Chapter 2
Non-renewable Distributed Generation Technologies: A Review

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2.1 Introduction

Distributed generation (DG) is an integration of small-scale renewable and non-renewable technologies into a conventional distribution system for the purpose of supplying electrical power at or near the consumer' load points. The DG technologies include diesel reciprocating engines, gas reciprocating engine, gas turbine, wind turbine, photovoltaic system, fuel cell, micro hydro and mini hydro can provide a grid-connected and a stand-alone power solution. The integration of the DG units in a power system offers a lot of technical, economic and environmental benefits. This section will only capture the reciprocating engine which is one of the common DG technologies in the world. The reciprocating engines are highly flexible and suitable for several applications, among which are electric power generation, combined heat and power generation (CHP) and mechanical prime

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movers for many equipment and propulsion. The reciprocating technologies can operate as a stand-alone to meet the power demands of consumers in remote locations or grid-connected power system, where it can feed the surplus to the grid having met the power requirements of the local consumers [1]. The reciprocating engines have been universally accepted by the power utilities as one of the DG units that can be effectively utilized to increase the reliability of a power system because they can be built, commissioned and become operational faster than other conventional DG technologies owing to their modular sizes and cost-effectiveness. The available statistical data have established that over $170 billion was invested on the reciprocating engines and other DG technologies in 2015. In the same year, around 142 GW of the DG technologies for power generation were installed globally. The DG capacity for power generation is projected to increase to 200 GW in 2020 with the installation of additional 58 GW. This represents an annual growth rate of 4.4%. The total investment in the DG technologies is also expected to increase from $170 to $206 in 2020 while the global electricity consumption will also increase from 20.8 to 26.9 TWh with an annual growth rate of 3.3% [2]. This target can only be met by encouraging utilization of the reciprocating engines despite of their short comings. The commercial production of reciprocating engines has improved the economic activities of many countries.

The reciprocating engines have played many crucial roles in the major sectors of the economy due to their fuel economy, sturdiness, reliability and rigidity. The benefits of using the reciprocating engines have been limited owing to the greenhouse gas emission which is one of the sources of the global warming, acid rain and ozone depletion [3]. The power generation from the reciprocating power units represents about 10–15% of the world power demand and have the capacity to supply 22.8% of the global electricity demand. The global acceptance of the reciprocating engine for over a decade is due to its high efficiency, durability and reliability of the engines that have been improved by the introduction of several technologies [4]. This has made the reciprocating engines to offer a very-low capital cost and can run on multiple fuels, such as light fuel oil, heavy fuel oil, biofuels, natural gas and crude oil [5]. The reciprocating engines are piston-driven internal combustion engines that use a number of reciprocating pistons to convert pressure into a rotating motion. This will cause the crankshaft of the engine to be turned by moving the pistons up and down in a cylinder. The reciprocating engines can be classified into the spark-ignition (SI) engine and the compression-ignition (CI) engine based on the methods of ignition [6]. The SI engine uses the spark plug to initiate the combustion process and a CI engine utilizes the heat of compression to initiate ignition of the fuel that has been injected into the combustion chamber of the engine. The reciprocating engines are more efficient than other non-renewable DG technologies but are prone to production of harmful gas emissions and dirty particles that have been a source of concern by the public, i.e. nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon dioxide (CO_2), carbon monoxide (CO) and particulate matter (PM). The statistical data has shown that over 70% of the global fuel consumed by the reciprocating engines is used for transportation. The quantity of gas emissions from the reciprocating engines will continue to increase if proper measures are not taking. The greenhouse gas emissions from the reciprocating engines can be reduced to legally acceptable levels with more effective environmental technologies and research activities [7, 8]. The efficiencies of the reciprocating engines can be improved to above 80% via CHP as well as the fuel consumption regulations. The maintenance costs of the reciprocating engines are higher than renewable DG technologies because of the complex nature of the engines and numerous parts of the engines [5].

In addition to this, the reciprocating engines are commercially available and widely used as prime movers for automobile and industrial equipment, combined heat and power (CHP) and power generation applications such as backup, peak shaving, standby/emergency and a grid support for critical power requirements of many organizations [4]. Due to the fuel flexibility and compact sizes of the reciprocating engines, they can be used to supply remote locations that are not connected to the grid or being used by the power utility as mobile emergency or standby power units. The utilization of the diesel engines should be encouraged in a situation where natural gas is not available or very expensive. The operations of diesel engines have been limited in some countries due to greenhouse gas emissions and the framework set up by some environmental protection regulatory bodies [4]. This section shall give a detailed description of the reciprocating engines and their operating characteristics such as technologies, efficiency, operation and maintenance costs, type of fuels and emissions.

2.1.1 Technology Description of the Reciprocating Engines

The reciprocating engines produce electrical and mechanical power for many domestic, commercial and industrial applications. The high efficiency and fuel flexibility coupled with an economic CHP option have made the reciprocating engines to be one of the widely used engines in the world. In addition to this, the reciprocation engine has the following performance characteristics, i.e. quick start-up, high availability, high reliability, low capital cost and low operating costs. The medium-speed, low-speed and high-speed reciprocating engines can be used as the grid support, base load and emergency power applications. They can also be used for the DG in some small towns and villages that are not tied to the utility power networks due to some technical and financial barriers [9]. They can be used as prime movers for automobiles, industrial equipment, ship propulsion and numerous machinery and equipment. The reciprocating engines are well-known technologies that have been accepted due to the characteristics presented in Table 2.1.

Table 2.1 Operation characteristics [4, 5]

Operation characteristics	Description
• Long life	Provided many years of optimal operations
• Quick start-up	Easy and quick to start-up for provision of electrical power for peaking and emergency power applications
• Availability	Reciprocating engines have excellent availability
• Reliable	Highly reliable
• Black-start capability	Reciprocating engines can start with battery in event of power outage
• Economical size range	Available in various sizes based on the power demand by consumers

Table 2.2 Technical, economic and benefits of the reciprocating engines [49–56]

Technical benefits			Economic benefits
Reliability	Security	Operational advantages	Low installation cost Moderate capital costs Reduced ancillary costs Lower capital cost per kW of capacity
Enhanced reliability of a power system. Minimized capacity release of a power system Enhanced generation diversity of a power system	Improved security of the critical loads in a power system No intermittent energy resource Improved security of the power supplied by the utilities. Long life span	Increased productivity Easy O&M Improved total efficiency Utilized small size of land for installation Simple operation High efficiency	

2.1.1.1 Comparative Analysis of the Reciprocating Engines

The reciprocating engines can be compared with other non-renewable energy by using some notable benchmarks that are applicable in the power systems. These characteristics are presented in Tables 2.2, 2.3 and 2.4.

2.1.1.2 Applications of the Reciprocating Engines

The reciprocating engines can be used for multiple applications such as power generation and prime movers to drive many industrial equipment and machinery.

Table 2.3 Comparative analysis of non-renewable technologies [23, 37, 57–59]

Non-renewable DG technologies				
DG technologies	Steam turbines	Reciprocating engines	Gas turbines	Microturbines
Capacity range	Any	Gas: 50 kW–5 MW Diesel: 20 kW–10 MW	1–20 MW	30–250 kW
Efficiency (%)	30–42	Gas: 28–42 Diesel: 36–43	21–40	25–30
Fuel	Coal, natural gas, oil and biogas	Diesel, gasoline, natural gas, LPG and biogas	Natural gas, heavy oil, LPG, LNG, crude oil, coal gas and ethanol	Natural gas, biogas, hydrogen, diesel, propane, LPG, kerosene, vegetable oil and CNG
Availability (%)	Near 100	Diesel: 90–95 Gas: 92–97	90–98	90–98
CO_2 emission (g/kWh)		Diesel: 650 Gas: 500–620	580–680	720
CO emission (g/kWh)		Diesel: 2.8 Gas: 1.8	0.42	0.47
Life time (year)	25	20	20	10
SO_2 emission (g/kWh)		Diesel: 0.032 Gas: 1.25	0.032	0.037
NO_x emission (g/kWh)	0.82	Diesel: 10 Gas: 0.2–1	0.3–0.5	0.1
Installation cost/kW (US$/kW)	800–1000	Diesel: 125–300 Gas: 250–600	300–600	500–750
O&M cost (US$/MWh)	4	Diesel: 5–10 Gas: 7–15	3–8	5–10

These engines are manufactured in the large quantity because of the following features: high start-up, highly reliable moderate fuel cost and moderate capital costs. The maintenance and operating costs, capital costs and fuel costs of reciprocating engines are very high when compared with the renewable DG technologies. The DG potential of the reciprocating engines in a conventional distribution power system includes peak shaving, standby and grid support. The reciprocating engines can also be used as prime movers for many equipment such as pumps, compressors, train, ship and vehicle. In addition to this, the waste heat from the reciprocating engines' exhausts can be recovered and converted to hot water and steam through the heat exchanger [4, 5].

