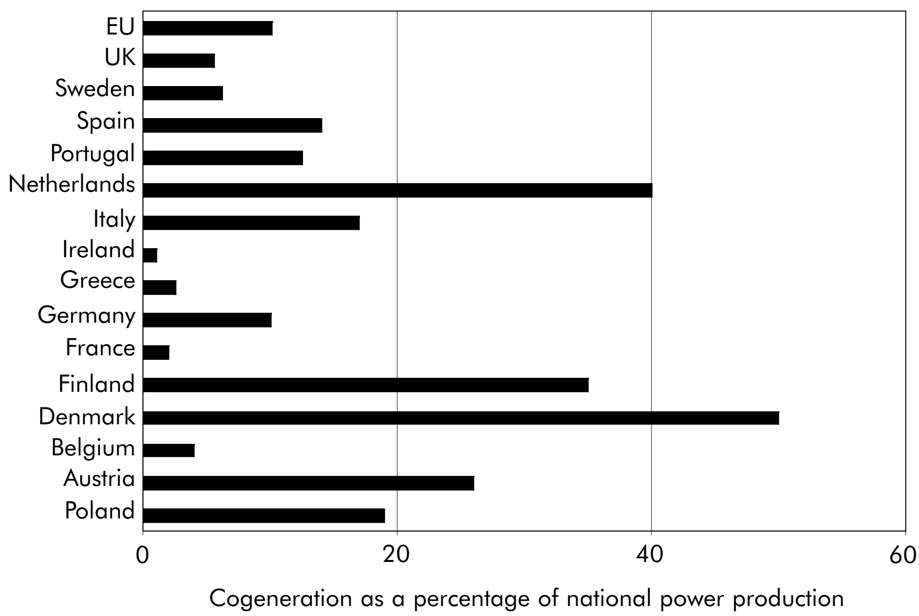


Figure 2 - Status of application of cogeneration in the EU as share (%) of national power production (source Cogen Europe)

climate, and is closely related to the structure and working of the electricity markets. Figure 2 shows the current status of cogeneration in several EU member states.

From Figure 2 it can be seen that the use of cogeneration in different countries varies from a few percent of overall production in Ireland to 50% in Denmark. In those countries with a high share (Denmark, Finland and the Netherlands) clear policy incentives have boosted the application of cogeneration. For instance, in the Netherlands, a special low gas price and a fair tariff guarantee for cogenerated electricity supplied to the grid led to considerable growth in cogeneration between 1990 and 2000. However, special tariffs for the cogeneration market are no longer possible and only genuine cogeneration schemes, involving the practical application of the produced heat, can survive in the liberalised market.

A well-designed and operated cogeneration unit will always provide higher energy efficiency than separate heating and electricity generation. A single fuel is used to generate heat and electricity, and the cost saving is dependent on the price differential between the cost of that fuel and the value of bought-in electricity that the cogeneration unit replaces. However, although the profitability of cogeneration generally derives from the cheapness of the electricity produced, its success depends on being able to put the heat to practical use. Therefore the prime criterion is the existence of a heat application that can viably be served by cogeneration. As a rule of thumb, cogeneration is likely to be viable where heat is in demand for at least 4500 hours per year. The best possible situation is one in which both the heat and the electricity can be fully used on the production site. In most instances, however, electricity production exceeds local demand when the cogeneration unit is deployed in line with the demand for heat.

This is illustrated in Figures 3 and 4. Figure 3 shows the situation in which the cogeneration unit is sized according to the demand for electricity. The electricity demand is, in this example, constant over the year, leading to a constant level of heat supply. Since heat demand is much higher in the winter months, additional heat production is required.

