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Residential cogeneration systems: review of the current technology

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Abstract

There is a growing potential for the use of micro-cogeneration systems in the residential sector because they have the ability to produce both useful thermal energy and electricity from a single source of fuel such as oil or natural gas. In cogeneration systems, the efficiency of energy conversion increases to over 80% as compared to an average of 30–35% for conventional fossil fuel fired electricity generation systems. This increase in energy efficiency can result in lower costs and reduction in greenhouse gas emissions when compared to the conventional methods of generating heat and electricity separately.

Cogeneration systems and equipment suitable for residential and small-scale commercial applications like hospitals, hotels or institutional buildings are available, and many new systems are under development. These products are used or aimed for meeting the electrical and thermal demands of a building for space and domestic hot water heating, and potentially, absorption cooling.

The aim of this paper is to provide an up-to-date review of the various cogeneration technologies suitable for residential applications. The paper considers the various technologies available and under development for residential, i.e. single-family ($<10\,\mathrm{kW_e}$) and multi-family (10–30 $\mathrm{kW_t}$) applications, with focus on single-family applications. Technologies suitable for residential cogeneration systems include reciprocating internal combustion engine, micro-turbine, fuel cell, and reciprocating external combustion Stirling engine based cogeneration systems. The paper discusses the state of development and the performance, environmental benefits, and costs of these technologies.

Keywords: Residential cogeneration; Fuel cell cogeneration; Internal combustion engine cogeneration; Micro-turbine cogeneration; Stirling engine cogeneration

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Contents

1. Introduction

Cogeneration (also known as combined heat and power, CHP) is the simultaneous production of electrical or mechanical energy (power) and useful thermal energy from a single energy stream such as oil, coal, natural or liquefied gas, biomass or solar [1].

Cogeneration is not a new concept. Industrial plants led to the concept of cogeneration back in the1880s when steam was the primary source of energy in industry, and electricity was just surfacing as a product for both power and lighting [2]. The use of cogeneration became common practice as engineers replaced steam driven belt and pulley mechanisms with electric power and motors, moving from mechanical powered systems to electrically powered systems. During the early parts of the 20th century, most electricity generation was from coal fired boilers and steam turbine generators, with the exhaust steam used for industrial heating applications. In the early 1900s, as much as 58% of the total power produced in the USA by on-site industrial power plants was estimated to be cogenerated [3].

The construction of central electric power plants and reliable utility grids led to the reduction in the cost of electricity, and many industrial plants began buying electricity from utility companies and stopped generating their own. Thus, on-site industrial cogeneration declined in the US accounting for only 15% of total electrical generation capacity by 1950 and dropped to about 5% by 1974. In addition, other factors that led to the decline of cogeneration were the increasing regulatory policies regarding electricity generation, low fuel costs, advances in technology resulting in products like packaged boilers, and tightening environmental controls. However, the downward trend started reverting after the first fuel crisis in 1973. Because of energy price increases and uncertainty of fuel supplies, systems that are efficient and can utilise alternative fuels started drawing attention. In addition, cogeneration gained attention because of the lower fuel consumption and emissions associated with the application of cogeneration. Today, because of these reasons, various governments especially in Europe, US, Canada and Japan are taking leading roles in establishing and/or promoting the increased use of cogeneration applications not only in the industrial sector but also in other sectors including the residential sector [3].

There is a growing potential in the use of micro-cogeneration systems in the residential sector because they have the ability to produce both useful thermal energy and electricity from a single source of fuel such as oil or natural gas with a high efficiency. In cogeneration systems, the efficiency of energy conversion increases to over 80% as compared to an average of 30–35% in conventional fossil fuel fired electricity generation systems. Fig. 1 illustrates how the internal energy from the fuel is converted into useful thermal energy and electrical energy for a conventional fossil fuel fired electricity generation and a cogeneration system [4].

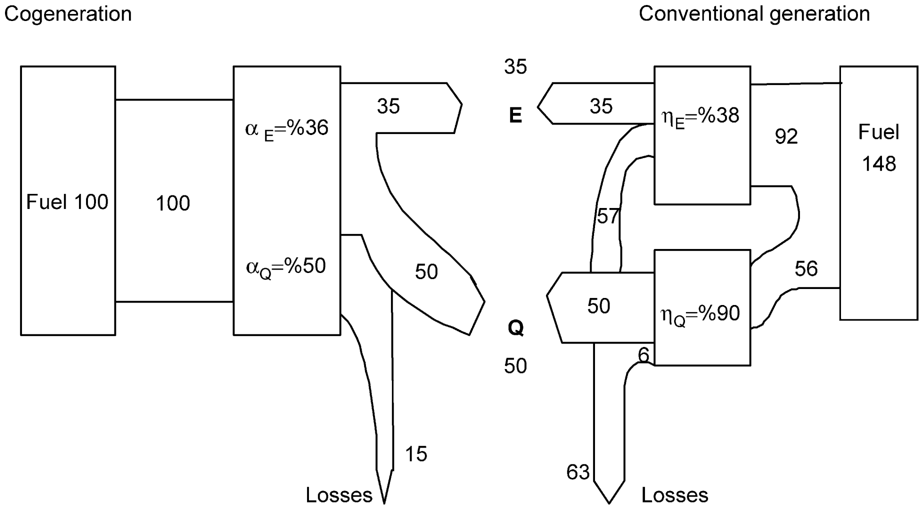

Fig. 1. Cogeneration versus conventional generation [4], where α_E, part of the energy transformed into electricity in a cogeneration unit, α_Q, part of the energy transformed into usable in a cogeneration unit, η_E, electrical yield of an electrical power plant (production of electricity only), η_Q, yield of a boiler (production of heat only), E, electricity demand, Q, heat demand.

The increase in energy efficiency with cogeneration can result in lower costs and reduction in greenhouse gas emissions when compared to the conventional methods of generating heat and electricity separately [5]. The concept of cogeneration can be related to power plants of various sizes ranging from small scale for residential buildings to large scale cogeneration systems for industrial purposes to fully grid connected utility generating stations. Organizations that would benefit from cogeneration are those that could use the electricity and heat energy produced by the system. Consequently, cogeneration is suitable for building applications provided that there is a demand for the heat energy produced.

Building applications suitable for cogeneration include hospitals, institutional buildings, hotels, office buildings and single- and multi-family residential buildings. In the case of single-family applications, the design of systems poses a significant technical challenge due to the non-coincidence of thermal and electrical loads, necessitating the need for electrical/thermal storage or connection in parallel to the electrical grid. However, cogeneration systems for multi-family, commercial or institutional applications benefit from the thermal/electrical load diversity in the multiple loads served, reducing the need for storage.

Cogeneration applications in buildings have to satisfy either both the electrical and thermal demands, or satisfy the thermal demand and part of the electrical demand, or satisfy the electrical demand and part of the thermal demand. Depending on the magnitude of the electrical and thermal loads, whether they match or not, and the operating strategy, the cogeneration system may have to be run at part-load conditions, the surplus energy (electricity or heat) may have to be stored or sold, and deficiencies may have to be made up by purchasing electricity (or heat) from other sources such as the electrical grid (or a boiler plant) [6]. The surplus heat produced can be stored in a thermal storage device such as a water tank or in phase change materials, while surplus electricity can be stored in electrical storage devices such as batteries or capacitors. In addition, the operation of a cogeneration system may be dependent on varying electricity prices, making cogeneration systems financially attractive in periods of high electricity prices.

Cogeneration applications in the residential sector offer opportunities in terms of improving energy efficiency and reduction of GHG emissions. Technologies like Stirling engines and fuel cells seem promising for small-scale cogeneration for residential buildings in the future because of their potential to achieve high efficiency and low emissions level, but currently, internal combustion engines are the only systems available at reasonable cost [7]. In addition, internal combustion engines are attractive for small-scale cogeneration applications because of their robust nature and well-known technology. The other cogeneration technology that has potential for residential applications is micro-turbine systems. However, reciprocating internal combustion engines have higher efficiencies in the lower power range and the capital cost of micro-turbines is higher compared to that of reciprocating internal combustion engine cogeneration systems [8].

The efficiency of a cogeneration system is measured as the fraction of the input fuel that can usefully be recovered as power and heat. The remaining energy is lost as low temperature heat within the exhaust gases and as radiation and convention losses from the engine and generator. Water is produced as a combustion product when hydrocarbon fuel is burnt in the presence of oxygen, and the water is vaporized to steam by the heat of reaction. Manufacturers of cogeneration systems relate efficiency to the lower heating value of the fuel (LHV). LHV is defined as the higher heating value of the fuel (HHV)[1] less the energy required to vaporize the water produced during combustion [5]. It is also known as the net calorific value (NCV). The efficiency is generally expressed in terms of both electrical efficiency and overall efficiency:

$$\text{Electrical efficiency} = \frac{\text{electrical output (kW)}}{\text{fuel input (kW)}} \tag{1}$$

$$\text{Overall efficiency} = \frac{\text{useful thermal} + \text{electrical output (kW)}}{\text{fuel input (kW)}} \tag{2}$$

The efficiency of a cogeneration system depends on the type of the prime mover, its size, and the temperature at which the recovered heat can be utilized. Also, the efficiency depends on the condition and operating regime of the cogeneration unit [5].

Operating regimes are critical because cogeneration systems are rarely operated at less than 50% of their rated output. At low load, electrical efficiency drops significantly except for fuel cell and Stirling engine based cogeneration systems that have better performance for handling partial loads [3]. Also at low load, the heat to power ratio is affected with a greater portion of the thermal energy being recovered from the cooling water. Low heat leads to fluctuation in delivered power, increased maintenance and reduced lifetime. Thermal efficiency is maximized when cogeneration systems are controlled to follow the thermal load of a building [5].

When designing a cogeneration system for building applications, the utilization level of the system should be considered. This level is typically more than 4500 h/year [5]. High levels of reliability and availability are vital especially between scheduled outages required for carrying out preventive maintenance. Major maintenance is usually carried out once annually. Unscheduled stoppages are undesirable for cogeneration users and therefore steps should be taken to minimize the effects of outages.

Reliability is determined by the amount of unscheduled outage as a result of equipment failure, while availability is the proportion of time the cogeneration plant is available for use when needed [5]. Detailed definitions [5] of reliability and availability are

$$\%\ \text{Reliability} = \frac{T-(S+U)}{T-S} \times 100 \tag{3}$$

$$\%\ \text{Availability} = \frac{T-(S+U)}{T} \times 100 \tag{4}$$

where S, scheduled maintenance time, h/year; U, unscheduled maintenance time, h/year; T, time plant is required to be in service, h/year.

Apart from the energetic performance of a cogeneration system for residential or commercial applications, factors such as economic cost (i.e. fuel and maintenance costs), the environmental benefits, and the electricity rate structure impact the techno-economic

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[1] Higher heating value (HHV) is the total heat generated by the combustion of a fuel.

feasibility of cogeneration. Large-scale cogeneration systems gain from economies of scale and tend to have lower installed cost per unit power output ($/kW[2]) [9]. On the other hand, small-scale cogeneration systems tend to have higher capital cost which poses an economic barrier to their implementation. In addition, the perceived low reliability and durability of small-scale cogeneration hardware, incompatibility with HVAC technology and lack of flexibility with electric grid interconnectivity so far has limited their use in the residential sector [10].

There is a need to perform a feasibility study or an economic analysis to decide on the adoption of a cogeneration system because the application must be economically viable in order to proceed with the investment. Reliable information on costs, i.e. both investment costs such as capital and installation costs, and ongoing costs such as fuel, operation and maintenance costs need to be considered when contemplating on installing cogeneration systems.

Capital costs depend on the components that comprise the system and their specifications. These components include the following: the prime mover and generator set, heat recovery and rejection system, exhaust gas system and stack, fuel supply, control board, piping, ventilation and combustion air systems, shipping charges, and taxes, if applicable. Installation costs consist of installation permits, land acquisition and preparation, building construction, and installation of equipment. Some of these costs may not be applicable to residential and small commercial cogeneration systems. Ongoing costs include fuel, personnel (if applicable), maintenance and insurance costs.

Cogeneration applications often involve the burning of fossil fuels, which gives rise to different combustion products that are damaging to the environment. The combustion products obtained from burning fossil fuels include carbon dioxide (CO_2), oxides of nitrogen (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), unburnt hydrocarbons and particulates. However, since the efficiency of fuel utilization in cogeneration systems is higher that the efficiency of conventional energy conversion systems, the level of specific emissions (i.e. emissions per unit of useful energy produced) from cogeneration systems is lower than those with conventional systems.

A variety of types of cogeneration systems are commercially available, or under research and development, for the single- and multi-family residential building market and small scale commercial applications. These include reciprocating internal combustion engine (spark ignition—gasoline, or compression ignition—diesel), micro gas turbine based systems, fuel cell based systems and Stirling engine based systems. These technologies could replace the conventional boiler in a dwelling and provide both electricity and heating, and potentially absorption cooling, possibly with the surplus electricity exported to the local grid and surplus heat stored in a thermal storage device.

2. Objective

The objective of this paper is to provide an up-to-date review of the various cogeneration technologies suitable for residential applications. The paper considers

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[2] Unless otherwise noted, kW refers to kW (electric), and kW h refers to kW h (electric).

the various technologies available and under development for residential, i.e. single-family (<10 kW) and multi-family (10–30 kW) applications, with focus on single-family applications. Technologies suitable for cogeneration systems in this size range are reciprocating internal combustion based cogeneration systems, micro-turbine based cogeneration systems, fuel cell based cogeneration systems, and reciprocating external combustion Stirling engine based cogeneration systems. The paper discusses the state of development and the performance, environmental benefits, and costs of these technologies. In addition, this paper will provide a comparative assessment of these technologies in terms of their advantages, disadvantages, costs, efficiency, emissions, durability and availability.

