Residential Cogeneration Systems: A Review of The Current Technologies

A Report of Subtask A of
FC+COGEN-SIM
The Simulation of Building-Integrated
Fuel Cell and Other Cogeneration Systems

Annex 42 of the
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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. The mission of one of those areas, the ECBCS - Energy Conservation for Building and Community Systems Programme, is to facilitate and accelerate the introduction of energy conservation, and environmentally sustainable technologies into healthy buildings and community systems, through innovation and research in decision-making, building assemblies and systems, and commercialisation. The objectives of collaborative work within the ECBCS R&D program are directly derived from the on-going energy and environmental challenges facing IEA countries in the area of construction, energy market and research. ECBCS addresses major challenges and takes advantage of opportunities in the following areas:

- exploitation of innovation and information technology;
- impact of energy measures on indoor health and usability;
- integration of building energy measures and tools to changes in lifestyles, work environment alternatives, and business environment.

The Executive Committee

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the executive committee on Energy Conservation in Buildings and Community Systems (completed projects are identified by (*)):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)

Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HEVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing
Annex 39: High Performance Insulation Systems
Annex 40: Building Commissioning to Improve Energy Performance
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM)
Annex 43: Testing and Validation of Building Energy Simulation Tools
Annex 44: Integrating Environmentally Responsive Elements in Buildings
Annex 45: Energy Efficient Electric Lighting for Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser
(*) - Completed

Annex 42

The objectives of Annex 42 are to develop simulation models that advance the design, operation, and analysis of residential cogeneration systems, and to apply these models to assess the technical, environmental, and economic performance of the technologies. This is being accomplished by developing and incorporating models of cogeneration devices and associated plant components within existing whole-building simulation programs. Emphasis is placed upon fuel cell cogeneration systems and the Annex considers technologies suitable for use in new and existing single and low-rise-multi-family residential dwellings. The models are being developed at a time resolution that is appropriate for whole-building simulation.

To accomplish these objectives Annex 42 is conducting research and development in the framework of the following three Subtasks:

- Subtask A: Cogeneration system characterization and characterization of occupant-driven electrical and domestic hot water usage patterns.
- Subtask B: Development, implementation, and validation of cogeneration system models.
- Subtask C: Technical, environmental, and economic assessment of selected cogeneration applications, recommendations for cogeneration application.

Annex 42 is an international joint effort conducted by 22 organizations in ten countries:

Belgium:
- University of Liège / Department of Electrical Engineering and Computer Science
- COGEN Europe

Canada:
- Natural Resources Canada / Building Simulation Team
- Natural Resources Canada / Integrated Energy Systems Group
- University of Victoria / Department of Mechanical Engineering
- National Research Council / Institute for Research in Construction
- Hydro-Québec / Energy Technology Laboratory (LTE)

Finland:
- Technical Research Centre of Finland (VTT) / Building and Transport

Germany:
- Research Institute for Energy Economy (FfE)

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Netherlands:
- Energy research Centre of the Netherlands / Renewable Energy in the Built Environment

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- Swiss Federal Laboratories for Materials Testing and Research (EMPA) / Energy Systems and Building Equipment Laboratory
- Swiss Federal Institute of technology (EPFL) / Laboratory for industrial energy systems (LENI)
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The assistance of the other members of Annex 42 in producing this review is also gratefully acknowledged.

Dr Ian Knight
Subtask A Leader

Abstract

The growing worldwide demand for less polluting forms of energy has led to a renewed interest in the use of cogeneration technologies in the residential sector due to their potential for significantly reducing the quantities of pollutants emitted in supplying residential electricity and heating.

Cogeneration systems in the residential sector have the ability to produce both useful thermal energy and electricity from a single source of fuel such as oil or natural gas. This means that the efficiency of energy conversion to useful heat and power is potentially significantly greater than by using the traditional alternatives of boilers or furnaces and conventional fossil fuel fired central electricity generation systems. If managed properly this increased efficiency can result in lower costs and a reduction in greenhouse gas emissions. Cogeneration also has the added advantage of diversifying electrical energy production, thus potentially improving security of energy supply in the event of problems occurring with the main electricity grid.

This report aims to provide an up-to-date review of the various cogeneration technologies suitable for residential applications. The report details are aimed providing basic information on these technologies to the computer modelling community, but the report will be of use to wider audiences as well.

As residential scale cogeneration technologies are still in their infancy, the potential for residential cogeneration energy and emissions savings is yet to be firmly established, and the emissions savings are determined by the emissions of the displaced fuels. However, a study of the actual performance of a domestic Stirling engine system installed in a house in France in 2003 showed a primary energy saving of 13%[1], and potential savings energy and emission savings of 28% have been claimed for this technology in the UK[2].

Technologies available and under development for residential, i.e. single-family (<10 kW) and multi-family (10 – 30 kW) applications, commercial (5 – 100 kW) and institutional cogeneration (20 – 100 kW) applications include:

- reciprocating internal combustion engine based cogeneration systems,
- micro-turbine based cogeneration systems,
- fuel cell based cogeneration systems, and
- reciprocating external combustion Stirling engine based cogeneration systems.

Since the focus of this report is on technologies that are suitable for single-family and multi-family

residential cogeneration applications (generally covered by systems of <10 kW_e and <25 kW_{th}), only the reciprocating internal combustion engine, fuel cell and Stirling engine based cogeneration systems are reviewed. The review covers the performance, environmental benefits, and cost of these technologies where the information was available. This information was collated from manufacturers and research organizations for the various technologies, and includes access to as yet unpublished material for the residential, commercial and institutional cogeneration sector.

Micro-turbine based cogeneration systems that are currently available have capacities larger than is suitable for single-family dwellings, and are therefore not reviewed in this report.

At the time of writing this report the use of small-scale commercial cogeneration plant in applications like hospitals, leisure facilities, (particularly those incorporating swimming pools), hotels or institutional buildings is well established and some of the technology fairly mature. These products are used to meet electrical and heat demands of a building for space and domestic hot water heating, and potentially absorption cooling of a building. However, the use of cogeneration plant for residential scale buildings has yet to become commercially viable though several manufacturers have developed products or are developing products suitable for residential scale use.

Résumé

La demande sans cesse croissante partout dans le monde de formes d'énergie moins polluante a entraîné un regain d'intérêt pour l'utilisation de techniques de cogénération dans le secteur résidentiel en raison de leurs capacités à réduire substantiellement la quantité de polluants produits pour fournir de la chaleur et de l'électricité aux habitations.

Les systèmes de cogénération dans le secteur résidentiel offrent la possibilité de produire de l'énergie thermique et électrique utile à partir d'une source unique de combustible comme le mazout et le gaz naturel. Cet état de fait signifie que l'efficacité de la transformation énergétique en chaleur et en électricité utiles par la cogénération peut s'avérer beaucoup plus grande qu'en optant pour des solutions de rechange plus classiques à base de chaudières, de chaudières industrielles et de systèmes centraux de production d'électricité alimentés par des combustibles fossiles courants. Gérée adéquatement, cette efficacité accrue pourrait se traduire par des coûts moins élevés et des émissions de gaz à effet de serre moins importantes. De plus, la cogénération présente l’avantage de diversifier la production d’énergie électrique, ce qui permettrait d’accroître la sécurité des approvisionnements en énergie au cas où le réseau électrique principal éprouverait des difficultés.

Le présent rapport contient un examen à jour des techniques de cogénération qui conviennent à des applications résidentielles. Les détails qui y sont donnés constituent des renseignements de base sur ces diverses techniques, lesquelles sont destinés surtout à la communauté des spécialistes en modélisation informatique. Toutefois, le rapport saura intéresser d’autres membres du grand public.

Comme les techniques de cogénération à échelle résidentielle en sont toujours à leurs premiers balbutiements, les possibilités offertes par celles-ci au chapitre des économies d’énergie et de la réduction des émissions restent à définir avec précision. D’autre part, la quantité des émissions éliminées est établie en fonction de celles qui proviendraient des combustibles remplacés. Néanmoins, une étude menée sur le rendement d’un système à base de moteur Stirling installé dans une maison de France en 2003 a abouti à des résultats de 13 p. 100 [i] en économies d’énergie primaires. Au Royaume-Uni, on prétend que le même procédé a signifié des économies d’énergie et une réduction des émissions de l’ordre de 28 p. 100 [ii].

Parmi les techniques qui sont actuellement sur le marché ou en voie de développement pour des applications unifamiliales (< 10 kW) et multifamiliales (de 10 à 30 kW), des applications commerciales (de 5 à 100 kW) et des applications institutionnelles (de 20 à 100 kW), on retrouve ce qui suit :

des systèmes de cogénération à base de moteurs alternatifs à combustion interne ;
des systèmes de cogénération à base de microturbines ;
des systèmes de cogénération à base de piles à combustible ;
des systèmes de cogénération à base de moteurs alternatifs Stirling à combustion externe.

Comme le présent rapport est axé sur les techniques qui conviennent à des applications de cogénération uni et multifamiliales (qui se rapportent généralement à des systèmes de <10 kW_e à <25 kW_e), il ne contient que l'examen des systèmes de cogénération à base de moteurs alternatifs à combustion interne, des systèmes de cogénération à base de piles à combustible et des systèmes de cogénération à base de moteurs alternatifs Stirling à combustion externe. Les renseignements dans le rapport concernent le rendement, les avantages environnementaux et les coûts (le cas échéant). Toutes ces données, recueillies auprès des fabricants et des organismes de recherche, englobent également des informations prises à même des documents non encore publiés traitant de la cogénation dans les secteurs résidentiel, commercial et institutionnel.

Les systèmes de cogénération à base de microturbines qui sont actuellement sur le marché offrent des capacités beaucoup plus importantes que les systèmes destinés aux maisons unifamiliales et, par conséquent, ne font l'objet d'aucun examen à l'intérieur du rapport.

Lorsque le rapport a été rédigé, les installations commerciales de cogénération à petite échelle étaient monnaie courante dans les hôpitaux, les établissements de loisirs (surtout ceux qui comprenaient des piscines), les hôtels et les bâtiments institutionnels. De fait, certaines de ces installations avaient fait leurs preuves depuis longtemps. Ces produits servaient à répondre aux besoins en électricité et en chaleur, en particulier pour le chauffage des espaces et de l'eau. Ils pouvaient également contribuer à la climatisation des bâtiments par absorption. Toutefois, les installations commerciales de cogénération pour des applications résidentielles restent à venir. Plusieurs fabricants, qui ont développé de tels produits, s'apprêtent à les mettre sur le marché.

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[i] Domestic Energy Optimisation (DEO) NNE5/1999/691, **Final Publishable Report,** Commission européenne DG TREN – Énergie et Transports, Programme de l'énergie de la CE, 27 février 2003, consulté en décembre 2004 à l'adresse http://www.ecde.co.uk/deo/docs/deo%20final%20report_v11.pdf

[ii] Tullar, M., « Micro-CHP : turning the vision into reality », Conférence PRASEG 2001, consulté en décembre 2004 à l'adresse www.praseg.org.uk/downloads/conf2001/mish%20tullar%20presentation.ppt\

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1 Objectives and scope

This review has been prepared by Annex 42 of the International Energy Agency's Energy Conservation in Buildings and Community Systems. The focus of Annex 42 is the simulation of residential cogeneration systems and the assessment of the technical, environmental, and economic performance of the technologies. Annex 42 considers technologies that could be suitable for use in new and existing single and low-rise-multi-family residential dwellings. Such technologies are called "residential cogeneration" in the context of this report..

The main aims of the review are:

- To gather together in one place currently available information relevant to the Annex pertaining to the modelling and application of residential cogeneration systems. This does not include existing models as these are covered by other aspects of the Annex.
- To establish the current state-of-the-art in residential cogeneration technologies.
- To act as a guide and aide memoir to the technologies which are being studied and modelled by the Annex.

The review is not exhaustive and much excellent work exists which has not been referenced or included in this review, however it is hoped that this work through its access to unpublished as well as publicly available material will form a useful guide to the state-of-the-art in residential scale cogeneration up to mid-2004. A revised and completed review incorporating the Annex's work is cuurently being discussed for publication at the end of the Annex in 2007.

2 Introduction

According to the definition given by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE)[3], Cogeneration[i] is the simultaneous production of electrical or mechanical energy (power) and useful thermal energy from a single energy stream such as oil, coal or natural gas. In some cases, the energy source can be provided from solar, geothermal, biomass or other type of renewable energy source[4].

There is growing potential for the use of 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 overall efficiency of energy conversion can increase

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[i] also known as Combined Heat and Power or CHP by the Chartered Institute of Building Services Engineers (CIBSE)

to over 80% based ons Higher Heating Value[v] for the fuel if all the heat produced can be usefully used, compared to an average of 30 – 35% at the point-of-use for electricity produced in conventional fossil fuel fired electricity generation systems and to an average of 80 - 95% for heat produced in boilers. The CHP efficiency figure whilst seemingly less efficient than that for boilers alone, can in fact lead to an overall increase in energy efficiency as well as result in lower costs and a reduction in greenhouse gas emissions when compared to the conventional methods of generating heat and electricity for residential buildings[5]. In order to fully realise these benefits the system design and operation must be carefully engineered. Cogeneration might not always be the most energy efficient and/or environmentally friendly solution, e.g. where highly efficient centralised electricity generation systems are available; where renewable energy generated electricity is available; etc., so it is important that local energy supply options are carefully appraised when considering installing cogeneration on energy efficiency or environmental grounds.

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. End-users that can benefit most from cogeneration are those that can fully use both 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, leisure facilities (particularly those incorporating swimming pools), 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 potential 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 can be designed to:

- satisfy both the electrical and thermal demands,
- satisfy the thermal demand and part of the electrical demand,
- or satisfy the electrical demand and part of the thermal demand
- or, most commonly, satisfy part of the electrical demand and part of the thermal demand.

In addition, cogeneration in buildings can be designed for peak shaving applications, i.e. the cogeneration plant is used to reduce either the peak electrical demand or thermal demand.