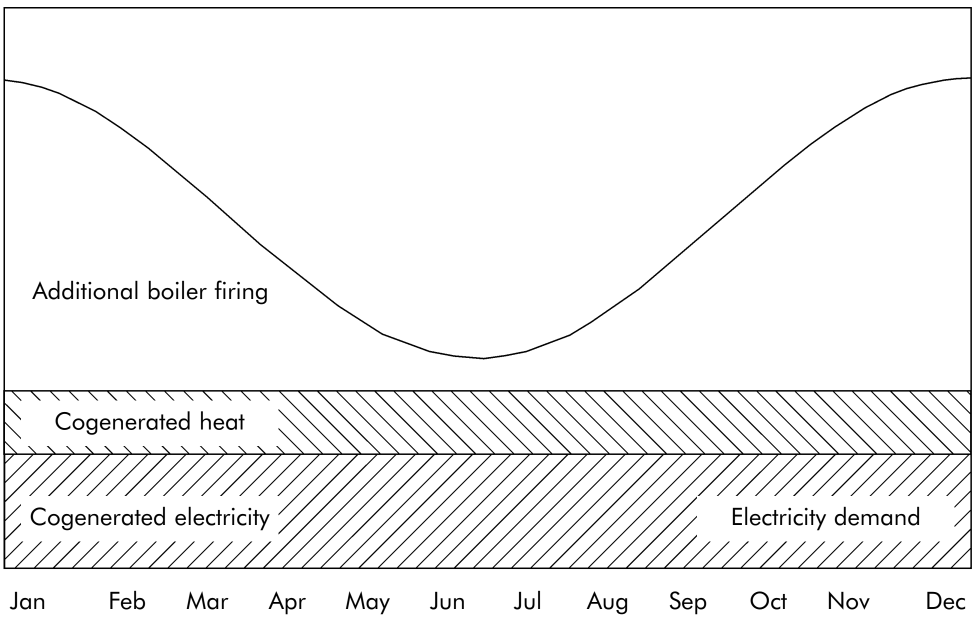


Figure 3 - Cogeneration unit set up to follow electricity demand

Figure 4 shows the situation in which the cogeneration unit is sized according to the heat demand. Electricity availability follows heat production while electricity demand remains constant. If electricity supply exceeds demand the shortfall can be purchased from the grid while excess electricity can be sold to the grid.

In most applications of cogeneration, the demand for heat is higher than that for electricity (seen over the year). In other words, the heat to power ratio is higher than 1. This ratio can, however, vary considerably

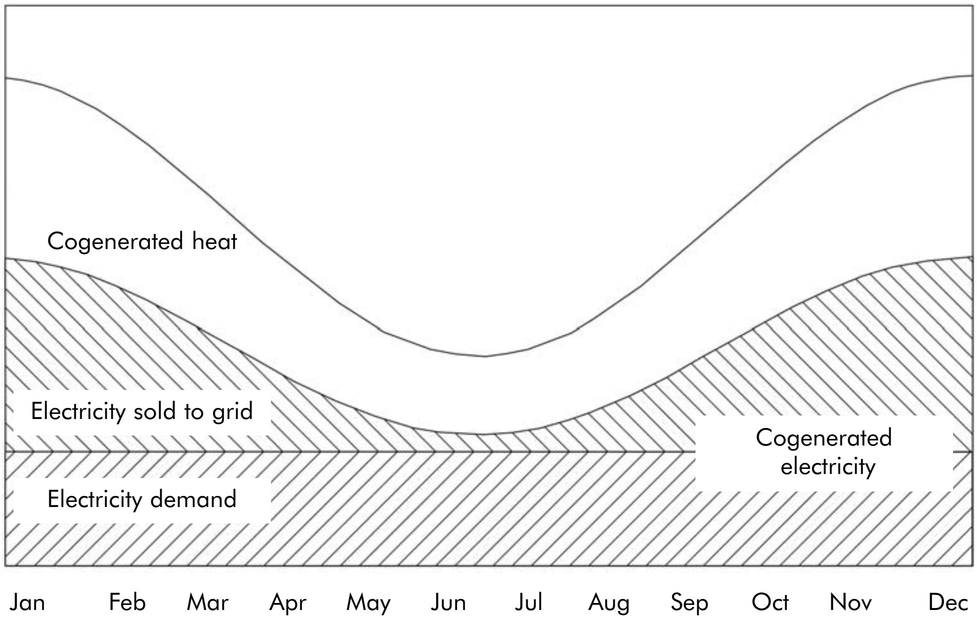


Figure 4 - Cogeneration unit set up to follow heat demand

during the year, and even during the day. From an environmental perspective it is always best for a cogeneration unit to follow the heat demand but from an economical perspective it is sometimes attractive to follow the electricity demand. When following the electricity demand there will be times (especially in the summer) when the heat produced cannot be used and has to be dissipated, with a negative effect on the overall efficiency of the cogeneration unit.

