CHAPTER 12

Combined Heat and Power

This chapter investigates the subject of combined heat and power (CHP). The general nature of CHP systems is discussed and the economic benefits appraised. In particular, CHP plant sizing strategies are evaluated and example design calculations presented.

12.1 The CHP Concept

From an energy point of view, the generation of electricity in thermal power stations is an extremely wasteful process. Most conventional thermal power stations exhibit efficiencies in the range 30–37% [1], while the newer combined cycle gas turbine stations still only achieve efficiencies in the region of 47% [1]. This means that over 50% of the primary energy consumed in the generation process is wasted and not converted into delivered electricity. This wasted energy is converted to heat which is ultimately rejected to the environment. The generation process also liberates considerable amounts of CO_2 into the atmosphere. It has been calculated that in the UK 0.43 kg of CO_2 is liberated for every 1 kWh of electrical energy delivered (2001 data) [2].

One easy way to appreciate the inefficiency of the electricity generation cycle is to consider the theoretical maximum efficiency of the process. The Carnot principle shows that the theoretical maximum thermal efficiency of any heat engine cycle can be determined by:

$$\eta_{carnot} = 1 - \frac{T_2}{T_1}$$

where T_1 is the maximum temperature available (K), and T_2 is the lowest temperature available (K).

For example, if the maximum temperature in a cycle is 1450 K and the cooling water minimum temperature is 285 K, then the maximum possible efficiency of the cycle is:

$$\eta_{carnot} = 1 - \frac{285}{1450} = 0.803 \text{ (or 80.3\%)}$$

The fact that this level of efficiency is not achieved in practice is due to the high degree of irreversibility in the process. Consequently, the efficiencies achieved in power stations are very much lower than the theoretical Carnot efficiency and are dependent on the type of prime mover used.

The low operating efficiencies achieved during the electricity generation process result in a great amount of energy being lost in the form of waste heat. Given the Earth's dwindling energy resources this is not a very satisfactory arrangement. It would be much better to collect the waste heat from the generation process and use it to heat buildings. By combining the *electrical generation* and *heat production* processes it is possible to produce a highly efficient system which makes good use of primary energy. It is the combination of the *electrical generation* and *heat production* processes which is the basis of the CHP, or *cogeneration*, concept. In a typical CHP installation, heat exchangers are used to reclaim waste heat from exhaust gases and other sources during the electricity generation process. In this way it is possible to achieve overall efficiencies in the region of 80%, if a system is correctly optimized [3].

CHP systems vary in size from large 'power stations' serving whole cities to small micro-CHP units serving individual buildings. The larger CHP systems tend to use gas or steam turbines, while smaller systems generally use internal combustion engines converted to run on natural gas. During the electricity generation process, waste heat is recovered from the exhaust gases, or used steam, and, in the case of micro-CHP systems, also from the engine jacket. Large cogeneration systems often use recovered heat to produce hot water for use in district heating schemes, while micro-CHP systems are generally used to heat single buildings.

CHP schemes enable electricity to be generated locally and eliminate much of the wastage of heat which normally occurs in conventional power plants. Through the use of CHP it is possible to:

- Improve national energy efficiency and preserve non-renewable energy reserves. This is particularly important for nations which have limited fossil fuel resources and which are dependent on imported energy.

- Reduce the cost of transporting electrical energy. The transportation of electricity over long distances involves the construction of expensive transmission networks (consisting of cables, pylons, transformers and switchgear). The need for these is reduced by the use of locally based CHP schemes. Localized CHP schemes also save energy because they avert the need to transport electricity over long distances. There is a 4–8% energy loss during the transportation of electricity over long distances.
- Reduce the amount of atmospheric pollution produced, due to more efficient fuel conversion.

Although CHP has many potential benefits, there are a number of problems associated with it, which have inhibited its widespread use:

- CHP plant requires considerable capital expenditure. This necessitates a full financial appraisal of future energy demands, fuel prices and maintenance costs. Such an appraisal may only be accurate in the short term, with the result that organizations often 'play safe' and rely on conventional systems with which they are familiar.
- There must be a demand for the heat from any proposed CHP plant. Although in most applications it is possible to fully utilize the electricity produced by CHP plant, it is often much more difficult to utilize the heat which is produced. Most building types do not have the all-year-round demand for heat which is required to successfully employ a CHP plant. On the contrary many building types require cooling for large parts of the year.
- Backup plant is often required in CHP installations, in order to ensure security of supply of electricity and heat. This 'backup' plant adds to the capital cost of the installation.

Given the considerable capital expenditure associated with CHP schemes it is essential that any proposed CHP application be carefully evaluated to determine its suitability. It should be remembered with caution that there are many so-called *energy-saving* schemes which have proved to be expensive liabilities.

12.2 CHP System Efficiency

It is possible to illustrate the energy-saving merits of CHP systems by comparing the primary energy consumption of a typical micro-CHP plant with that consumed by a conventional system in which heat is produced in a boiler and electrical power is purchased from a utility company. Example 12.1 presents the energy balance for the two alternative systems.