With each of these potential system designs there are constraints on the practical and economic viability:

- For a cogeneration unit designed to fully meet the electrical demand of the building; if the heat demand is less than the thermal output from the cogeneration plant, the plant unit will either throttle back to operate under part load conditions, or will switch on and off, or will require that the surplus heat is dumped to atmosphere/stored in a thermal storage device such as the heat distribution system, the building structure or in water or phase change materials. On the other hand, if the heat demand of the building is higher than the cogeneration capacity, a secondary heat raising system such a boiler is often used to 'top-up' the heat output[6].
- For a cogeneration unit designed to fully meet the thermal demand of the building; if the electrical demand of the building is less than the electrical output from the cogeneration plant the cogeneration unit can either be throttled back, or the surplus electricity produced can be exported to the utility grid or possibly stored in an electrical storage device such as batteries or capacitors. On the other hand, if the electrical demand of the building is higher than the output of the cogeneration plant, the lack of electricity is usually covered by importing electricity from the utility grid.
- The economic viability of such systems is critically dependent on the installed cost of each system, system maintenance costs and retail prices for the cogeneration system fuel and centrally generated electricity as well as the electricity exportation price if electricity is exported to the grid. The economic viability of cogeneration in the residential sector benefits from the much higher retail prices paid by residential consumers for grid supplied electricity, though currently this is usually more than offset by the high cost of the cogeneration systems per kW_e and kW_{th}. Cogeneration systems are financially more attractive in periods of high electricity prices and low fossil fuel prices. Due to its higher specific investment cost, a careful cogeneration system design procedure is needed in order to define the best sizes of the equipment in the system, accounting for not only the cogeneration equipment but also the heat storage devices and the advanced control systems that will forecast the heat requirement and decide the optimal control using model based predictive control algorithms.
- To meet the full electrical or thermal demand of a building using cogeneration it is usually necessary to install cogeneration systems which are oversized in both their electrical and thermal outputs. Unless there is a use outside the building for the surplus heat and power this usually has the unwanted consequence that the unit's running time will decrease due to an insufficient load being available. This reduction in run hours will make the economics of the system poorer. For this reason, cogeneration devices are usually sized to meet only a part of the electrical and thermal need.

Currently, in both residential and commercial sectors, buildings are being built with high levels of insulation, which helps in reducing the space-heating requirements. Heat demand in buildings often follows both daily and seasonal variations due to behavioral pattern of the inhabitants and meteorological conditions[6].

Future forecasts (i.e. POLES, IEA, and World Bank) of energy supply indicate an increased demand across the globe[7]. The POLES model shows almost a doubling of the world primary energy supply between 2000 and 2020[7]. Electricity demand and CO_2 emissions are projected to increase over the same period due to increasing proliferation of advanced technologies in developed countries and the increasing level of industrialization and advancement in developing countries leading to increased use of fossil fuels[7], thus necessitating the need for cogeneration applications to try and reduce the growth in emissions whilst allowing the projected industrialisation to still occur. In addition, the POLES model projected that energy processes are still largely dependent on fossil fuels and are still likely to be around 90% in 2020 with oil, coal and natural gas having the largest share of energy supply[7]. If the CO_2 emissions of the cogeneration system itself are higher than that of a boiler delivering the same amount of heat, the cogeneration allows for an overall reduction in CO_2 emissions by avoiding the need for centralised production of electricity and sometimes by the fuel switch from high (fuel oil) to low (natural gas) CO_2 content fuels. Compared to a natural gas-fired boiler, a cogeneration device will have a marginal overall efficiency of ~80% (energy out/energy in), but the avoided centrally generated electricity element means that its CO_2 emissions performance is superior to both the boiler and all the best centralised power plants using the same fuel. Lower CO_2 emissions are derived from using natural gas for cogeneration applications compared to other fossil fuels because of their relative CO_2 forming potential[8]. In addition, natural gas is widely available and reliable for cogeneration applications.

In 1999, for example, about 17% of the total energy consumed in Canada was for residential use making the sector the third largest consumer of energy after the industrial sector (39%) and transportation sector (28.7%)[9]. In comparison, in the United Kingdom in 2003[ii], the Industrial Sector consumed 20% of all energy use; the transport sector consumed 33% and the residential sector 28%; whereas in Nigeria in 1999 the residential sector consumed nearly 80% of all energy use[iii].

These figures reveal that the residential sector is likely to be a significant energy consumer in all countries, with commensurate opportunities for significant energy savings.

[ii] Digest of United Kingdom Energy Statistics 2004

[iii] http://earthtrends.wri.org/pdf_library/country_profiles/Ene_cou_566.pdf

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[10]. In addition, internal combustion engines are attractive for small-scale cogeneration applications because of their robust nature and well-known technology. The other commercially available 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[7]. Also, currently micro-turbine based cogeneration systems are only available in the 30-75 kW range which is substantially larger than both the electrical and thermal loads encountered in the single-family residential sector, though they have a higher potential for useful heat recovery. The combination of the above factors, along with potential operating issues in a domestic setting, means that micro-turbines are therefore **not** considered in this report.

Apart from the energy 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 feasibility of cogeneration[11]. Large-scale cogeneration systems gain from economies of scale and tend to have lower installed cost per unit power output ($/kW)[11]. On the other hand, small-scale cogeneration systems tend to have higher capital costs per unit power output which poses an economic barrier to their implementation. In addition, the perceived low reliability and durability of small-scale cogeneration hardware and lack of flexibility with electric grid interconnectivity so far has limited their use in the residential sector[12].

As residential scale cogeneration technologies are still in their infancy, the potential for residential cogeneration energy and emissions savings is yet to be firmly established, and the emissions savings are determined by the emissions of the displaced fuels. However, a study of the actual performance of a domestic Stirling engine system installed in a house in France in 2003 showed a primary energy saving of 13%[13], and potential savings energy and emission savings of 28% have been claimed for this technology in the UK[14].

Presently, several manufacturers have developed products or are developing products suitable for residential or small-scale commercial cogeneration applications like hospitals, leisure facilities, (particularly those incorporating swimming pools), hotels or institutional buildings.

3 The use of Cogeneration Systems

Combined heat and power generation is a well-established concept. Industrial plants led to the concept of cogeneration back in the 1880s when steam was the primary source of energy in industry and electricity was just surfacing as a product for both power and lighting[15]. The use of cogeneration became common practice as engineers replaced steam driven belt and pulley mechanism with electric power and motors, moving from mechanical powered systems to electrically powered systems. During the early parts of the 20th century power used by industry was mainly co-generated. Most electricity generation at that time was derived using coal fired boilers and steam turbine generators, with the exhaust steam used for industrial applications[16]. 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[16].

The construction of central electric power plants and reliable utility grids led to the decrease of electricity cost 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[16]. 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 crises in 1973[16]. 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 decreased fuel consumption and lower 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[16].

Specific circumstances that improve the attractiveness of cogeneration applications include regulatory policies (or exemption from regulatory policies), monetary incentives, and financial support for research and development. Research, development and demonstration projects over the last twenty-five years have caused a significant growth of the technology, which is now mature and reliable[16].

Conventional fossil fuel fired electricity generation achieves an electricity efficiency of about between 35 - 60% at the power station, however distribution losses mean that this efficiency figure drops dramatically by the time it reaches the residential sector. From IEA statistics[17] (2001) the efficiency of generation at the power station of the EU mix is 40% and the US is 37.6%

(without losses), with losses it reaches 35% and 32% for the US.

These quoted efficiencies account for nuclear production whose efficiency (33%) definition is not necessarily accounted appropriately since it only concerns the thermal efficiency of the plant not the energy content of uranium.

From the viewpoint of achieving additional electricity capacity with a microcogeneration system the efficiency of an equivalent new central generation installation should be considered, i.e. 56% for a combined cycle system at the power station, i.e. around 50% with losses. However where a microgen system is considered to be replacing existing central generating capacity then the existing figures quoted might be used. An overall central generating efficiency figure of ~35% is assumed in this report. Boiler heat generation efficiencies are normally up to 90% efficient. By comparison, cogeneration systems have a typical overall efficiency of 85%, resulting in primary fuel savings of around 35%, which give rise to direct savings in fuel costs, reduced consumption of fossil fuel and reduction in CO_2 emissions[5]. Figure 1 illustrates, using example figures, the difference in primary energy consumption required to produce the same amount of heat and power in a household using conventional fossil fuel fired electricity generation and boiler system compared to a cogeneration system.

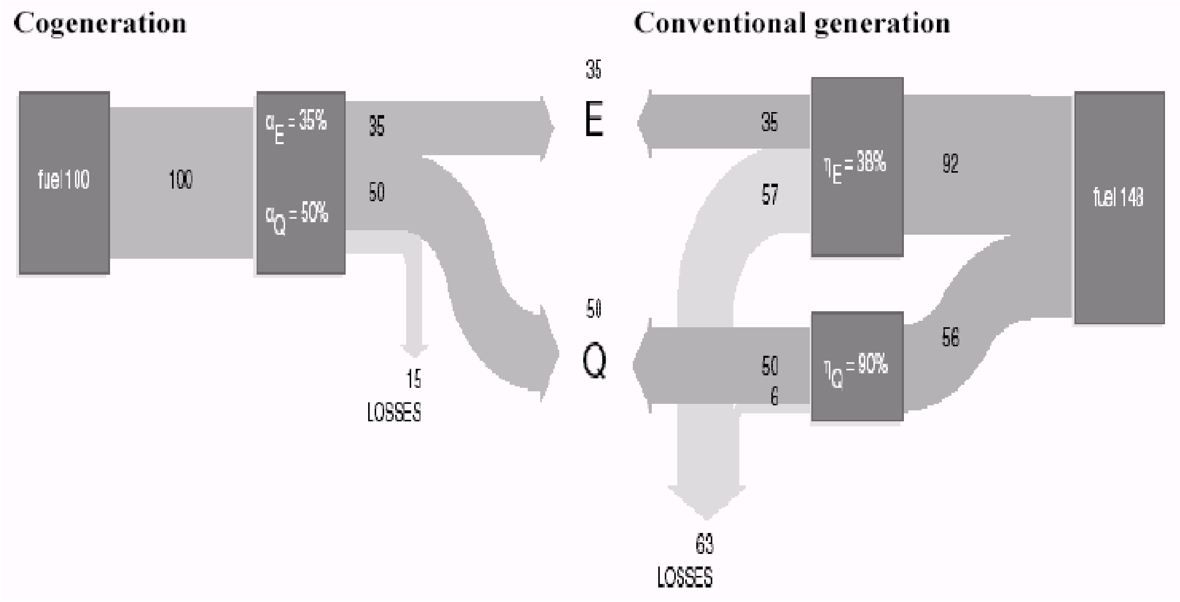

Figure 1: Cogeneration versus conventional generation

Where
α_E = part of the energy transformed into electricity in a cogeneration unit
α_Q = part of the energy transformed into usable heat 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 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)[iv]. LHV is also defined as the higher heating value of the fuel (HHV)[v] 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:

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

$$Thermal\ efficiency = \frac{\text{thermal output (kW)}}{fuel\ input\ (kW)} \qquad (2)$$

$$Overall\ efficiency = \frac{\text{useful thermal} + \text{electrical output (kW)}}{fuel\ input\ (kW)} \qquad (3)$$

The overall 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].

The overall efficiency is however a first law efficiency that does not represent the quality of the electrical and heat production i.e. was the heat and electricity produced usefully used. For cogeneration systems it is worth considering the exergy efficiency of the system, i.e. the availability or capacity of the system to perform useful work. The exergy efficiency is expressed as being the

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[iv] LHV is the energy obtained by cooling down the combustion gases of the stoichiometric combustion of a fuel under standard conditions without condensing the water formed in the combustion.

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

ratio between the exergy delivered by the system and the exergy entering with the fuel.

Whichever means we choose to assess efficiency, 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[18]. 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 demand leads to fluctuation in delivered power, increased maintenance and reduced lifetime.

The maximum energy efficiency is reached when the energy delivered by the cogeneration equipment equals the energy requirement of the building, however this is not necessarily the maximum CO_2 efficiency. Consider a case where the cogeneration system is meeting part of the electrical demand and all of the heating demand for a building. If we were to increase the electrical output, and hence the heat output, of the engine we would displace centrally generated more CO_2 intensive electricity, but would have to dump some of the extra thermal output of the engine. The most efficient CO_2 situation for the building is achieved when the additional CO_2 benefits of the additional electricity are balanced by the CO_2 costs of the heat thrown away.

When designing a cogeneration system for building applications, the utilization level of the system should be considered. This level is typically more than 4,500 hours/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:

$$\%\ \text{Reliability} = \frac{T - (S + U)}{T - S} \text{x}100 \qquad (4)$$

$$\%\ \text{Availability} = \frac{T - (S + U)}{T} \text{x}100 \qquad (5)$$

where, S = scheduled maintenance time, hours/year

U = unscheduled maintenance time, hours/year
T = time plant is required to be in service, hours/year

There is a need to perform a feasibility study or an economic analysis to decide on the adoption of a cogeneration system because, amongst other requirements, 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, site preparation, building construction, and installation of equipment. Some of these costs may not be applicable to all residential and small commercial cogeneration systems. Ongoing costs include fuel, 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 than 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 available, or under research and development, for single- and multi- family residential buildings and small scale commercial applications. These include reciprocating internal combustion engines (ICE) based on spark ignition (gasoline) or compression ignition (diesel); gas micro-turbine based systems; fuel cell based systems and Stirling engine based systems. These technologies could replace or supplement the conventional boiler in a dwelling and provide both electricity and heating to the dwelling, possibly with the surplus electricity exported to the local grid and surplus heat stored in a thermal storage device. As stated earlier micro-turbines are currently considered unsuitable for residential cogeneration and will not be considered in this report.

3.1 A note on quoted efficiency figures

The efficiencies quoted for various systems in this report have been derived from many sources, not all of which provide exact details of how the calculations were undertaken. For example, are auxiliary parasitic loads such as fans and pumps included in calculating the useful energy output from each system? The manufacturers are not explicit about this, so we cannot make any assumption in this area. Also it is not always made clear in these sources whether the higher[v] (HHV) or lower (LHV) heating values[iv] of the fuel consumed are used in assessing efficiency, or the dates when the data were obtained. Unless otherwise stated it should be assumed that the LHV has been used in assessing efficiency for the reasons discussed previously, On this basis a condensing boiler could achieve an 'efficiency' of over 100%, as it is capable of recovering the latent heat.

These general caveats should be borne in mind when attempting to use the figures quoted in this report in any calculations. [vi]

3.2 Residential Cogeneration

The objective of this review is to provide a better understanding of, and up-to-date information for, the various non-renewable energy based cogeneration technologies suitable for residential applications. Various technologies available and/or under development for residential, i.e. single-family (<4 kW_{el}) and multi-family (5 – 30 kW_{el}) applications, commercial (5 – 100 kW_{el}) and institutional cogeneration (20 – 100 kW_{el}) applications were reviewed, with **a focus on single- and multi- family residential cogeneration applications (<10 kW_{el} and <25 kW_{th})[vii].**

It is recognised that these are fairly arbitrary figures and may well be exceeded in many markets, particularly the huge retrofit market for older properties where thermal loads can easily exceed this figure. To this end a number of figures and tables in the report refer to equipment that is outside our 'ideal' range but might be of interest to larger schemes.

By reaching high enough temperatures, cogeneration systems are suitable for retrofitting in existing buildings, which is not the case for conventional heat pumping options. Technologies suitable for the residential cogeneration market are:

- reciprocating internal combustion based cogeneration systems,
- fuel cell based cogeneration systems, and

[vi] The reader is advised to contact the cogeneration system manufacturer should they require completely accurate and up-to-date figures. The systems described in this review are subject to constant revision.