When a cogeneration unit is set up to follow heat demand, there will be times (especially in the winter) when a lot of the electricity produced will have to be sold to the grid. If the market price of electricity is low at these times, this will have a negative effect on the overall economic performance of the unit.

Cogeneration technology

Prime movers

At present, the two main cogeneration prime mover technologies are gas turbines and internal combustion engines. Fuel cells, micro turbines and Stirling engines show promise as prime movers for cogeneration in the near future. A comparison of prime movers is given in Table 1.

Gas turbines

The gas turbine has become the most widely used prime mover for large-scale cogeneration, typically generating between 1 and 100 MWe. Fuel is burnt in a pressurised combustion chamber using air supplied by a compressor. The hot pressurised gases (temperature about 1200°C) are used to turn a series of fan blades, and the shaft on which they are mounted, to produce mechanical energy. This mechanical energy is normally used to produce electricity with a generator. The hot exhaust gases can be used (either directly or via a steam conversion step) to meet the local heat demand, to produce steam in a waste heat boiler for industrial processes or to produce electricity by allowing it to expand in a steam turbine. This configuration of gas turbine, waste heat boiler and steam turbine is called a 'combined cycle gas turbine'

Internal combustion engines

Internal combustion engines operate on the same principles as automotive engines. They give a higher electrical efficiency than gas turbines, but the heat they produce is more difficult to use because it is

Prime mover	Fuel	Size range (MWe)	Electrical efficiency	Typical overall efficiency	Heat
Combined-cycle gas turbine	Gas	3 – >300	35 – 55%	73 - 90%	Medium-grade steam or high-temperature hot water
Gas turbine	Gas	0.3 - >50	25 – 42%	65 – 87%	High-grade steam or hot gas (500 – 600°C)
Diesel engine	Gas oil	0.2 to 20	35 – 45%	65 - 90%	Low-pressure steam. Low and medium-temperature hot water
Gas engine	Gas, biogas	0.003 to 6	25 - 43%	70 - 92%	Low and medium-temperature hot water
Fuel cell	Hydrogen, natural gas	0.001 to 100	40 - 60%	90%	Steam or hot water
Micro turbine	Gas, gas oil, biogas	0.03 - 1	27%	90%	Hot exhaust gas or hot water
Stirling engine	All fuels	0.001- 0.005	10 – 15%	95%	Hot water

Table 1 - Comparison of prime mover technologies

generally at lower temperatures and is divided approximately evenly between exhaust gases (high temperature of about 400°C) and the engine coolant (low temperature at around 100°C). In many applications the heat recovered from the cooling circuits and exhaust gases is cascaded to produce a single heat output, typically producing hot water at around 100°C. With the increased interest in renewable energy, internal combustion engines fuelled by biogas (which requires only minor engine modifications) are increasingly being used.

Fuel cells

In a fuel cell, fuel (natural gas, methanol or hydrogen) is transformed into electricity and heat via an electrochemical process. Hydrogen (from the fuel) and oxygen (from the atmosphere) are converted into water, electricity and heat. Fuel cells are attractive because of their high electrical efficiency (up to 60%) and the elegance of conversion without moving parts.

There are different types of fuel cells which, although they all operate on the basic principle described above, differ considerably in terms of the materials used, the fuels they run on and their operating characteristics (operating temperature, power output, fuel purity requirements, etc). As a result, they also differ in terms of the fields of application for which they are suitable. Two fuel cell technologies that are presently in the early stages of commercial development, and have the potential to enter general use within the next ten years, are the solid oxide fuel cell (SOFC) and the proton exchange membrane (PEM) fuel cell. The SOFC is suitable for stationary large-scale cogeneration applications (up to 100 MWe) and produces high-temperature heat (600 to 1000°C). The PEM fuel cell is especially suitable for small-scale applications and, with temperature levels of 70 to 150°C, it can be used as micro CHP units for the heating of individual houses.

Micro turbines

In recent years, gas turbine developers have succeeded in making much smaller units (down to about 30 kWe). These micro turbines, as they are known, are just entering commercial use, being particularly suitable for cogeneration in the horticulture and office accommodation sectors. They are attractive in comparison with gas engines because they have low NO_x emissions and need little servicing. They also produce higher-temperature heat. However, micro turbines cannot match the electrical efficiency of gas engines.