Example 12.1

A building has an electrical power requirement of 80 kWe (i.e. 80 kW of electrical power) and a heat load of 122 kW. The owners of the building are considering installing a micro-CHP unit which utilizes an internal combustion engine converted to run on natural gas. Compare the primary energy consumption and unit energy costs of the CHP scheme with a conventional separate system.

Data:

Efficiency of the conventional electricity supply process = 35%
Efficiency of conventional boiler plant = 70%
Mechanical efficiency of CHP unit = 32%
Efficiency of CHP electricity generator = 95%
Heat recovery efficiency of CHP unit = 68.16%
Unit cost of gas = 0.9p/kWh
Unit cost of electricity = 5.0p/kWh

Solution

The two options considered are as follows:

Option 1: Conventional system

$$\text{Primary fuel power input to generate electicity} = \frac{80}{0.35} = 228.6 \text{ kW}$$

and

$$\text{Power input to boilers} = \frac{122}{0.70} = 174.3 \text{ kW}$$

Therefore,

$$\text{Total primary power input} = 228.6 + 174.3 = 402.9 \text{ kW}$$

Therefore,

$$\text{Overall system efficiency} = \frac{80 + 122}{402.9} \times 100 = 50.1\%$$

and

$$\text{Energy cost for 1 hour's operation} = \frac{(80 \times 5.0) + (174.3 \times 0.9)}{100} = £5.57$$

Option 2: CHP system

$$\text{Fuel power input to CHP unit} = \frac{80}{0.32 \times 0.95} = 263.2 \text{ kW}$$

The waste heat produced by the CHP unit is passed through a heat exchanger with an efficiency of 68.16%, therefore:

$$\text{Recoverable heat power} = (263.2 \times (1 - 0.32)) \times 0.6816 = 122.0 \text{ kW}$$

Therefore,

$$\text{Overall system efficiency} = \frac{80 + 122}{263.2} \times 100 = 76.7\%$$

and

$$\text{Energy cost for 1 hour's operation} = (263.2 \times 0.9) = £2.37$$

Example 12.1 clearly shows that there are large potential energy cost savings to be gained through utilizing CHP in buildings.

12.3 CHP Systems

CHP systems can range from small 'micro' installations, designed to serve the needs of a single building, to large systems which satisfy the heating and electrical power requirements of whole towns. Micro-CHP systems utilizing internal combustion engines tend to be used in applications where electrical demand does not exceed 1 MWe. Gas turbines are popular on larger installations, while steam turbines are often used on the largest schemes.

12.3.1 Internal Combustion Engines

Internal combustion engines are often used to drive small micro-CHP systems. Mechanical power from this type of engine is used to drive a generator and heat is recovered from the engine exhaust, jacket water and lubricating oil. Micro-CHP units typically operate in the range 15 kWe to 1 MWe electrical output. Modified automotive derived engines are the most widely used systems up to 200 kWe electrical output, whereas more rugged stationary industrial engines are generally used for higher outputs [3]. The automotive engines used are generally modified lorry engines, which are converted to run on gas. These engines usually operate at a much slower and constant speed, typically 1500 rpm, than normal automotive engines. The engine life of a typical CHP prime mover is thus considerably longer than that of a typical automotive engine. Spark ignition gas engines tend to exhibit a heat-to-power ratio around 1.7:1 [3], whereas compression ignition diesel engines have heat-to-power ratios nearer 1:1.

12.3.2 Gas Turbines

Where a natural gas supply is available, gas turbines are often used as the prime mover for larger CHP systems. Gas turbines have a relatively low capital cost and are reliable. The peak-load mechanical efficiency of gas turbines is around 30%, which gives an optimum heat-to-power ratio of around 3:1 [4]. However, under part-load conditions efficiency can be substantially reduced. Gas turbines are usually fuelled by natural gas, but oil and pulverized coal have also been successfully employed.

A typical gas turbine CHP arrangement is shown in Figure 12.1. An air compressor, turbine and generator are mounted on a single shaft, with the turbine being the prime

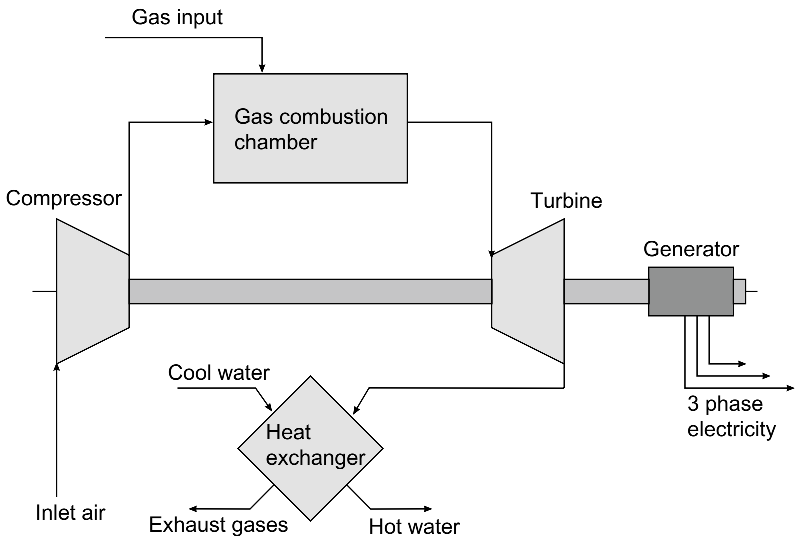

FIG 12.1 Schematic diagram of a gas turbine.