[vii] For information, an average of 14 kW_{th} is needed to meet both space and water heating demands for a single North American home, while an average of 5 kW_{el} is enough to satisfy the electrical requirements[vii].

- external combustion Stirling engine based cogeneration systems.

The report considers the performance, environmental benefits, and cost of these technologies. Information has been collated from manufacturers and research organizations for the various technologies, and in addition, the status and market approach of the product developers is discussed.

Industrial cogeneration technologies such as steam and gas turbines are not discussed. There are also a number of other cogeneration technology variants which are not considered due to a lack of detailed information on their likely performance, though this is not to conclude that they will have no role to play. Examples of these technologies are:

- Enginion / Hoval, 4.6 kWe steam turbine[19] [20]
- BTB OTAG steam engine Lion linear motor[21]
- Hoval Agrolyt Stirling, in combination with wood boiler[22]

4 Methodology

This review is based on existing published data for residential cogeneration as well as unpublished material derived from the Annex 42 membership.

Several studies have been considered on cogeneration for residential buildings[23 4 7 16 37], though this list is not exhaustive. Most of these studies focused on one technology, usually a reciprocating internal combustion engine cogeneration based system because of their suitability for small-scale cogeneration applications. However other studies have been done individually on fuel cell based cogeneration systems, micro-turbine based cogeneration systems and Stirling engine based cogeneration systems [100 24 25].

The report form aims to provide a comprehensive study and up-to-date review that considers the various technologies available for residential cogeneration, though in some instances the information presented has had to be derived from experience gained in the commercial and institutional sectors.

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.

This review provides information at a number of levels to facilitate decision making regarding which technology or product is suitable for a particular situation or application. In addition, the available technologies are compared and contrasted in terms of their advantages, disadvantages, costs, performances, environmental issues, durability and availability.

5 Cogeneration Technologies For Residential Application

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, residential 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.

5.1 Reciprocating Internal Combustion (IC) Engine Based Cogeneration Systems

Reciprocating engine based cogeneration systems are the prime mover of choice for small scale cogeneration applications[16], providing electricity and thermal energy through heat recovery from the exhaust gas, engine oil and cooling water. This is attributed to their well-proven technology, robust nature, and reliability. However, they do need regular maintenance and servicing to ensure availability. They are available over a wide range of sizes ranging from a few kilowatts to more than ten megawatts, and can be fired on a broad variety of fuels with excellent availability[15], making them suitable for numerous cogeneration applications in residential, commercial, institutional and small-scale industrial loads.

Reciprocating IC engines are based on the Otto cycle (spark ignition) or the Diesel cycle (compression ignition). In the Otto engine, the mixture of air and fuel is compressed in each cylinder before ignition is caused by an externally supplied spark. The Diesel engine involves only the compression of air in the cylinder and the fuel is introduced into the cylinder towards the end of the compression stroke, thus the spontaneous ignition is caused by the high temperature of the compressed mixture[16].

Reciprocating IC engines used for residential cogeneration applications of less than 30 kW are frequently based on spark ignition engines[5]. The mechanical power derived from the engine turns the generator to produce electrical power; the heat from hot exhaust gases, cooling water and engine oil is harnessed to meet the thermal requirement of the building.

Packaged internal combustion engine cogeneration systems of 50 – 100 kW capacities are currently in use in the commercial sector. While such systems are suitable for multi-family residential buildings and small-scale commercial applications like hotels, leisure centres, institutional buildings, or hospitals, single-family residential cogeneration applications will most likely be based on cogeneration units with capacities less than 4 kW[12].

5.1.1 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[16].

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 20bar steam output[16]. 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[viii] 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[26]. 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[26].

[viii] 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.

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.[27], are available that can be used for a 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.

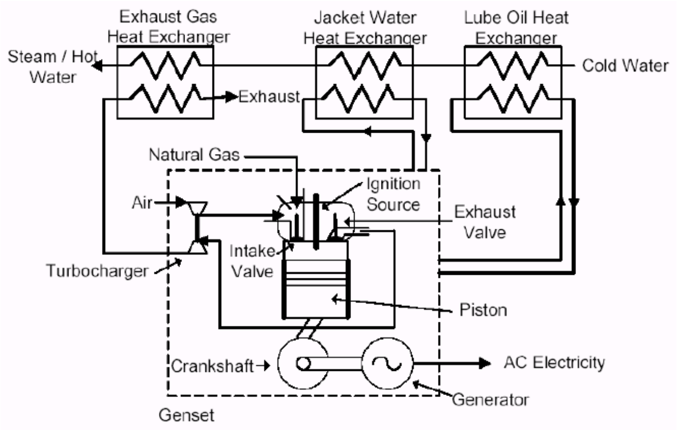

Figure 2: Typical packaged internal combustion engine based (spark ignited) cogeneration system[26]

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 Figure 2[26].

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[26].

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.

Both automotive and industrial type engines can be used in cogeneration systems. Automotive engines have a life expectancy of about 20,000 hours. 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[26].

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.

Table 1: Reciprocating engines speed classifications[26]

Speed Classification	Engine Speed (rpm)	Stoichiometric Burn, Spark Ignition (MW)	Lean Burn, Ignition (MW)	Dual Fuel (MW)	Diesel (MW)
High Speed	1,000–3,600	0.01–1.5	0.15–3.0	1.0–3.5	0.01–3.5
Medium Speed	275–1,000	None	1.0–6.0	1.0–25	0.5–35
Low Speed	58–275	None	None	2.0–65	2–65

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[26]. Also, to boost the output of small displacement engines by as much as 40 percent, 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[28].

5.1.2 Performance characteristics

5.1.2.1 *Efficiency*

Reciprocating internal combustion engines have mechanical efficiencies that range from 25-30%. 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[26].

Reciprocating internal combustion engines are generally rated at ISO conditions of 25°C and 1bar pressure[26]. Both output and efficiency of a reciprocating internal combustion engine degrades by approximately 4% per 300 m of altitude above 300 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 ten 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.

Table 2: Cogeneration efficiencies obtained at ten UK sites[5]

	Design Specification	Monitored Performance (average)
Electrical Output (kWe)	35	35.2
Thermal Output (kWth)		
– cogeneration	70	68.4
– condensing heat exchanger	10	12.4
Electrical Efficiency (% HHV)	26	25.5
Overall Efficiency (% HHV)		
– cogeneration	78	75.1
– condensing heat exchanger	85	84.1

As shown in Table 2, the results obtained from the project indicate that the units performed close to their design specifications. There were a few unscheduled stoppages resulting from computer power supply, faulty sensor, battery charger malfunction, cooling water blockage and a broken valve spring. The control systems installed with the units were able to detect and report these faults on time.

5.1.2.2 Part load performance

Reciprocating internal combustion engines used in cogeneration applications and power generation generally drive a synchronous generator[ix] at constant speed to produce a steady alternating current

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[ix] 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.

(AC). The performance map and heat balance for a representative reciprocating internal combustion engine are given in Figure 3 and Figure 4 respectively.[x]

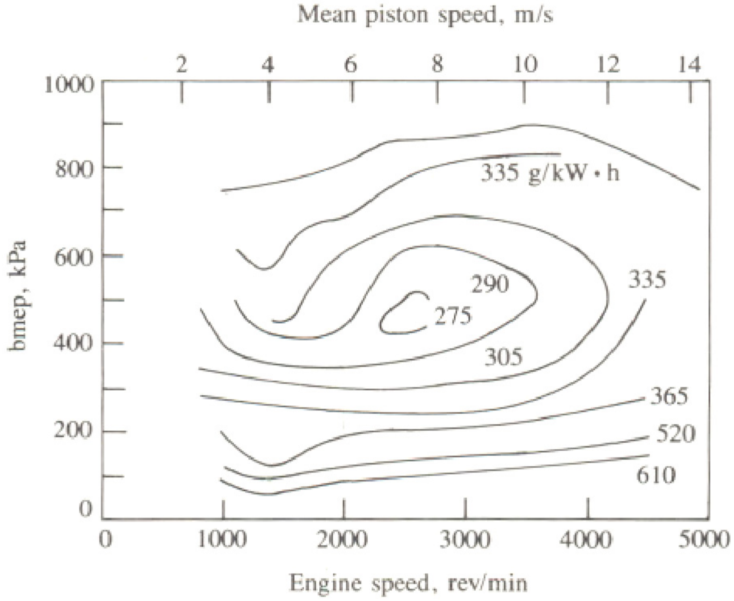

Figure 3: Performance map for a spark-ignition engine[28]

Figure 3 illustrates the performance map of a spark ignition engine showing contours of constant brake specific fuel consumption (bsfc) in g/kWh. The minimum bsfc point is achieved close to mid-range in speed and load[28]. Increasing the load (expressed as brake mean effective pressure, bmep, in the figure) 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.

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

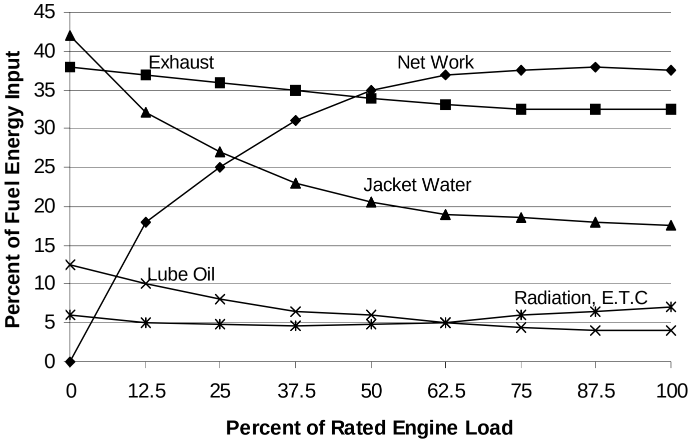

Figure 4: Heat balance of reciprocating internal combustion engine[29]

For cogeneration applications, the heat to power ratio of the engine is critical. It can be seen in Figure 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 kWh of electricity produced at lower partial loadings, thereby leading to decreased efficiency. Also from Figure 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 useful heat derived from a cogeneration system increases as the efficiency of electric power delivered decreases.

5.1.2.3 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 to 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[4 26].

Table 3: Internal combustion engine co-generation process[4]

(Values in bold represent useful energy)

	Without Heat Recovery	With Heat Recovery
Engine output at Flywheel	**35%**	**35%**
Un-Recoverable heat	65%	21%
Recoverable heat	0%	**44%**
Total useful energy	**35%**	**79%**

The heat recovered from the engine jacket as hot water is often between 85 – 90^{0}C, while the heat recovered from the engine exhaust gases as hot water or low-pressure steam is from 100 to 120^{0}C[26]. 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.

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 only with natural gas fired systems because of corrosion problems associated with other fossil fuels[5].

5.1.2.4 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 500-2,000 hours. Manufacturers often recommend a time interval for overhaul, from 12,000-15,000 hours of operation for a top-end overhaul and 24,000-30,000 hours 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 $/kWh (0.008 to 0.012 €/kWh)[30].

With proper maintenance, modern internal combustion engine based cogeneration systems operate at high levels of availability. In a demonstration project conducted in the U.K. 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].

5.1.2.5 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. 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.[26]. Particulate matter is an issue for Diesels operated with liquid fuels.

Carbon monoxide is caused by the incomplete combustion of fossil fuels due to inadequate oxygen or insufficient residence time at high temperature. In addition, 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[26].

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.

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[26].

Table 4: Representative NO_x Emissions from Reciprocating Engines [26]

Engines	Fuel	NO_x (ppmv)	NO_x (gm/kWh)
Diesel Engines (high speed and medium speed)	Distillate	450-1,350	7-18
Diesel Engine (high speed and medium speed)	Heavy Oil	900-1,800	12-20
Lean Burn, Spark ignition Engine	Natural Gas	45-150	0.7-2.5

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[xi]. A three-way catalytic converter treats the exhaust gases with 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 [26]. 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 [26]. 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 to 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]. NOx emission levels decrease as spark timing is retarded from maximum brake torque timing[xii] (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 NOx emission levels[28]. 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 [26]. 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 NOx 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 [26].

[xi] A three-way catalytic converter is the basic catalytic converter process that reduces concentrations of all three major pollutants - NOx, CO and unburned hydrocarbons with an air-fuel ratio at or close to stoichiometric. NOx 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).

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

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 [26].

Particulates are the product of 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 [26]. However, diesel engines produce less CO emissions compared to lean burn SI engines. Manufacturer's emissions characteristics 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

Emissions Characteristics	Cummins[xiii]						Coasterintelligen *[xiv]	
Electrical Power (kW)	7.5	16	16	20	35	50	55	80
Fuel Type	Diesel	Natural Gas	Diesel	Natural Gas	Diesel	Diesel	Natural Gas	Natural Gas
Emissions Control Device	None	None	None	None	None	Turbo-charger	Catalytic converter	Catalytic converter
Air-Fuel ratio		16.8		16.6				
Compression Ratio	18.5:1	9.4:1	18.5:1	9.4:1	17.3:1	16.5:1		
NOx (g/MWh)	1300	810	1300	850	720	820	<20	<20
NOx (gm/bhph)	12.6	7.8	12.6	8.2	6.99	7.97	<0.15	<0.15
CO (g/MWh)	320	3810	320	3990	130	80	<60	<60
CO (gm/bhph)	3.13	36.8	3.13	38.6	1.26	0.75	<0.6	<0.6
Unburned hydrocarbon (g/MWh)	170	130	170	120	50	40	<20	<20
Unburned hydrocarbon (gm/bhph)	1.64	1.3	1.64	1.2	0.5	0.4	<0.15	<0.15
SO2 (g/kWh)					0,06	0,06		
SO2 (gm/bhph)					0.62	0.6		
Particulates (g/kWh)	0.07	Negligible	0.07	Negligible	N/A	0,01		
Particulates (gm/bhph)	0.66	Negligible	0.66	Negligible	N/A	0.13		

* : Emissions corrected to 15% O_2

CR: Compression ratio; NG: Natural gas; SI: Spark ignition; N/A: not available

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[xiii] http://www.cumminspower.com/library/datasheets/home.jhtml

[xiv] http://www.coastintelligen.com/pdfs/cogen_induction.pdf

5.1.3 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%[27]. Tokyo Gas launched a 6 kW gas engine cogeneration system in February 2002, with an overall efficiency of 86%[31]. The Yanmar Diesel Engine Co. in collaboration with Osaka Gas Co. has developed a gas engine cogeneration package (9.8 kW/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[32]. Cummins Inc. also offers internal combustion engine based cogeneration systems ranging from 7.5–1750 kW, which run on diesel or natural gas, and are suitable for the single and multi-family applications[33]. Similarly, the natural gas fuelled systems from Lister-Petter Inc. (5 kW-400 kW), Alturdyne Power Systems Inc. (25 kW-2 MW) and the 60-75 kW natural gas fuelled units of Tecogen Inc. can be used for residential, commercial and institutional applications [4]. The R-series products manufactured by DTE Energy ranging from 8-1000 kW natural gas fuelled and 10-1000 kW diesel fuel fuelled systems are also suitable for residential, commercial and institutional applications[33]. Germany based company Senertec, has a cogeneration unit appropriate for single-family residential application, with 5.5 kW electrical output and 12.5 kW thermal output[34].