Table 2.4 Advantages and disadvantages of the reciprocating engines

Advantages	Disadvantages
• High reliability and more rugged • Longer life spans • Modularity • Diversity of use • It does not occupy much space • High efficiency • High capacity factor • High availability • Lower lead times to construct • Easier to install • Flexibility to upgrade the plant • Short start-up times • Black-start capability • Multi-fuel capability • Low investment cost	• Long payback time • High emissions • High vibrations in reciprocating engines • Relatively high maintenance cost • Frequent maintenance intervals • Relatively dependency of fossil fuels • Cold start difficulty • Higher noise

Standby Power

The standby power generating unit is an independent electric power source that provides electric power supply to some loads in an event of power failure or outage from the utility so that consumers' facilities will continue to operate satisfactorily based on the specifications of the manufacturers [10]. The reciprocating engines are installed in a conventional distribution system to act as standby units, so that the power supply will be restored back into the power system automatically or manually in the event of power interruption from the utilities. The standby power units are installed in the public, commercial and residential buildings to provide an alternate source of power so that certain critical devices and equipment will be allowed to operate effectively during a power outage. The failure of these equipments would expose the health and safety of the personnel in the buildings or facilities to perpetual risk. The reciprocating engines are usually preferred because of quicker start-up, low capital cost and low installation costs. Due to a short duration of using reciprocating engines as standby units in a power system, some key performance indicators such as emissions, capital costs, efficiency and operation and maintenance costs are not likely to be prioritized. The reciprocating engines are the most popular choice for power generation due to the low cost of installation when compared to other types of DG technologies and short starting time. The reciprocating engines can also run on diesel as well as natural gas through a dual fuel configuration [4, 5].

Peak Shaving

The reciprocating engines are utilized by various consumers to supply electrical power into their facilities during the peak periods. The peak shaving generating units are owned by the electricity consumers, rather than by the utility. The reciprocating engines can be used for peak shaving application because of portable size, low capital cost, modular size, quick start-up and high reliability characteristics. The integration of reciprocating engines into a conventional power system for peak shaving applications has a lot of benefits for the consumers that have poor load factors. The economic operation of the reciprocating engines for peak shaving is high, if they can be combined with other functions such as standby and CHP. The benefits are summarized as follows:

- deferred investment on generation, transmission and distribution facilities,
- increased reliability,
- improved power quality,
- avoided ancillary service costs and reduced load shedding, and
- reduce the operational cost of power generating units.

Grid Support

The grid support plants normally run when there is a high power demand that cannot be met by the existing power generating units. The power utilities use a number of the reciprocating engines at various substations and power plants to provide a grid support during the peak demand. This will balance the power shortage that arises from the generating units' outage in a power plant. The integration of the reciprocating engines into a power system as the grid support units will defer any investment on extension or upgrading of the transmission and distribution facilities, reduced load shedding, optimized operational costs, reduced economic cost that is associated with power outages and increase the peaking capacity of a power system. The diesel engines and SI engines can be strategically incorporated into the distribution system due their operational characteristics. The grid support generating units can be used to increase the output power of a power plant. This can be achieved once the grid support units have been synchronized to the grid in response to the generating units' outages in a power plant.

Combined Heat and Power

The reciprocating engines can be used for generation of power and production of heat simultaneously. The combined processes of generating power and heat concurrently is more energy efficient than the separate generation of electrical power and heat from different DG technologies [11]. The CHP technology reduces the total fuel consumption and greenhouse gas emissions of the reciprocating engines, since both electrical power and heat are from the same source of fuel. The heat recovered from the reciprocating engines can also be used for cooling applications. The CHP can provide electricity, mechanical power to drive compressor, pumps and fan and heat energy that can be used for steam or hot water. The application of the reciprocating engines for production of heat and power separately has a combined heat efficiency of about 45%, while cogeneration system that combines heat and power generation processes can be up to 80% efficient [11]. The reciprocating engines have been widely accepted for CHP applications due to the following features: quick start-up, high efficiency, portability and flexibility of fuel. The reciprocating engines can offer the following benefits if they are used for the CHP applications:

- reduced GHG emissions,
- reduced economic losses due to power outage,
- reduced power lost in the transmission and distribution (T&D) systems,
- reduced congestion in the distribution system, and
- deferred investments in new T&D facilities.

2.1.2 Classes of Reciprocating Engines

The reciprocating engines can be classified into various categories by using the following criteria.

2.1.2.1 Methods of Igniting the Fuels

The reciprocating engines are classified into the CI/diesel engines and the SI engines based on the methods of igniting the fuels. The SI engines run on multiple fuels such as natural gas, propane, gasoline, *compressed natural gas* (*CNG*), *methanol*, *ethanol*, bioethanol, liquefied petroleum gas (LPG) and hydrogen. The CI engines or diesel engines are designed by the original equipment manufacturers (OEMs) to operate with any available fuel. The diesel engines are designed with the modern technology to run on both natural gas and diesel through a dual fuel configuration. They are the most popular reciprocating engines due to some technical characteristics, but their operations have been limited to emergency and standby in some countries due to emission constraints set up by the environmental protection regulators. The natural gas-fired SI engine has become widely accepted owing to the public awareness of environmental hazard of carbon emissions and higher duty cycle. These engines are now available at a commercial level in various sizes. The natural gas-fired reciprocating engines offer the following benefits, i.e. high availability, quick start-up and high reliability. These benefits are subject to proper maintenance of the engines. The different types of the reciprocating engines and their characteristics are presented in Table 2.5.

Table 2.5 Types of the reciprocating engines and their characteristics [4, 5]

Reciprocating engines	Spark ignition	Diesel
Size range (kW)	30–5000	30–5000
Electrical efficiency (%)	31–42	26–43
Overall efficiency (%)	80–89	85–90
NO_x emissions (g/kWh)	0.7–42	6–22
CO emissions (g/kWh)	0.8–27	1–8
Packaged cost ($/kW)	300–700	200–700
Installation cost ($/kW)	150–600	150–600
Electricity cost (cents/kWh)	7.6–13.0	7.1–14.2
Applications	Continuous power, peak power and CHP	Continuous power, peaking power, premium power and CHP
Cogeneration cost (cents/kWh)	6.1–10.7	5.6–10.8
Availability (%)	90–97	90–97
Start-up time (s)	5–10	10
Planned schedule (h)	1000–2000	1000–2000
Time between overhauls (h)	10000–24000	10000–24000
Noise levels (dB)	80–100	67–92

2.1.2.2 Operation of a Diesel Engine

The diesel engine is one of the efficient engines that are available in the market owing to its simple operation and fuel economy. The diesel engine is an internal combustion engine that operates based on the principle of compressing the fresh air that is introduced into the engine cylinder during the intake stroke. The engine is designed in such a way that it will allow the motion of the intake valve to be controlled by the crankshaft, while the exhaust valve remains closed during the intake stroke operation. The compression ratio that has a range of 12:1–22:1 is used for compressing the air in the cylinder during the compression stoke. The fuel injector is utilized to inject fuel into the combustion chamber at the end of the compression stoke, this will initiate the combustion process in the engine. The air inside the cylinder is compressed so that it raises its temperature and pressure to match the auto ignition temperature of the diesel during the power stoke. The fuel will absorb heat from the hot air in the cylinder and vaporise, this will result in

Table 2.6 Characteristics of the compression-ignition or diesel engines [4, 5]

Advantages	Disadvantages
• Fuel economy • More efficient than spark-ignition engines • Produce very little amount of carbon dioxide • Produced little waste heat during cooling and exhaust processes • They are durable than spark-ignition engines • Diesel fuel is safer than petrol and natural gas engines • Diesel engines have advantage of higher torque • Diesel engines can run at a cooled temperature than spark-ignition engines • Lower running speeds • Diesel fuel is less flammable than petrol • Fumes from diesel engine are less toxic and polluting than petrol engines • Simple to design and operate • Portable and required little space • High quick start • Low initial start • Lower fuel consumption	• Diesel engine must provide more torque to produce the same output power as spark-ignition engines • Noisier than spark-ignition engines • Required high compression ratios for ignition to take place in the cylinder • They are bigger and heavier than spark-ignition engines of the same power output • Starting is often difficult because it requires more starting torque • Produce black soot from their exhaust • Retrofitting is difficult in most of the cases • Friction loss due to many moving parts • Limited compression ratio lowers efficiency • High cost of maintenance • High cost of lubricants • Small power generation capacity compared with thermal power plants

combustion and subsequently generation of energy that can be used for different applications. The high efficiency of the diesel engine has been attributed to its high expansion ratio and intrinsic burn. The characteristics of the CI or diesel engines are presented in Table 2.6.