mover. Gas turbines employ an open cycle in which air is drawn into a compressor and compressed to a high pressure before being introduced into a combustion chamber where natural gas is burnt. On leaving the combustion chamber the pressurized combustion gases are forced at temperatures between 900°C and 1200°C [4] through a turbine, which in turn rotates a generator. On exiting the turbine, the hot combustion gases, at 450–550°C [4], pass through a heat exchanger to recover the waste heat.

12.3.3 Steam Turbines

Steam turbines are often used as the prime mover in larger CHP installations. Steam turbines can employ open or closed cycles, depending on whether or not the steam itself is used as the site-heating medium. In the closed system, high-pressure steam from a boiler is forced through a turbine, which in turn rotates a generator. Heat is then recovered from the steam by passing it through a condenser on its way back to the boiler. In open cycle systems the steam exiting the turbine is used directly to meet site-energy needs. The power produced by the steam turbine is therefore dependent on the extent to which the steam pressure is reduced through the turbine. The simplest open cycle arrangement is the *back-pressure* system, which employs a pressure regulator after the turbine, so that the steam is exhausted at the pressure required by the site. As the exhaust steam pressure is raised, so the temperature and heat output increase. However, this increase in heat output is at the expense of the power output, which reduces. By regulating the exhaust steam pressure it is possible to control the heat-to-power ratio of the CHP plant thus creating a very flexible system. Lower steam pressures can be used in the summer when less heat is required, resulting in higher electricity generating efficiencies. In winter when higher temperatures are required, steam pressure can be raised. Consequently, the heat-to-power ratio of steam turbine CHP schemes can be variable, ranging from 3:1 to as much as 12:1 [4].

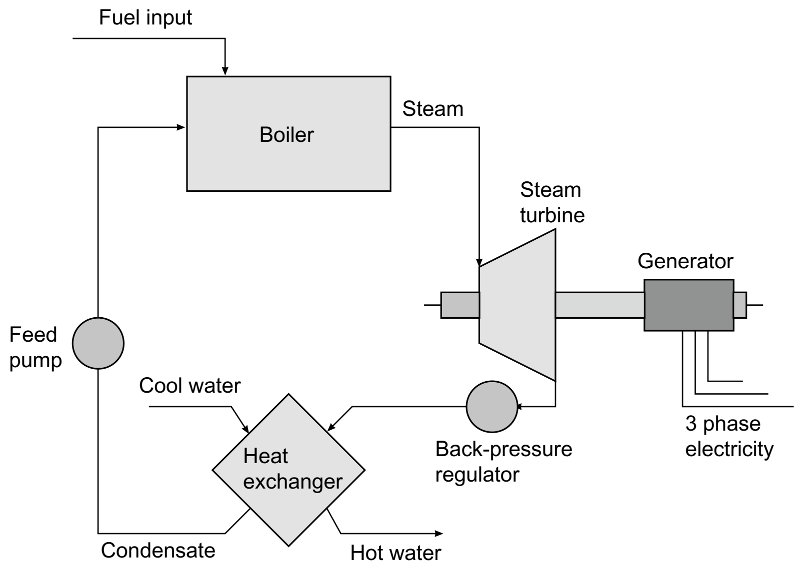

FIG 12.2 Schematic diagram of *back-pressure* steam turbine CHP system.

They are therefore best suited to schemes in which there is a high all-year-round heat requirement. A typical *back-pressure* steam turbine CHP arrangement is shown in Figure 12.2.

Because a boiler is employed to produce the steam to drive a turbine, a wide variety of fuels can be used, including refuse. Therefore, steam turbines are a good solution for *waste-to-energy* CHP schemes in which refuse is incinerated and the heat used to produce steam. In Scandinavia it is common practice to burn the waste products from the timber industry to produce steam in CHP schemes.

12.4 Micro-CHP Systems

Stand-alone micro-CHP units are a popular solution for many small- and medium-sized commercial applications. Micro-CHP units use an internal combustion engine as a prime mover and generally comprise an engine, an electricity generator, a heat recovery system, an exhaust and a control system (as shown in Figure 12.3).