Table 6: Typical reciprocating ICE cogeneration system specifications

Specifications	**Honda**	**Senertec**		**Cummins**	**Alturdyne**	**Coast-intelligen**	**Tecogen**	**MAN**
Electrical Capacity (kW_e)	1	5.5 (Gas)	5.3 (Fuel oil)	10	40	55	60	100
Electrical Efficiency[xv] (%)	21.3	27	30			30	26.4	30.6
Overall Efficiency[xvi] (%) HHV	85	88	89			78	83.1	81
Engine Speed (rpm)				3,600	1,500	1,825		1,800
Thermal Output (kW_{th})	3.00	12.5	10.5			87.9	128.96	125.00
Fuel Input (kW)	4.7	20.5	17.9			183.3	227.4	277.78
Natural Gas Consumption (m^3/h)				5.4 at full load	13.8 at full load			

[xv] Electrical efficiency = electrical output (kW)/ fuel input (kW)

[xvi] Overall efficiency = useful heat recovered (kW) + electrical output (kW)/ fuel input (kW)

Table 6 summarizes the specifications for typical commercially available reciprocating internal combustion based cogeneration systems over the 1 kW to 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[26].

Generally, reciprocating internal combustion based cogeneration systems less than 500 kW in size cost between 800 and 3,020 $/kW (630 and 2,370 €/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 hours before an overhaul is needed. On the other hand, industrial engines will operate for 30,000 - 40,000 hours before an overhaul is carried out[5].

Maintenance cost for the 5.5kW Senertec reciprocating internal combustion engine cogeneration system presented in Table 7 is estimated to be 0.014 $/kWh (0.012 €/kWh), with a maintenance interval of 3,500 hours. 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 $/kWh (0.006 – 0.010 €/kWh). The lowest figure reported was 0.005 $/kWh (0.004 €/kWh) and the highest, for smaller systems, were up to 0.032 $/kWh (0.025 €/kWh) [5]. Also, data obtained from the UK demonstration projects[5] show that maintenance costs for reciprocating internal combustion engine cogeneration systems ranged from 0.008-0.026 $/kWh (0.006 – 0.020 €/kWh) and averaged 0.014 $/kWh (0.011 €/kWh), thus agreeing with the information obtained from the manufacturers survey[5].

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

Cost Component	Senertec(*)	North American Cogeneration Systems[35]			MAN[33]
Electrical Capacity (kW)	5.5	7.1- 10.7	20.1-23.3	30.3-35.0	100.0
Electrical Efficiency (%)	27	28.1	37.4	33.1	30.6
Thermal Efficiency (%)	61	56.5	50.0	51.2	50.4
Installed Cost ($/kWe)	3,020	2,800	1,600	1,300	1,080
Installed Cost (€/kWe)	2,370	2,196	1,255	1,020	847

(*)The Senertec installed cost was provided by FfE, an Annex 42 member

These figures and data are not exhaustive and other systems are available, for example the BTB / PowerPlus Technology EcoPower Mini-ICE cogen unit with a nominal 4.7 kWe and 12.5 kWth, though the available data is not as detailed as for the above systems. It is likely that there are other products not found during this study which would also be worthy of consideration.

5.2 Fuel cell based cogeneration systems

Fuel cells[36] are still considered an emerging technology, which has the potential for both power generation and cogeneration applications with performance advantages and in an environmentally friendly fashion. The direct conversion of chemical energy of a fuel to electrical energy by a hydrogen-oxygen fuel cell was first achieved in 1839 by William Grove, in London[16]. Since then, research has been ongoing and the results achieved have been fruitful. Several plants have been built and operated successfully[16]. Fuel cell cogeneration based systems have perhaps the greatest potential in residential and small-scale commercial applications because of the ability to produce electricity at relatively high efficiency, compared to conventional power plants, with a significant reduction of greenhouse emissions. This technology has been used over the last three decades by NASA for space applications to provide reliable power, but only recently due to technological advancement are fuel cells becoming more affordable[37]. Certain types of fuel cells are available or are undergoing 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 cell (DMFC)[16]. When used for cogeneration application, fuel cells are expected to achieve electrical efficiencies between 30 – 60%, with an overall efficiency of 70 – 90%[38]. This range of efficiencies arises due to method of producing the fuel – some systems need to reform the fuel at the cell whilst others are able to use the fuel directly, but the energy losses may have occurred outside the system in producing a suitable fuel. Not all of these fuel cell types will be suitable for residential cogeneration.

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%[39]. 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[39] [16].

5.2.1 Principle of operation

In a fuel cell, the chemical reaction of combustion is made using an electrochemical reaction where the reactants are separated by a tight membrane that only allows ions crossing. To complete the electrical balance, electrons have to move through a circuit, which produces a current. Depending on the type of membranes, the ions that will cross the membrane will be different : H^+ for PEMFC or O^{2-} in SOFC.

Proton Exchange Membrane Fuel Cell (PEMFC) 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:

Anode: $H_2 \rightarrow 2H^+ + 2e^-$ (6)

Cathode: $2H^+ + \frac{1}{2}O_2 + 2e^- \rightarrow 2H_2O$ (7)

Total Reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ (8)

The amount of electricity that can be produced by the reaction is limited by the Gibbs free energy the remaining enthalpy of reaction is converted into heat. Furthermore, in order to maintain a sufficient driving force for the ions transfer through the membrane, the combustion can not be complete , the remaining fuel will be burned in an afterburner that will produce heat useful for cogeneration. The temperature of operation of the fuel cell has to be controlled according to the membrane specification.

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). Amongst these, PEM and SO fuel cells have the highest potential for the residential sector.

5.2.1.1 Polymer Electrolyte Membrane Fuel Cells (PEMFC)

A 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^oC, typically 80^oC. 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^oC) and favorable cost[16].

5.2.1.2 Solid Oxide Fuel Cells (SOFC)

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. In SOFC fuel cells, the Oxygen ions cross the membranes. They are classified as high temperature fuel cells with an operating temperature of 750-1000^oC. 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 offer a product based on SOFC technology, suitable for residential cogeneration with 1kW electrical output[34].

5.2.2 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[40]. Through various demonstration projects, such as the U.S. Department of Defense Fuel Cell Demonstration Program[41], utility demonstration programs[42] and others[18], 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[18 43 44]. 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 the 1960's[45].

5.2.2.1 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[25]. 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 factors determining the electrical efficiency of a fuel cell include the fuel cell efficiency, the fuel conversion and the non converted fuel processing. The electrical efficiency is expressed by the ratio between the net electricity produced and the fuel consumed. The system efficiency is influenced by the quality of the system integration, for example the use of the depleted fuel to satisfy the energy requirement of the fuel processing:

Performance data for fuel cell systems collated by Energy Nexus Group are presented in Table 8[25]. 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. In the table, effective electrical efficiency is defined as follows:

Effective Electrical Efficiency = (Cogeneration electrical energy generated) / [(Total fuel into cogeneration system) – (Total heat recovered/0.8)]

Table 8: Performance characteristics for representative commercially available and developmental natural gas fuel cell based cogeneration systems[25].

Fuel Cell Type	PEMFC	PEMFC	PAFC	SOFC	MCFC
Nominal Electricity Capacity (kW)	10	200	200	100	250
Electric Heat Rate (MJ/kWh), HHV	12	10.3	10	8	8.4
Electrical Efficiency (%) HHV	30	35	36	45	43
Fuel Input (MJ/hr)	105	2,110	2,005	845	2,110
Operating Temperature [^oC]	70	70	200	950	650
Cogeneration Characteristics					
Heat Output (MJ/hr)	42	760	780	200	465
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 (MJ/kWh)	6.7	5.5	5.1	5.5	6
Effective Electrical Efficiency (%) HHV	53.6	65.0	70.3	65.6	59.5

5.2.2.2 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[25]. Figure 5 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 25°C (77°F) and 1 bar pressure[25]. Both output and efficiency of fuel cell systems can reduce as ambient temperature or elevation increases. Ancillary equipment such as air handling blowers or compressor, accounts for the reduction of fuel cell systems performance. Performance reduction is higher for pressurized systems operating with turbo-chargers or small air compressors[25]. When pressurized systems are used, the fuel cell loses part of its advantage because of the presence of a blower which produces noise.

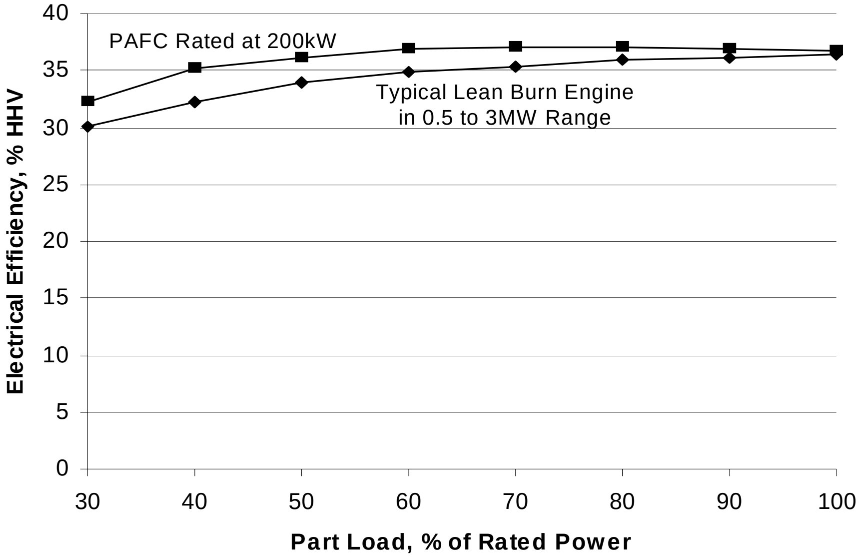


Figure 5: Comparison of part load efficiency of a PAFC Fuel Cell with a typical lean burn natural gas engine[25].

5.2.2.3 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 residential water heating. The waste heat is produced from the reformer and fuel cell 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 – 100°C, while the reformer generates heat around 120ºC, though this is dependent on the quality of its integration. 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 a peak of 35 kW thermal output[16] obtained through use of an auxiliary burner).

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[46]. Water-cooled and latent heat-cooled prototype units for recovering heat from the PEMFC system were built and evaluated. As shown in Figure 6, for the water-cooled unit, the heat exchangers used to recover waste heat from the reformer and 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.

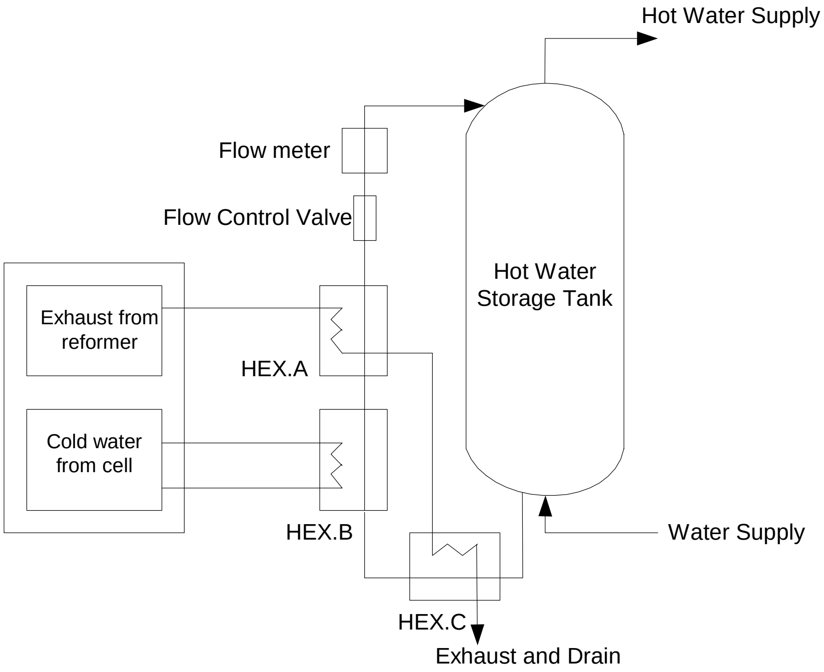


Figure 6: Heat recovery system for water-cooled cell stacks (auto-circulation system)

5.2.2.4 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[40].

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[25]. Stack replacement is expected between every four to eight years[xvii]. 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 2,000 to 4,000 hours[25]. The maintenance cost for the commercially available PAFC systems (200 kW) including an allowance for periodic stack replacements is from 0.02 - $5 $/kWh (0.016 – 3.92 €/kWh)[31]. It is assumed that the higher costs have been obtained from laboratory trials. Periodic stack replacement alone for the commercially available 200 kW PAFC fuel cell is estimated to be around 0.0193 $/kWh (0.0151 €/kWh). The cost to replace a 10kW PEM fuel cell stack is estimated to be 0.0188 $/kWh (0.0147 €/kWh), while the estimated cost to replace a 200kW PEM fuel cell stack is 0.0132 $/kWh (0.0104 €/kWh), and 0.0125 $/kWh (0.0098 €/kWh) to replace a 100 kW SOFC fuel cell stack[25].

Fuel cells are expected to have higher availability and reliability than reciprocating engines since they have fewer moving parts[31]. The commercially available 200kW PAFC has been operated continuously for more than 5,500 hours, which is comparable to other power plants. Limited test data for this unit show 96% availability and 2500 hours between forced outages[31]. 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 15-21 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 hours with an average individual availability of 95.8%[47].

[xvii] These replacement intervals have yet to be obtained in practice for all fuel cell types, and this is a critical area of on-going research.

5.2.2.5 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 [25]. The temperature of this lean combustion process, if maintained below 1,000°C, prevents the formation of oxides of nitrogen (NO_x). In addition, the catalytic reactions, level of temperature and the air excess will guarantee the oxidation of carbon monoxide (CO) and unburnt hydrocarbons. As Sulphur is a poison for the catalysts used in the fuel processing and the fuel, it is removed by a catalytic reaction before entering the fuel processing section. Table 9 illustrates emission characteristics of fuel cell systems based on fuel cell system manufacturers' goals and prototype characteristics [25].