3. Cogeneration technologies and products suitable for residential applications

Cogeneration, or combined heat and power (CHP) technology, is the combined production of electrical power and useful heat. In electricity generation from fossil fuels, the waste heat can be recovered from the cooling water and combustion gases to be used in heating purposes such as space heating, domestic water heating and to drive absorption chillers for cooling applications. Cogeneration technologies for residential, commercial and institutional applications can be classified according to their prime mover and from where their energy source is derived.

Apart from reciprocating engine and micro-turbine based cogeneration systems for residential, commercial and institutional applications, technologies most likely to be successful long term are fuel cell based cogeneration systems and Stirling engine cogeneration systems because of their potential to achieve high efficiency and low emission levels.

3.1. Reciprocating internal combustion engine based cogeneration systems

Reciprocating internal combustion engines are suitable for small-scale cogeneration applications because of their robust and well-proven technology; however they do need regular maintenance and servicing to ensure availability. They are available over a wide range of sizes ranging from tens of kilowatts to more than 10 MW, and can be fired on a broad variety of fuels with excellent availability [2], making them suitable for numerous cogeneration applications in residential, commercial, institutional and small-scale industrial loads.

3.1.1. Principle of operation

Reciprocating internal combustion engines are classified by their method of ignition: compression ignition (Diesel) engines and spark ignition (Otto) engines.

Diesel engines are primarily used for large-scale cogeneration, although they can also be used for small-scale cogeneration. These engines are mainly four-stroke direct injection engines fitted with a turbo-charger and intercooler. Diesel engines run on diesel fuel or heavy oil, or they can be set up to operate on a dual fuel mode that burns primarily natural gas with a small amount of diesel pilot fuel. Stationary diesel engines run at speeds between 500 and 1500 rpm. Cooling systems for diesel engines are more complex in comparison to the cooling systems of spark ignition engines and temperature are often lower, usually 85 °C maximum, thus limiting the heat recovery potential [3].

Compared to Diesel engines, spark ignition (SI) engines are more suitable for smaller cogeneration applications, with their heat recovery system producing up to 160 °C hot water or 20 bar steam output [3]. In cogeneration applications, spark ignition engines are mostly run on natural gas, although they can be set up to run on propane, gasoline or landfill gas. SI engines suitable for small cogeneration applications (e.g. residential) are open chamber[3] engines. Many SI engines derived from Diesel engines (i.e. they use the same engine block, crankshaft, main bearings, camshaft, and connecting rods as the diesel engine) operate at lower brake mean effective pressure (BMEP) and peak pressure levels to prevent knock. Consequently, because of the derating effects of lower BMEP, the SI versions of Diesel engines usually produce 60–80% of the power output of the parent diesel [11]. Currently, the emission profile of natural gas fired SI engines has improved significantly through better design and control of the combustion process and through the use of exhaust catalysts. In addition, natural gas fired SI engines offer low first cost, fast start up, and significant heat recovery potential [11].

Today, highly efficient packaged cogeneration units, as small as 1 kW electric and 3 kW thermal, such as the unit manufactured by Honda Motor Co. [12], are available that can be used for variety of residential, commercial and institutional applications. These robust and high-efficiency cogeneration units are currently being used for meeting the base load requirement of a building or facility, as well as for backup or peak shaving applications. The advantages packaged reciprocating internal combustion cogeneration technology have over other cogeneration technologies are low capital cost, reliable onsite energy, low operating cost, ease of maintenance, and wide service infrastructure.

The basic elements of a reciprocating internal combustion engine based cogeneration system are the engine, generator, heat recovery system, exhaust system, controls and acoustic enclosure. The generator is driven by the engine, and the useful heat is recovered from the engine exhaust and cooling systems. The architecture of a typical packaged internal combustion engine based cogeneration system is shown in Fig. 2 [13].

The engines used in cogeneration systems are lean/stoichiometric mixture engines since they have lower emission levels, and the excess oxygen in the exhaust gases can be used for supplementary firing. However, in lean burn engines, the increased exhaust gas flow causes a temperature decrease, resulting in lower heat recovery from the exhaust boiler [11].

In most cogeneration systems, the engine is cooled using a pump driven forced circulation cooling system that forces a coolant through the engine passages and the heat exchanger to produce hot water. Natural cooling systems cool the engine by natural circulation of a boiling coolant through the engine, producing low-pressure saturated steam from the engine jacket.

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[3] Open chamber engine design has the spark plug tip exposed in the combustion chamber of the cylinder, directly igniting the compressed air/fuel mixture. Open chamber ignition is applicable to any engine operating near the stoichiometric air/fuel ratio up to moderately lean mixtures.

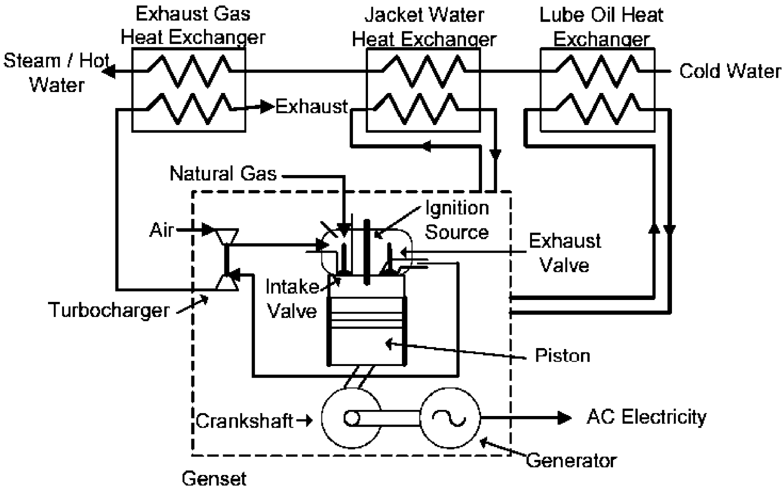

Fig. 2. Typical packaged internal combustion engine based (spark ignited) cogeneration system [13].

Both automotive and industrial type engines can be used in cogeneration systems. Automotive engines have a life expectancy of about 20,000 h. They are cheaper but less reliable than industrial engines that normally last up to 20 years. For capacities of 30 kW and less, derated automotive diesel engines modified for spark ignition are used [5]. This is because smaller engines are converted from diesel engine blocks for stationary applications as a result of the development of the natural gas infrastructure [11].

Depending on the engine size and type, high, medium and low speed engines can be used in cogeneration applications. The standard speed ranges for stationary engines are given in Table 1. High-speed engines generally have the lowest $/kW production costs of the three types of engines. This is because the engine power output is proportional to the engine speed, making high speeds engines to achieve the highest output per unit of displacement (cylinder size) and the highest power density. However, high-speed engines tend to have higher wear rates, thus resulting in shorter periods between minor and major overhauls [11]. Also, to boost the output of small displacement engines by as much as 40%, turbochargers are used. The higher operating pressure of turbocharged engines result in higher efficiency and lower fuel consumption, but makes spark ignition engines more susceptible to engine knock [14].

Table 1
Speed classification of reciprocating engines [11]

Speed classification	Engine speed (rpm)	Stoichiometric burn, spark ignition (MW)	Lean burn, spark ignition (MW)	Dual fuel (MW)	Diesel (MW)
High speed	1000–3600	0.01–1.5	0.15–3.0	1.0–3.5	0.01–3.5
Medium speed	275–1000	None	1.0–6.0	1.0–25	0.5–35
Low speed	58–275	None	None	2.0–65	2–65

3.1.2. Performance characteristics

Cogeneration systems are required to have high annual usage, usually with extensive periods of almost continuous operation in order to be profitable. Factors such as unscheduled outages that lead to high maintenance costs, the inconvenience caused by switching supply source and arranging or getting service engineer to investigate and correct faults, and costs associated with buying energy at unfavorable tariffs reduces the performance of cogeneration systems [5]. Thus, the performance of a cogeneration system is commonly measured in terms of its efficiency, reliability, availability, maintenance requirements and emissions.

3.1.2.1. Efficiency. Reciprocating internal combustion engines have efficiencies that range from 25 to 45%. In general, diesel engines are more efficient than spark ignition engines because of their higher compression ratios. However, the efficiency of large spark ignition engines approaches that of diesel engines of the same size [11].

Reciprocating internal combustion engines are generally rated at ISO conditions of 25 °C and 1 bar pressure [11]. Both output and efficiency of a reciprocating internal combustion engine degrades by approximately 4% per 333 m of altitude above 333 m, and about 1% for every 5.6 °C above 25 °C.

Results obtained from a survey of manufacturers show that the overall efficiency for reciprocating internal combustion engine based cogeneration systems is in the range of 85–90% with little variation due to size [5]. The electrical efficiency was shown to be in the range of 28–39%, and this increases as engine size becomes larger.

A project carried out in the UK [5] used remote monitoring systems to monitor the performance of cogeneration systems at 10 different sites over a period of 18 months. Each of the 35 kW capacity reciprocating internal combustion engine based cogeneration systems installed in the project showed high reliability, with an average overall efficiency of 75.1% based on the fuel HHV. When used with a condensing heat exchanger, the efficiency achieved was raised to 84.1%. The sites chosen for the project include two office buildings, residential blocks, a hospital, a leisure center, and an airport. As shown in Table 2, the results obtained from the project indicate that the units performed close to their design specifications. There were few unscheduled stoppages resulting from computer power supply, faulty sensor, battery charger malfunction, cooling water

Table 2
Cogeneration efficiencies obtained at 10 UK sites [5]

	Design specification	Monitored performance (average)
Electrical output (kW_e)	35	35.2
Thermal output (kW_{th})		
Cogeneration	70	68.4
Condensing heat exchanger	10	12.4
Electrical efficiency (%)[a]	26	25.5
Overall efficiency (%)[a]		
Cogeneration	78	75.1
Including condensing heat exchanger	85	84.1

[a] Efficiencies based on the HHV of the fuel.

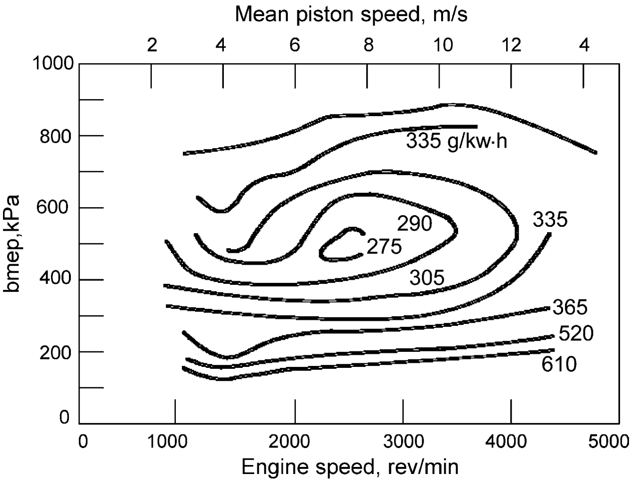

Fig. 3. Performance map for a spark-ignition engine [14].

blockage and a broken valve spring. The control systems installed with the units were able to detect and report these faults on time.

3.1.2.2. Part load performance. Reciprocating internal combustion engines used in cogeneration applications and power generation generally drive a synchronous generator[4] at constant speed to produce a steady alternating current (AC). The performance map and heat balance for a representative reciprocating internal combustion engine are given in Figs. 3 and 4, respectively.[5] Fig. 3 illustrates the performance map of a spark ignition engine showing contours of constant brake specific fuel consumption (bsfc) in g/kW h. The minimum bsfc point is achieved close to mid-range in speed and load [14]. Increasing the load at constant speed from the minimum bsfc point will cause an increase in bsfc since mixture enrichment is necessary to increase engine torque. Decreasing load at constant speed from the minimum bsfc standpoint will also cause an increase in bsfc because of the increase in the relative magnitude of the pumping work and heat losses that decrease engine efficiency.

For cogeneration applications, the heat to power ratio of the engine is critical. It can be seen in Fig. 4 that the percentage of fuel energy input used in producing mechanical work, which results in electrical generation, remains fairly constant until 75% of full load, and thereafter starts decreasing. This means that more fuel is required per kW h of electricity produced at lower partial loadings, thereby leading to decreased efficiency. Also from Fig. 4, it can be seen that the amount of heat generated from the jacket coolant water and exhaust gases increases as electrical efficiency of the engine decreases; i.e. the amount of

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[4] Synchronous is the condition whereby generator frequency and voltage levels match those of the public supply. When operating in parallel mode, it is mandatory to maintain these levels within closely specified limits.

[5] Engine characteristics vary with engine size and design. The trends shown in Figs. 3 and 4 can be considered to be representative.

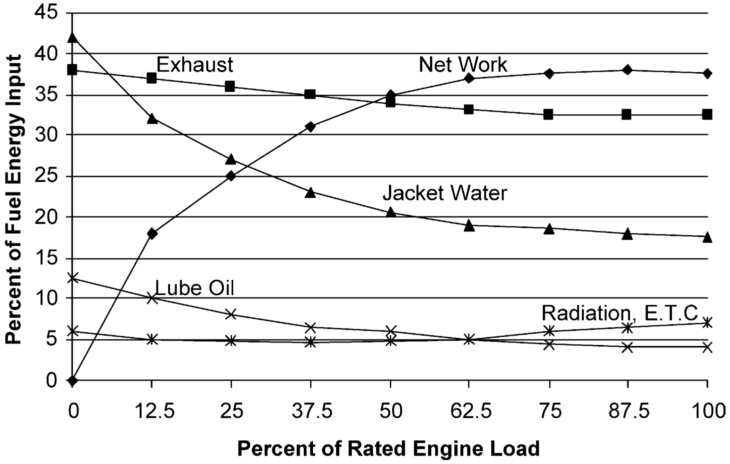

Fig. 4. Heat balance of reciprocating internal combustion engine [46].

useful heat derived from a cogeneration system increases as the efficiency of electric power delivered decreases.