In a micro-CHP system, optimum efficiency is achieved by maximizing the heat recovered from the engine and exhaust gases. In theory as much as 90% of the heat produced by the generation process can be recovered. Achieving this level of heat recovery requires the use of several heat exchangers, which makes the capital cost high. It is therefore more typical to recover around 50% of the fuel input as useful high-grade heat, with a further 10% recovered as low-grade heat [3]. The high-grade heat can be used to provide heating water in the region of 70–90°C and the low-grade heat to provide water at 30–40°C [3]. Most of the heat is recovered from the engine jacket, which has a temperature of approximately 120°C, while the rest is recovered from the

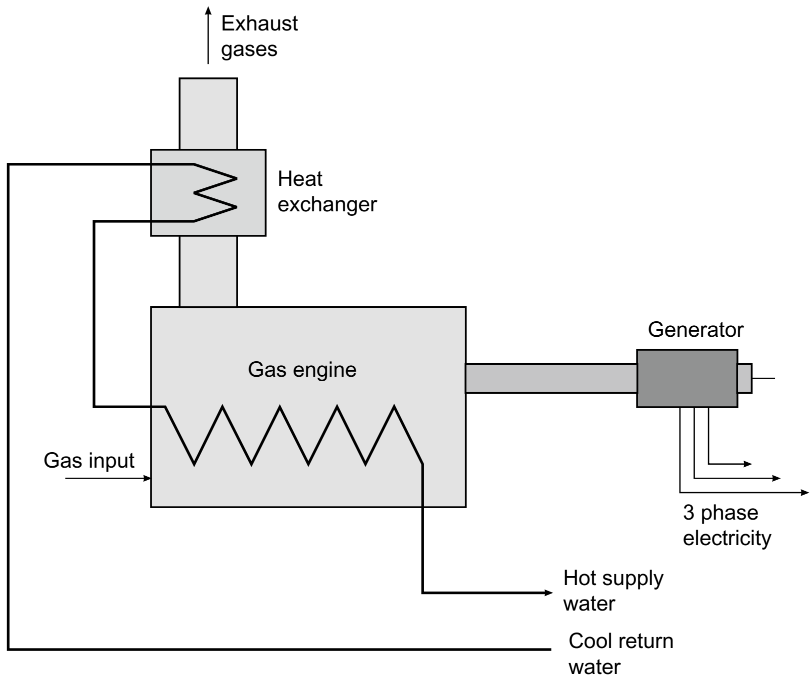

FIG 12.3 Schematic diagram of a micro-CHP unit.

exhaust gases, which can be at 650°C [4]. Both sensible and latent heat can be recovered from the exhaust gases.

Although most micro-CHP units provide low temperature hot water (LTHW) in the region 70–80°C, it is equally possible to provide medium temperature hot water (MTHW) (i.e. 90–120°C).

However, because of the higher water temperatures involved, heat recovery is reduced. Conversely, it is possible to increase heat recovery, and therefore the efficiency of a micro-CHP system, by reducing the hot water supply temperature to below 70°C. As most micro-CHP systems are required to produce domestic hot water (DHW), which must be stored at above 60°C to prevent the growth of *Legionella* spp., in practice the flow water temperature should be 70°C or above.

Micro-CHP units are often used in conjunction with boilers. In such systems the CHP unit should satisfy the base heating load, with the boilers only being used during periods of peak demand. This necessitates coupling the micro-CHP unit to the boilers, so that the two can work effectively together. In existing installations, where a CHP unit is replacing some old boilers, it is common practice to connect the CHP unit and boilers in series as this causes minimum interference to existing systems. In new installations, CHP units are often connected in parallel with boilers. Figure 12.4 illustrates both arrangements. No matter which arrangement, it is essential that the CHP unit operates as the lead 'boiler', as this maximizes its operating hours.