Stirling engines

Another 'new' technology used in several micro-CHP projects is the Stirling engine. In fact the concept was developed in 1816, before the Otto internal combustion engine used in cars; it has been described as the 'longest-lasting most-promising technology'. However, the Stirling engine requires high-quality materials, because the principle involves the continuous external heating of a heat exchanger. It is said that, if suitable materials had been available at the time, Stirling engines would power cars today.

The Stirling engine converts a temperature difference across the machine into mechanical power. It works by the repeated heating and cooling of an amount of gas (air, hydrogen or helium). This is accomplished by moving the gas between hot and cold heat exchangers, the hot heat exchanger being a chamber in thermal contact with an external heat source, e.g. a fuel burner, and the cold heat exchanger being a chamber in thermal contact with an external heat sink. Several developers are close to making Stirling engines commercially available for supplying energy (heat and electricity) to individual homes. The electrical efficiency of the Stirling engine is a little more than 10%.

Generators used in cogeneration

A generator converts the mechanical energy of a rotating shaft into electricity. Generators can be either synchronous or asynchronous. A synchronous generator can operate in isolation from the grid and can act as a standby generator continuing to supply power during grid failures.

An asynchronous generator can only operate in parallel with other generators, usually via the grid. The unit will stop if it is disconnected from the grid or if the mains supply fails, so they cannot be operated as standby units. However, connection to, and interfacing with, the grid is simple.

Synchronous generators with outputs below 200 kWe are usually more expensive than asynchronous units because of the additional control, starting and interfacing equipment that is required. In general, at outputs of more than 200 kWe, the cost advantages of asynchronous over synchronous types disappear. There is a trend, however, towards the use of synchronous generators even in cogeneration units with low power outputs.

Costs and benefits

Table 2 shows the cost-benefit balance. Cogeneration is a relatively capital-intensive activity so investment has to be properly assessed and justified. Costs can be quantified relatively easily, but valuing the heat and electricity that will be produced is more difficult. It is not possible to objectively divide the costs between electricity production and heat production, hence the value of the produced heat and electricity is normally calculated on the basis of avoided cost. The value of cogenerated heat is calculated from the cost of producing heat in a boiler and that of the cogenerated electricity is determined from the avoided cost of purchasing electricity or, if the power is supplied to the grid, the cost of centralised electricity production.

Costs	Benefits
Capital	Heat
Operation and maintenance	Electricity
Fuel	- less purchasing
	- sales to the grid

Table 2 – Costs and benefits of cogeneration

The capital cost of a cogeneration unit can generally be broken down as follows:

- Cost of the prime mover
- Cost of the generator
- Cost of the heat recovery equipment
- Cost of installation
- Cost of grid connection.

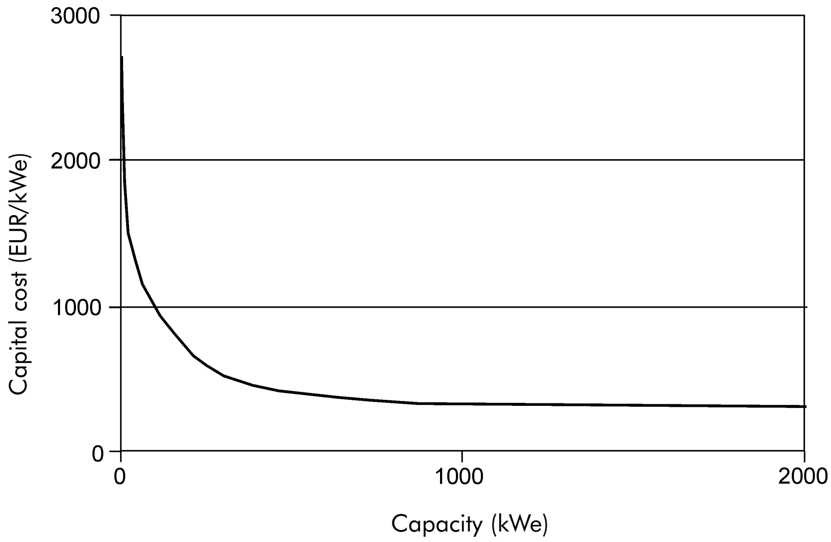


Figure 5 - Specific capital cost of CHP

A general indication of the capital cost per kWe of installed capacity is given in Figure 5. It reflects the specific capital cost of a gas-engine cogeneration unit, including prime mover, generator, heat recovery equipment and grid connection.