2.1.2.3 Operation of a Spark-Ignition Engine

The SI engine uses three basic components such as piston, connecting rod and crankshaft for its operation. The intake valve opens to allow the mixture of air and fuel to be injected into the cylinder during the intake stroke. The mixing of air and fuel process is achieved by using a can and follower mechanism. The exhaust valve remains closed during the intake stroke. The piston moves the mixture of fuel and air from the injector into the cylinder. The intake and exhaust valves are designed by the original equipment manufacturer to remain closed during this process so that the piston will be able to compress the mixture of air and fuel in the cylinder effectively. The mixture of air and fuel is compressed to a high pressure as a means to allow combustion to take place in the engine. A spark is produced by the spark plug located in the cylinder head after the compression has completed. The exhaust and the intake valve are closed during this stroke for optimal operation of the engine. The spark from the spark plug burns the mixture of air and fuel. This will

Table 2.7 Characteristics of the spark-ignition engines [4, 5]

Advantages	Disadvantages
• Lower capital costs • Lower maintenance costs • Can be easily retrofitted for alternative fuels • Light in weight and portable • Higher running speeds	• Less overall fuel efficiency and economy • High service requirement • Not durable • Lower efficiency • More expensive fuel

result in combustion and generation of mechanical energy that can be used as a prime mover for many applications. During the exhaust stroke, the exhaust valve is opened by using a configuration that will allow the exhaust gasses to escape out of the cylinder. The efficiency of spark engines is lower than the CI engine because of the difference in the compression ratio. In addition to this, the poor oxidation of fuel in the SI engine also contributes to its low efficiency. The characteristics of SI engines are presented in Table 2.7.

2.1.2.4 Operating Cycle or Number of Strokes

The reciprocating engines are also classified based on the operating cycle it requires to complete a combustion cycle. A stroke is the full travel of the piston from the top of the cylinder to the bottom of the cylinder. The SI and CI engines are designed by the manufacturers to operate effectively on both two-stroke cycle and four-stroke cycle. A two-stroke reciprocating engine operates in such a way that it can complete its combustion cycle in one revolution of the crankshaft. The two-stroke engines are lighter, cost effective and simple to manufacture, because they do not have valves. A four-stroke reciprocating engine completes its combustion cycle in four strokes during two revolutions of the crankshaft. The four-stroke engines have been produced in a large quantity by different manufacturers because of their durability, fuel economy, low emissions, simple operation and high torque.

2.1.2.5 Speed

The reciprocating engines can be categorized based on the speed of the crankshaft. The speed of a reciprocating engine depends on its weight and capacity of the power output. The ranges of the reciprocating engines are presented as follows.

High Speed

The high-speed engines are designed to operate at the speed range of 1000–3600 rpm. The reciprocating engines can operate at 1500 rpm (50 Hz) for power generation applications. They have the lowest capital cost among the three classes of reciprocating engines based on their speed but have poor efficiency [4, 5].

Medium Speed

The medium-speed diesel reciprocating engines operate within the approximate speed range of 275–1000 rpm. The capital costs and efficiency of the medium-speed engines are more than high-speed engines and also have flexible operation on various fuels. They can be used as prime movers for the locomotive and marine engines. They can also be used for the grid support, emergency, base load and peak shaving power generation units [4, 5].

Low Speed

The low-speed diesel reciprocating engines are designed to operate within the speed range of 58–275 rpm. These engines are used for propulsion units of the ship because of the simplicity to couple them directly to the shaft and propeller. They operate effectively on lower grade fuels than medium- and high-speed engines. They are also more efficient and cost effective than medium- and high-speed engines. The low-speed engines can be utilized in a situation where the prices of natural gas and heavy oil are extremely expensive for the power utilities. They can also be used for different application wherever the natural gas and heavy oil are not available [4, 5].

Ratings

The reciprocating engines can be classified into three classes based on the power generation applications, i.e. continuous, prime or standby based on their mode of operations.

Standby Generators

The standby generators are designed to run only in a situation when there is an interruption of power supply from the utility grid. The need for standby unit arises whenever there is a short-term power disruption in an event of faults in the primary supply networks. This happens when the power supply from the main grid goes out due to some faults which can quickly be rectified by the utility so that power will be restored back to the systems. The standby reciprocating generating units have the following advantages over other non-renewable technologies that have been assigned to perform the same application:

- Standby reciprocating units can cool down naturally without using artificial cooling system such as fan, water cooling system and lube oil cooling system.
- Scheduled or breakdown maintenance activities are carried out by the assigned personnel without disrupting the power supply to the grid.

- These units do not need emission control units.
- Standby units do not need an elaborate cooling system.

Prime Generators

The prime generators are designed by the original equipment manufacturers to operate for long durations at variable loads. The prime generators can be used in the locations where there is no access to connect consumers to the distribution networks or national grid provided by the power utility [12]. The prime generators are subject to the applications that will cause a continuous flow of current in the alternator winding of the generator. This will lead to an enormous quantity of heat to be generated through the alternator's winding. This will increase the capital cost of the prime power plant due to the procurement of a large cooling system. The temperature build up in a prime generator can be reduced with the incorporation of a cooling system. This will subsequently improve the efficiency and optimal operation of the system.

Continues Generators

The continuous generator sets are designed by the original equipment manufacturer to operate continuously with a constant load without power interruption. The continuous generators are primarily used in remote locations where there is no access to tie their power systems to the grid due to some financial and technical constraints [12]. The continuous generating units can also be used when there is a limitation on the maximum amount of electric power that can be drawn from the utilities' distribution and transmission lines. The power limitation is imposed on some oil and gas companies by the regulators so that they can utilize the available resources (crude oil, natural gas and LPG) within their vicinity to generate power for their consumables. The continuous operation of the reciprocating generating unit does not allow the engine to be cooled down naturally. The water cooling system, lube oil cooling system and fan cooling system are incorporated into the continuous generating units as a measure to cool all the complicated parts of the engines. This will improve the optimal operation and efficiency of the generating units without exposing the consumers to the intermittent power interruption or load shedding.

2.1.3 Performance of Reciprocating Engines

The key performance indicators that are affecting the operations of the reciprocating engines are presented as follows:

- heat rate,
- efficiency,
- capacity factor and
- load factor.

2.1.3.1 Heat Rate

The heat rate is the quantity of energy that an electrical generator used to generate one kilowatt-hour of electricity. This is achieved as a result of the engine's energy conversion process. The reciprocating engines have been configured to be running at the optimal operating rate at the lower heat rate. The heat rate can be used by the power utilities as a standard to compare the performances of different generating units in the same plant or at different sites. The heat rate can be used to reduce the operating cost of a reciprocating power unit. Due to the fact that the cost of the heat rate is directly proportional to the fuel cost. As a result of power deregulation, the power utilities must operate their generating units at the lowest operating cost that will allow them to compete with other investors or competitors in the power sectors and at the same time maximize their profits. This can be achieved by monitoring the heat rate so that it will not deviate from the manufacturer's specifications. The heat rate of a reciprocating engine can be expressed mathematically as:

$$\text{Heat rate} = \frac{H}{E}(\text{kJ/kWh}), \tag{2.1}$$

where H is the thermal energy of the power plant (kJ) and E is the electrical energy output of the power plant (kWh).

2.1.3.2 Efficiency

The efficiency is a ratio of the output power of a power plant to the energy input of the system, and it increases with the engine's size. An optimal operation of the reciprocating engines is a serious challenge for the utilities because of fuel cost, operation and maintenance costs, reliability, emissions, etc. The operators of the reciprocating power plants derive a lot of benefit from running the engines at high efficiency. These benefits are not limited to fuel economy, optimization of greenhouse emissions and reduction of emission without installing emission control equipment. The efficiency of a reciprocating engine can be used as a long-term tool to reduce the greenhouse gas emissions that are associated with the reciprocating engines. The efficiency of a reciprocating engine can be estimated as follows:

$$\text{Efficiency} = \frac{\text{Output power (kW)}}{\text{Input energy (BTU/h)}} \tag{2.2}$$

2.1.3.3 Capacity Factor

The capacity factor of a reciprocating power plant is the ratio of the average value of the load to rated value of the generating unit for a period of time. This is an important measure to estimate the electric generator usage and how intensively a generating unit is running. It is used by the power utility to estimate how fully a unit's capacity is utilized. The base load generating units have high capacity factors, while the peak load generating units have low capacity factors based on their performance features and mode of operation. The stochastic renewable sources such as solar and wind also have lower capacity factors due to the intermittent characteristics of their local RER [13]. The capacity factor of a reciprocating power plant can be expressed mathematically as:

$$\text{Capacity Factor} = \frac{\text{AL}}{\text{RC}} * 100(\%), \tag{2.3}$$

where AL = average load (kW) and RC = rated capacity (kW).