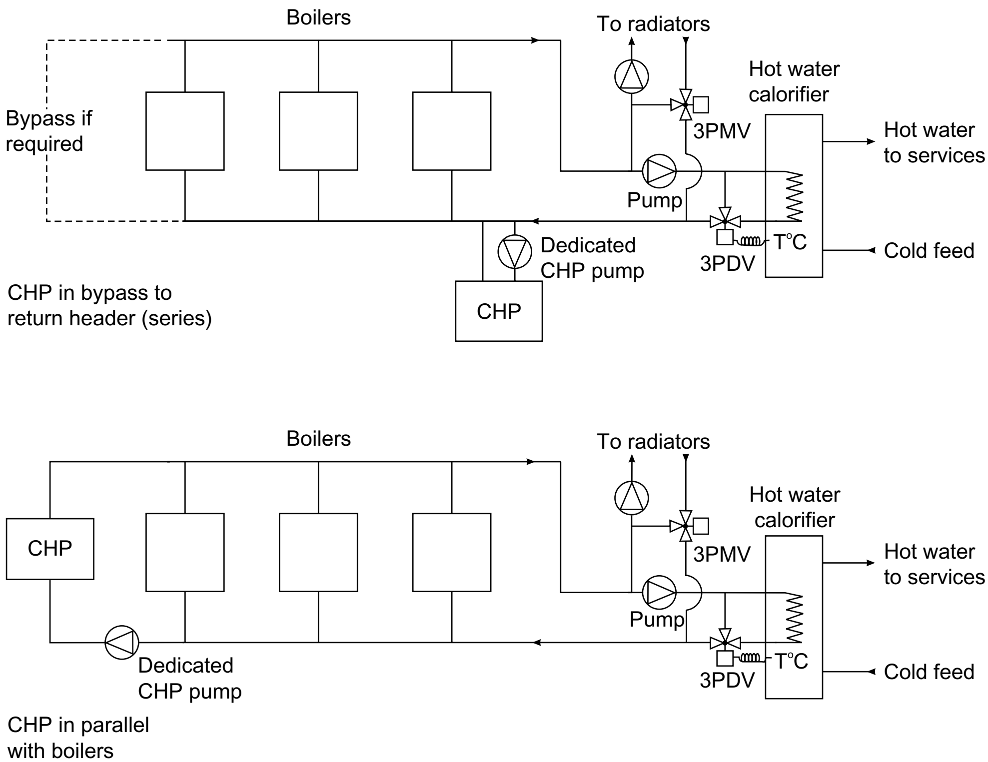

FIG 12.4 CHP piping arrangement. Crown copyright: reproduced with the permission of the Controller of Her Majesty's Stationery Office and the Queen's Printer for Scotland [3].

Many micro-CHP units incorporate a continuous monitoring facility as part of their control system. This enables building heat and power requirements to be monitored so that optimum performance of the plant is achieved. It also enables the system to be audited, so that the return on the capital investment can be calculated.

12.5 District Heating Schemes

Many larger CHP units are coupled to district heating schemes in which the pipework and pumping costs are dominant. In such schemes it is important to minimize both pipe diameters and water flow rates, by operating at a peak-flow water temperature of approximately 120°C, with a return water temperature of 70°C. This reduces both capital and operating costs. It is also common practice to vary supply water temperature with ambient air temperature so that system heat losses are minimized.

If LTHW is required in individual buildings on a district heating scheme, this can be achieved by installing remote heat exchangers in each building. This maintains hydraulic separation between the district heating water and the LTHW and makes the overall system safe and flexible. In Europe, variable temperature district heating schemes with heat exchangers are very popular.

12.6 CHP Applications

CHP systems are considered to be efficient users of primary energy because the waste heat produced by the generation process is utilized to satisfy heating requirements. If 'waste' heat cannot be utilized effectively, overall efficiency will drop dramatically. In simple terms, there is no point in installing a CHP system in an application which does not have an all-year-round demand for heat. CHP systems are therefore suitable for buildings such as leisure centres, swimming pools, hotels, hospitals and residential establishments, all of which have extensive DHW requirements for most or all of the year. Office buildings are generally thought to be unsuitable, since they frequently have a cooling load for much of the year and are only open during the day time. However, if the heat from a CHP unit is used to drive absorption refrigeration plant, then CHP can become a feasible option for office buildings.

Although the operational costs associated with CHP systems are low, the capital costs are high. It is therefore desirable to run a CHP unit for as long as possible in order to achieve the greatest return on the initial capital investment. It has been calculated that in order to achieve a simple payback of 3–4 years it is necessary to operate a CHP unit between 4500 and 6000 hours per year [3], which is equivalent to approximately 12.3–16.5 hours of operation for each day of the year. It is much better to undersize a CHP unit than to oversize it, since this will ensure that the unit runs continuously when in operation, with any shortfall in output being made up by backup boilers and bought-in electricity. It is therefore common practice to use the CHP unit to satisfy base heat load requirements. Ideally a CHP unit should be able to supply the entire summer heat load and a proportion of the winter load. Although it may be relatively small (possibly with a rated output of only 33–50% of the peak heating demand), it is possible to supply 60–90% of a building's annual heat requirement with a CHP unit because it supplies the base heat load.

In certain situations, where a CHP unit generates more electricity than can be consumed on site, it is possible to export power to the local utility company. This depends on the willingness of the utility company to purchase the electricity. It also requires the installation of an export meter. Therefore, for small-scale CHP installations it is not generally considered economic to export electricity. Micro-CHP units should therefore be sized so as not to exceed the base electrical load.

It is possible to use a CHP unit as a standby generator if so required. If used in this way its size will be governed by the required peak emergency electrical load. For normal operation it will be necessary to modulate down the output to match the reduced heat and power requirements, with the result that efficiency will be compromised. In such circumstances it may be more economical to install two smaller CHP units.