3.1.2.3. Heat recovery. Not all of the heat produced in an internal combustion engine based cogeneration system can be captured in on-site electric generation, because some of the heat energy is lost as low temperature heat within the exhaust gases, and as radiation and convection losses from the engine and generator.

There are four sources, where usable waste heat can be derived from a reciprocating internal combustion based cogeneration system: exhaust gas, engine jacket cooling water, and with smaller amounts of heat recovery, lube oil cooling water and turbocharger cooling. Heat from the engine jacket cooling water accounts for up to 30% of the energy input while the heat recovered from the engine exhaust represents 30–50%. Thus, by recovering heat from the cooling systems and exhaust, approximately 70–80% of the energy derived from the fuel is utilized to produce both electricity and useful heat as shown in Table 3 [11,15].

The heat recovered from the engine jacket as hot water is often between 85 and 90 °C, while the heat recovered from the engine exhaust gases as hot water or low-pressure steam is from 100 to120 °C [11]. The recovered heat can therefore be used to generate hot water or low-pressure steam for space heating, domestic hot water heating, or absorption cooling.

Table 3
Internal combustion engine co-generation process [15]

	Without heat recovery (%)	With heat recovery (%)
Engine output at flywheel	35[a]	35[a]
Un-recoverable heat	65	21
Recoverable heat	0	44[a]
Total useful energy	35[a]	79[a]

[a] Values represent useful energy.

Heat recoveries from reciprocating internal combustion engine based cogeneration systems cannot be made directly to a building's heating medium because of problems associated with pressure, corrosion, and thermal shock. Therefore, shell and tube heat exchangers or plate heat exchangers are used to transfer heat from the engine cooling medium to the building's heating medium. Condensing heat exchangers can be employed to recover the latent heat that would otherwise be lost, however, they are suitable with natural gas fired systems because of corrosion problems associated with other fossil fuels [5].

3.1.2.4. Maintenance. Routine inspections, adjustments and periodic maintenance are required with reciprocating internal combustion engines. These involve changing of engine oil, coolant and spark plugs, often carried out for every 500–2000 h. Manufacturers often recommend a time interval for overhaul, from 12,000 to 15,000 h of operation for a top-end overhaul and 24,000–30,000 h of operation for a major overhaul. A top-end overhaul involves a cylinder head and a turbo-charger rebuild, while a major overhaul involves piston/ring replacement as well as replacement of crankshaft bearings and seals. A typical maintenance cost for reciprocating internal combustion engines that include overhaul is from 0.01 to 0.015 $/kW h [16].

With proper maintenance, modern internal combustion engine based cogeneration systems operate at high levels of availability. In a demonstration project conducted in UK involving three reciprocating internal combustion engine based cogeneration systems, the availability was found to be in the 87–98% range, which agrees well with the manufacturers' specifications [5].

3.1.2.5. Emissions. The primary pollutants associated with reciprocating internal combustion engines are oxides of nitrogen (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs—unburned, non-methane hydrocarbons). Other pollutants like oxides of sulphur (SO_x) and particulate matter are primarily dependent on the type of the fossil fuel and type of the engine used. Generally, SO_x emissions are related to large, slow speed diesel engines fuelled by heavy oils [11]. Particulate matter is an issue for Diesels operated with liquid fuels.

NO_x emissions are critical with reciprocating internal combustion engines. They are produced by burning fossil fuels in the presence of oxygen. NO_x production is dependent on temperature, pressure, combustion chamber geometry and air–fuel mixture of the engine. In most cases, they are a mixture of NO and NO_2 in variable proportion. Lean burn natural gas fired engines produce the lowest while diesel engines produce the highest NO_x emissions as shown in Table 4 [11].

Low NO_x emission levels are achieved with lean burn (and ultra lean burn) engines fitted with air/fuel ratio controllers [5], and stoichiometric engines fitted with three-way catalytic converters[6]. A three-way catalytic converter treats the exhaust gases with

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[6] Three-way catalytic converter is the basic catalytic converter process that reduces concentrations of all three major pollutants—NO_x, CO and unburned hydrocarbons with an air–fuel ratio at or close to stoichiometric. NO_x and CO emissions are reduced by 90% or more while unburned hydrocarbons are reduced approximately 80% in a properly controlled three-way catalytic system. The three-way catalytic converter process is also called non-selective catalytic reduction (NSCR).

Table 4
Representative NO_x emissions from reciprocating engines [11]

Engines	Fuel	NO_x (ppmv)	NO_x (gm/kW h)
Diesel engines (high speed and medium speed)	Distillate	450–1350	7–18
Diesel engine (high speed and medium speed)	Heavy oil	900–1800	12–20
Lean burn, spark ignition engine	Natural gas	45–150	0.7–2.5

catalysts to convert NO_x back to nitrogen and oxygen. The three-way catalytic converter temporarily binds with the oxygen in the NO_x, thereby releasing the nitrogen, and the oxygen reacts with any CO or hydrocarbon present to form CO_2 and water [5]. Three-way catalytic converter technology is not applicable to lean burn gas engines or diesel engines because conversions of NO_x to N_2 and CO, and hydrocarbons to CO_2 and H_2O will not take place in excess amount of air [11]. An approach that involves selective catalytic reduction (SCR) can be used to remove NO_x from lean burn engines [5]. Selective catalytic reduction is normally used with large (>2 MW) lean burn reciprocating internal combustion engines because it can severely impact on the economic feasibility of smaller engines [11]. In selective catalytic reduction, a NO_x reducing agent like ammonia is injected into the hot exhaust gas before it passes through a catalytic reactor. NO_x reductions of 80–90% are achievable with selective catalytic reduction.

Currently, both high efficiency and low NO_x formation do not go together because to achieve low NO_x formation, spark timing needs to be optimized and air/fuel ratio of about 1.5–1.6 is required [5]. NO_x emission levels decrease as spark timing is retarded from maximum brake torque timing[7] (MBT). Retarding ignition timing from MBT increases exhaust temperature, and both engine efficiency and heat loss to the combustion chamber walls are decreased in the process. Ignition timing also depends on load. As load and intake manifold pressure are decreased, ignition timing is controlled to maintain optimum engine performance, thereby increasing NO_x emission levels [14]. Consequently, because of these factors, many product developers of lean burn gas engines offer different versions of an engine that include a low NO_x version and a high efficiency version [11]. These versions are based on different tuning of the engine controls and ignition timing. Achieving highest efficiency will result in conditions that produce about twice the NO_x. On the other hand, achieving lowest NO_x formation will result in sacrificing efficiency. In addition, engines optimized for low NO_x formation can result in higher CO and unburnt hydrocarbon emissions because if the mixture is too lean, misfiring and incomplete combustion occur, increasing CO and unburned hydrocarbons emissions [11].

Sulphur dioxide emissions are caused by the combustion of fossil fuels that contain sulphur. It has corrosive effect on cogeneration units, especially heat exchangers and the exhaust system. Reciprocating internal combustion engines operating on natural gas or de-sulphurized distillate oil produce negligible amount of SO_x emissions.

Carbon monoxide is caused by the incomplete combustion of fossil fuels due to inadequate oxygen or insufficient residence time at high temperature. In addition,

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[7] Maximum brake torque timing is a particular spark timing, which gives maximum engine torque at a fixed engine speed, mixture composition and flow rate.

CO emissions can occur at the combustion chamber walls as a result of cooling and due to reaction quenching in the exhaust process. Also, too lean conditions can lead to incomplete and unstable combustion and increasing the CO emission levels. CO is a poisonous gas, but its emission is negligible when the air–fuel ratio is controlled satisfactorily [11].

Unburned hydrocarbons are caused by incomplete oxidation during combustion of long chain hydrocarbons. They are particles of solid matter, often in small size, and their emissions from reciprocating internal combustion engines are often reported as non-methane hydrocarbons that contain a wide range of compounds, some of which are hazardous air pollutants.

Use of oxidation catalysts can reduce CO and unburned hydrocarbon emissions. These catalysts promote the oxidation of CO and hydrocarbons to CO_2 and water in the presence of excess oxygen. CO and non-methane hydrocarbon conversion levels of 98–99% are achievable while methane conversion may approach 60–70%. Currently, oxidation catalysts are being used for all types of engines especially with lean burn gas engines to reduce their relatively high CO and unburned hydrocarbon emissions [11].

Particulates are the product from poorly adjusted combustion processes, i.e. incomplete combustion of fuel hydrocarbon [5]. They are solid particles and appear as exhaust coloration or smoke. Particulate emissions are produced from engines, especially diesels that use a liquid fuel [11]. However, diesel engines produce less CO emissions compared to lean burn SI engines. Emissions characteristics provided by manufacturers for a range of reciprocating internal combustion engines are given in Table 5.

Table 5
Emission characteristics of reciprocating internal combustion engines used in cogeneration units

	Cummins						Coastintelligen	
Electrical output (kW)	7.5	16	16	20	35	50	55	80
Engine/fuel type	Diesel/ diesel	SI/NG	Diesel/ diesel	SI/NG	Diesel/ diesel	Diesel/ diesel	SI/NG	SI/NG
Emission control device	None	None	None	None	None	Turbocharger	Advanced catalytic converter	Advanced catalytic converter
Air–fuel ratio		16.8		16.6				
CR	18.5:1	9.4:1	18.5:1	9.4:1	17.3:1	16.5:1		
NO_x, (g/bhph)	12.6	7.8	12.6	8.2	6.99	7.97	<0.15[a]	<0.15[a]
CO, (g/bhph)	3.13	36.8	3.13	38.6	1.26	0.75	<0.60[a]	<0.60[a]
Unburned hydrocarbon (g/bhph)	1.64	1.3	1.64	1.2	0.50	0.4	<0.15[a]	<0.15[a]
SO_2, (g/bhph)					0.62	0.6		
Particulates (g/bhph)	0.66	Negligible	0.66	Negligible	N/A	0.13		

CR, compression ratio; NG, natural gas; SI, spark ignition; Sources of data: http://www.cumminspower.com/library/datasheets/home.jhtml, http://www.coastintelligen.com/pdfs/cogen_induction.pdf

[a] Emissions corrected to 15% O_2.

3.1.3. Commercially available reciprocating internal combustion engine based cogeneration systems and their costs

A number of reciprocating internal combustion engine based cogeneration systems suitable for the residential sector are currently available in the market. For example, Honda Motor Co. has developed a cogeneration unit specifically for single-family residential applications. Based on a natural gas fired internal combustion engine, the unit has 1 kW electrical and 3 kW thermal output. The overall energy efficiency of the unit is reported to be 85% [12]. Tokyo Gas lunched a 6 kW gas engine cogeneration system in February 2002, with an overall efficiency of 86% [17]. The Yanmar Diesel Engine Co. in collaboration with Osaka Gas Co. has developed a gas engine cogeneration package (9.8/8.2 kW) with an overall efficiency of 81.55/80.0%, and heat recovery rate of 58.0/56.5%. The unit has a high power generation load factor of 95% when combined with multi-switching equipment [18]. Cummins, Inc. also offers internal combustion engine based cogeneration systems ranging from 7.5 to 1750 kW, which run on diesel or natural gas, and are suitable for the single- and multi-family applications [19]. Similarly, the natural gas fuelled systems from Lister-Petter, Inc. (5–400 kW), Alturdyne Power Systems, Inc. (25–2 MW) and the 60–75 kW natural gas fuelled units of Tecogen, Inc. can be used for residential, commercial and institutional applications [15]. The R-series products manufactured by DTE Energy ranging from 8 to 1000 kW natural gas fuelled and 10–1000 kW diesel fuel fuelled systems are also suitable for residential, commercial and institutional applications [19]. Germany based company Senertec, has a cogeneration unit appropriate for single-family residential application, with 5.5 kW electrical output and 10 kW thermal output [20]. Table 6 summarizes the specifications for typical

Table 6
Reciprocating IC cogeneration system specifications

Specifications	Honda	Senertec		Cummins	Alturdyne	Coast-intelligen	Tecogen	MAN
Electrical capacity (kW)	1	5.5 (gas)	5.3 (fuel oil)	10	40	55	60	100
Electrical efficiency (%)[a]	21.3	27.5	30.5			30	26.4	30.6
Overall[a] efficiency[b] (%) HHV	85	90	90			78	83.1	81
Engine speed (rpm)				3600	1500	1825		1800
Thermal output (kW)	3.00	12.50	10.40			87.9	128.96	125.00
Fuel input (kW)	4.7	20	17.4			183.3	227.4	277.78
Natural gas consumption (m^3/h)				5.4 at full load	13.8 at full load			

[a] Electrical efficiency = electrical output (kW)/fuel input (kW).
[b] Overall efficiency = useful heat recovered (kW) + electrical output (kW)/fuel input (kW).

commercially available reciprocating internal combustion based cogeneration systems over the 1–100 kW size range.

The basic cost of a reciprocating internal combustion engine based cogeneration system depends on its rated output. Smaller packaged reciprocating internal combustion engines typically run at a higher RPM than larger systems and they are often modified from automotive or truck engines. These two factors combined make smaller packaged engines cost less than larger, slow speed engines. The smaller reciprocating internal combustion engines are skid mounted, and the package includes the necessary radiators, fans, starting, control and fuel systems, and piping connections. Some of the packaged systems are manufactured with an enclosure, integrated heat recovery system, and basic electric paralleling equipment [11].