Table 3 gives a percentage breakdown of the capital cost of a typical CHP installation by component.

Component	Attributable percentage of overall capital cost
Prime mover + generator	40 - 60%
Heat recovery equipment	15 - 30%
Electrical connection + safety	5 - 15%
Installation	5 - 10%

Table 3 – Capital cost of a typical CHP system by component

In operation, the profitability of a CHP installation depends largely on electricity and gas prices. A CHP installation that is set up to follow the demand for heat does not have much flexibility to respond to changes in the price of electricity. It is not therefore easy to make a CHP plant profitable. Figure 6 shows typical cost breakdowns for different types of cogeneration plant once in operation. Figure 7 shows the other side of the operational balance, the benefits. From the figures it is clear that fuel is the most important cost component, while the values of the electricity and heat production flows are the main components on the benefit side. Once a plant is operating, the only cost component that the owner can influence is the operating and maintenance (O&M) costs.

At present, the cost of operating a CHP plant exceeds the benefit in several EU countries. Subsidisation in recognition of the environmental benefits of these energy-efficient plants is therefore necessary to make CHP projects viable and to prevent a slowdown in the development of CHP.

Policy and regulation

In 1997 the European Commission published 'Strategy to Promote Combined Heat and Power' which set targets for cogeneration in member states. By 2010, cogeneration should account for 18% of all electricity production. The Commission sees the cogeneration of heat and power (CHP) as an important contributor to the realisation of the EU's Kyoto targets. As well as having great energy-saving potential,