Table 9: Estimated fuel cell emission characteristics – with natural gas fuel [25]

Emissions Analysis	System 1	System 2	System 3	System 4	System 5
Fuel Cell Type	**PEMFC**	**PEMFC**	**PAFC**	**SOFC**	**MCFC**
Nominal Electrical Capacity (kW)	10	200	200	100	250
Electrical Efficiency (% HHV)	30	35	36	45	46
Emissions Characteristics					
NOx (ppmv @ 15% O2)	1.8	1.8	1.0	2.0	2.0
NOx [lb / MWh]	0.06	0.06	0.03	0.05	0.06
NOx [g / MWh]	27	27	14	23	27
CO [ppm_V @ 15% O_2]	2.8	2.8	2.0	2.0	2.0
CO [lb / MWh]	0.07	0.07	0.05	0.04	0.04
CO [g / MWh]	32	32	23	18	18
Unburned Hydrocarbons [ppm_V @ 15% O_2]	0.4	0.4	0.7	1.0	0.5
Unburned Hydrocarbons [lb / MWh]	0.01	0.01	0.01	0.01	0.01
Unburned Hydrocarbons [g / MWh]	5	5	5	5	5
CO_2 [lb / MWh]	1360	1170	1135	910	950
CO_2 [kg / MWh]	617	531	515	413	431
Carbon [lb / MWh]	370	315	310	245	260
Carbon [kg / MWh]	168	143	141	111	118

Notes: Emissions adjusted to 15% oxygen. Emissions do not account for cogeneration operations.

5.2.3 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 (5kW 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[46]. 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[44], 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[48].

Fuel cell based cogeneration system capital costs consist of the following [25]:

- 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.

Currently manufacturers are only selling residential-scale fuel cell cogeneration units as hand-built prototypes, and therefore the costs are nowhere close to those we would expect for commercial units. As the manufacturers are unable to commit to even a range of likely commercial costs we are therefore unable to state likely commercial costs for any of the units discussed.

A breakdown of the likely cost proportions for the systems shows that the stack subsystem is estimated to represent 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 represent 5-15% of equipment costs [25].

Maintenance costs for fuel cell systems include maintenance labour 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 bed catalysts and nitrogen for shutdown purging.

Table 10: Estimated operating and maintenance costs for current technology fuel cell based cogeneration systems in the 2003/04 timeframe (2002$/kWh) [25]

Fuel Cell Type	PEMFC	PEMFC	PAFC	SOFC	MCFC
Nominal Electricity Capacity (kW)	10	200	200	100	250
Variable Service Contract ($/kWh)	0.0121	0.0087	0.0087	0.0102	0.0072
Variable Consumables ($/kWh)	0.0002	0.0002	0.0002	0.0002	0.0002
Fixed ($/kW-yr)	18.0	6.5	6.5	10.0	5.0
Fixed ($/kWh @ 8,000 hrs/yr)	0.0023	0.0008	0.0008	0.0013	0.0006
Stack Fund[xviii] ($/kWh)	0.0188	0.0132	0.0193	0.0125	0.0350
Stack Life (yrs)	4	4	5	8	4
Recovery Factor[xviii] (%)	50	35	30	20	30
Net O & M cost ($/kWh)	0.033	0.023	0.029	0.023	0.043

Also included in fuel cell system maintenance costs are major overhaul costs that involve shift catalyst replacement (that occurs every three to five years), reformer catalyst replacement (five years), and stack replacement (four to eight years) [25]. Table 10 illustrates estimated maintenance costs based on 8,000 annual operating hours.

As of February 20, 2002, a survey carried out by Fuel Cell Today shows that an estimated 550 residential style fuel cell systems have been built and operated worldwide[49]. 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.

[xviii] Stack replacement costs = (stack original cost*(1-recovery factor))/(stack life*8000hrs/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.

5.2.4 Fuel Cell Manufacturers and Systems

A reasonably comprehensive review of fuel cell manufacturers and their systems is given in alphabetical order below. Please note that the information shown is that supplied by the manufacturers. It is not always clear whether the efficiencies quoted refer to the LHV or HHV of the fuel input. Normal practice is to refer to the LHV but the user should make sure this is the case if this information is important to them. In all the tables n/a indicates that the information was not available.

5.2.4.1 Acumentrics (United States)

Figure 7: RP-SOFC (courtesy of Acumentrics)

Acumentrics[50] is currently producing SOFC systems for several different purposes. The company offers CHP systems for commercial and industrial power, ranging in size from 2 to 100 kW_e. They produce UPS systems for backup power such as critical communications networks, available in sizes from 2 to 10 kW_e. Also, two units have been designed for residential stationary and CHP use. The RP-SOFC-5000 and the RP-SOFC-10000 provide 5 and 10 kW_e respectively electrical power. All of Acumentrics' units are based on their patented tubular SOFC technology, which allows direct injection of many fuels and produces negligible emissions of NO_x and SO_x. The 10-kW_e unit incorporates heat exchangers to provide space and water heating.

Table 11: SOFC Specifications from Acumentrics[50] [51]

Model	RP-SOFC-5000	RP-SOFC-10000
Type	stationary system	stationary CHP
Fuel	natural gas, methane, propane, ethanol, methanol, hydrogen, and other light hydrocarbon fuels	
Electrical Power	5 kW	10 kW
Thermal Power	n/a	4 kW
Electrical Efficiency	40–50% LHV	40–50% LHV
Overall Efficiency	n/a	75% LHV
Emissions	negligible NOx, SOx	

5.2.4.2 Aperion (United States)

Figure 8: Power Generation Module (courtesy of Aperion)

For information on Aperion Energy Systems[52], see Avista Labs.

5.2.4.3 Arcotronics (Italy)

Figure 9: Penta H2 (left) and Electrum (right) (courtesy of Arcotronics)

Arcotronics[53] is currently producing fuel cells with output power ranging from 0.5 to 50 kW. They offer a stationary CHP system called the Penta H2, scalable from 2.5 to 10 kW, and a portable electric-only system, producing 1 kW. Both are complete systems with enclosures offering instant startup time. They advertise that the systems are suitable for indoor use due to its zero emissions and quite operation. The target market is battery replacement, backup power and auxiliary power. K Rudisuela of Arcotronics (personal communications, June 11, 2004) was kind enough to provide some of the details about their products.

Table 12: PEMFC Specifications from Arcotronics[53] [51]

Model	Electrum	Penta H2
Type	portable system	stationary CHP
Fuel	H_2	H_2
Electrical Power	1 kW	5 kW
Thermal Power	n/a	3 kW
Electrical Efficiency	n/a	40%

5.2.4.4 Avista Labs (United States)

Figure 10: Independence 1000 (courtesy of Avista Labs)

Avista Labs[54], now known as ReliOn, is currently producing one system, the Independence 1000. One or more of these units can be used to provide the required power in increments of 1 kW. They can be obtained directly from Avista Labs or from their distributor, Aperion Energy Systems[52]. The system is easily scalable and can serve as a battery replacement or as backup power. They are not marketed as CHP systems. The Independence system is uniquely composed of hot-swappable cartridges to reduce down-time and to increase reliability. The cartridges can be replaced while the rest of the system continues to deliver power. It is fueled by hydrogen and produces water vapor (S. Saathoff, personal communications, June 11, 2004).

Table 13: PEMFC Specifications from Avista Labs[51][52][54]

Model	Independence 1000
Type	scalable system
Fuel	99.95% H_2
Electrical Power	1 kW
Electrical Efficiency	36–40%

5.2.4.5 Axane (France)

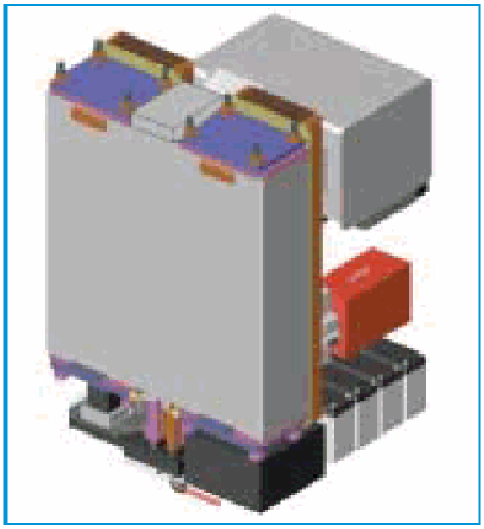


Figure 11: 2.5-kW Evopac (courtesy of Axane)

Air Liquide, an international group interested in industrial and medical gases, created Axane Fuel Cell Systems[55] in May 2001. Axane's fuel cell systems are based on a unique modular design, such that a variety of systems can be manufactured for outputs between 0.5 and 10 kW. Their Polar Pac proved its reliability and endurance when taken on a polar ice cap mission. Their designs range from low-output backpacks, to portable integrated systems. Currently no CHP system option.

Table 14: PEMFC Specifications from Axane [51][55]

Model	many
Type	customizable for most applications
Fuel	99.95% H_2
Electrical Power	0.5–10 kW (scalable)

5.2.4.6 Ballard (Canada)

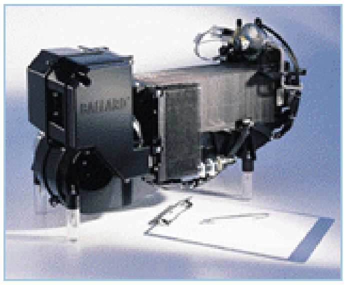


Figure 12: Nexa (courtesy of Ballard)

"Ballard Power Systems is recognized as the world leader in developing, manufacturing and marketing zero-emission proton exchange membrane fuel cells"[56]. They powered the world's first fuel-cell car in 1993 and have partnerships with some of the strongest companies in the world, namely Ford, DaimlerChrysler, FirstEnergy, Ebara, Alstom [51]. Even Osaka Gas[57] is working together with Ebara Ballard towards a commercial fuel cell product. Ballard mainly produces hydrogen-fueled PEM fuel cells for portable, stationary, and automotive applications, although Ebara is working on a natural gas unit. Their portable unit is the AirGen, which provides 1 kW of electrical power with zero emissions, suitable for indoor use. The Nexa module is designed to incorporate into other systems, and the Nexa RM is designed to rack-mount, making both systems scalable.

Table 15: PEMFC Specifications from Ballard [51 56]

Model	AirGen	Nexa	Nexa RM
Type	portable system	OEM module	rackmount module
Fuel	99.99% dry H_2	99.99% dry H_2	99.99% dry H_2
Electrical Power	1 kW	1200 W (scalable)	1 kW (scalable)
Electrical Efficiency	40%, 50% peak	40%, 50% peak	40%, 50% peak

Ebara Ballard is working on a 1-kW cogeneration unit, fueled by natural gas, for Japanese homes.

Table 16: PEMFC Specifications from Ballard and Ebara[51 56]

Type	stationary CHP
Fuel	natural gas
Electrical Power	1 kW
Electrical Efficiency	55%
Overall Efficiency	90%

Ballard and MGE UPS Systems are working on 3 UPS systems: a 3.2 kVA single-phase, a 7 kVA single-phase, and a 10 to 30 kVA three-phase (G. Schubak, personal communications, June 7, 2004).

Table 17: PEMFC Specifications from Ballard and MGE UPS Systems[51] [56]

Model	Pulsar EX RT	n/a	n/a
Type	stationary UPS	stationary UPS	stationary UPS
Fuel	99.99% dry H_2	99.99% dry H_2	99.99% dry H_2
Electrical Power	3.2 kVA, 1-phase	7 kVA, 1-phase	10–30 kVA, 3-phase
Electrical Efficiency	40%, 50% peak	40%, 50% peak	40%, 50% peak

Finally, Ballard and Sanmina SCI are working on a backup power supply of 6 kW, capable of weathering all 4 seasons outside (G. Schubak, personal communications, June 7, 2004).

Table 18: PEMFC Specifications from Ballard and Sanmina[51] [56]

Type	stationary system
Fuel	99.99% dry H_2
Electrical Power	40%, 50% peak

5.2.4.7 Ceramic Fuel Cells (Australia)

Figure 13: Residential CHP concept (courtesy of Ceramic Fuel Cells)

Ceramic Fuel Cells[58] is developing fuel cell systems based on their planar SOFC stack. The stacks are assembled together to form modules from 1 to 2 kW, around which are added the balance of plant components. While Ceramic Fuel Cells does not have a commercial product, they have designed and tested a market-entry system for residential CHP use. The unit integrates systems for space and water heating and is directly fuelled by natural gas. With the aid of an external reformer, the system can be modified to handle propane or butane, as well as renewable sources such as biodiesel or ethanol.

Table 19: SOFC Specifications from Ceramic Fuel Cells [51] [58]

Model	CHP Product Concept
Type	stationary CHP
Fuel	(internally reformed) natural gas (externally reformed) propane, butane, ethanol, biodiesel
Electrical Power	1 kW
Thermal Power	1 kW
Electrical Efficiency	40%
Overall Efficiency	80%

5.2.4.8 DTE Energy (United States)

Figure 14: Energy|now (courtesy of DTE Energy)

For information on DTE Energy[59], see Plug Power.

5.2.4.9 European Fuel Cell (Germany)

Figure 15: Home Energy Center (courtesy of EFC)

European Fuel Cell[60] has completed a cogeneration test unit for use in single family homes. It features a 1.5 kW electrical output and a 2.9 kW thermal output with additional heat generation from an integrated boiler for up to 15 kW of heat. The unit is fuelled by natural gas with steam reformer kept at around 800°C as the water used in the reformer is condensed and reused. Since this unit is still in beta testing phase, K. Binnewies of European Fuel Cell was unable to provide emissions data (personal communications, June 8, 2004).

Table 20: PEMFC Specifications from EFC [51] [60]

Model	Home Energy Center
Type	stationary CHP
Fuel	natural gas
Electrical Power	1.5 kW
Thermal Power	3 kW, 15 kW with additional integrated boiler
Electrical Efficiency	20% in beta unit
Overall Efficiency	80%

5.2.4.10 Fuel Cell Technologies (Canada)

Figure 16: Stationary 5 kW (courtesy of Fuel Cell Technologies)

Fuel Cell Technologies[61] is producing a 5-kW fuel cell based on SOFC technology. Their system is designed for CHP installations and has an overall efficiency of about 80%. The expectations are that the typical homeowner will see a pay back on a commercial unit in less than 4 years. The Ford Motor Company in Michigan has installed a 5-kW unit in their Detroit plant to produce electricity from paint fumes.

Table 21: SOFC Specifications from Fuel Cell Technologies [51] [61] [62]

Model	5 kW SOFC system
Type	stationary CHP
Fuel	hydrocarbons
Electrical Power	2–4.5 kW
Thermal Power	6 kW
Overall Efficiency	80%
Emissions	5% O_2 2.5% CO_2 <0.2 ppm NO_x <1 ppm CO <3 ppb SO_4 balance N_2 & H_2O

5.2.4.11 Fuji (Japan)

Fuji Electric Holdings[63] has been working on PEMFC since 1989. They have produced a stationary demonstration unit producing 1 kW_e containing a hot water unit and an inverter unit. The system reformed natural gas to hydrogen with less than 10 ppm CO content. Then 60 to 70% of the hydrogen is used for power generation while the remaining is used to fuel the reformer. The electrical output can be manually adjusted between 30 and 100%, and the system automatically maintains 60°C water in the water reservoir. Besides the fuel reformer, the system also has a desulfurizer, a CO shift converter, and a CO remover. Not currently a CHP product.