Generally, reciprocating internal combustion based cogeneration systems less than 500 kW in size cost between 800 and 1300 $/kW, with higher cost for smaller cogeneration systems [5]. Estimated capital costs of various sizes of reciprocating internal combustion based cogeneration systems are given in Table 7. These costs reflect a generic representation of reciprocating internal combustion engine based cogeneration systems in each size category, and indicate that the cost per unit capacity decreases with increasing engine size.

Maintenance costs differ with the type, speed, size, and number of cylinders of an engine. These costs include maintenance labor, engine components and materials such as oil filter, air filters, spark plugs, gaskets, valves, piston rings, and oil. In addition, maintenance costs include minor and major overhauls. Small automotive derived engines may operate for 15,000–20,000 h before an overhaul is needed. On the other hand, industrial engines will operate for 30,000–40,000 h before an overhaul is carried out [5].

Maintenance cost for the 5.5 kW Senertec reciprocating internal combustion engine cogeneration system presented in Table 7 is estimated to be 0.014 $/kW h, with a maintenance interval of 3500 h. Data obtained from a manufacturer's survey [5] suggests that the maintenance costs for reciprocating internal combustion engine based cogeneration systems lie in the cost band of 0.008–0.013 $/kW h. The lowest figure reported was 0.005 $/kW h and the highest, for smaller systems, were up to 0.032 $/kW h [5]. Also, data obtained from the UK demonstration projects [5] show that maintenance costs for reciprocating internal combustion engine cogeneration systems ranged from

Table 7
Estimated capital costs ($/kW) for reciprocating engine cogeneration systems

Cost Component	Senertec[a]	North American cogeneration systems [9]			MAN [19]
Electrical capacity (kW)	5.5	7.1–10.7	20.1–23.3	30.3–35.0	100.0
Electrical efficiency (%)	27.5	28.1	37.4	33.1	30.6
Thermal efficiency (%)	62.5	56.5	50.0	51.2	50.4
Installed cost ($/kW)	2720	2800	1600	1300	1080

[a] The Senertec installed cost was based on an investment cost of $15,030 provided in the manufacturer's catalog. http://www.senertec.de/show_pdf.php?name=englisch

0.008 to 0.026 $/kW h and averaged 0.014 $/kW h, thus agreeing with the information obtained from the manufacturers survey [5].

3.2. Micro-turbine based cogeneration systems

Micro-turbine systems are scaled down versions of combustion turbines that provide reasonable electrical efficiency of about 30%, multi-fuel capability, low emission levels, and heat recovery potential, and need minimal maintenance [15]. For cogeneration applications, an overall efficiency of 80% and above can be achieved [8]. Existing micro-turbine systems range in size from 25 to 80 kW, a range suitable to meet the thermal and electrical requirements of multi-family residential, commercial or institutional buildings. In addition, research is ongoing for systems with capacities less than 25 kW, e.g. 1 and 10 kW [8], which will be suitable for the single-family residential buildings.

Micro-turbines offer a number of advantages when compared to reciprocating internal combustion based cogeneration systems. These include compact size, low weight, small number of moving parts and lower noise. In addition, micro-turbine based cogeneration systems have high-grade waste heat, low maintenance requirements (but require skilled personnel), low vibration and short delivery time. However, in the lower power ranges, reciprocating internal combustion engines have higher efficiency. Besides the use of natural gas, other fuels like diesel, landfill gas, ethanol, industrial off-gases and other bio-based liquids and gases can be used [8].

3.2.1. Principle of operation

The thermodynamic process of a micro-turbine involves the pressurization of intake air by the compressor. The compressed air and a suitable fuel are mixed and ignited in a combustion chamber. The resulting hot combustion gas expands turning the turbine, which drives the compressor and provides power by rotating the compressor turbine shaft. With a recuperator, the hot exhaust gas helps pre-heat the air as it passes from the compressor to the combustion chamber.

As shown in Fig. 5, the basic components of micro-turbine systems are the compressor, turbine generator and the recuperator. The compressor-turbine package is the heart of

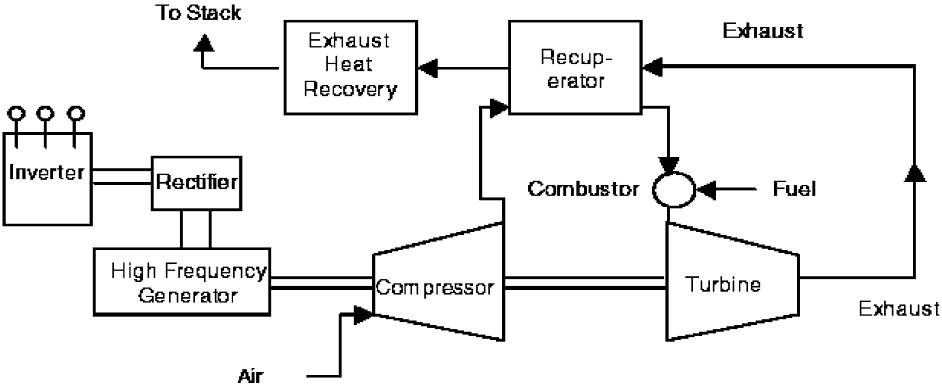

Fig. 5. Schematic of a recuperated micro-turbine based cogeneration unit [21].

a micro-turbine, which is mounted on a single shaft along with the electric generator. Two bearings support the single shaft. Micro-turbine systems with one shaft design have the potential for reducing maintenance needs and enhancing overall reliability. There are micro-turbines with two shaft designs, in which the turbine on the first shaft directly drives the compressor while the second shaft drives a gearbox and electrical generator producing 60 Hz power. The two-shaft design features more moving parts. However, they do not require complicated power electronics to covert high frequency AC power output to 60 Hz [21].

In micro-turbines, the turbo-compressor shaft generally turns at high rotational speeds of about 80,000–120,000 rpm. The physical size of components and rotational speed of micro-turbine systems are strongly influenced by the specific turbine and compressor design characteristics. For a specific design, as the power rating decreases, the shaft speed increases; hence the high shaft speed of the small micro-turbines [21].

Most micro-turbines are based on single-stage radial flow compressors. This is attributed to the size range of micro-turbines (0.23–2.3 kg/s of air/gas flow). For this range, radial flow components offer minimum surface and end wall losses, and provide highest efficiency when compared to large axial flow turbines and compressors. Radial flow turbine-driven compressors are similar to small reciprocating engine turbochargers in terms of design and volumetric flow [21].

3.2.2. Performance characteristics

Whereas performance of reciprocating internal combustion engines is well established and quantified, there is scant performance information on micro-turbine systems that is obtained from a limited number of demonstration projects. Data regarding actual efficiency, longevity, operating and maintenance costs of tested units are not widely known due to limited field-testing [13]. Similarly, information on reliability and availability for micro-turbines is still not sufficient due to limited field experience, even though manufacturers claim availability to be in the range of 90–95% [16]. To collect reliable performance information, including data availability and reliability information for micro-turbine systems, it is important to collect data while operating in different environments, operating modes and utility interconnections through extensive reliability, availability, maintainability and durability (RAMD) testing [22].

3.2.2.1. Efficiency. Micro-turbine designs are more complex than conventional simple-cycle gas turbines because of the addition of a recuperator to reduce fuel consumption, thereby substantially increasing efficiency. A recuperator has two performance parameters: effectiveness and pressure drop. Higher effectiveness recuperation necessitates large recuperator surface area, resulting in higher pressure drop as well as higher cost. In addition, the connections that attach the recuperator to the compressor discharge, the expansion turbine discharge, the combustion chamber inlet, and the system exhaust pose a challenge for product designers to make the recuperator connections in such a manner that will keep pressure loss and manufacturing cost low without compromising system reliability. However, as seen in Fig. 6, increasing recuperator effectiveness increases micro-turbine efficiency. Fuel savings of 30–40% can be derived from preheating using the most conventional metal recuperators [8]. Materials used for recuperators are stainless

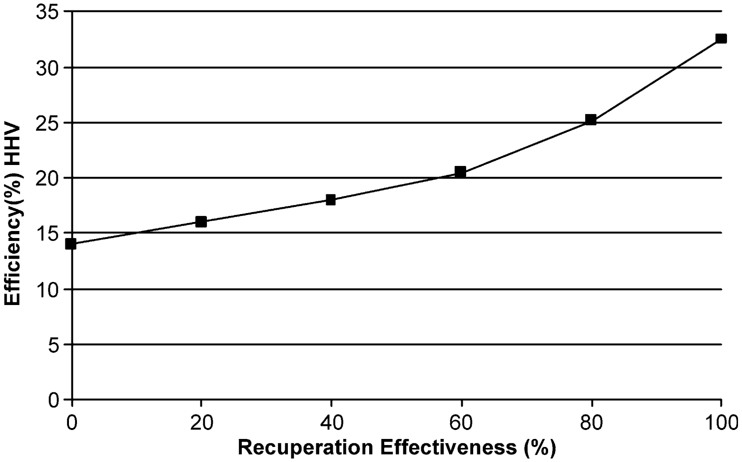

Fig. 6. Micro-turbine efficiency as a function of recuperator effectiveness [21].

steel when maximum operating temperature is 650 °C, Inconel for operating temperature of 800 °C, and ceramics for temperature greater than 870 °C.

The performance characteristics of several commercially available micro-turbine based cogeneration systems are summarized in Table 8. As seen from this table, electrical

Table 8
Micro-turbine cogeneration system performance characteristics [21]

	Capstone model 330 micro-turbine	IR energy systems 70LM(two shaft)	Turbec T100
Nominal electricity capacity (kW)	30	70	100
Electric heat rate (Btu/kW h), HHV	14,581	13,540	12,639
Electrical efficiency (%) HHV[a]	23.4	25.2	27.0
Fuel input (MMBtu/h)	0.437	0.948	1.264
Required fuel gas pressure (psig)	55	55	75
Cogeneration characteristics			
Exhaust flow (Ibs/s)	0.72	1.40	1.74
GT exhaust temperature (F)	500	435	500
Heat exchanger exhaust temperature (F)	150	130	131
Heat output (MMBtu/h)	0.218	0.369	0.555
Heat output (kW equivalent)	64	108	163
Total overall efficiency (%) HHV	73	64	71
Power/heat ratio[b]	0.47	0.65	0.62
Net Heat Rate (Btu/kW h)	5509	6952	5703
Effective electrical efficiency (%) HHV[c]	62	49	60

Notes: available thermal energy calculated based on manufacturer's specifications on turbine exhaust flows and temperatures, cogeneration heat recovery estimates are based on producing hot water for process or space heating applications.

[a] Electrical efficiencies are net parasitic and conversion losses.

[b] Power/heat ratio = cogeneration electrical power output (Btu)/useful heat output (Btu)

[c] Effective electrical efficiency = (cogeneration electrical power)/(total fuel into cogeneration system) − (total heat recovered/0.8).

efficiency increases as the electricity capacity of micro-turbines increase. Each manufacturer presented in Table 8 uses a different recuperator design, and tradeoff is often made between cost and performance. Micro-turbine performance involves the extent to which the recuperator effectiveness increases cycle efficiency and the recuperator pressure drop decreases cycle power. The pressure ratio is also an important factor; however, the pressure ratio is generally limited by material selection since the maximum temperature in the cycle increases with pressure. The data in Table 8 also indicate that electrical and the overall efficiencies of micro-turbine based cogeneration systems are lower than those of reciprocating engines and fuel cells.

The efficiency of micro-turbine based cogeneration systems can be increased by increasing the peak pressure and temperature in the cycle, requiring the development of high-temperature materials suitable for this purpose. However, higher temperatures can lead to higher NO_x emissions, necessitating the use of sophisticated combustor design to reduce NO_x emissions [8].

3.2.2.2. Part load performance. The output of a micro-turbine system is reduced by a combination of mass flow rate reduction (i.e. decreasing the compressor speed) and turbine inlet temperature reduction. Consequently, along with the output, the efficiency of a micro-turbine operating at part load is reduced. The variation of efficiency of a 30 kW micro turbine is given in Fig. 7.

Ambient conditions affect the power output and the efficiency of micro-turbine systems. Both power and efficiency decreases at elevated inlet temperatures. The power decrease is attributed to the decreased air mass flow rate (since density of air decreases as temperature increases), and the efficiency decrease is due to the higher power requirement by the compressor to compress air of higher temperature. For the same reasons, power output and efficiency decreases with decreasing pressure and increasing altitude. Figs. 8 and 9 show the variation in power and efficiency as a function of ambient temperature while Fig. 10 illustrates the altitude derating.

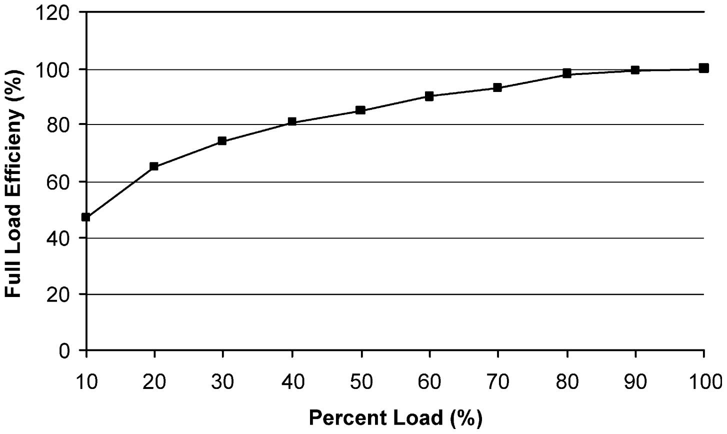

Fig. 7. Micro-turbine part-load power performance for a 30 kW micro-turbine (single shaft, high speed alternating system) [21].