12.7 Operating and Capital Costs

The capital and installation costs of CHP plant can be significantly higher than those for conventional boiler plant. One significant cost which can easily be overlooked is the requirement of CHP systems to be synchronized in parallel with the local utility

TABLE 12.1 CHP installation and maintenance costs (1996 data) [5]

CHP engine size (kWe)	Installed capital cost (£/kWe)	Maintenance cost (p/kWhe)
45	1230	1.04
54	1170	1.02
90	1020	0.98
110	960	0.95
167	810	0.89
210	730	0.85
300	660	0.79
384	605	0.73
600	520	0.62

company's distribution grid, so that the grid and the CHP unit can work together to meet peak-site electrical demand. This involves the installation of expensive electrical switching equipment. In contrast to the capital costs, the operating costs associated with CHP are relatively low and comprise the fuel and maintenance costs. For micro-CHP units maintenance costs are generally in the range of 0.5–2.0p per kWhe of electricity generated [3], with the maintenance cost reducing for larger systems. Typical capital and maintenance costs for various-sized CHP units are shown in Table 12.1.

12.8 CHP Plant Sizing Strategies

In order to correctly size a CHP installation it is important to obtain as much accurate energy data as possible for the given application. Ideally these data should include:

- Monthly electricity and heat energy consumption data in kWh.
- Base- and peak-load demands (in kW) for both electricity and heat.
- The operational characteristics of the particular application.
- Unit cost data for electricity and gas (or oil).

Because it is important not to oversize a CHP plant it is advisable to undertake all the possible no-cost and low-cost energy efficiency measures before sizing the plant. This will avoid the CHP unit being oversized and should reduce the capital cost of the installation.

When determining the size of a CHP unit the most commonly used approach is to size the unit to meet the base heating load, as shown in Figure 12.5. This ensures that the CHP unit can run all year round, thus guaranteeing that the payback period on the initial capital investment is short. Backup boilers can then be used to meet the peak-load heating requirements. A CHP unit sized in this way usually generates less electricity than is required to meet the base electrical demand and therefore additional electrical energy must be purchased all year round from the local utility company. An alternative

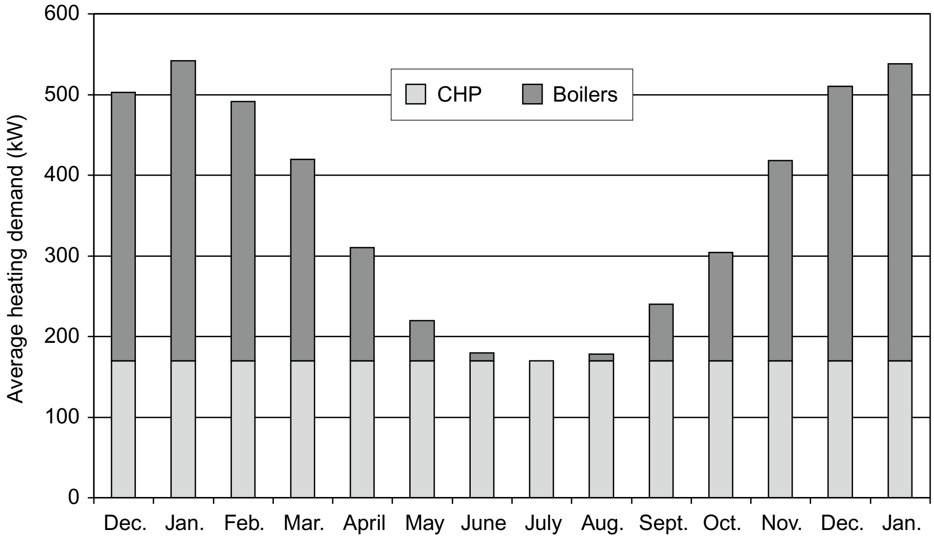

FIG 12.5 Base heat load sizing strategy for CHP plant.

approach is to size the CHP unit to meet the electrical base load. This usually means that for part of the year heat will have to be dumped because the heat produced by the CHP unit will exceed the base-load requirement. However, despite the dumping of heat this can be the most economic solution, since the unit cost of electricity can be as much as five times that of a unit of heat.

12.9 The Economics of CHP

For most of the small-scale CHP applications three factors dominate economic viability. These are:

- The capital cost of the installation.
- The potential number of operating hours per year.
- The relative costs of 'bought-in' electricity and gas (or fuel oil).

If any of these three variables are not favourable, then a particular CHP scheme may become non-viable. Given that fuel prices can be unstable, the last point is of particular importance. For example, if the unit cost of mains electricity should fall or the cost of gas rise, there will come a point when a particular CHP unit ceases to be economically viable. Other lesser factors which may influence the economic performance of a CHP scheme are:

- The heat-to-power ratio of the particular CHP plant.
- The difference in maintenance costs between a CHP scheme and a conventional scheme.
- The cost of having mains electricity as a backup system in case of breakdown or maintenance.

Given these costs, it is important to undertake a full economic appraisal of any proposed CHP scheme. Example 12.2 illustrates how a simple appraisal might be undertaken.

Example 12.2

An existing hotel building has an average electrical demand of 80 kWe and an average combined heating and hot water demand of 180 kW. The average annual load factor for the building is 0.75. The heating and hot water demand is currently served by two gas-fired boilers and mains electricity is bought in. It is proposed to install a micro-CHP plant which will run on gas and have a heat-to-power ratio of 1.7:1. The existing boilers will supplement the heat output from the CHP unit. If the initial cost of the CHP installation is £76,000, determine the simple payback period.