2.1.3.4 Load Factor

The load factor for a reciprocating power plant is the ratio of average load demand to peak load. The greatest challenge for the power utilities is how to operate their reciprocating power generating units at a high load factor. The high load factor can be attained if the reciprocating power plants are operating at the lower fuel cost per unit with more output. At a high load factor and spark spread, it is mandatory for the power utilities to sell their electricity. The load factor can be used by the power plant operators to determine the load capacity of the reciprocating power plant. If all the reciprocating generating units in a power plant are running at 100% load factor, it shows that the power plant is operating at the optimum capacity, i.e. full load of the installed capacity. The performance of a reciprocating power plant is directly proportional to the load factor. One of the advantages of high load factor is that it can be used to reduce power plant forced outages. The load factor is the key indicator that can be used to estimate the performance of a reciprocating power plant. The load factor of a reciprocating power plant can be expressed as:

$$\text{LF} = \frac{\text{AL}}{\text{PL}} * 100\%, \tag{2.4}$$

where AL is the average load (kW); LF is load factor (%); and PL is the peak load (kW).

2.1.4 Emissions

The rapid increase in the global emission of greenhouse gas emissions has been attributed to the economic growth, coupled with the accelerated industrialization and urbanization. This has led to a sudden increase in the electric power demand that is difficult to meet in some countries. The electrical power demand can only be met by harnessing all the available energy resources, i.e. renewable and non-renewable energy resources. The total electric power generation from different sources worldwide was estimated in 2014 to be 4892 TWh. This statistical data showed that 77.2% of the global power demand came from fossil fuels and nuclear, while 22.8% came from RER [13]. The largest percentage of global greenhouse gas emission come from the fossil fuels fired conventional power plants. The reciprocating engine which is one of the notable conventional power plants emits some unburnt fuel particles and a number of pollutants such as CO, CO_2, SO_2 and NO_x [5]. The emissions from the fossil-based reciprocating plant have become a serious public concern due to the harmful effects on property, animals and human beings.

2.1.4.1 Sulphur Oxides Emissions

The Sulphur oxides (SO_2) are produced in the combustion chamber of a reciprocating engine through the oxidization process. The SO_2 will be formed whenever the oxidized sulphur enters the atmosphere and combined with water. The SO_2 will return to the earth's surface in the form of acid rain which has many adverse effects on human beings, animals, plants, environment and buildings. The SO_2 from the fossil fuels fired reciprocation power plant depends on the sulphur content of the fuels [14]. This is contrary to the CO_2 and NO_2 emissions that depend on design and operating conditions of the power plants. The SO_2 emission has become a serious issue because of the environmental effects such as acid rain, eye irritation and breathing difficulty [15].

2.1.4.2 NO_x Emissions

NO_x are formed when nitrogen and oxygen react with each other. The formation of NO_x is influenced by the concentration of oxygen and the flame temperature in the combustion chamber when fuel is burned. The NO_x emissions have become a great concern because emissions from the diesel engines are the highest among the DG technologies. The NO_x emissions depend on the fuel and combustion process as well as on the fuel to air ratio and fuel and air mixing pattern [16]. The diesel engines emit a large quantity of the NO_x emissions compared with the natural gas generators. The poor emissions profile of the diesel generators has discouraged the utilities to install them in some non-attainment locations [16].

2.1.4.3 CO_2 Emissions

The carbon dioxide (CO_2) emissions are produced from the combustion of fossil fuels for different applications. The quantity of CO_2 emitted from the reciprocating engines that used diesel or natural gas is a function of the carbon content of the fuel used and the efficiency of the engines [16, 17]. The CO_2 emissions have become a great challenge due to its contribution to climate change and adverse effects on human beings.

2.1.4.4 CO Emissions

The carbon monoxide is a result of incomplete combustion that takes place in the reciprocating engines owing to inadequate oxygen to complete the combustion process of the fuels. The CO emissions are a direct waste of fuel energy due to incomplete combustion of fossil fuels. The CO emission's costs constitute the greatest part of the power plant running costs [16]. The cooling of the combustion chamber is one of the factors that contribute to incomplete combustion and increase in CO emissions. carbon monoxide is a dangerous gas that can impair human's health. The concentration of CO in the atmosphere can cause depletion of the ozone layer. Some measures must be introduced to reduce the menace of CO emissions in the reciprocating power plants [17].

2.1.4.5 Emission Control

The CO_2, NO_x, CO and SO_2 emissions profile of the reciprocating engines have been reduced through the efforts made by the manufacturers in designing of better and optimally operated engines [16]. This peculiar landmark is achieved by the integration of emission reduction and controlling techniques such as catalyst reduction and air/fuel ratio control. Some modern techniques to control the combustion process were also embedded into the reciprocating engines. The methods of reducing these emissions of PM include the following: a bag house, selective catalytic reduction, oxidation catalysts, three-way catalyst systems, an electrostatic precipitator (ESP), cyclone collector and diesel particulate filter [17].

2.1.5 Plant Availability

The availability of a reciprocating engine power plant is the number of time that the power plant is able to generate electricity over a certain period of time [18]. It can also be defined as the number of time that the reciprocating power plant is in upstate to perform its functions [19]. This depends on the type of engine, speed of the engine, the quality of the fuel and proper maintenance. The reciprocating power plant availability is associated with the proper management of the reciprocation power plants [20]. The reciprocating engines required a lot of maintenance that must be frequently carried out based on the schedule of the manufacturers or breakdown maintenance that is normally carried out during the power outages to restore back power supply to the system [16]. The availability of a power plant can be increased to 96% if the proper maintenance schedule is put in place and implemented.

2.1.6 Fuels

The reciprocating engines have an advantage to operate on various fuels such as diesel, natural gas liquids, gasoline and jet fuel, as well as alternative gas fuels such as LPG, propane, biogas, sour gas, industrial gas and synthetic gases. The reciprocating engines have been designed to use any available fuel that meets the specifications of the original equipment manufacturers. The CI engines can utilize both diesel and heavy fuel oil for their optimal operations. Also, the SI engine can operate with natural gas, petrol and alternative fuels [16]. The current state-of-the-art technology of the reciprocating engines with the modern features allows them to operate effectively on both natural gas and diesel through a dual fired configuration. The dual fuel reciprocating engines are designed by the original equipment manufacturers with the capability of running on liquid fuels, alternative fuels and gaseous fuels. The dual fuel reciprocating engines can use any available fuel that has been allocated as a backup by the power utility [16]. The fuel will be utilized to run the engine whenever there is an interruption of the main supply from the source. The flexible fuel operation of the duel fuel reciprocating engine allows easy conversion from one fuel to another while in operation. This benefit allows the power plant operators to switch to the more economically viable fuel among the available fuels. For the optimal operation of the reciprocating to be achieved, the low-cost fuel and the high-cost fuel can be used simultaneously to run a reciprocating plant based on the load schedule, i.e. peak load and base load [17]. The combination of low-fuel cost and high-fuel cost provides a number of benefits for the power utilities.

2.1.6.1 Liquid Fuels

The liquid fuels are combustible molecules that can be used to produce mechanical energy for power generation and automobile and industrial machinery. The liquid fuels are usually in liquid forms, i.e. diesel, gasoline, biodiesel and kerosene [16]. The high-speed diesel engines have been designed to operate with a good quality fuel with good combustion property. The fuels must meet the requirements of the manufacturer such as low sulphur content, combustible and good flashpoint. The poor quality fuel may damage the injection pump or the injector and results in total

Table 2.8 Major constituents of natural gases [16, 21]

Fuel component	Natural gas
Methane, CH_4 (% vol.)	80–97
N_2 (% vol.)	0–14
Higher C_xH_{2x+2} (% vol.)	0–0.2
CO_2 (% vol.)	0–1.8
H_2 (% vol.)	0–0.1
LHV (BTU/scf)	830–1075
Ethane, C_2H_6 (% vol.)	3–15
Butane, C_4H_{10} (% vol.)	0–0.9
Propane, C_3H_8 (% vol.)	0–3

failure of the reciprocating engines [16, 17]. The high-speed diesel engines are not designed by the manufacturers to operate with heavy oil, because it may have an adverse effect on the optimal operation of the engine. The medium-speed engines and low-speed reciprocating engines can run on both heavy oil and low-grade fuels.