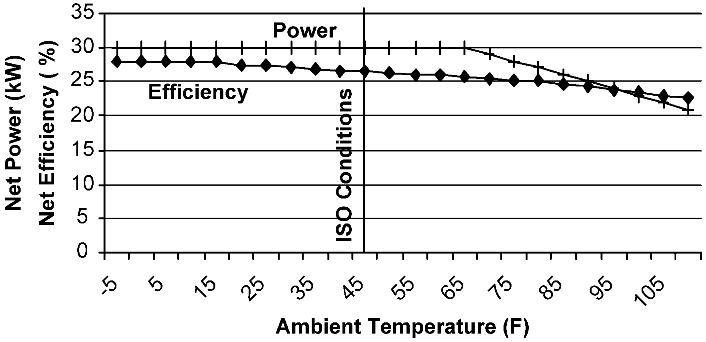

Fig. 8. Ambient temperature effects on a 30 kW Capstone micro-turbine performance source: http://www.microturbine.com/

3.2.2.3. Heat recovery. The exhaust gas of a micro turbine based cogeneration system is the source of heat recovery. Commonly, an integrated heat exchanger is used to extract heat from the exhaust gas before releasing the gas to the atmosphere. Depending on the application, hot water or steam may be produced. For example, the 80 kW micro turbine cogeneration system available from Kohler provides hot water in the 70–90 °C temperature range, and up to 350 kPA with plans to increase the temperature and pressure of the unit to interface with absorption chiller and refrigeration systems [23].

Use of a recuperator increases the electrical efficiency of a micro turbine cogeneration system, but reduces the recoverable heat from the exhaust gas. This may or may not be desirable depending on the application.

3.2.2.4. Maintenance. Due to their simple construction and few moving parts, micro-turbine systems have the potential for lower maintenance costs than that of reciprocating

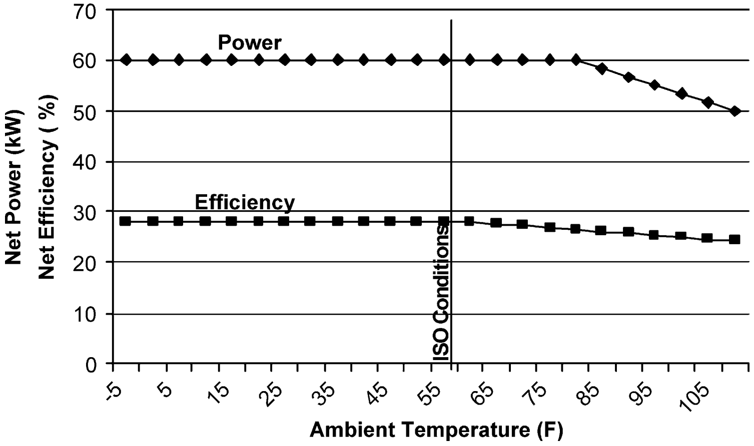

Fig. 9. Ambient temperature effects on a 60 kW Capstone micro-turbine performance. Source: http://www.microturbine.com/

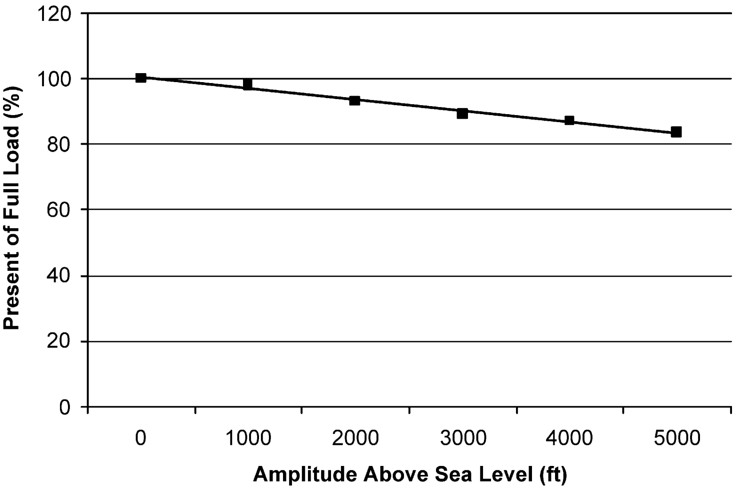

Fig. 10. Altitude effects on micro-turbine performance [21].

internal combustion engines. For example, since the lubricating oil is isolated from the combustion products, micro-turbines do not require frequent oil changes. Moreover, if air bearings are used in single shaft machines, there is no requirement for lubricating oil or water, reducing maintenance requirements even further. Normally, scheduled maintenance is carried out once annually, with maintenance costs in the 0.006–0.01 $/kW h range [16]. Most product developers offer 0.01 $/kW h for specialized maintenance that includes periodic inspections of the combustor, oil bearing in addition to regular air and oil filter replacements. An overhaul is required every 20,000–40,000 h depending on the product developers, design, and service [21]. An overhaul involves the replacement of the main shaft with the compressor and turbine attached, and if necessary, replacing the combustion chamber. In addition, other components are inspected to determine if wear has occurred so that necessary replacements can be made.

3.2.2.5. Emissions. Micro-turbines have the potential for producing low emissions. They are designed to achieve low emissions at full load, however, emissions are higher when operating under reduced load. The main pollutants from the use of micro-turbine systems are NO_x, CO and unburnt hydrocarbons, and negligible amount of SO_2. Emission characteristics of micro-turbine systems based on manufacturers' guaranteed levels are given in Table 9 [21].

NO_x is a mixture of mostly NO and NO_2 in variable composition. NO_x is formed by three mechanisms: thermal NO_x, prompt NO_x, and fuel-bound NO_x. The main NO_x formation mechanism associated with micro-turbines is the thermal NO_x, which is the fixation of atmospheric oxygen and nitrogen at high combustion temperatures. Thermal NO_x levels are affected by flame temperature and residence time. Prompt NO_x is formed from early reactions of nitrogen elements in combustion air and hydrocarbon radicals from the fuel. Fuel-bound NO_x are formed when the fuel contains nitrogen as part of

Table 9
Micro-turbine emission characteristics [21]

	Capstone model 330 micro-turbine	IR energy systems 70LM (two shaft)	Turbec T100
Nominal electricity cap.(kW)	30	70	100
Electrical efficiency (%) HHV	23	25	27
NO_x, ppmv	9	9	15
NO_x, lb/MW h[a]	0.54	0.50	0.80
CO, ppmv	40	9	15
CO, lb/MW h	1.46	0.30	0.49
THC, ppmv	<9	<9	<10
THC, lb/MW h	<0.19	<0.17	<0.19
CO_2, lb/MW h	1928	1774	1706
Carbon, lb/MW h	526	484	465

[a] Conversion from volumetric emission rate (ppmv at 15% O_2) to output based rate (lbs/MW h) for both NO_x and CO based on conversion multipliers provided by Capstone Turbine Corporation and corrected for differences in efficiency.

the hydrocarbon structure. Natural gas has negligible chemically joined fuel nitrogen; therefore produces negligible fuel-bound NO_x emissions [21].

CO emissions in micro-turbines occur as a result of incomplete combustion of fossil fuel. Insufficient residence time at high temperature and failure to achieve CO burnout from combustor wall cooling air may result in CO emissions. CO is often controlled to levels below 50 ppm both for health and safety reasons. At low loads, micro-turbines tend to have incomplete combustion, resulting in increased CO emissions [21].

Like reciprocating internal combustion engines, CO_2 emissions from micro-turbines have no direct effect on public health. However, CO_2 emissions are of concern because of their potential contribution to the greenhouse effect. CO_2 emission from micro-turbines is a function of both fuel carbon content and system efficiency. Use of natural gas in micro-turbine cogeneration systems and the high overall efficiency results in low CO_2 emissions.

3.2.3. *Commercially available micro-turbine based cogeneration systems and their costs*

Micro-turbine based cogeneration systems are being introduced into the market by manufacturers to meet the electrical and thermal demands of both building and industrial applications. Existing micro-turbine system sizes vary from 25 to 80 kW, but research is being carried out to develop systems in sizes less than 25 kW, for example 1 and 10 kW [8]. Today, several U.S manufacturers have micro-turbine units suitable for multi-family residential, commercial and institutional cogeneration applications. For example, Capstone Turbine Corporation has a 30 kW, and Honeywell Power Systems has a 75 kW capacity cogeneration units that can either be connected in parallel to the grid[8], or act as a standalone unit (i.e. not connected in parallel to the grid) to provide lower cost electricity and reliable backup [15]. Also, Elliot/Bowman Company has 45 and 80 kW

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[8] Parallel connection is a self contained system that monitors the grid around the clock; and whenever the system cost is less than that of the utility, it kicks off automatically supplying power to the site from the system.

Table 10
Micro-turbine based cogeneration systems specifications

Type of fuel used	Capstone micro-turbine[a]					Elliot/ Bowman[b]	Turbec[c]
	Natural gas/ gaseous propane	Diesel or kerosene	Biogas (landfill or digester gas)	Natural gas		Natural gas, propane, LPG, and butane	Natural gas
Electrical capacity (kW)	30	30	30	28	60	80	105
Electrical efficiency (%) LHV	26	25	26	25	28	28	30
Overall efficiency (%) LHV	91	90	91	91	89	75	78
Engine speed (rpm)	96,000	96,000	96,000	96,000	96,000		70,000
Thermal output (kW)	85	85	85	85	150	136	167
Fuel input (kW)	126.91	127.49	126.91	123.09	235.64	288	350

[a] http://www.microturbine.com/
[b] http://www.bowmanpower.com/DataSheets/TG80RC-G.pdf
[c] http://www.socalgas.com/business/powergeneration/docs/Turbec_100kW.pdf

units, and Kohler Power Systems has a 80 kW unit [23], and Turbec has a 105 kW unit [24]. Northern Research and Engineering Company is developing several products in the 30–250 kW range [22]. Specifications of a number of commercially available micro-turbine based cogeneration systems in the 30–100 kW size range are given in Table 10.

Other companies in the US, such as Allison Engine Company, Williams International, and Teledyne Continental Motors, as well as European (Volvo and ABB) and Japanese (Toyota) companies have indicated interest in developing micro-turbine based cogeneration products [22].

Installed costs of micro-turbines can vary depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, emission control requirements, current labor rates, and whether the system is a new or retrofit application.

Micro-turbine packages are comprised of the turbo-generator package and power electronics. They offer interconnection and paralleling functionality as part of the package cost. In addition, they often come with an integrated heat exchanger heat recovery system and a gas booster compressor [21]. Comprehensive cost estimates for micro-turbine cogeneration systems supplying electricity and hot water are given in Table 11, assuming that the cogeneration system produces hot water.

3.3. Fuel cell based cogeneration systems

Fuel cell technology is an emerging technology with a potential for both electricity generation and cogeneration applications with performance advantages and in an

Table 11
Estimated capital costs for micro-turbine based cogeneration systems [21].

	Capstone model 330 micro-turbine	IR energy systems 70LM (two shaft)	Turbec T100
Nominal electricity cap (kW)	30	70	100
Equipment costs ($):			
Micro-turbine	1000	1030	800
Gas booster compressor	Included	Included	Included
Heat recovery	225	Included	Included
Controls/monitoring	179	143	120
Total equipment	1403	1173	920
Labor/material costs ($):			
Project and construction Mgt	418	336	226
Engineering and fees	154	146	112
Project contingency	72	58	45
Project financial (Interest during construction)	40	32	25
Total plant cost ($/kW)	2516	2031	1561

environmentally friendly fashion. The advantages of fuel cell cogeneration systems include low noise level, potential for low maintenance, excellent part load management, low emissions, and a potential to achieve an overall efficiency of 85–90% even with small units. Stationary power fuel cells typically burn natural gas, and release fewer environmentally harmful emissions than those produced by a combustion cogeneration plant. With a fuel cell, carbon dioxide emissions may be reduced by up to 49%, nitrogen oxide (NO_x) emissions by 91%, carbon monoxide by 68%, and volatile organic compounds by 93% [25]. Low emissions and noise levels make fuel cells particularly suitable for residential, commercial and institutional applications. However, the high cost and relatively short lifetime of fuel cell systems are their main drawback. Ongoing research to solve technological problems and to develop less expensive materials and mass production processes are expected to result in advances in technology that will reduce the cost of fuel cells [3].

3.3.1. Principle of operation

Fuel cell technology involves the reaction of hydrogen with oxygen in the presence of an electrolyte to produce electricity without combustion and mechanical work. Water and heat are produced as by-products. The reaction is achieved through the electrochemical oxidation of a fuel (hydrogen) and the electrochemical reduction of oxygen. The following equations illustrate the electrochemical reactions:

$$\text{Anode}: H_2 \rightarrow 2H^+ + 2e^- \tag{5}$$

$$\text{Cathode}: 2H + 1/2O_2 + 2e^- \rightarrow H_2O \tag{6}$$

$$\text{Totalreaction}: H_2 + 1/2O_2 \rightarrow H_2O \tag{7}$$

The overall reaction is exothermic; therefore, the released heat can be harnessed for space and domestic hot water heating for residential, commercial or institutional applications. The hydrogen used as fuel can be produced from different sources such as natural gas, propane, coal, or through the electrolysis of water.