Data:

Efficiency of existing boilers = 70%
CHP unit electric power output = 80 kWe
CHP unit gas power input = 286 kW
Unit price of electricity = 5.0p/kWh
Unit price of gas = 0.9p/kWh
Existing plant maintenance cost = £1000 per year
CHP scheme maintenance cost = £5000 per year

Solution

$$\begin{aligned}\text{Annual operating hours} &= \text{load factor} \times \text{total hours per year}\\ &= 0.75 \times 8760 = 6570 \text{ hours}\end{aligned}$$

Considering the present scheme:

$$\text{Electricity cost} = \frac{80 \times 6570 \times 5.0}{100} = £26,28.00$$
$$\text{Gas cost} = \frac{180 \times 6570 \times 0.9}{0.7 \times 100} = £15,204.86$$

and

$$\text{Maintenance cost} = £1000.00$$

Therefore,

$$\begin{aligned}\text{Annual cost} &= 26,280.00 + 15,204.86 + 1000.00\\ &= £42,484.86\end{aligned}$$

Considering the proposed CHP scheme:

$$\text{The average shortfall in CHP heat production} = 180 - (80 \times 1.7) = 44 \text{ kW}$$

Therefore,

$$\text{Annual CHP unit fuel cost} = \frac{286 \times 6570 \times 0.9}{100} = £16,911.18$$
$$\text{Annual boiler fuel cost} = \frac{44 \times 6570 \times 0.9}{0.7 \times 100} = £3,716.74$$

and

$$\text{Maintenance cost} = £5000.00$$

Therefore,

$$\text{Annual operating cost} = 16,911.18 + 3716.74 + 5000.00 = £25,627.92.$$

Now

$$\text{Payback} = \frac{\text{Capital cost}}{\text{Annual cost saving}}$$

Therefore,

$$\text{Payback} = \frac{76,000}{(42,484.86 - 25,627.92)} = 4.51\ \text{years}$$

While the analysis undertaken in Example 12.2 gives some indication of the economic viability of a CHP scheme, the method used is simplistic and has a number of inherent weaknesses. It assumes that the electrical and heating demands are constant at 80 kWe and 180 kW respectively. In reality this will not be the case. For long periods during the year demand will be higher than this, while at other times it will be lower. This means that during periods of high electrical demand (i.e. when the electrical demand exceeds 80 kWe), electricity will have to be purchased from the local utility company. However, during periods of low demand the CHP unit will be producing electricity and heat which cannot be utilized. As a result the analysis overestimates the potential cost savings achievable through using CHP.

A more sophisticated approach which overcomes some of the shortfalls described above is illustrated in Example 12.3.

Example 12.3

A new sports centre is to be built which will have a predicted annual heat load of 2,600,000 kWh and an annual electrical load of 830,000 kWhe. The peak winter heating and hot water demand is predicted to be 1000 kW and the base heat demand is 350 kW. The base electrical demand is 130 kWe. The sports centre plant will operate for 5130 hours per year. Given the following data, appraise the financial viability of three proposed schemes:

(a) Conventional scheme in which boilers produce all the heat, and electricity is purchased from a utility company.
(b) A CHP scheme in which the CHP plant is sized to meet the base electrical load.
(c) A CHP scheme in which the CHP plant is sized to meet the base heat load.

Data:

Efficiency of boilers = 70%
Mechanical efficiency of CHP unit = 30%
Efficiency of CHP electricity generator = 95%

Heat recovery efficiency of CHP unit = 70%
Unit cost of gas = 0.9p/kWh
Unit cost of electricity = 5.0p/kWh
Cost of maintaining boilers = 0.1p/kWh
CHP scheme maintenance cost = 0.9p/kWhe
Capital cost of boiler only scheme = £26.50 per kW
Capital cost of CHP scheme =£900 per kWe

Solution

(a) *Considering the conventional scheme*:

$$\text{Electricity cost} = \frac{830{,}000 \times 5.0}{100} = £41{,}500.00$$

$$\text{Gas cost} = \frac{2{,}600{,}000 \times 0.9}{0.7 \times 100} = £33{,}428.57$$

and

$$\text{Maintenance cost} = \frac{2{,}600{,}000 \times 0.1}{100} = £2600.00$$

Therefore

$$\text{Annual cost} = 41{,}500.00 + 33{,}428.57 + 2600.00 = £77{,}528.57$$

and

$$\text{Capital cost} = 26.50 \times 1000 = £26{,}500.00$$

(b) *Considering the CHP scheme, sized to meet the base electrical load*:

$$\text{Fuel power input to CHP unit} = \frac{130}{0.3 \times 0.95} = 456.14 \text{ kW}$$

The waste heat produced by the CHP unit is passed through a heat exchanger with an efficiency of 70%, therefore:

$$\text{Recoverable heat power} = (456.14 \times (1 - 0.3)) \times 0.70 = 223.51 \text{ kW}$$