Table 22: PEMFC Specifications from Fuji[51 63]

Type	stationary CHP
Fuel	natural gas
Electrical Power	1 kW
Electrical Efficiency	38% based on LHV

5.2.4.12 Hydrogenics (Canada)

Figure 17: HyPORT-E (courtesy of Hydrogenics)

Hydrogenics Corporation[64] is producing three units in the 0.5 to 10 kW range. The HyPORT-E system is unique because it produces its own fuel by electrolyzing water. The downside to this is that the system must be regenerated after producing 15 kWh, and must be refilled with water every four charges. Considering that this unit produces 5 kW, it may need recharging after 3 hours. The HyPORT-C system stores its fuel in a modular chemical-hydride storage with a capacity of 10 kg H_2. This system will run for 20 hours at 500 W output. The HyPM 10 uses a modular design and can be scaled up into larger systems. The company does not currently market a CHP product.

Table 23: PEMFC Specifications from Hydrogenics [51 64]

Model	HyPORT-C	HyPORT-E	HyPM 10
Type	portable system	portable system	module
Fuel	H_2	electrolyzed H_2O	99.99% H_2
Electrical Power	0.5 kW	5 kW	10 kW
Electrical Efficiency	n/a	n/a	53%
Overall Efficiency	80%	n/a	n/a

5.2.4.13 IdaTech (United States)

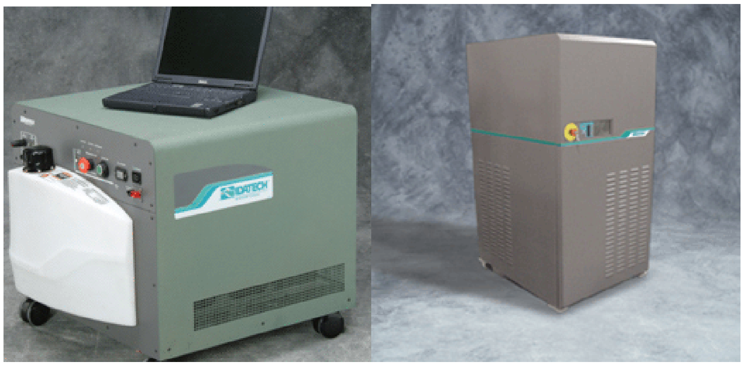


Figure 18: FCS 1200 (left) and FCS NG (right) (courtesy of IdaTech)

IdaTech[65] used to focus on ease of use and system integration built around fuel cells bought from other companies, particularly Ballard's Nexa, but their newer model incorporates IdaTech's own stack. The company offers two units fitted with fuel reformers and simple controls. Their FCS 1200 is a portable unit that reforms a methanol/de-ionized water mix and produces 850W AC or 1000W DC. Their FCS NG is a stationary CHP unit that reforms natural gas or propane and produces 4.6 kW_e net of electrical power, 7 kW thermal. Their new EtaGen5 is a stationary CHP unit incorporating their proprietary fuel reformer which achieves greater than 99.5% H_2 with less than 3 ppm CO. K. Bowels of IdaTech (personal communications, June 15, 2004) indicated that the company also produces liquid-hydrocarbon systems and hydrogen backup-power units and that these product descriptions are available with a non-disclosure agreement.

Table 24: PEMFC Specifications from IdaTech [51 65]

Model	FCS 1200	FCS NG	EtaGen5
Type	portable system	stationary CHP	stationary CHP
Fuel	methanol/de-ionized water mix	natural gas, propane	natural gas, propane
Electrical Power	850W AC, 1 kW DC	4.6 kW net	0.8–4.6 kW net
Thermal Power	n/a	7 kW	6.0 kW

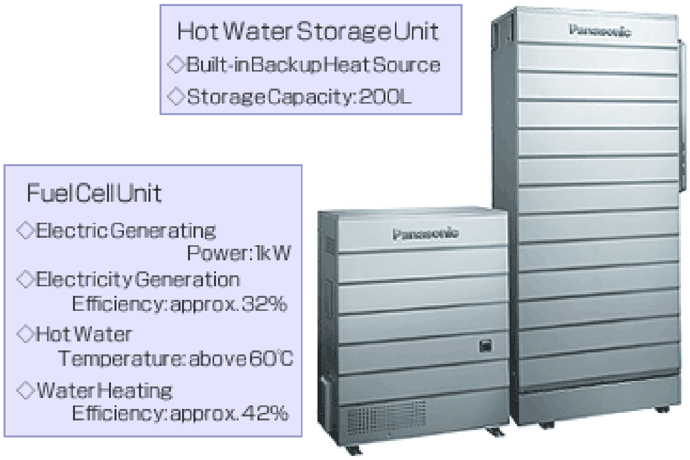
5.2.4.14 IHI (Japan)

Ishikawajima-Harima Heavy Industries[66] has been working on a prototype stationary CHP unit rated at 5 kW_e. They plan to use natural gas, liquefied petroleum gas, and other fuels. The unit is designed for outdoors, and the enclosure contains the fuel cell stack, fuel processor, controller, inverter, pump, radiator, ancillary facilities, and nitrogen gas cylinder to replace fuels during down-time. These specifications are the targets that IHI is working towards.

Table 25: PEMFC Specifications from IHI [51] [66]

Type	stationary CHP
Fuel	natural gas, liquefied petroleum gas, others
Electrical Power	5 kW
Electrical Efficiency	35%
Overall Efficiency	75%
Emissions	<10 ppm NO_x

5.2.4.15 Matsushita (Japan)



Matsushita Electric Industrial[67] [68] through their Panasonic subsidiary, claimed in February 2005 to have produced the world’s first commercial Household Fuel Cell Cogeneration System. The system is currently on display at the Panasonic Center Tokyo.

The system on offer is a stationary CHP unit, powered by natural gas, with a 1 kW_e output and 1.3kW_{th} output.

Table 26: PEMFC Specifications from Matsushita/Panasonic [51 67 68]

Type	**stationary CHP**
Fuel	natural gas
Electrical Power	1 kW
Electrical Efficiency	32%
Thermal Power	1.3 kW
Thermal Efficiency	42%
Overall Efficiency	74%

5.2.4.16 Mini Hydrogen (Denmark)

Figure 19: VE1000 (courtesy of Mini Hydrogen)

Mini Hydrogen[69] is currently concentrating on small fuel cells, the VE1000 being their only 1 kW model. M. Sloth of Mini Hydrogen (personal communications, June 7, 2004) indicated that after summer 2004, the company would be restructured into two divisions, one selling small fuel cells, and the other larger industrial products. After that time, they will be able to supply a 2.5 kW portable system and a 5 kW stationary UPS system. There are no obvious indications that a CHP unit will be produced.

Table 27: PEMFC Specifications from Mini Hydrogen [51 69]

Type	portable system
Fuel	H_2
Electrical Power	1 kW

5.2.4.17 Nuvera (United States / Italy)

Figure 20: H2E (left) and Avanti (right) (courtesy of Nuvera)

Nuvera Fuel Cells[70] produces two units in the 0.5 to 10 kW range. The H2E unit (hydrogen to electricity) generates power from 1 to 6 kW and uses pure hydrogen. The Avanti unit is designed for distributed generation and combined heat and power. It produces 3.7 kW electrical power and 5.7 kW thermal.

Table 28: PEMFC Specifications from Nuvera [51 70]

Model	H2E	Avanti
Type	OEM module	stationary CHP
Fuel	99.95% H_2	natural gas
Electrical Power	1–6 kW	3.7 kW
Thermal Power	n/a	5.7 kW
Electrical Efficiency	n/a	31.5% LHV
Overall Efficiency	n/a	80%

5.2.4.18 Osaka Gas (Japan)

Osaka Gas[57] is the main supplier of natural gas in the areas of Osaka and Kyoto, Japan. Not surprisingly, they are largely interested in reforming, but they are also interested in the development of PEMFC cogeneration (CHP) systems for the Japanese residential market (K. Hirai, personal communications, June 10, 2004). They are developing these systems with manufacturers such as Ebara Ballard and Toshiba International Fuel Cells. While Osaka Gas does not have a finished product, K. Hirai was kind enough to provide some of the companies target specifications. The future models will feature heat recovery to maintain a 60°C water reservoir, a grid connection without reverse sending, and continuous operation with stepwise load following.

Table 29: PEMFC Specifications from Osaka Gas[51][57]

Model	TBD	TBD
Fuel	88.9% CH_4, 6.9% C_2H_6, 3.1% C_3H_8, 1.2% C_4H_{10}	
Electrical Power	250–500 W	300–1000 W
Electrical Efficiency	28.0–31.5% HHV	27.0–31.5% HHV
Thermal Efficiency	25.5–35.5% HHV	24.0–41.0% HHV

5.2.4.19 Panasonic (Japan)

See Matsushita entry.

5.2.4.20 Phocos (Germany)

Figure 21: FC1000 (courtesy of Phocos)

Phocos[71] has produced a hybrid demonstration unit powering a PEMFC with solar and hydrogen. It is based on Ballard's Nexa module (G. Rimpler, personal communications, June 14, 2004) and is their only system in the 0.5 to 10 kW range. The system controls the battery charging from the solar panel and the fuel cell, while protecting the battery from overcharging. For specifications of FC1000, see section on Ballard Nexa module. No indications that a CHP unit will be produced.

5.2.4.21 Plug Power (United States)

Figure 22: GenCore (left) and GenSys (right) (courtesy of Plug Power)

Plug Power[72] was founded in 1997 as a joint venture with DTE Energy[73] and Mechanical Technologies Inc. It also has partnerships with Celanese, Engelhard, General Electric, Honda R&D, and Vaillant. J. Buijk of DTE Energy (personal communication, June 9, 2004) indicated that the Plug Power fuel cell is the only system under 10 kW in their portfolio. Plug produces two small stationary systems, the GenCore and the GenSys (J Goberish, personal communications, June 10, 2004). The GenCore system is designed for backup power with low emissions (less than 1 ppm). It produces up to 5 kW with adjustable voltage and current. The GenSys system is a stationary CHP system producing 5 kW electrical power and 9 kW thermal.

Table 30: PEMFC Specifications from Plug Power [51] [72]

Model	GenCore	GenSys
Type	stationary system	stationary CHP
Fuel	99.95% H_2	natural gas
Electrical Power	5 kW	5 kW
Thermal Power	n/a	9 kW
Emissions	<1 ppm CO, CO_2, NO_x, SO_2	<1 ppm NO_x, SO_x

5.2.4.22 Proton Motor (Germany)

Proton Motor Fuel Cell[74] is interested in all parts of the PEMFC and system integration. The company will also design the right system according to the customer's specifications. They have produced automotive and stationary systems in with outputs of 5, 18, 60, and 150 kW. B. Eska (personal communications, June 16, 2004) provided some details about their 5-kW system operating in stationary mode.

Table 31: PEMFC Specifications from Proton Motor [51] [74]

Type	stationary CHP
Fuel	99.999% H_2
Electrical Power	5 kW
Thermal Power	7 kW
Electrical Efficiency	43%

5.2.4.23 Sigen (United Kingdom)

Figure 23: FC-UPS1K (courtesy of Sigen)

Sigen Fuel Cell Power Solutions[75] does not manufacture any systems; they offer system integration only (D. McGrath, personal communications, June 8, 2004). Their two systems are based on Avista's Independence systems, which operate on hydrogen but are also available with a natural gas reformer. Their systems come in 1- and 5-kW models with power factor correction, frequency conversion, internal and manual bypass capability, and network monitoring. The hydrogen can either be provided from pressurized cylinders or metal hydride storage trays. No CHP unit capability at present.

Table 32: PEMFC Specifications from Sigen [51] [75]

Model	FC-UPS1K	FC-UPS5K
Type	rackmount system	stationary system
Fuel	99.95% H_2	99.95% H_2
Electrical Power	700 W AC, 1 kW DC	4 kW AC, 5 kW DC
Electrical Efficiency	36–40%	n/a
Emissions	n/a	<1 ppm CO, CO_2, NO_x, SO_x

5.2.4.24 Sulzer Hexis (Switzerland)

Figure 24: HXS 1000 (courtesy of Sulzer Hexis)

Sulzer Hexis[76] is responsible for most of the SOFC installations in the world to date. The company started a large demonstration project with its 1-kW HXS 1000 PREMIERE, a stationary CHP unit designed for residential applications. They are aiming towards electrical efficiencies greater than 30%. The units have auxiliary burners large enough to meet the thermal demands of a home or small office. Currently Sulzer Hexis is developing a near-series-system which has the same performance data as HXS 1000 Premiere, but a more simple design. The aim is that in the future it will be easier to combine into multiple units (personal correspondence with Volker Nerlich, Sulzer Hexis, December 2004).

Table 33: SOFC Specifications from Sulzer Hexis [51 76]

Model	HXS 1000 PREMIERE	Follower system
Type	stationary CHP	SOFC
Fuel	natural gas	natural gas
Electrical Power	1 kW	1 kW
Thermal Power	2.5 kW (12, 16, 22 kW with auxiliary burner)	~2 kW (~22 kW with auxiliary burner)
Electrical Efficiency	25–30%	25–30%
Overall Efficiency	85%	85%

5.2.4.25 Vaillant (Germany)

Figure 25: FCU 4600 (courtesy of Vaillant)

Vaillant[77] has been working on fuel cell technology since 1999. From 2003 to 2005 a field test with 55 units of the Euro 2 model is being undertaken. In the laboratory Vaillant is working on the Euro 3 model with higher efficiency, simplified technology, less parts, and therefore better opportunities for cost reduction. The target values of the Euro 3 (FCU 4600) model are illustrated in Table 34. The technology isn't expected to be ready for market before 2007. Vaillant is continuing to optimize the cogeneration system by developing and testing different plant schemes for several applications.

Table 34: PEMFC Specifications from Vaillant[77]

Model	FCU 4600
Type	stationary CHP
Fuel	natural gas
Electrical Power	1 - 4.6 kW grid connected
Thermal Power	1.5 - 7 kW
Electrical Efficiency[xix]	>35%
Overall Efficiency[xix]	>80%

5.2.4.26 Others

Due to a lack of current information from some companies, their products were unable to be included in this report in more detail; the outline information shown below comes from "Fuel Cell Today," [51].

Ascent Power Systems (United States)[78] provides little information about the current status of their operations, but they do indicate that they will be marketing small stationary SOFC systems from ITN Energy Systems[79] in the range of 1 to 30 kW. They use a direct oxidation system that eliminates the

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[xix] target values for the commercial units (expected onto the commercial market not before 2007)

need for a fuel reformer.

CellTech Power (United States)[80] deserves to be mentioned in this section. While they don't yet have a commercial product, they have operated demonstration units that use their unique variation of the SOFC. Their cell design operates similarly to the SOFC, but it uses a liquid metal anode (currently tin). Oxygen, ionized in the cathode, passes through the electrolyte and oxidizes the anode material. Similarly to a battery, this allows it to operate without the need for fuel, and current will flow until the anode is fully oxidized. When fuel is supplied, the system reduces the anode back to its original state. If fueled continuously, the system operates as a normal fuel cell. A major benefit to this new technology is its ability to adjust power output to match the demand within microseconds.