2.1.6.2 Natural Gas

The natural gas is a hydrocarbon that is made up of compounds of hydrogen and carbon, and it can be found by itself or in association of the crude oil [16]. The major constituents of natural gas are presented in Table 2.8. The natural gas-fired reciprocating engines are used for power generation and industrial applications, i.e. compressors, pumps and ship propeller.

2.1.6.3 Alternative Gas Fuels

The reciprocating engines can operate on a number of alternative gaseous fuels such as LPG, sour gas, biogas, industrial waste gases and synthetic gases [21]. The optimal operation of the reciprocating engines on the alternative gaseous fuels depends on the following factors: volumetric heating value, auto ignition characteristics, detonation tendency, contaminants and hydrogen [16].

2.1.7 Fuel Cost

The fuel cost required to generate electrical power in a reciprocating power station depends on fuel price per unit of energy and the net power plant efficiency [16]. The profit margin of a power plant depends on the fuel cost which carries the largest percentage of the power plant operating cost. The fluctuation of fuel prices has a significant effect on the profit margin of the reciprocating power plant [21]. The fuel cost function of a power generating unit can be expressed by a quadratic function of power output P_i as:

$$\mathrm{FC} = H\left\{\sum_{i=1}^{n} a + bP_i + cP_i^2\right\}(\$/\mathrm{h}), \tag{2.5}$$

where a, b and c are fuel cost coefficients of the generating unit; H is the fuel price (\$/L); n is the number of the generation unit; P_i is the active power of the ith generating unit (kW).

2.1.8 Cost of Electricity Production

The cost of electricity production for various reciprocating plants can be estimated by using the following parameters, i.e. capital cost, operations and maintenance, cost of fuel and initial investment. The levelized cost of electricity (LCOE) is the price at which electricity from various sources of energy must be sold in order to break even over the economic life of the power plant [22, 23]. The optimal operations of different reciprocating power plants can be compared based on their LCEOs, but this comparison depends on a number of main parameters such as fuel price and plant utilization rate. The LCOE of a reciprocating power plant can be estimated as [22, 23]:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}(\$/\mathrm{kWh}), \tag{2.6}$$

where I_t is the investment costs in the year t; M_t is the O&M costs in the year t; F_t is the fuel costs in the year t; E_t is the electricity generation in the year t; r is the discount rate; and n is the economic life of the system.

2.1.9 Maintenance

Maintenance is a periodic activity that is being carried out on a reciprocating generating unit in order to put the unit in a good working condition at all time. This includes breakdown maintenance, preventive maintenance, periodic maintenance, predictive maintenance and corrective maintenance. The reciprocating engines' maintenance is comprised of periodical inspections, replacements of parts and engine oil, coolant and spark plugs, servicing, greasing, retightening of loosed bolts and nuts and cleaning of the engines. The periodic maintenance is always carried on the reciprocating generating unit every 500–2000 h, this depends on the type and size of the engine [24]. The maintenance time interval for the reciprocating engines based on the specifications of their manufactures is 12,000–15,000 h for minor overhaul and 24,000–30,000 h for a major overhaul [24]. The maintenance cost of the reciprocating engine is high due to the fact that it has many moving parts. The maintenance cost of the reciprocating power plant is $10/MWh, which is very high when compared with the gas turbine that has a maintenance cost of $4.5/MWh [16]. The low O&M costs of the reciprocating engines have increased the economic benefits of using the engines for different applications. The economic operating life span of the diesel generator can be increased with a proper maintenance program which must be scheduled based on the manufacturer' specifications. The economic operating life span of a reciprocating engine depends on the capacity of the engine, availability of spare parts and the maintenance culture of the reciprocating engines' operators [16].

2.2 Microturbines in Distributed Generation System

2.2.1 Brief Descriptions

DG system can be defined as a small-scale technology used to produce energy in the form of power or heat at or near the point of consumption. The system can be either operated as a stand-alone or connected to the main grid at the lower voltage distribution network and hence be a part of the microgrid. Various technologies including renewable energy, fossil fuel and energy storage can be used in DG system. DG units based on renewable energy technologies include, for instance, solar, wind, hydro, biomass and geothermal, while those based on fossil fuel include, mainly, reciprocating engines and microturbines (MTs). Energy storage systems such as batteries, fuel cells, flywheels, pumped hydro, supercapacitors, hydrogen production and storage form also part of the DG system. With DG systems, both economic and technical benefits are achieved. On the one hand, installing power generating units at the end-users means no transmission or distribution will be required by the utilities, thus leading to investment cost savings. On the other hand, this also means that no extra power loss will be incurred by the electrical grid, thus leading to the grid efficiency improvement.

Although DG systems based on renewable energy have gained much attention in the past, due to their environmental benefits, the lack of dispatchability of most of these technologies has limited their spread. On the other hand, with DG technologies based on MTs, the power output can be adjusted to meet the load consumption at any time. Another advantage of MTs is that they can be used as a cogeneration to produce both electrical power and heat, referred to as combined heat and power (CHP), with less pollution and noise [25, 26]. Because of the above reasons, MTs are considered as a relatively new DG technology, suitable for small industries and commercial buildings [26]. The main focus of this work is to give a review on different technologies used in MTs, energy model, economic analysis, systems optimization, advantages and limitations.

2.2.2 Technology Description

2.2.2.1 Working Principle

A MT is a small gas turbine-based power generation system whose capacity generally ranges between 20 and 500 kW [25–27] and usually used for applications, such as peak shaving, remote power control and cogeneration [28, 29]. The working principle of a MT is similar to that of the gas turbine, which is based on Bryton cycle, with about 30% thermal efficiency [26, 30]. The fossil fuel is burnt by the MT to create high rotation speed to an electrical generator shaft. Most MTs have single-stage centrifugal turbine and compressor, and radial flow [27].

2.2.2.2 Classification of Microturbines

MTs are generally classified based on the number of shafts as follows [26].

Single-Shaft Microturbine

The schematic of a single shaft is shown in Fig. 2.1. The single-shaft MT is simple, easy but expensive to build. Its simplicity and ease of manufacturing make this technology to be the most used [27]. The main components of a single-shaft MT are the compressor, recuperator, combustor, power turbine and electrical generator. The inlet ambient air is firstly compressed to a higher pressure by the compressor. The pressured air is then preheated in the recuperator using the exhaust. The pressured

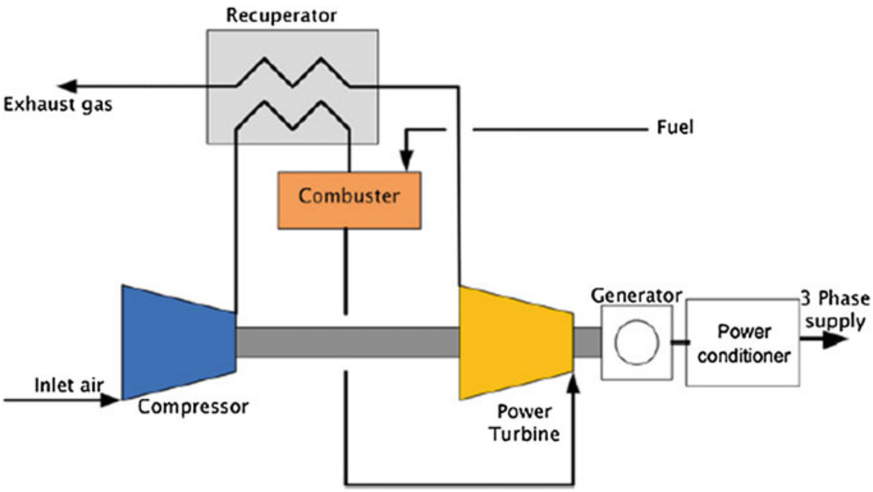

Fig. 2.1 Schematic diagram of a single-shaft microturbine [26]

and heated air is thereafter mixed with the fuel in the combustor. The resulting hot combustion gas expands through a power turbine by transforming gas pressure into mechanical power. A 3-phase electrical generator is directly coupled to the power turbine in order to convert available mechanical power into electrical power. Single-shaft MTs rotate at high speed, between 50,000 and 120,000 rpm.

As shown in Fig. 2.1, only one shaft is used to transmit the mechanical power from the power turbine to the compressor and generator. This configuration will make the generator to also rotate at the same speed as the turbine, which is high. With this, the electrical frequency of the special high-speed AC generator used will range between 1500 and 4000 Hz, which will require the use of a power conditioner as an interface to synchronize the frequency with that of the utility grid (50 or 60 Hz). However, the use of a special high-speed AC generator and power conditioner justifies the high initial investment cost of the single-shaft MT. Since high-speed DC electrical generators are easily manufactured, these can also be used with a simple inverter to produce AC power.