A fuel cell system consists of several subsystems, which include the fuel cell processor (i.e. hydrogen reformer), fuel cell stack, auxiliary systems required for operation and the inverter. The process of producing hydrogen from a fuel source such as natural gas is called reforming, and the process can either be internal reforming or external reforming depending on the type of fuel cell. The general design of most fuel cells is similar except for the type of electrolyte used. Currently, there are various types of fuel cell technologies in different stages of development. These include alkaline fuel cells (AFC), polymer electrolyte membranes (PEM), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), and lately, direct methanol fuel cells (DMFC).

Alkaline fuel cells have been used in the past for NASA's Apollo mission and are still being used for space applications. Potassium hydroxide (KOH) is often used as electrolyte with concentration of about 30%. Alkaline fuel cells are characterized as low temperature fuel cells because they operate at a temperature of 60–80 °C. Units of up to 100 kW have been constructed. Manufacturers such as Acumentrics have developed products ranging from 2 to 100 kW. In addition, Astris Energi, Inc. has developed products ranging from 1 to 5 kW [26].

PEMFC consists of a solid polymeric membrane electrolyte, situated between two platinum catalyzed porous electrodes—the anode and cathode. At the anode, hydrogen fuel dissociates into free protons (positively charged hydrogen ions) and electrons. The electrons are conducted as usable electric current through the external circuit. The protons migrate to the cathode where they combine with oxygen from the air and electrons from the external circuit to form water and heat. The reaction is an exothermic reaction. PEMFCs are classified as low temperature fuel cells due to their relatively low operating temperature of under 100 °C, typically 80 °C. Units of up to 100 kW have been constructed and are proving to be appropriate for residential applications because of their low operating temperature (under 100 °C) and favorable cost [3].

Phosphoric acid fuel cells are the most advanced fuel cells for terrestrial applications and the first type of fuel cell to be commercialized [3]. Their operating temperature, around 200 °C makes them attractive for cogeneration applications. The electrolyte used for PAFC is phosphoric acid with air as the oxidizer. The hydrogen used as fuel is produced from an external reformer fuel such as natural gas or methanol. Packaged units of 200–250 kW are available on the market while demonstration systems of 25–11 MW have been constructed in Europe, USA and Japan [3]. Fuji Electric Co. Ltd has developed a 100 kW PAFC [17], suitable for the commercial or institutional application.

A molten carbonate fuel cell uses a mixture of molten alkali carbonate retained in a porous lithium aluminate matrix, used as electrolyte. In the liquid phase, the electrolyte operates at a temperature from 600 to 700 °C. This high operating temperature makes internal reforming possible. The fuel used consists of a gaseous mixture of H_2, CO and CO_2, which is produced from reforming hydrocarbon such as natural gas, or coal gasification. MCFC technology is still in the developmental phase with experimental units being constructed. They have good prospects for industrial applications especially in the utility sector. Their electrical efficiency is expected to be higher than 50% [3].

Solid oxide fuel cells are a solid-state power system that uses ceramic material called yttria-stabilized zirconia ($Y_2O_3ZrO_2$) as the electrolyte layer. They are classified as high temperature fuel cells with an operating temperature of 950–1000 °C. The fuel used to produce hydrogen or a mixture of H_2 and CO can be derived from internal reforming of hydrocarbons or coal gasification. Their high operating temperature and the high-grade residual heat produced can be utilized for space heating and water heating loads for residential, commercial or institutional applications. Manufacturers such as Sulzer Hexis offers a product based on SOFC technology, suitable for residential cogeneration with 1 kW electrical output [20].

Direct methanol fuel cells are the newest member to the fuel cell family. They are similar to PEMFC because they both use polymer membrane as electrolyte. However, for the DMFC, the anode catalyst draws the hydrogen from the liquid methanol towards itself, eliminating the need for a reformer. Fuel Cell Resources, Inc. has developed DMFC products ranging from 1 to 7 kW (stack only) [26].

3.3.2. Performance characteristics

Unlike reciprocating engines, performance data for fuel cell systems are based on limited number of demonstration projects, however, they have the potential to offer the highest efficiency for small-scale applications [13]. Through various demonstration projects, such as the US. Department of defense fuel cell demonstration program [27], utility demonstration programs [28] and others [29], the potential benefits of fuel cells for building applications have been demonstrated in a variety of climates. As indicated by various researchers, for small-scale cogeneration applications in the 1–50 kW range, PEMFC and SOFC based cogeneration systems promise the advantage of high cogeneration efficiencies (as high as 80%), reduced fuel use, reduced environmental impacts, and a good match for the residential thermal/electric (*T*/*E*) load ratios [29–31]. PEM fuel cells are considered to be in the forefront of all types of fuel cells, because of the significant advances made in this technology since 1960's [32]

3.3.2.1. Efficiency. The performance of fuel cell systems is a function of the type of fuel cell and its capacity. The optimization of electrical efficiency and performance characteristics of fuel cell systems poses an engineering challenge because fuel cell systems are a combination of chemical, electrochemical, and electronic subsystems [33]. Due to the several subsystem components of a fuel cell system laid out in series, the electrical efficiency of the system is a multiple of the efficiencies of the individual sections. The electrical efficiency of a fuel cell can be expressed as [33]:

Electrical efficiency = (FPS eff)(H_2 utilization)(stack Eff)(PC Eff), where FPS = fuel processing system efficiency = heating value of H_2 generated/heating value of fuel consumed, H_2 utilization = portion of H_2 actually consumed in the stack, Stack efficiency = operating voltage/oxidation potential, PC efficiency = AC power delivered/ DC power generated.

Table 12
Performance characteristics of fuel cell based cogeneration systems [33]

Fuel cell type	PEMFC	PEMFC	PAFC	SOFC	MCFC
Nominal electricity capacity (kW)	10	200	200	100	250
Electric heat rate (Btu/kW h), HHV	11,370	9750	9480	7580	7930
Electrical efficiency (%) HHV	30	35	36	45	46
Fuel input (MMBtu/h)	0.1	2.0	1.9	0.8	2.0
Operating temperature (F)	150	150	400	1750	1200
Cogeneration characteristics					
Heat output (MMBtu/h)	0.04	0.72	0.74	0.19	0.44
Heat output (kW equivalent)	13	211	217	56	128
Total overall efficiency (%) HHV	68	72	75	70	65
Power/heat ratio	0.77	0.95	0.92	1.79	1.95
Net heat rate (Btu/kW h)	6370	5250	4860	5210	5730
Effective electrical efficiency (%) HHV	53.6	65.0	70.3	65.6	59.5

For example for a PAFC, the electrical efficiency can be calculated as:

(84% FPS)(83% H_2 utilization)(0.75 V/1.25 V)(95% PC) = 39.7% electrical efficiency (LHV) = 39.7% × (0.9 HHV/LHV) = 36% electric efficiency (HHV).

Performance data for fuel cell systems collated by Energy Nexus Group are presented in Table 12 [33]. The data are taken from manufacturers' specifications (including UTC Fuel Cells, Toshiba, Ballard Power, Plug Power, Fuel Cell Energy, Siemens–Westinghouse, H-Power, Hydrogenics, Honeywell, Fuji, IHI, Global Thermal, Mitsubishi Heavy Industries, and Ztek), and are representative values for developmental systems except for the commercially available 200 kW PAFC system.

3.3.2.2. Part load performance. In both power generation and cogeneration applications, fuel cell systems have excellent load following characteristics. Fuel cell stack efficiency improves at lower loads, resulting in an increase in system electrical efficiency that is relatively steady down to one-third to one-quarter of rated capacity [33]. Fig. 11 shows the part load efficiency curve of a PAFC fuel cell in comparison to a typical lean burn natural gas engine.

Fuel cells are rated at ISO conditions of 77 F and 1 bar pressure [33]. Both output and efficiency of fuel cell systems can degrade as ambient temperature or elevation increases. Ancillary equipment such as air handling blowers or compressor, accounts for the degradation of fuel cell systems performance. Performance degradation is higher for pressurized systems operating with turbo-chargers or small air compressors [33].

3.3.2.3. Heat recovery. The heat recovery process for fuel cell cogeneration systems are similar to that of other cogeneration systems because they produce waste heat that is easily harnessed for space and domestic water heating. The waste heat is produced from the reformer and fuel stack. The PEMFC and the PAFC operate at lower temperature and produce lower grade of waste heat appropriate for residential, commercial and institutional applications. For a typical PEMFC, the fuel stack operates around 80 °C, while

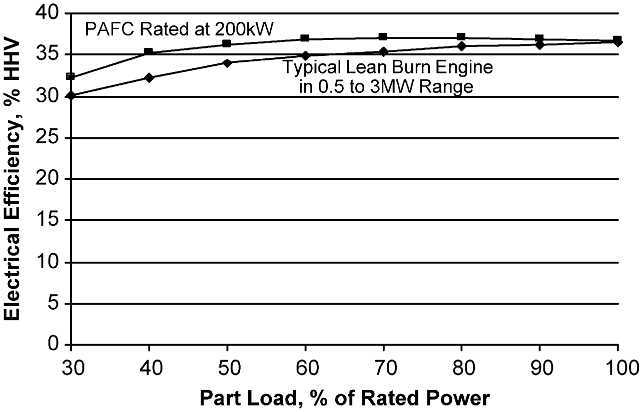


Fig. 11. Comparison of part load efficiency [33].

the reformer generates heat around 120 °C. The MCFC and SOFC generate heat at much higher temperatures sufficient to produce additional electricity with the use of a steam turbine, making them suitable for hybrid systems. However, manufacturers have developed cogeneration products using the SOFC based technology suitable for residential, commercial and institutional applications (as with the case of Sulzer Hexis cogeneration system with 1 kW electrical output and 35 kW thermal output [3]).

Recently, Japan Gas Association (JGA) developed a PEMFC system for residential cogeneration applications, in view of maximizing the power output and heat recovery of the product [34]. Water-cooled and latent heat-cooled prototype units for recovering heat from the PEMFC system was built and evaluated. As shown in Fig. 12, for the water-cooled unit, the heat exchangers used to recover waste heat from the reformer and

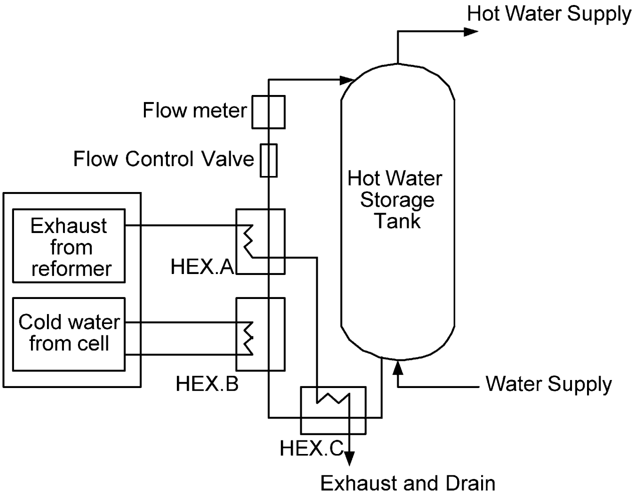


Fig. 12. Heat recovery system for water-cooled cell stacks (auto-circulation system).

cell stacks are located at the bottom of the circulation line, thus causing the water to flow naturally due to the difference in the specific gravity between the water tank and the circulation line. Therefore, the need for a circulation pump is eliminated. For the latent heat-cooled unit, the heat exchangers are used to recover waste heat from the reformer and the cell cathode. An integrated heat exchanger was developed to improve radiation loss, heat transfer efficiency and pressure drop. Hot water was recovered at 60 °C from the latent heat cooled PEMFC unit, when the stack operating temperature was 63 °C.

3.3.2.4. Maintenance. Fuel cells have the potential for very low maintenance costs because they have fewer moving parts when compared to reciprocating engines and micro-turbines. However, maintenance of ancillary systems such as pumps and fans needed for operating fuel cell systems can increase maintenance costs. In addition, these ancillary systems can cause an increase in both scheduled and unscheduled downtime [13].

Fuel cell system maintenance requirements vary with the type of fuel cell, size and maturity of the equipment. Major overhaul of fuel cell systems involves shift catalyzer replacement, reformer catalyzer replacement, and stack replacement [33]. Stack replacement is expected between every 4 and 8 years. Routine maintenance includes replacement of ancillary parts such as fuel filters, reformer igniter or spark plug, water treatment beds, flange gaskets, valves, electronic components, sulfur absorbent bed catalysts and nitrogen for shutdown purging. Periodic filter replacement is often carried out from 2000 to 4000 h [33]. The maintenance cost for the commercially available PAFC systems (200 kW) including an allowance for periodic stack replacements is from 0.02 to 5 $/kW h [17]. Periodic stack replacement alone for the commercially available 200 kW PAFC fuel cell is estimated to be around 0.0193 $/kW h. The cost to replace a 10 kW PEM fuel cell stack is estimated to be 0.0188 $/kW h, while the estimated cost to replace a 200 kW PEM fuel cell stack is 0.0132 $/kW h, and 0.0125 $/kW h to replace a 100 kW SOFC fuel cell stack [33].

Fuel cells are expected to have higher availability and reliability than reciprocating engines since they have fewer moving parts [17]. The commercially available 200 kW PAFC has been operated continuously for more than 5500 h, which is comparable to other power plants. Limited test data for this unit show 96% availability and 2500 h between forced outages [17]. In demonstration projects at different US Department of Energy locations, several pre-commercial PEM fuel cell units suitable for residential application have been operational. Ten 5 kW PEM fuel cells developed by Plug Power operated from 15 to 21 January 2002 in three of the US Department of Energy locations. As of August 31, 2002, these units have been operated for total of 51,967 h with an average individual availability of 95.8% [35].