Ceres Power (United Kingdom)[81] plans to use experience gained from years of research with Imperial College to manufacture intermediate-temperature SOFCs. Their design allows the system to start producing power very quickly upon startup and can operate at 500 to 600°C. They plan to produce units in the 1 to 25 kW range for remote, APU, UPS, and CHP installations.

Clean Fuel Generation (United States)[82] focuses on developing components for key markets utilizing established fuel infrastructures. Among fuel reforming products, they plan to develop PEMFCs between 1 and 10 kW most applications.

Dais Analytic (United States)[83] is interested in developing PEMFC systems for portable, residential, and small commercial applications. They are working on the DuraWatt 1.5 kW system and the RPG 5 kW system.

Elcogen (Estonia)[84] is developing SOFCs for stationary applications in the range of 1 to 100 kW. They are using tubular cell design, which is fueled by hydrocarbons and uses air as the source of oxygen.

Electrocell Group (Brazil)[85] produces PEM fuel cells with or without accessories such as converters, inverters, controls, cooling, humidifiers, leak detectors, and automatic shutdown if necessary (V. Ett, personal communications, June 16, 2004). As they don't yet have a full production line, they are currently assembling units tailored to the customer's needs. Some previously manufactured units in the 0.5 to 10 kW range include 1.2-kW units for laboratory use and 3- to 10-kW systems for residential applications. Electrical and thermal efficiencies are typically about 40% each. Their cells are usually fueled by hydrogen, but some smaller units have been fitted to reform a 3% methanol, 97% water mixture. The hydrogen-powered units produce no emissions, and the methanol, ethanol, or natural gas units produce mainly carbon dioxide.

EnergyOr Technologies (Canada)[86] is in the process of redesigning their PEMFC units and should have more information in late summer 2004 (R. Roberge, personal communications, June 8, 2004). They indicate that their high electrical efficiencies will be impressive.

Entwicklungs- und Vertriebsgesellschaft Brennstoffzelle (Germany)[87], or EBZ for short, was founded in early 2000 with the goal of producing SOFCs for small stationary CHP units ranging from 1 to 20 kW. According to their roadmap, they should be in the process of developing prototype units and performing field tests.

Helion (France)[88] is focusing on producing PEMFC systems from several kW to several hundred kW. They have produced a 3-kW beta unit and a 5-kW beta unit. They plan to produce a 10-kW prototype soon.

Intelligent Energy (United Kingdom)[89] has built extremely compact PEMFC systems with outputs of 4 and 15 kW. They plan to produce complete systems and develop fuel processors to integrate into future models.

Materials and Electrochemical Research Corporation (United States)[90], or MER Corp, is developing PEMFC generators with AC outputs from 1 to 3 kW. They are focusing on low cost, modular designs, with a closed-loop cooling system.

Mitsubishi Heavy Industries (Japan)[91] has developed a 1-kW PEMFC system, fueled by natural gas, which they claim is the most compact system in the world. The system is apparently powered by natural gas and has an output of 1 kW.

Mitsubishi Materials Corporation (Japan)[92] developing stationary SOFCs for residential, commercial, and industrial use. They are developing these systems around a SOFC with newly developed lanthanum-based electrodes. They have prototyped a 1-kW unit and plan to market a 3- to 5-kW unit in the near future. They also have goals to produce 10- to 100-kW systems operating at 800ºC and 50% electrical efficiency for industrial applications.

Nippon Oil (Japan)[93] is planning to commercialize residential and small commercial PEMFC systems. It seems they have tested a 1-kW system powered by liquefied petroleum gas, and a 10-kW system powered by kerosene.

Teledyne Energy Systems (United States)[94] is one of the few companies whose fuel cells are designed for use with pure oxygen on the cathode side. Their NG series of fuel cell stacks can operate on many combinations of fuel mixtures including hydrogen/oxygen, hydrogen/air, dilute hydrogen/air, and reformate/air. Although they have extensive knowledge of PEM stack, they do not produce specific models of stationary systems. They do, however, advertise that Teledyne FTU Fuel Cell Systems are available on custom order between 1 and 50 kW.

Toshiba International Fuel Cells (Japan)[95] and **UTC Fuel Cells** (United States)[96] have agreed to the joint development of PEMFC systems for stationary and automotive applications. They are developing a 5-kW system for commercial use and a 1 kW system for residential use. UTC itself focuses on PEMFC system for large commercial applications.

Viessmann Manufacturing (Germany)[97] is working on a residential stationary CHP unit with a 2-kW electrical output. This system does not use any fuel or air compression components, making it unique and longer lasting.

A detailed and comprehensive list of fuel cell installations around the world can be found at the Fuel Cells 2000 website[98].

5.3 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[99]. 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[16].

The principle of the Stirling engine has been known for a long time. Unlike reciprocating internal combustion engines, the heat supply is from external sources via a heater or heat exchanger, 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[100]. The operating gas is compressed at low temperature in the compression cylinder and expands at high temperature in the expansion cylinder. 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[16].

There is an increasing interest in the use of Stirling engine based cogeneration systems for residential and commercial cogeneration because of their prospect for high efficiency, good performance at partial load, fuel flexibility, low emission level, low vibration and noise level[16]. A patent for the first Stirling engine was first granted to Robert Stirling, in 1816. This technology was used during the 19th century for various applications including ship propulsion and ventilation. However, Stirling engine technology usage was eliminated from the marketplace early in the 20th century due the robust and reliable quality of the internal combustion engines, as well as the cost reductions derived from the mass production of internal combustion engines together with the use of liquid petroleum fuels for transportation applications. Today, due to several factors including increased environmental concerns, cogeneration applications, increased demand for electricity and the deregulation of the electricity industry, the market is attracting opportunities for Stirling engines development[101].

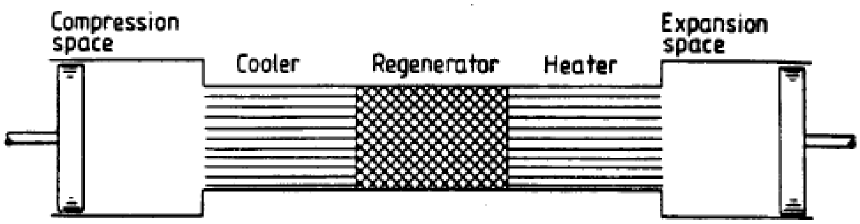
There are lack of statistical data for the reliability and availability of Stirling engine technology. However, it is expected that Stirling engine reliability and availability will be comparable to that of diesel engines[16].

5.3.1 Principle of operation

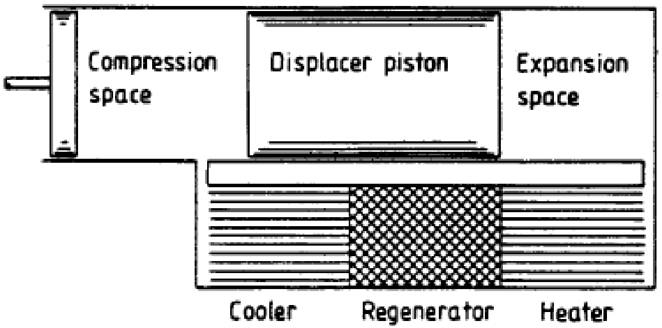
Stirling engines operate on the Stirling cycle, which is similar to the Otto cycle, with the adiabatic processes of that cycle replaced with isothermal processes. Stirling cycle engines have been developed in recent years as external combustion engines with regeneration, in which case the cycle resembles the ideal Carnot cycle[102].

Stirling engines are classified according to their arrangement: the Alpha, Beta and the Gamma arrangements as shown in Figure 26. 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 [16] [103].

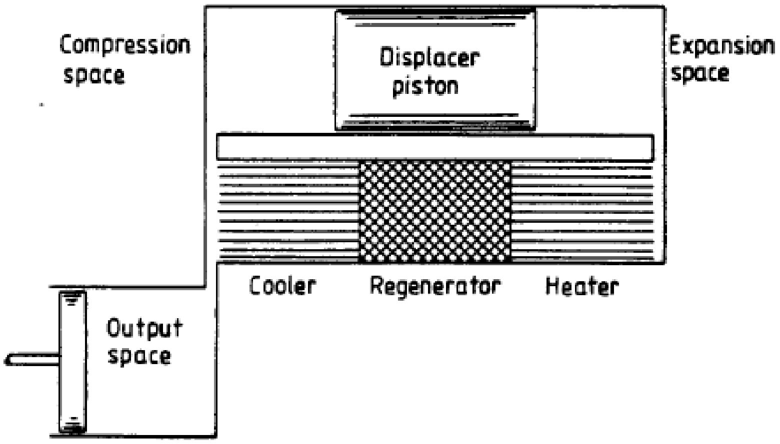
Stirling engine drive methods are based on kinematic drive and free piston drive. Kinematic drives utilize conventional mechanical elements like the cranks, connecting rods and flywheels in series that move in a prescribed manner. On the other hand, the free piston drives move the reciprocating elements using the pressure variations produced by the working gas, with the work being harnessed by a linear alternator [16].



(a) Alpha engine



(b) Beta engine



(c) Gamma engine

Figure 26: Classification of Stirling cycle engines[103]

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 ten 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[103]. Today, free piston engines are limited to several tens of kilowatts, a range suitable for residential and small-scale commercial applications.

5.3.2 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[16]. 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.

5.3.2.1 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 1.2-1.7. 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 [16].

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[16].

5.3.2.2 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 CHP 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% based on HHV depending on the amount of heat utilized[104].

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[105]. 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 12-17%.

5.3.2.3 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 5,000 to 8,000 hours, which are long compared with Otto gas engines of the same range. This considerably reduces the operating costs compared with Otto gas engines[104]. 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 ten years.

5.3.2.4 Emissions

Emissions from current Stirling burners can be ten 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[104]. 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 NOx and 40-60 mg/m^3 CO, and traceable hydrocarbon and soot emissions. Figure 27 illustrates the emission values for Stirling engine cogeneration units compared with conventional engines[104].

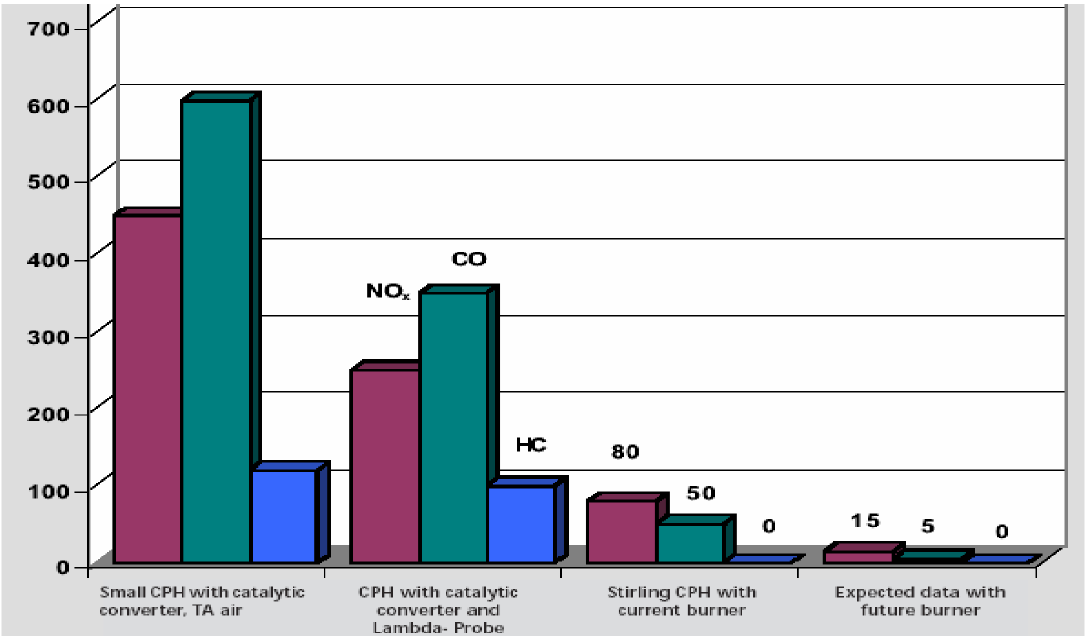


Figure 27: Emission of NO_x, CO, particles/HC from conventional and Stirling engine cogeneration units (mg/m^3)[102]

The efficiency and emission characteristics of Stirling engine units in the 2-25 kW range are given in Table 35.

Table 35: Stirling Engine Emissions Characteristics – natural gas fuel

Emissions Characteristics	**SOLO**[xx]	**DTE Energy**[xxi]	
Electrical Capacity (kW)	2-9	20	25
Electrical Efficiency (%)	22-24	29.6	29.6
Overall Efficiency (%)	> 90	82	82
NOx, (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)

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

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

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

under 20 kW have service internals from 5,000 to 8,000 hours, which are long compared with Otto gas engines of the same range. This considerably reduces the operating costs compared with Otto gas engines[104]. Due to the tight sealing of the casing, the free piston Stirling engines are expected to eliminate mechanical contact, friction and wear, therefore eliminating mechanical maintenance during an operating lifetime of about ten years.

5.3.3 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 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.

Stirling engines have a limited number of demonstration projects because they are still considered an emerging technology, however a field trial carried out for the 2 - 9 kW electric and 8 - 26kW thermal SOLO Stirling engine unit[106] shows the system operating without error and achievable maintenance operating times are more than 5000 hours. As of 2001, the total investment cost for the unit was estimated to be \$13,000 (10,200 €), from which \$10,400 (8,200 €) was for the engine cost while \$2,600 (2,050 €) was estimated for auxiliaries and technical interconnection. In addition, an estimated maintenance cost for the unit was 0.013 \$/kWh (0.010 €/kWh)[106]. 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 \$/kWh (0.010 €/kWh) as compared with \$0.018 \$/kWh (0.014€/kWh) of internal combustion engine driven cogeneration systems. Maintenance costs are expected to drop down to 0.0065 \$/kWh (0.0051€/kWh) with the mass production of Stirling engines[106].

Several manufacturers are involved in the development of Stirling engines suitable for small-scale cogeneration applications. These are detailed below:

5.3.3.1 Microgen (United Kingdom)

Figure 28: MicroCHP (courtesy of Microgen)

Microgen Energy Limited[107], a licensee of Sunpower and part of BG Group, is producing a wall-mountable cogeneration unit for residential and small-office use. The unit is small enough and quiet enough to mount in the kitchen. It is based on Sunpower's free-piston Stirling engine (J. Crawford, personal communications, June 1, 2004) and provides a supplementary burner to heat larger and less-efficient homes. It is fuelled by natural gas, with the possibility of using petroleum in the future. While neither Microgen nor BG Group provide details of emissions of the unit, BG Group claims that the Microgen unit can reduce CO_2 emissions by 25% and NO_x by 40% as compared to the average boiler. This unit also has the capability of modulating down to 5 kW thermal power output when demand is low.