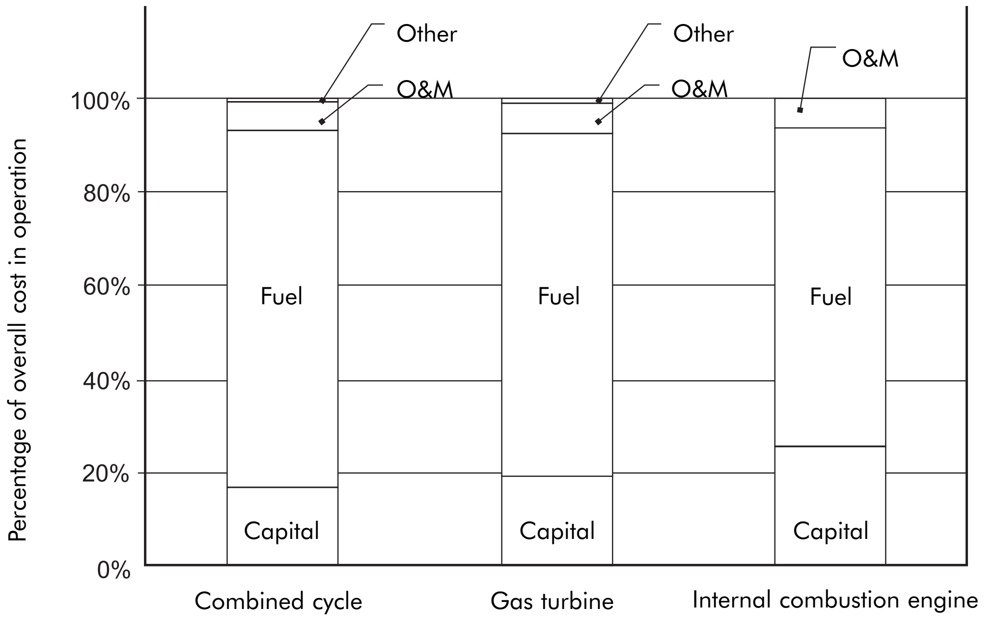


Figure 6 - Cost breakdowns for different types of CHP installation in operation

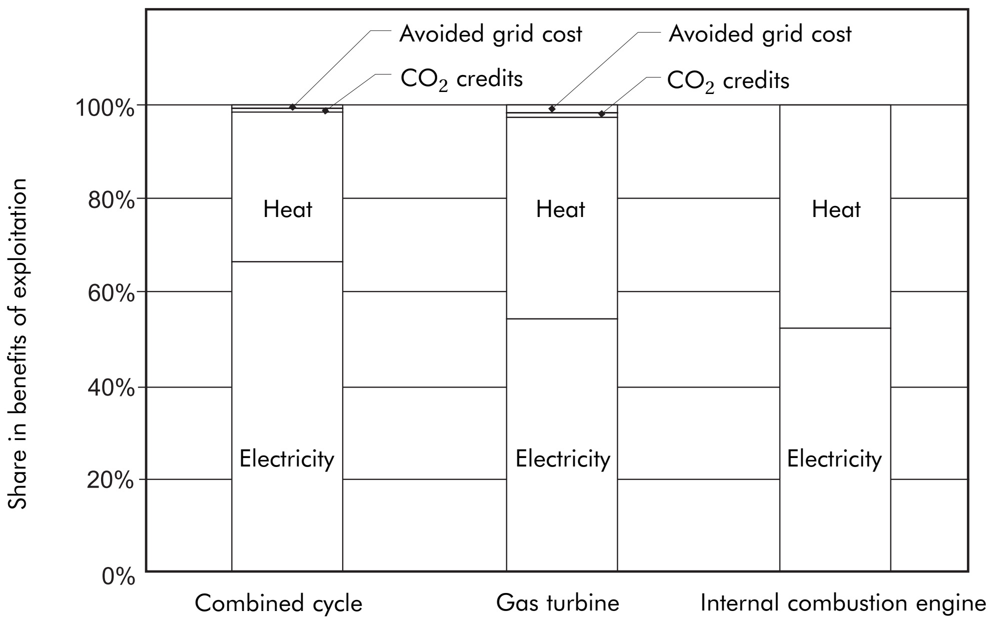


Figure 7 - Benefit breakdowns for different types of CHP installation in operation

CHP can help to avoid network losses, reduce emissions and increase the security of energy supply. According to the Commission, the scope for cogeneration is not being fully utilised and it therefore wants to promote high-efficiency cogeneration based on the useful heat demand. To this end, the EU Directive on the promotion of cogeneration based on a useful heat demand in the internal energy market was published in 2004. The aim of this Directive is as follows:

'The purpose of this Directive is to increase energy efficiency and improve security of supply by creating a framework for promotion and development of high efficiency cogeneration of heat and power based on useful heat demand and primary energy savings in the internal energy market, taking into account the specific national circumstances especially concerning climatic and economic conditions.'

The key features of this Directive, which has to be implemented by the EU member states, are as follows:

- A system of guarantee of origin (certificates) for cogenerated electricity has to be established
- Member states have to analyse the national potential for cogeneration
- Member states have to report every four years on the progress made towards increasing the percentage of energy production accounted for by cogeneration
- Support schemes for cogeneration have to be based on useful heat demand and primary energy savings.

It is expected that the implementation of this Directive will further increase the use of cogeneration in the EU. Environmental and other quality indicators for electricity from CHP units have to be determined and discussions are presently in progress about reference values for comparison with conventional separate heat and electricity production.

Other EU policy developments that are important for the further development of CHP in Europe are:

- The system of emission trading in carbon dioxide (CO_2). Since CHP contributes to a reduction of CO_2 emissions, trade in CO_2 credits can promote the use of CHP.
- The EU's energy policy will place considerable emphasis on energy efficiency in the coming years. This will promote the use of CHP. Two important directives that focus on energy efficiency improvement are:
  - The Energy Performance of Buildings Directive (2002/91/EC). This Directive has to be implemented in EU member states' national legislation by 2006. It calls for harmonised principles for the determination of the energy performance of buildings, minimum requirements for this energy performance and the certification of energy performance. CHP (especially small-scale) can play a role in meeting these requirements.
  - The Directive on Energy End-use Efficiency and Energy Services (2006/32/EC, 5 April 2006). The purpose of the implementation of this Directive is to improve cost-effective energy end-use efficiency in the member states. Use of CHP is mentioned in this Directive as an important measure.
- In 2006, a new EU Directive will be developed for promoting the use of renewable heat (e.g. heat from a biomass CHP unit).

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