3.3.2.5. Emissions. Fuel cell systems do not involve the combustion processes associated with reciprocating internal combustion engine and micro-turbine systems. Consequently, they have the potential to produce fewer emissions. The major source of emissions is the fuel processing subsystem because the heat required for the reforming process is derived from the anode-off gas that consists of about 8–15% hydrogen, combusted in a catalytic or surface burner element [33]. The temperature of this lean combustion process, if maintained below 1000 °C, prevents the formation of oxides of nitrogen (NO_x).

Table 13
Estimated fuel cell emission characteristics [33]

Fuel cell type	PEMFC	PEMFC	PAFC	SOFC	MCFC
Nominal electricity capacity (kW)	10	200	200	100	250
Electrical efficiency (%) HHV	30	35	36	45	46
Emissions					
NO_x (ppmv at15% O_2)	1.8	1.8	1.0	2.0	2.0
NO_x (Ib/MW h)	0.06	0.06	0.03	0.05	0.06
CO (ppmv at 15% O_2)	2.8	2.8	2.0	2.0	2.0
CO (Ib/MW h)	0.07	0.07	0.05	0.04	0.04
Unburnt hydrocarbons (ppmv at 15% O_2)	0.4	0.4	0.7	1.0	0.5
Unburnt hydrocarbons (Ib/MW h)	0.01	0.01	0.01	0.01	0.01
CO_2 (Ib/MW h)	1360	1170	1135	910	950
Carbon (Ib/MW h)	370	315	310	245	260

Notes: Emissions adjusted to 15% oxygen. Emissions do not account for cogeneration operations. Emissions expressed in lb/MW h do not account for cogeneration operations.

In addition, the temperature is sufficiently high for the oxidation of carbon monoxide (CO) and unburnt hydrocarbons. An absorbed bed helps in removing other pollutants such as oxides of sulphur (SO_x). Table 13 illustrates emission characteristics of fuel cell systems based on fuel cell system manufacturers' goals and prototype characteristics [33].

3.3.3. Commercially available fuel cell based cogeneration systems and their costs

PEMFC based residential cogeneration systems have reached demonstration stage, with a variety of FC developers reporting on their latest products, including Ebara Ballard's 1 kW cogeneration stationary system, Plug Power's GenSys 5C system (5 kW electric, 9 kW thermal) and Hpower's 4.5 kW RCU. By 2005, Japan Gas Association plans to market a high efficiency PEMFC residential cogeneration system with a hot water storage tank equipped with a back-up burner, a battery for electrical storage, and a self-diagnostic system [34]. In addition to PEM fuel cells, solid oxide fuel cells (SOFC) are suitable for residential cogeneration applications because they run efficiently at high temperatures, and have a favorable thermal/electric ratio. These and other advantages of SOFC based systems in residential cogeneration applications are summarized in Krist and Wright [31], and the various design and operating strategies to match the thermal/electric load ratio of a building with that supplied by a FC cogeneration system are considered in Collella [36].

As of February 20, 2002, a survey carried out by Fuel Cell Today shows that an estimated number of 550 residential style fuel cell systems have been built and operated worldwide [37]. Apart from units installed in homes, the figures include units in the range of 0.5–20 kW that have been operated in stationary applications, such as uninterruptible and backup power supply in commercial and remote locations. The survey results indicate that there are numerous companies actively involved in the development of residential fuel cell systems. For example:

- Ebara Ballard is developing 1 kW PEMFC stationary cogeneration systems in collaboration with Tokyo gas (a reforming technology company).

- Fuel Cell Technologies Ltd is developing SOFC systems suitable for residential applications to provide heat and power, making use of Siemens Westinghouse 5 kW stacks.
- H Power in partnership with Osaka Gas is developing 500 W and 1 kW PEMFC systems.
- Hamburg Gas Consult GmbH in collaboration with Dais Analytic has completed field-testing for a number of 3.5 kW Alpha PEMFC cogenerator prototypes in Europe. Testing for the beta systems is to be carried out in 2003 and commercialization is expected by 2004–2005.
- Idatech is developing a 4 kW methanol fuel cell system for remote residential applications. Field trial for the Alpha units has been completed and that of Beta units is currently underway.
- Matsushita Electric Industrial Co. Ltd is developing residential PEMFC cogeneration systems with the intention of introducing the product in 2004. Japan Gas Association is currently testing two 1.3 kW systems on behalf of Matsushita Electric Industrial Co. Ltd.
- Nuvera in partnership with RWE is developing 5 kW PEMFC systems to act as primary or auxiliary backup power for residential applications. In addition, the company is developing a prototype aimed at reducing capital cost.
- Texas based Reliant Energy is developing 7.5 kW PEMFC products for residential and small commercial applications. A prototype has been tested in 2001.
- Sanyo Electric Co. Ltd in collaboration with Osaka Gas (a reforming technology company) plans to introduce 1 kW residential PEMFC product into the market from 2003 to 2005.
- Toyota is developing 1 kW PEMFC cogeneration system for residential applications with a target date of 2008 for the commercialization of the product.
- UTC Fuel Cells is currently designing a 5 kW PEMFC for residential and small commercial applications. UTC Fuel Cells has over 30 years experience in developing residential fuel cells, having installed 4 kW prototypes fuelled by natural gas in Ohio in 1968.
- Hydrovolt has developed a 3.5 kW SOFC cogeneration system for residential and commercial applications with an electrical efficiency of approximately 50% and overall efficiency of approximately 80% [26].
- Hydrogenics Corp. has 1–5 kW PEMFC cogeneration systems suitable for single-family applications with an overall efficiency of about 80% [26]. In addition, Hydrogenics Corp. has products in the range of 10–25 kW based on the PEMFC technology suitable for multi-family, commercial and institutional cogeneration applications.
- Global Thermoelectric, Inc. has a 2 kW SOFC cogeneration systems suitable for single-family applications with an overall efficiency of about 85%, as well as a 10 kW SOFC systems with an overall efficiency of about 85% [26].

Other companies are also developing fuel cell products suitable for residential and small-scale cogeneration applications. These include, Proton Motor GmbH (Germany) in collaboration with Robert Bosch GmbH and some governmental bodies. They are developing products based on the PEMFC technology. Also participating in the development of fuel cell systems suitable for residential and small-scale applications are Avista Labs, DCH Technology, Sanko Jidokiki, Teledyne, and Vaillant [37]. A detailed and comprehensive list of fuel cell installations around the world can be found at the Fuel Cells 2000 website [38].

Fuel cell based cogeneration system capital costs consist of the following [33]:

- Stack subsystem such as fuel cell stack, feed gas manifolds, and power takeoffs.
- Fuel cell processing subsystem such as fuel management controls, reformer, steam generators, shift reactors, sulphur absorbent beds, and ancillary components.
- Power and electronic subsystem such as solid state boost regulator, DC to AC inverters, grid interconnect switching, load management and distribution hardware, and inverter controller and overall supervisory controller.
- Thermal management subsystem such as stack cooling system, heat recovery and condensing heat exchangers.
- Ancillary subsystems such as process air supply blowers, water treatment system, safety controls and monitoring, cabinet ventilation fans and other miscellaneous components.

The estimated equipment and installation costs for the five fuel cell systems shown in Table 12 are given in Table 14.

The stack subsystem is estimated to represents 25–40% of equipment costs, the fuel processing subsystem represents 25–30% of equipment costs, the power and electronics subsystem represents 10–20% of equipment costs, the thermal management subsystem represents 10–20% of equipment costs, and ancillary subsystems represents 5–15% of equipment costs [33].

Maintenance costs for fuel cell systems include maintenance labor cost, ancillary parts replacement and material costs like air and fuel filters, reformer igniter or spark plug, water treatment beds, flange gaskets, valves, electronic components, sulphur adsorbent

Table 14
Estimated capital costs for current technology fuel cell based cogeneration systems in the 2003/2004 timeframe (2002 $/kW) [33]

Fuel cell type	PEMFC	PEMFC	PAFC	SOFC	MCFC
Nominal electricity capacity (kW)	10	200	200	100	250
Equipment costs					
Packaged cost	4700	2950	3850	2850	4350
Grid isolated breakers	250	100	100	120	100
Materials and labor	100	272	272	250	280
Total process capital	5050	3322	4222	3220	4730
Other Site Costs					
Proj. and const. mgmnt	280	124	124	168	112
Engineering and fees	90	52	52	72	60
Contingencies	80	94	94	30	90
Interest during construction	0	8	8	10	8
Total installed cost (2002 $/kW)	5500	3600	4500	3500	5000

Table 15
Estimated operating and maintenance costs for current technology fuel cell based cogeneration systems in the 2003/04 timeframe (2002$/kW h) [33]

Fuel cell type	PEMFC	PEMFC	PAFC	SOFC	MCFC
Nominal electricity capacity (kW)	10	200	200	100	250
Variable service contract ($/kW h)	0.0121	0.0087	0.0087	0.0102	0.0072
Variable consumables ($/kW h)	0.0002	0.0002	0.0002	0.0002	0.0002
Fixed ($/kW-yr)	18.0	6.5	6.5	10.0	5.0
Fixed ($/kW h at 8000 hrs/yr)	0.0023	0.0008	0.0008	0.0013	0.0006
Stack fund ($/kW h)[a]	0.0188	0.0132	0.0193	0.0125	0.0350
Stack life (yr)	4	4	5	8	4
Recovery factor (%)	50	35	30	20	30
Net O and M cost ($/kW h)	0.033	0.023	0.029	0.023	0.043

[a] Stack replacement costs = (stack original cost × (1-recovery factor))/(stack life × 8000 h/yr). Stack life was estimated based on type of fuel cell. Recovery factor was based on catalyst recovery, metal scrap value and non-repeat hardware value at end of life. All estimates are considered first cut projections and have an uncertainty of ± one year and ± 15%. The small PEM recovery factor was increased due to its higher non-repeat component cost.

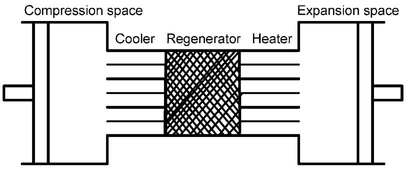
bed catalysts and nitrogen for shutdown purging. Also included in fuel cell system maintenance costs are major overhaul costs that involve shift catalyst replacement (that occurs every three to 5 years), reformer catalyst replacement (5 years), and stack replacement (4–8 years) [33]. Table 15 illustrates estimated maintenance costs based on 8000 annual operating hours.

3.4. Stirling engine based cogeneration systems

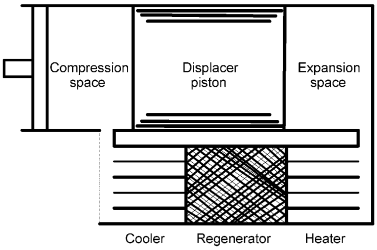
Stirling engines are beginning to stage a comeback to the market since the development of the modern 'free piston' Stirling engines [39]. The technology is not fully developed yet, and it is not widely used; however, it has good potential because of its ability to attain high efficiency, fuel flexibility, low emissions, low noise/vibration levels and good performance at partial load [3]. Unlike reciprocating internal combustion engines, the heat supply is from external sources, allowing the use of a wide range of energy sources including fossil fuels such as oil or gas, and renewable energy sources like solar or biomass. Since the combustion process takes place outside the engine, it is a well-controlled continuous combustion process, and the products of combustion do not enter the engine. As a result of the continuous combustion process, two power pulses per revolution, and fewer moving parts compared to reciprocating internal combustion engines, Stirling engines have low wear and long maintenance free operating periods, and are quieter and smoother than reciprocating internal combustion engines [3].

3.4.1. Principle of operation

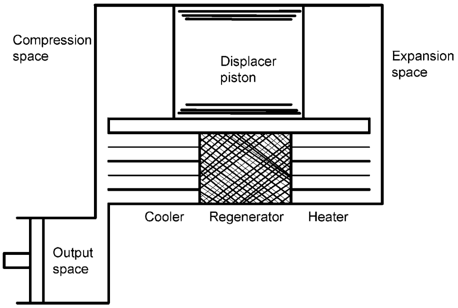
Stirling engines operate on the Stirling cycle, which is similar to the Otto cycle, with the adiabatic processes of that cycle replaced with isothermal processes. Stirling cycle engines have been developed in recent years as external combustion engines with regeneration, in which case the cycle resembles the ideal Carnot cycle [40].



(a) Alpha engine



(b) Beta engine



(c) Gamma engine

Fig. 13. Classification of Stirling cycle engines [41].

Stirling engines are classified according to their arrangement: the Alpha, Beta and the Gamma arrangements as shown in Fig. 13. The Alpha configurations have two pistons in separate cylinders connected in series by a regenerator, heater and cooler. Both the Beta and the Gamma configurations use the displacement piston arrangement, but the Beta arrangement has the piston and the displacer in the same cylinder while the Gamma arrangement uses different cylinders [3,41].

Stirling engine drive methods are based on kinematic drive and free piston drive. Kinematic drives utilize conventional mechanical elements like the cranks, connecting rods and flywheels in series that move in a prescribed manner. On the other hand, the free piston drives move the reciprocating elements using the pressure variations produced by the working gas, with the work being harnessed by a linear alternator [3].