Two-Shaft Microturbines

The configuration of a two-shaft MT, also called split-shaft MT is shown in Fig. 2.2. In contrast to the single-shaft MT, a two-shaft MT is a two-stage device where the compressor shaft is separated from the generator shaft by adding a second turbine and gearbox. In this configuration, the hot combustion gas expands through the first turbine coupled only to the compressor, while the exhaust gas from this turbine is used to expand through a second turbine (power turbine) connected to the electrical generator through a gearbox. The first shaft coupling the first turbine with the compressor will still rotate between 50,000 and 120,000 rpm as in the

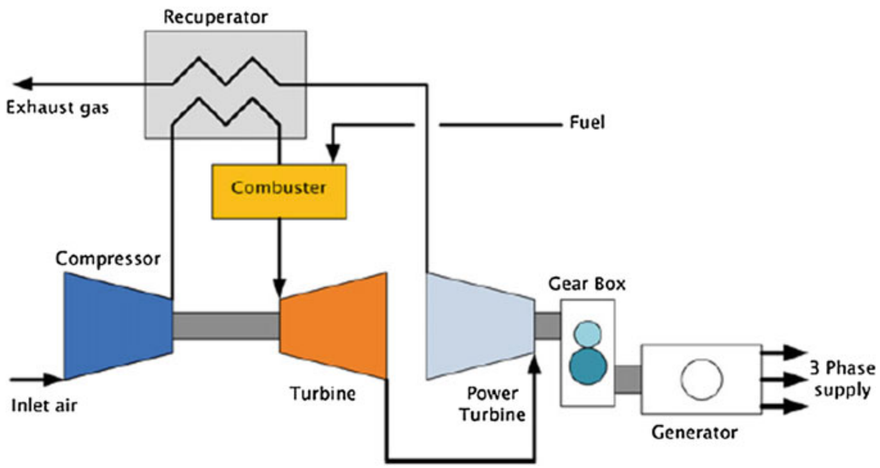

Fig. 2.2 Schematic of a two-shaft microturbine [26]

single-shaft configuration, while the second shaft coupling the power turbine with the gear box will rotate at a lower speed between 3000 and 3600 rpm. The addition of a gearbox will make the generator to rotate at low speed, hence a 3-phase induction or synchronous generator can be used, while avoiding the use of a power conditioner. However, although the two-stage MT configuration will generally lead to a lower initial investment cost due to the avoidance of using high-speed generator and power conditioner, additional moving parts, such as the second turbine and shaft, and gearbox will result in a higher maintenance cost.

2.2.2.3 Comparison Between Single and Two-Shaft Microturbines

Comparison between single-shaft and two-shaft MTs is given in Table 2.9 based on both technical and economic parameters.

Table 2.9 Comparison between single-shaft and two-shaft microturbines [26]

Parameter	Microturbine type	
	Single shaft	Two shaft
Power turbine speed (rpm)	50,000–120,000	3000–3600
Generator frequency (Hz)	1500–4000	50 or 60
Coupling	Direct coupling of power turbine and electrical generator	Indirect coupling: gearbox is used for coupling of power turbine with electrical generator
Power electronic interface	Needed to convert the high frequency from the generator to low frequency of the grid frequency (50 or 60 Hz)	Not needed
Type of generator	Usually permanent magnet synchronous generator, but DC generator can also be used	Usually induction generator, but permanent magnet synchronous generator can also be used
Maintenance level	Lower	Higher due to additional moving parts (second turbine and shaft, and gearbox)
Initial capital cost	Higher due to the use of special high-speed electrical generator and power electronic converter	Lower
Failure level	Higher probability due to the presence of power electronic converter	Lower probability due to the robustness of gearbox compared to power electronic converter
Dimension and weight	Lower	Higher due to the presence of additional moving parts (second turbine and shaft, and gearbox) and gearbox lubricating system

2.2.2.4 Combined Heat and Power

Because of the high temperature of the exhaust gas of MTs during power generation, the waste heat can be recovered and used in a heat exchanger for water or space heating. Since the energy is produced in form of both power and heat, the MT is referred to as combined heat and power (CHP) or cogeneration system. The configuration of a CHP system is depicted by Fig. 2.3, where it is shown that the gas product #6 from the recuperator (II) is used as a heat source to the heat water in a heat exchanger (III) instead of being dissipated in the atmosphere as the case with traditional MTs (see Figs. 2.1 and 2.2).

The aim of this technology is to improve the efficiency of the traditional MT from 30 to about 85–90% [30]. CHP or generation system is widely recognized as cleaner technology compared to the traditional centralized fossil fuel-based power plants. With CHP, multiple benefits are achieved. Some of these benefits are as follows:

- cost-effectiveness due to its high thermal efficiency, higher than 80%,
- lower CO_2 and SO_x emissions with the use of natural gas as fuel,
- increase security level of energy supply due to its stand-alone ability,
- energy savings by reducing the base load electricity and hot water,
- reduced investment cost of installing new boilers,
- energy cost savings due to energy savings,
- potential benefits from renewable heat Incentives, and
- reduced transmission losses from the grid since installed at the end-users.

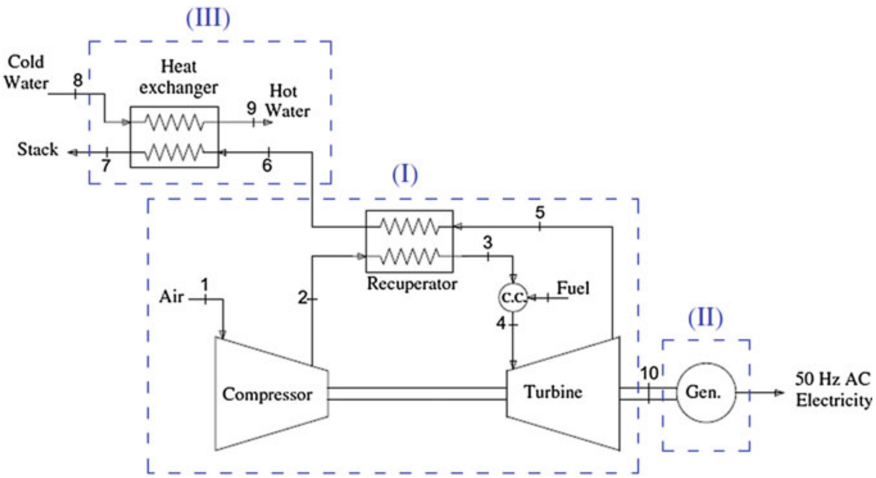

Fig. 2.3 Schematic diagram of a combined heat and power (CHP) system [30]

2.2.2.5 Fuels

One of the advantages of a MT is its flexibility in using a variety of fuels, such as natural gas, propane, diesel and light oil, as opposed to reciprocating engines when diesel is the most used fuel.

2.2.2.6 Thermal Modelling of a Microturbine

The objective of the MT thermal model is to estimate the generated electrical power energy. To achieve this, expressions of mass balance and energy balance need to be known. Since the MT is a CHP system with addition of heat exchanger, the thermal model of CHP will also include that of MTs.

Mass Balance

Based on the principle of conservation of fluid mass between the input and output of each component, the following equations are obtained:

Compressor:

$$q_{m1} = q_{m2} = q_{m12} \tag{2.7}$$

Turbine:

$$q_{m4} = q_{m10} = q_{m4-10} \tag{2.8}$$

Recuperator:

$$q_{m2} = q_{m3} = q_{m2-3} \tag{2.9}$$

$$q_{m5} = q_{m6} = q_{m5-6} \tag{2.10}$$

Heat exchanger: with assumption of negligible heat loss

$$q_{m6} = q_{m7} = q_{m6-7} \tag{2.11}$$

$$q_{m8} = q_{m9} = q_{m8-9} \tag{2.12}$$

Combustion:

$$Q_{m4} = q_{m3} + q_{\text{mf}} \tag{2.13}$$

In Eqs. (2.7)–(2.13), $q_{m1,\ldots,10}$ denote the mass flow rates of the gas or water (in kg/s) at different point of the cycle, and q_{mf} is the mass flow rate of the fuel (in kg/s).