Therefore,

$$\text{Annual electricity produced by CHP unit} = 130 \times 5130 = 666{,}900 \text{ kWhe}$$

and

$$\text{Annual heat produced by CHP unit} = 223.51 \times 5130 = 1{,}146{,}606.3 \text{ kWh}$$

Therefore,

$$\text{Annual CHP unit fuel cost} = \frac{454.14 \times 5130 \times 0.9}{100} = £21{,}059.98$$

$$\text{Annual boiler fuel cost} = \frac{(2{,}600{,}000 - 1{,}146{,}606.3) \times 0.9}{0.7 \times 100} = £18{,}686.49$$

$$\text{Annual cost of electricity purchased } \frac{(830{,}000 - 666{,}900) \times 5.0}{100} = £8155.00$$

and

$$\text{Maintenance cost} = \frac{0.9 \times 666{,}900}{100} = £6002.10$$

Therefore,

$$\begin{aligned}\text{Annual operating cost} &= 21{,}059.98 + 18{,}686.49 + 8155.00 + 6002.10\\ &= £53{,}903.57\end{aligned}$$

and

$$\text{Capital cost of CHP scheme} = 900.00 \times 130 = £117{,}000.00$$

Therefore,

$$\begin{aligned}\text{Increased capital expenditure compared with scheme (a)} &= 117{,}000.00 - 26{,}500.00\\ &= £90{,}500.00\end{aligned}$$

and

$$\begin{aligned}\text{Annual operating cost saving (compared with scheme (a))} &= 77{,}528.57 - 53{,}903.57\\ &= £23{,}625.00\end{aligned}$$

Therefore,

$$\text{Payback on increased capital expenditure} = \frac{90{,}500.00}{23{,}625.00} = 3.8 \text{ years}$$

(c) *Considering the CHP scheme, sized to meet the base heat load*:

$$\text{Heat produced for each kWe of electrical power generated} = \frac{223.51}{130} = 1.719$$

Therefore, the heat-to-power ratio of the CHP unit is 1.719:1. Assuming that the CHP unit is sized to meet the base heat load of 350 kW, then:

$$\text{Electrical power output from CHP unit} = \frac{350}{1.719} = 203.61\,\text{kW}$$

Unfortunately, since the average electrical demand of the building is only 161.79 kWe, the CHP unit produces more electricity than can be consumed by the building.

Unless the electricity can be exported to the local utility company, the CHP unit will either have to be reduced in size, or else its output will have to be modulated down considerably.

If it is assumed that electricity can be exported at, say, 3.0p/kWhe, then:

$$\text{Annual revenue generated through exporting electricity} = \frac{(203.61 - 161.79) \times 5130 \times 3.0}{100} = £6436.10$$

and

$$\text{Annual heat produced by CHP unit} = 350 \times 5130 = 1,795,500 \text{ kWh}$$
$$\text{Annual electricity produced by CHP unit} = 161.79 \times 5130 = 830,000 \text{ kWhe}$$

NB: The CHP unit provides all the electricity for the building.

$$\text{Fuel power input to CHP unit} = \frac{203.61}{0.3 \times 0.95} = 714.42 \text{ kW}$$

Therefore,

$$\text{Annual CHP unit fuel cost} = \frac{714.42 \times 5130 \times 0.9}{100} = £32,984.77$$
$$\text{Annual boiler fuel cost} = \frac{(2,600,000 - 1,795,500) \times 0.9}{0.7 \times 100} = £10,343.57$$

and

$$\text{Maintenance cost} = \frac{0.9 \times (203.61 \times 5130)}{100} = £9400.67$$

Therefore,

$$\text{Annual operating cost} = 32,984.77 + 10,343.57 + 9400.67 - 6436.10 = £46,292.91$$

and

$$\text{Capital cost of CHP scheme} = 900.00 \times 203.61 = £183,249.00$$

Therefore,

$$\text{Increased capital expenditure (compared with scheme (a))} = 183,249.00 - 26,500.00 = £156,749.00$$

and

$$\text{Annual operating cost saving (compared with scheme (a))} = 77,528.57 - 46,292.91 = £31,235.66$$

Therefore,

$$\text{Payback on increased capital expenditure} = \frac{156,749.00}{31,235.66} = 5.02 \text{ years}$$

Example 12.3 clearly demonstrates that both CHP schemes achieve substantial cost savings compared with the conventional scheme (a). However, it should be noted that although scheme (c), sized to meet the base heat load, produces the greatest annual cost savings, scheme (b) appears to be the more cost-effective of the two proposals. This is because:

- The capital cost of scheme (c) is much higher than that of scheme (b).
- Much of the electricity produced under scheme (c) is underutilized (i.e. exported for a relatively low return).

Example 12.3 therefore reinforces the conclusion that it is unwise to oversize a CHP plant and confirms that it is preferable to size the CHP plant to meet the electrical base load.

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