The kinematic drives require special sealing to prevent leakages associated with the high pressure working gas, its loss to the environment, and passing of the lubricated oil from the crankcase to inside of the cylinder. The free piston engine technology based on the Beta configuration was developed to alleviate the technical barrier posed by leakage problems. The free piston with the attached linear alternator can be tightly sealed to prevent the leakage of the working gas for a substantial period of time. In addition, the working gas acts as the lubricant. Free piston Stirling engines are expected to eliminate mechanical contact, friction and wear, and provide tight sealing of the casing, thus requiring no mechanical maintenance during an operating lifetime of about 10 years. The major advantages of free piston engines include input and output versatility, quiet operation, zero wear, zero maintenance, long life, ease of interfacing with the electric grid, continuous power operation and potential for high efficiency [41]. Today, free piston engines are limited to several tens of kilowatts, a range suitable for residential and small-scale commercial applications.

3.4.2. Performance characteristics

A well-designed Stirling engine has two power pulses per revolution and the combustion is continuous. These qualities make Stirling engines operate smoothly, resulting in lower vibration, noise level and emissions than reciprocating internal combustion engines [3]. Also, the external combustion process allows the use of a large variety of fuels and longer fuel retention times in the combustion chamber compared to internal combustion engines. As a result, the control, and hence the efficiency of combustion is higher.

3.4.2.1. Efficiency and part load performance. Stirling cycle has the potential of achieving higher efficiency than those of the Rankine or Joule Cycles, because it more closely approaches the Carnot cycle. While an electrical efficiency of 50% is expected, presently the electrical efficiency is about 40%, and the overall efficiency of a Stirling engine cogeneration system is 65–85% with power to heat ratio between 1.2 and 1.7. Stirling engines also have good capability to operate under part-load conditions. It is expected that while the full load efficiency can be 35–50%, the efficiency at 50% load can be expected to be in the 34–39% range. [3].

Since the technology is still in the development phase, there is no statistical data for the reliability and availability of Stirling engines. However, it is expected that the reliability of Stirling engines will be comparable to that of diesel engines, with an expected annual average availability in the 85–90% range [3].

3.4.2.2. Heat recovery. In a natural gas fuelled Stirling engine, the sources of heat for heat recovery are the gas cooler, exhaust gas heat exchanger, and to a lesser extent, the cylinder walls and the lubricating oil. In the gas fuelled Stirling engine developed by Solo Company, the gas leaves the pre-heater at a temperature of 200–300 °C before entering the exhaust gas heat exchanger where the temperature is reduced to approximately 30 °C above the entry temperature of the cooling water. Depending on the level of the entry temperature and the correspondent condensation, 2–4 kW thermal output can be gained in the process. The Solo Stirling 161 CHO cogeneration module has an electrical power output of 2–9.5 kW, a thermal output of 8–26 kW. While the electrical efficiency is in the 22–24% range, the total efficiency can be as high as 92% depending on the amount of heat utilized. [42]

Sunpower and its partners are developing a biomass fired Stirling engine residential cogeneration product that involves a two-stage combustion process where fuel is first pyrolyzed at about 550 °C to generate a fuel gas, and then this gas is burned in a separate chamber at about 1200 °C [43]. Some of the resulting heat is used by the free piston Stirling engine to derive an electrical load. The rest of the heat is used partly in the recuperator for preheating, and partly to satisfy the user's thermal load. A system with the smallest burner cogenerates approximately 4 kW of heat for each 1 kW of electricity. Depending on the amounts of heat recuperated to combustion air and lost in exhaust, biomass to electricity conversion efficiencies vary from 12 to 17%.

3.4.2.3. Maintenance. Unlike the reciprocating internal combustion engines, Stirling engines have sealed operating chambers resulting in low wear with long maintenance intervals. Stirling engines with small capacity under 20 kW have service internals from 5000 to 8000 h, which are long compared with Otto gas engines of the same range. This considerably reduces the operating costs compared with Otto gas engines [42]. Due to the tight sealing of the casing, free piston Stirling engines are expected to eliminate mechanical contact, friction and wear, therefore eliminating mechanical maintenance during an operating lifetime of about 10 years.

3.4.2.4. Emissions. Emissions from current Stirling burners can be 10 times lower than that emitted from gas Otto engines with catalytic converter, making the emissions generated from Stirling engines to be comparable with those from modern gas burner technology. The Stirling engine unit developed by Germany based company, SOLO, uses high level preheated air for combustion to achieve high combustion efficiency while achieving low exhaust emissions [42]. The internal exhaust gas from the recirculation systems, preheated air and fuel gas are combined to limit the maximum temperature to within the oxidation range of below 1400 °C, thereby suppressing the formation of nitrogen oxide. In addition, continuous combustion considerably lowers the emission level when compared to conventional fired fossil fuel cogeneration units. Despite the high level of pre-heated air used for combustion, the emission level is low with only 80–120 mg/m^3 NO$_x$ and 40–60 mg/m^3 CO, and traceable hydrocarbon and soot emissions. Fig. 14 illustrates the emission values for Stirling engine cogeneration units compared with conventional engines [42]. The efficiency and emission characteristics of Stirling engine units in the 2–25 kW range are given in Table 16.

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3.4.3. Commercially available Stirling engine based cogeneration systems and their costs

Historically, Stirling engines have been developed in capacities ranging from 1 W to 1 MW, but the optimum size relative to other type of technologies suitable for the same application is an issue when considering the economics of Stirling engines. Free piston

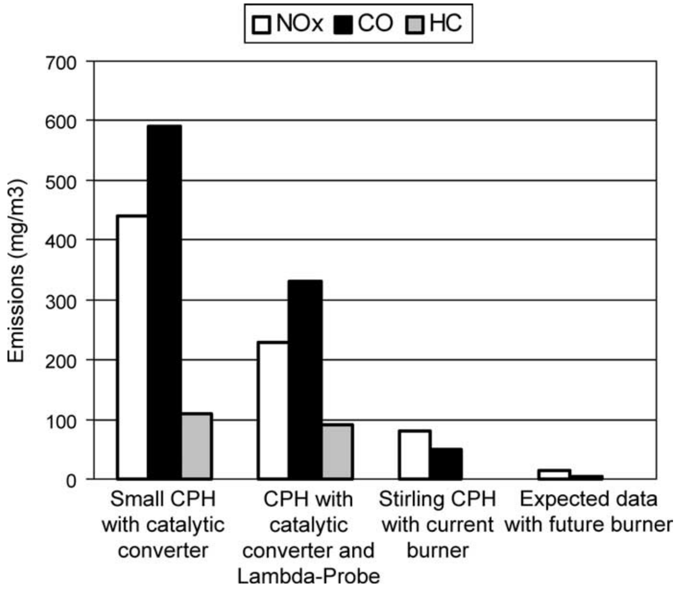

Fig. 14. Emission of NO_x, CO, particles/HC from conventional and Stirling engine cogeneration units (mg/m^3) [42].

Stirling engines are believed to be attractive with other competing technologies at power level less than 20 kW, a range suitable for residential, commercial or institutional applications. This advantage tends to increase as the power range decreases.

Several manufacturers are involved in the development of Stirling engines suitable for small-scale cogeneration applications. For example:

- Both Enatec and BG group have developed a 1 kW cogeneration unit based on linear free piston technology. The electrical efficiency of the unit is reported to be 16% [20].
- New Zealand based WhisperTech has developed 1 kW units based on the kinematic engine with low electrical conversion efficiency of 12% [20].

Table 16
Stirling engine emissions characteristics

Emissions characteristics	SOLO[a]	DTE energy[b]	
Electrical capacity (kW)	2–9	20	25
Electrical efficiency (%)	22–24	29.6	29.6
Overall efficiency (%)	> 90	82	82
NO_x (gm/bhph)	0.08–0.12	0.288 (Standard) 0.15 (Ultra low)	0.288 (Standard) 0.15 (Ultra low)
CO (gm/bhph)	0.04–0.06	0.32 (Standard) 0.32 (Ultra low)	0.32 (Standard) 0.32 (Ultra low)

[a] http://www.stirling-engine.de/engl/index.html

[b] www.dtetech.com/pressroom/pdf/enx_25_spec.pdf

- Norway based Sigma is developing a 3 kW_e electrical output and 9 kW thermal output appropriate for a single-family dwellings. The electrical efficiency of the unit is reported to be ($>25\%$).The product is expected to be commercially available by 2005 [20].
- Germany based company, SOLO, has developed a natural gas fuelled cogeneration Stirling engine unit. The unit is reported to have an electrical output of 2–9 kW, thermal output of 8–24 kW and an overall efficiency of 92–96% [42].
- Sunpower Inc is developing a free piston Stirling engine fuelled by biomass (e.g. wood, wood pellets, sawdust, chips, and biomass waste). The system is expected to generate 7 kW of electrical power to meet residential cogeneration and small-scale commercial requirement [39].
- DTE Energy Technologies introduced an external combustion engine utilizing Stirling Engine technology, rated at 55 kW. The engine can operate on a number of fuel sources (e.g. natural gas, propane, flare gas, coal bed methane, biogas, landfill gas) with a typical net electrical efficiency of over 30%. A key advantage to the Stirling engine compared to traditional reciprocating engines is that it has 50% fewer moving parts. [44] DTE Energy offers Stirling engines up to 1 MW with an overall electrical/thermal efficiency of 84%.

Stirling engines have limited demonstration projects because they are still considered an emerging technology, however a field trial carried out for the 4–9 kW electric and 12–25 kW thermal SOLO Stirling engine unit [45] shows the system operating without error and achievable maintenance operating times are more than 5000 h. As of 2001, the total investment cost for the unit was estimated to be $13,000, from which $10,400 was for the engine cost while $2600 was estimated for auxiliaries and technical interconnection. In addition, an estimated maintenance cost for the unit was 0.013 $/kW h [45]. Presently, the investment cost for the unit is still about twice as high as an internal combustion engine driven cogeneration unit of the same capacity, although it is more economical when considering the maintenance costs of Stirling engines (i.e. 0.013 $/kW h as compared with $0.018 $/kW h of internal combustion engine driven cogeneration systems. Maintenance costs are expected to drop down to 0.006 $/kW h with the mass production of Stirling engines [45].

4. Conclusion

A review of the current technologies for residential and small-scale commercial cogeneration applications has been presented. These technologies are becoming more important due to the development of commercially available small traditional reciprocating internal combustion systems as well as small turbine systems, fuel cells and Stirling engines. With the exception of micro-turbine systems, these technologies are suitable for single-family residential applications (<10 kW). Currently existing micro-turbine systems range in size from 25 to 80 kW, a range suitable for multi-family residential, commercial and institutional applications. In addition, research is ongoing for systems with capacities less than 25 kW, e.g. 1 and 10 kW. On the technological (not economical) side, fuel cell and Stirling engine cogeneration systems seem promising for residential and small-scale commercial applications. Fuel cell, micro-turbine and Stirling engine technologies remain to be proven so that the technologies are sufficiently robust and affordable for residential and small-scale commercial cogeneration applications. Currently, well-proven and robust systems available for residential as well as small-scale commercial cogeneration applications at reasonable cost are based on reciprocating internal combustion engines.

The electrical efficiency of reciprocating internal combustion engines is higher compared to micro-turbines and Stirling engines. On the other hand, fuel cells promise to offer the highest electrical efficiency for residential and small-scale cogeneration applications in comparison with the other technologies, but are challenged by lack of demonstrated performance. Unlike a reciprocating engine, which derive its usable thermal output from the jacket water and exhaust gases, all the usable thermal output from a micro-turbine comes from the exhaust, which gives it an advantage over reciprocating engines in that heat recovery is from one stream.

Reciprocating internal combustion engines require more periodic maintenance than competing technologies, making them having more mandatory downtime. Micro-turbines have the potential to have lower maintenance requirements than reciprocating engines due to simplicity in their design and few moving parts. However, the longevity of the main components have not been fully proven and currently projected maintenance costs are nearly the same as for reciprocating engines. Fuel cells have few moving parts and therefore have the potential to have very low maintenance. However, support systems such as pumps and fans necessary for the operation of fuel cells can be costly to maintain and result in increases in both scheduled and unscheduled downtime. Stirling engines have sealed operating chambers resulting in low wear with long maintenance intervals. Stirling engines with small capacity under 20 kW have service internals from 5000 to 8000 h, which are long compared with that of Otto gas engines of the same range. This considerably reduces the operating costs compared with Otto gas engines. Installed costs for emerging technologies like micro-turbines, fuel cells and Stirling engines are currently more expensive, with fuel cell offering the highest installed cost, than the competing reciprocating engine units.

Reciprocating internal combustion engines have higher emissions of CO, NO_x, and particulates than competing technologies for residential and small scale cogeneration applications, and are thus at a disadvantage in geographical areas with stringent emission criteria. Using catalysis to reach acceptable emission levels is often desirable, but expensive. Micro-turbines have a strong advantage over reciprocating internal combustion engines in terms of emissions. Current expectations for NO_x emissions from micro-turbines are already below those of reciprocating engines. Fuel cells by nature of their lack of a combustion process have extremely low emissions of NO_x and CO. Their CO_2 emissions are also generally lower than other technologies due to their higher efficiency. Emissions from current Stirling burners can be 10 times lower than that emitted from gas Otto engines with catalytic converter, making the emissions generated from Stirling engines to be comparable with those from modern gas burner technology.

While performance and price data for reciprocating internal combustion engines are well established, data for micro-turbines, fuel cells and Stirling engines are based on limited number of demonstration projects. More operational hours are needed to prove these technologies (micro-turbine, fuel cell and Stirling engine). Data on longevity, actual efficiencies, and operating and maintenance costs of tested units for these technologies are not widely known, and in many cases, complete and reliable information is not available. This uncertainty makes it difficult for an accurate comparison to be carried out between reciprocating internal combustion engines and these technologies. These emerging technologies will continue to fight an uphill task against the reciprocating internal combustion engine for residential and small-scale cogeneration application until more data from demonstration projects become available, and they meet or surpass current expectations.

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