Energy Balance

Based on thermodynamic analysis, the energy balance applied at different components of the CHP system depicted in Fig. 2.3 can be written as follows:

Turbine:

$$E_{\mathrm{T}} = q_{m4-10} * (h_4 - h_{10}) \tag{2.14}$$

Compressor:

$$E_{\mathrm{C}} = q_{m1-2} * (h_2 - h_1) \tag{2.15}$$

Recuperator: with assumption of negligible heat loss

$$q_{m2-3} * (h_3 - h_2) = q_{m5-6} * (h_5 - h_6) \tag{2.16}$$

Heat exchanger: with assumption of negligible heat loss

$$q_{m6-7} * (h_6 - h_7) = q_{m8-9} * (h_9 - h_8) \tag{2.17}$$

Generator:

$$\mathrm{EG} = \eta_{\mathrm{G}} * \mathrm{E}_{\mathrm{T}}. \tag{2.18}$$

Combustor:

$$E_{\mathrm{f}} = q_{\mathrm{mf}} * \mathrm{LHV}_{\mathrm{f}} \tag{2.19}$$

In Eqs. (2.14)–(2.19), E_{T} is the output mechanical power of the macroturbine (in kW); E_{C} is the input mechanical power of the compressor (in kW); E_{G} is the generated electrical power (in kW); E_{f} is the fuel energy (in kW); $\mathrm{LHV}_{\mathrm{f}}$ is the lower heating value of the fuel (in kJ/kg); $h_{4,\ldots,10}$ are the specific enthalpies of the gas or water at different point of the cycle (in kJ/kg); and η_{G} is the overall efficiency of the generator (in %).

2.2.3 Microtubines in Hybrid Energy Systems

MTs have proven their ability to be used in a hybrid energy system in combination with other small-scale power generation systems, such as solar, wind, hydro, fuel cell, tidal and battery storage. The use of MTs in a hybrid system where renewable energy systems, such as solar photovoltaic and wind are used will help to improve the grid stability (smooth power) by compensating the intermittency characteristics of these renewable energy systems.

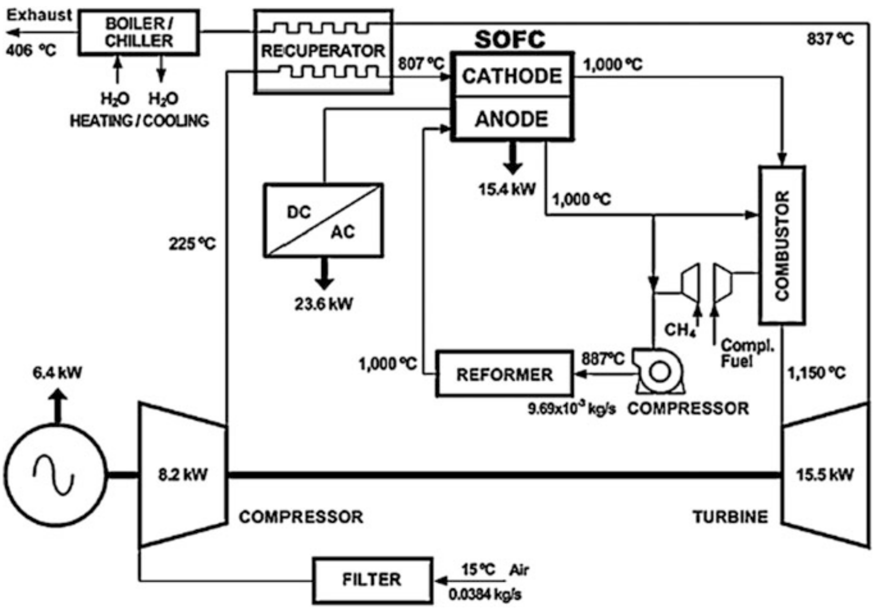

Fig. 2.4 Schematic diagram of a fuel cell/microturbine hybrid system [32]

2.2.3.1 Hybridization of Fuel Cell with Microturbine

Research studies conducted in Refs. [31–33] show that the hybridization of a solid oxide fuel cell with MT will improve the efficiency of both the MT and fuel cell systems, with a global efficiency up to 95.9% [32]. In fuel cell-microturbine hybrid system as shown in Fig. 2.4, the compressed air is preheated by both the recuperator and high temperature fuel cell in order to use less fuel in the combustor and produce more energy through the power turbine, hence improving the efficiency of the system.

2.2.3.2 Hybridization of Microturbine with Multiple Energy Sources

In Ref. [34], a microturbine is hybridized with a wind turbine, tidal turbine and battery storage system to supply an offshore load. The resulting hybrid system has shown the effectiveness of supplying isolated loads (Fig. 2.5).

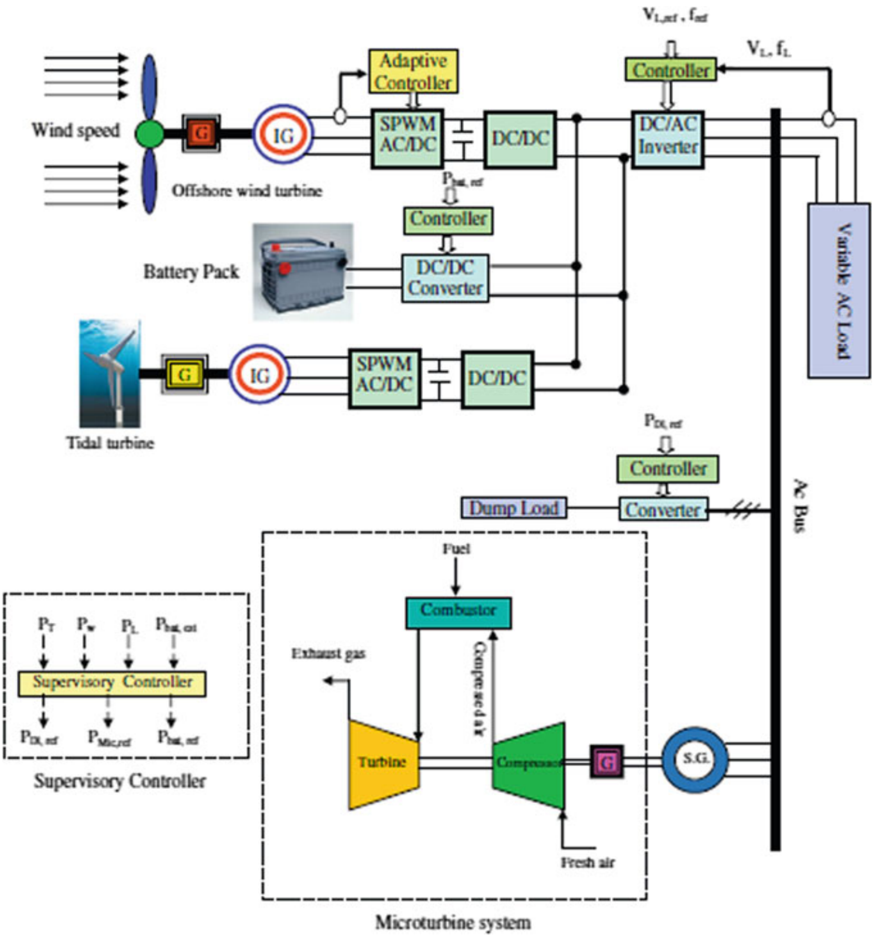

Fig. 2.5 Schematic diagram of a microturbine/renewable hybrid energy system [34]

2.2.3.3 Hybridization of Microturbine with Residential Rooftop Solar PV System

The application of grid-connected PV system has found more market in commercial and industrial sectors than residential sectors. For urban residential buildings, a grid-connected solar PV system might not be cost effective owing to the fact that most electricity usage will not be offset by the investment cost of the solar PV system. The reason is that unlike industrial and commercial customers, in urban residential buildings, more amount of electricity is needed during the evening than during the day, while the PV panels produce power only during the day. To solve this issue, several approaches are possible. The first one is to sell the excess power to the utility grid during the day when the residential load demand is insignificant.

However, selling a large amount of PV excess power to the distribution network will lead to a less cost-effective residential solar PV system because of the less attractive feed-in tariff (FIT) offered by many utility grids. The second solution is to use battery for storing the excess power during the day and use it later in the morning and evening when the load demand is high. However, the use of battery bank may not lead to a cost-effective residential rooftop solar PV project due to the high initial investment cost and low lifetime of the battery bank. Another solution is the use of a solar PV/CHP hybrid energy system [35]. Although the initial capital cost of a CHP maybe relatively high, the technology has shown to have an attractive payback period of between 4 and 10 years [30]. The reason is that CHP has a long lifetime (up to 20 years) and a relatively low maintenance cost.

2.2.4 Economic Analysis of a Microturbine

The cost-effectiveness of any system can be analyzed based on various economic performance indicators, such as payback period (PBP), net present value (NPV) or net present worth (NPW), internal rate of return (IRR), benefits/cost ratio (BCR) and life cycle cost (LCC), also called net present cost (NPC) [36]. However, the LCC is one of the most used methods due to the fact that it takes into account the total costs and revenues of the system components over the project lifetime. Another feature of LCC is that it helps to make choice between more than one alternative in order to have an optimal economic decision-making. For this reason, LCC is considered in this work. However, since the energy yield is another useful performance index for energy generation systems, a ratio between LCC and the energy yield, referred to as levelized cost of energy (LCOE) is usually used as the performance indicator for these systems.