Table 36: Stirling Engine Specifications from Microgen[107] [108] [109]

Type	beta
Design	free-piston
Electrical Power	1.1 kW
Thermal Power	15–36 kW (modulating down to 5 kW)
Electrical Efficiency	28%
Overall Efficiency	90%
Fuels	natural gas, petroleum (future)

5.3.3.2 Solo (Germany)

Figure 29: Stirling 161 (courtesy of Solo)

Solo[110] is currently producing a cogeneration module aimed at homes and small businesses. The unit integrates into heating and electrical systems with computer-controlled operation. It is powered by an alpha-type Stirling engine operating with helium gas and can be fueled by either natural gas or liquid gas. Once combustion has begun and the engine is up to operating temperature, the system uses an exhaust gas recirculation system to convert into a flameless oxidation mode to reduce emissions. The computer monitors important temperatures and pressures to ensure smooth operation, as well as the speed and power outputs. The operating-gas pressure can be automatically or manually adjusted to control power output. S. Luft of Solo (personal communications, May 28, 2004) indicated that the company is developing new CHP-modules for use with biogenic fuels but that the project will take until late 2005.

Table 37: Stirling Engine Specifications from Solo[110]

Model	Stirling 161
Type	alpha
Operating Gas	He
Electrical Power	2–9.5 kW (modulating)
Thermal Power	8–26 kW (modulating)
Electrical Efficiency	22–24%
Overall Efficiency	92–96%
Fuels	natural gas, liquid gas, biomass (future models)
Emissions	50 mg/m^3 CO 80 mg/m^3 NO$_x$ 2 mg/m^3 HC

5.3.3.3 STC (United States) & Enatec (Netherlands)

Figure 30: RG-1000 (courtesy of Stirling Technology Company)

Stirling Technology Company provides their RemoteGen Stirling engine to power the Enatec cogeneration units. The engines are so reliable and efficient that NASA will be using STC's generating units for future space exploration. STC claims that their engines can use virtually any energy source, and have successfully operated them with natural gas, propane, white gas, solar energy, biomass, diesel, and radioisotope fuel sources. They currently produce engines in five power outputs. STC notes that their units can be tailored to provide the desired ratio of heat to electricity (P, Dailey, personal communications, June 2, 2004). As the units are custom-made, thermal power, electrical efficiency, and emissions all depend on the specific application as well as the fuel used.

Table 38: Stirling Engine Specifications from STC

Model	Electrical Power	Thermal Power	Overall Efficiency
RG-55	60–80W	not available (zero)	29%
RG-350	350 W	not available (zero)	23%
RG-450	450–550 W	not available (zero)	30%
RG-1000	1000–1250 W	6–24 kW (modulating)	23%
RG-3000	3000 W	not available (zero)	39%

STC notes that the overall efficiency values do not include the burner efficiency, which is application dependent. Since all other specs are very similar, they have been combined into the following table. This table also includes the Enatec unit specifications which are slightly different to the STC figures.

Table 39: Stirling Engine Specifications from STC[111] [112] and Enatec[113]

	STC	Enatec
Type	Beta	Beta
Design	free-piston	free-piston
Electrical Power	60 W – 3kW	600 W – 1 kW
Thermal Power	0 – 6 kW (24 with auxiliary burner)	5.4 – 9 kW (18 with auxiliary burner)
Electrical Efficiency	23 – 35%	25%
Overall Efficiency	23 – 39% (does not include burner efficiency - application dependent)	10% (based on burner efficiency of 40% and Stirling efficiency of 25%)
Fuels	most HCs (liquid and gaseous), biomass, solar, others	Natural Gas
Emissions	<15 ppm CO, CO_2, NO_x	<15 ppm NO_x (dry, air free) <3 ppm CO (dry, air free)

5.3.3.4 STM Power & DTE Energy (United States)

Figure 31: ENX 55 (courtesy of STM Power)

Stirling Thermal Motors[114] has teamed with DTE Energy[73] to develop and sell the "Energy|now" cogeneration module. This unit is powered by STM's 4-260 Stirling engine. This unit, as well as being one of the largest on the market, is likely the most versatile in terms of fueling. It is designed to operate on natural gas, propane, hydrogen, alcohol, or liquid petroleum, but this unit can also operate on renewable energy such as biomass, hydrogen, landfill gas, gas from anerobic digesters, flare gas, and waste heat from other high-temperature (greater than 760°C) processes. Solar energy can also be directed to power the unit, as well as hybrid models that can operate without sunlight. Current products are designed to operate in conjunction with the electric grid, but future models plan to have the ability to operate independently from it. It can also produce electricity at both 50 and 60 Hz. DTE Energy Technologies is the local distributor for the STM Stirling engines (J. Buijk, personal communications, June 1, 2004).

Table 40: Stirling Engine Specifications from STM Power[73] [114]

Model	ENX 55
Type	alpha
Design	4-cylinder swash plate (fixed or variable stroke)
Operating Gas	H_2
Electrical Power	55 kW (modulating or non-modulating)
Thermal Power	91 kW (modulating)
Electrical Efficiency	31%
Overall Efficiency	>80%
Fuels	most HCs (liquid and gaseous), biomass, waste heat, others
Emissions	(0.01 g/kWh CO) (0.1 g/bhp-hr CO) (0.03 g/kWh NO_x) (0.3 g/bhp-hr NO_x) (0.03 g/kWh HC) (0.3 g/bhp-hr HC)

5.3.3.5 Sunpower (United States)

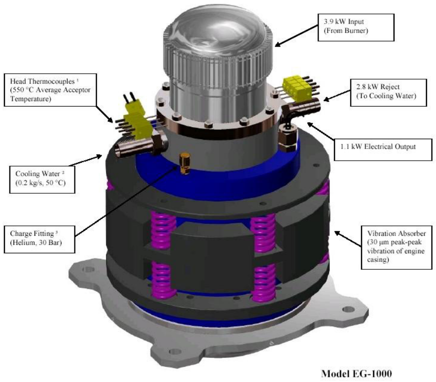

Figure 32: Stirling Engine (courtesy of J. Crawford)

Sunpower, Inc.[109] was formed after William Beale invented the free-piston Stirling engine. The company then became a leader in the development of the free-piston design[115]. Due to the success of the design, several companies became either subsidiaries or licensees of Sunpower, such as Stirling Technology Inc, Global Cooling, External Power, and Microgen. Stirling Technology Inc[116] manufactured the ST-5, a 5 kW engine capable of burning a large variety of fuels; unfortunately, the ST-5 is no longer in production in the US, and no additional information was received on the state of production elsewhere. Global Cooling concentrates on cryocoolers, and it appears that External Power lost the license to Sunpower's Stirling engine. Since Sunpower itself does not produce full cogeneration modules, specs on the Sunpower Stirling engine can be found under Microgen, who is using Sunpower's engine to power their CHP unit.

5.3.3.6 Whisper Tech (New Zealand)

Figure 33: WhisperGen AC (courtesy of Whisper Tech)

Whisper Tech[117] offers two cogeneration units, one producing DC electricity, the other AC. Both units have a self-managing burner and engine control system with both remote and local programming options. Intelligent temperature management software ensures that the engine runs smoothly. The DC model is being sold primarily for marine applications in Western Europe. It is designed to charge batteries commonly found on yachts or mobile homes, and is fuelled by either diesel or kerosene. The AC model, on the other hand, is fuelled by either natural gas or petroleum. It is designed to act as an urban or remote power station, with the option to interface with the electric grid. Whisper Tech provides most of the important information except for efficiencies and emissions.

Table 41: Stirling Engine Specifications from Whisper Tech[117]

Model	WhisperGen DC	WhisperGen AC
Type	alpha	alpha
Design	4-cylinder wobble-yoke	4-cylinder wobble-yoke
Operating Gas	N_2	N_2
Electrical Power	750 W (modulating)	850 W (modulating)
Thermal Power	6 kW (modulating)	8 kW (modulating)
Fuels	diesel, kerosene	natural gas, petroleum

A. Kay (personal communications, June 4, 2004) was kind enough to provide the following test results for the AC model.

Table 42: AC Whispergen test data

Test Number	1	2
Electrical Output	850 W	1200 W
Heat Input	7.3 kW	9.5 kW
Electrical Efficiency	11.6%	12.6%
Overall Efficiency	96%	94%
NOx	170 ppm (0% O_2)	330 ppm (0% O_2)
CO	<100 ppm (0% O_2)	<300 ppm (0% O_2)

5.3.3.7 *Others*

Due to a lack of current information from some companies, their products were unable to be included in this report in more detail; the basic information shown below is from the “Stirling Engine and Hot Air Engine Home Page”[118].

Cussons Technology (United Kingdom)[119] specializes in producing Stirling engines for educational purposes. They are expensively priced and are in experimental stages.

Omachron (Canada)[120] was preparing to produce experimental Stirling-cycle engines, partnering with Fantom Technologies Inc., for commercialization in Canada and the United States. Unfortunately, Fantom lost its financial backing after September 11, 2001, causing Omachron to abandon the project. Subsequent events led Omachron to develop an entirely new engine, entirely its own. The Omachron Family of Companies, as it is now known, will be announcing its commercial plans in the near future.

Sigma Elektroteknisk (Norway) was developing a Stirling engine to be used in cogenerating applications. They were working on a single-cylinder, beta-type Stirling using helium as the working fluid. It produced 1.5 kW of electrical power and 9 kW of thermal power with an overall efficiency of 95% and low emissions: 50 ppm CO, 2.5 to 4 ppm NO_x, 0.3 to 1 ppm HCs. Unfortunately, their website has disappeared along with email communications, and no current news about the company has surfaced.

Stirling Advantage (United States)[121] is developing a cogeneration solution that can be fueled by steam, waste heat, or combustion. They advertise a 4-cylinder, 200-kW Stirling engine in standard Philips configuration. This free-piston engine will power a hydraulic drive system, allowing for a variable stroke and phase relationship. Interestingly, it is designed to operate at 5 to 15 Hz, rather than the typical 50 to 60 Hz, and at a lower temperature than the typical Stirling engine, ~525 °C as opposed to 750+ °C.

Suction Gas (Japan)[122] is developing a 100-W and a 1-kW Stirling engine operating on low temperature differential. They are using an alpha-type Stirling engine with a phase angle of 150 degrees and a high-pressure working gas. Unfortunately, most of the important links on their website are broken, leaving out much of the details.

Tamin Enterprises (United States)[123] has been developing a single-cylinder Stirling with almost 1 kW output. Their research and development team is working on CHP modules and automotive applications. Their website leaves out any other details.

6 Conclusions

A review of the current cogeneration technologies for single- and multi- family residential cogeneration applications has been presented. These technologies are becoming more relevant due to the development of commercially available small traditional reciprocating internal combustion systems as well as fuel cell, Stirling engine and micro-turbine based cogeneration systems. With the exception of micro-turbine systems, these technologies are suitable for single- and multi- family residential applications (1 - 10kW). From the technological perspective, fuel cell and Stirling engine cogeneration systems seem promising for residential applications; however, before these systems can see wide spread acceptance, their affordability and reliability must be improved significantly. 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.

While the electrical efficiency of reciprocating internal combustion engines is higher compared to Stirling engines, fuel cells promise to offer the highest electrical efficiency for residential and small-scale cogeneration applications. Reciprocating internal combustion engines theoretically will require more periodic maintenance than competing technologies, reducing their availability and increasing maintenance costs. Fuel cells have few moving parts and therefore have the potential to have very low maintenance, though this has yet to be achieved in practice. 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 (< 20 kW) have service internals from 5000 to 8000 hours, which are long compared with spark ignition reciprocating internal combustion (Otto) engines of comparable capacity. This long service interval considerably reduces the operating costs compared with Otto engines. Installed costs for emerging technologies like fuel cells and Stirling engines are currently more expensive, with fuel cell offering the highest installed cost.

Reciprocating internal combustion engines have higher CO, NO_x, and particulate emissions than competing technologies for residential applications, and are thus at a disadvantage in geographical areas with stringent emission criteria. Using catalysis to reach acceptable emission levels is often possible, but costly. Fuel cells, by nature of the electrochemical and catalytic oxidation process, have extremely low emissions of NOx and CO. Their CO_2 emissions are also generally lower than other technologies due to their higher efficiency when the CO_2 emissions related to the electricity produced is accounted for as being avoided at the grid mix level. Emissions from current Stirling burners can be ten times lower than that emitted from Otto engines fitted with catalytic converters, making the emissions generated from Stirling engines comparable with those from modern gas burners.

While performance and price data for reciprocating internal combustion engines is well established, data for fuel cells and Stirling engines are based on limited number of demonstration projects. More operational hours are needed to prove fuel cell and Stirling engine based systems. 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 to carry out a meaningful and accurate comparison of reciprocating internal combustion engines, fuel cells and Stirling engines. These emerging technologies will continue to fight an uphill task against the reciprocating internal combustion engine for residential cogeneration applications until more data from demonstration projects become available and they meet or surpass current expectations.

A summary comparison table for reciprocating internal combustion engine (ICE), fuel cell and Stirling engine based single-family residential cogeneration systems is presented in Table 43. The information presented in the table is representative of the technologies, and provides an opportunity to make an approximate, yet direct comparison of the three technologies.

Table 43: Summary table of properties – Single- and multi- family residential cogeneration systems

Parameter range	ICE	Fuel Cell	Stirling
Electrical Capacity (kW$_e$)	1-100	0.5-100	1-55
Electrical[xxii] Efficiency (% HHV)	20-40	30-50 PEMFC 40-50 SOFC	20-35 Current 35-50 Possible
Heat Recovery Efficiency (% HHV)	50-60	40-60	40-60
Temperature of heat available (°C)	85-110	80-100 PEMFC 950-1000 SOFC	200
Overall[xxiii] Efficiency (% HHV)	80-90	70-90 PEMFC 70-95 SOFC	65-95
Thermal Output (kW$_{th}$)	3-300	1-300	3-150
Availability (%)	85-98	95	85-90
Part Load performance efficiency?	Good	Best	Better
Maintenance – cost (US$/kW$_e$h) (€/kW$_e$h)	0.01-0.015 0.008-0.012	0.02-0.03 0.016-0.024	0.006-0.012 0.005-0.01
Emissions – NOx, SOx, Cox, Particulates	Low	Lowest	Lower
Cost (US$/kW$_e$) (€/kW$_e$)	1,000-2,800 785-2,200		

[xxii] Electrical efficiency = electrical output (kW)/ fuel input (kW) based on Higher Heating Value or Gross Calorific Value

[xxiii] Overall efficiency = useful heat recovered (kW) + electrical output (kW)/ fuel input (kW) based on Higher Heating Value or Gross Calorific Value

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