2.2.4.1 Life Cycle of a Microturbine

The LCC or NPC condenses all the costs (positive) and revenues (negative) occurring within the MT lifetime project. In contrast to the NPV calculation, the cash outflows or costs in NPC are considered to be positive, and cash inflows or revenues are negative.

Costs/cash outflows of the MT include the following:

- Initial capital investment costs: include the purchase cost, installation labour and interconnection and permitting costs.
- Operation and maintenance (O&M) costs: the cost of operating the MT to maintain its performance efficiency over its lifetime. This cost therefore includes the maintenance labour and consumable and spare parts. The cost of continual personnel training may also be included. O&M costs may also include insurance and taxes, such as the one due to carbon emissions.

- Fuel costs.
- Replacement costs: are actual costs to replace the MT system at its current market value. This will occur if the MT system is not operated until the project lifetime due. This may happen if the project lifetime is longer than the MT lifetime or the MT is accidently damaged before the end of its lifetime.
  Revenues/cash inflows include the MT:
- Income or energy cost savings: from selling power to the grid and/or thermal energy to the heat network,
- Salvage value: estimated resale value of MT at the end of the project lifetime.

Since all cash flows except the initial investment cost, occur at some future periods after installation, these are discounted at their present worth (PW) for the calculation of the LCC [36]. Hence, the LCC will consist of the MT initial capital investment of MT (C_0), PW of its O&M costs (C_{OM}), PW of its fuel costs (C_F), PW of its replacement costs (C_R), PW of its emission costs (C_E), PW of its energy cost savings (C_{ES}) and PW of its salvage value (S).

The LCC or NPC of a MT can be written as below:

$$\mathrm{LCC} = C_0 + C_{\mathrm{OM}} + C_{\mathrm{F}} + C_{\mathrm{R}} + C_{\mathrm{E}} + C_{\mathrm{ES}} + S \tag{2.20}$$

where C_0 is the initial capital investment; C_{OM} is the PV of the operation and maintenance cost; C_R is the PV of the replacement cost and is the salvage value. The formula that discounts future worth (FW) of C_{OM}, C_F, C_R, C_E, C_{ES} and S occurring at nth year, to their PW is given as follows [37]:

$$\mathrm{PW} = \mathrm{FW} * (1 + i)^{-n}, \quad (0 \leq n \leq N) \tag{2.21}$$

where n is the year at which the FW occurs; N is the project lifetime; $(1 + i)^{-n}$ is the present value factor or discount factor; and i is the interest or discount rate. Equation (2.21) shows that at year 0, PW = FW, which is the initial capital cost.

2.2.4.2 Levelized Cost of a Microturbine

After calculating the LCC, the LCOE of a MT can be obtained by dividing the annualized LCC, noted $(\mathrm{LCC})_A$ by the MT annual energy supplied as follows [38, 39]:

$$\mathrm{LCOE} = \frac{(\mathrm{LCC})_{\mathrm{A}}}{\sum_{m=1}^{12} N_{\mathrm{d}} * L_m} = \frac{\mathrm{LCC} * \mathrm{CRF}}{\sum_{m=1}^{12} N_{\mathrm{d}} * L_m} \tag{2.22}$$

where N_d is the number of days per month, L_m is the monthly daily total electrical and thermal energy supplied by the microturbine per month; CRF is the capital recovery cost, expressed as below:

$$\mathrm{CRF} = \frac{i(1+i)^N}{(1+i)^N - 1}. \tag{2.23}$$

2.2.5 Systems Optimization

The overall efficiency of most energy systems can be improved on four different levels, namely technology (T), equipment (E), operation (O) and performance (P). This is referred to as POET concept [40]. While technology efficiency improvement occurs during the design phase by using efficient energy conversion methods, equipment and operation efficiency are achieved during operation of the system. Equipment efficiency is usually through retrofitting of old components of the energy conversion system by new and efficient components. However, this will often require high investment costs and long payback periods. The operation efficiency is achieved through optimal coordination of the system variables and working time. This, on the other hand, will require lower investment cost and shorter payback period. The well-known example of operation efficiency improvement on energy generation systems is the economical load dispatch (ELD), which consists of scheduling different fossil fuel generators to produce optimal powers in such a way to meet the system load consumption at the possible lowest fuel cost, while meeting the transmission network and generator operation constraints.

Systems optimization has also been widely applied to industrial processes as a supervisory control system, sitting at the upper control layer [41]. The aim of this is to optimally adjust in real time, the set points of the lower control layer, usually referred to as regulatory control system, in such a way to either minimize costs or maximize profits. Hence, depending on the performance indices, different control objective, such as minimization of energy consumption, energy cost [41–44], emissions and downtime, and maximization of total plant throughput and product quality can be considered.

ELD is also a kind of systems optimization that has shown great potential to be applied to microgrids composed of multi-area MT or CHP energy production where the cost of power production (for MT microgrid) or cost of both power and heat (for CHP microgrid) and sometime the cost of emission are minimized while satisfying the demand and operational limitations. References such as [45–48], the ELD problem is applied to a multi-area CHP system by using different optimization algorithms, such as linear programming, Cuckoo search, group search optimization, double benders decomposition to minimize the total cost associated with the production of power, heat and emissions.

The optimization problem of a multi-area CHP network can be generally formulated as a multi-objective optimization problem as follows [10, 49–51]:

$$\text{Min } C_{\mathrm{P}} + C_{\mathrm{H}} + C_{\mathrm{E}}, \tag{2.24}$$

where C_{P} is the total power production cost from all CHPs; C_{H} is the total heat production cost from all CHPs; and C_{E} is the total emission production from all CHPs.

Subject to

(a) power balance,
(b) heat balance,
(c) power generation limits and
(d) heat generation limits.

2.2.6 Comparison with Reciprocating Engines

2.2.6.1 Advantages

Some of the advantages of MT systems are given as follows:

- high system reliability: the simple working principle of MT due to its pure rotation motion and smaller number of moving parts provides higher reliability compared to reciprocating engines.
- stability: the MT provides a shorter response time in terms of load variations. The steady-state frequency regulation is also much better compared to most generation systems.
- light weight and compact size: MTs are very light and can be installed in a reduced space when compared to reciprocating engines.
- higher power-to-weight ratio: for a given weight, MTs produce higher power when compared to reciprocating engines.
- fuel flexibility: MTs can use a wide range of fuels, such as natural gas, propane, diesel or light oil.
- higher efficiency in cogeneration: since the exhaust gas has high temperature in MTs, higher system efficiency can be achieved in large MT systems.
- lower emission: the combustion products are cleaner than that from reciprocating engines, especially when natural gas is used as fuel.
- lower maintenance cost: the service interval is higher compared to that reciprocating engines since foil bearings and air-cooling operating without lubricating oil, coolants or other hazardous material are used.
- Noise level: MTs provide a quieter operation than reciprocating engines.

2.2.6.2 Disadvantages

- high investment cost: MTs require a higher investment cost due to the high temperature materials used.

- higher skills: MTs require extremely skilful and knowledgeable workers due to the higher level technology involved.
- robustness: the efficiency of MTs is more sensitive to ambient conditions than reciprocating engines.
- low fuel to electricity efficiency: the fuel efficiency of MTs is lower than that a well-designed reciprocating engines.

2.3 Conclusion

DG is a small-scale technology used to produce energy in the form of power or both power and heat at or near the consumer load points. DG can be classified as renewable and non-renewable DG technologies. DG units based on renewable energy technologies include, for instance, solar, wind, hydro, biomass and geothermal, while those based on fossil fuel include, mainly, reciprocating engines and MTs. Non-DG technologies have gained a lot of popularity because of their economic and technical benefits such as fuel economy, quick start-up, high availability, high efficiency, reliability, rigidity, multiple fuels operation, durability, low capital cost, low operating cost, high efficiency, low cost of installation and utilization for multiple applications. These characteristics have made non-renewable DG technologies to be widely accepted for industrial, commercial and domestic applications. Currently, non-renewable DG technologies are being used as prime movers for automobiles, industrial equipment, ship propulsion and numerous machinery and equipment. They are also flexible and suitable for electrical power generation and CHP applications. Non-renewable DG technologies can be utilized by the utilities and consumers to offer power solutions through stand-alone, peak shaving, grid support, backup, CHP, standby or emergency, prime and continues applications.

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