Review of Existing Residential Cogeneration Systems Performance Assessments and Evaluations

A Report of Subtask C 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 programme 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 programme 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
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings
Annex 48: Heat Pumping and Reversible Air Conditioning
Annex 49: Low Exergy Systems for High Performance Buildings and Communities
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential 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 were 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 was accomplished by developing and incorporating models of cogeneration devices and associated plant components within existing whole-building simulation programs. Emphasis was placed upon fuel cell cogeneration systems and the Annex considered technologies suitable for use in new and existing single and low-rise-multi-family residential buildings. The models were developed at a time resolution that is appropriate for whole-building simulation.

To accomplish these objectives Annex 42 conducted 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 was an international joint effort conducted by 26 organizations in 10 countries:

Belgium	▪ University of Liège / Department of Electrical Engineering and Computer Science ▪ COGEN Europe ▪ Catholic University of Leuven
Canada	▪ Natural Resources Canada / CANMET Energy Technology Centre ▪ 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)
Italy	▪ National Agency for New Technology, Energy and the Environment (ENEA) ▪ University of Sannio ▪ Second University of Napoli
Netherlands	▪ Energy Research Centre Netherlands (ECN) / Renewable Energy in the Built Environment
Norway	▪ Norwegian Building Research Institute (NBRI) ▪ Telemark University College
United Kingdom	▪ University of Strathclyde / Energy Systems Research Unit (ESRU) ▪ Cardiff University / Welsh School of Architecture
United States of America	▪ Penn State University / Energy Institute ▪ Texas A&M University / Department of Architecture

- National Institute of Standards and Technology
- National Renewable Energy Laboratory
- National Fuel Cell Research Center of the University of California-Irvine

Switzerland

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Viktor Dorer
Subtask C Leader

Abstract

The aim of this report is to give an overview of available studies and projects that cover the performance assessment and the empirical evaluation of residential cogeneration systems. Assessments are made in terms of environmental criteria such as energy demand and green house gas (GHG) emissions, technical criteria including the operation and control of cogeneration systems, and economic criteria. This review was conducted to support the research of IEA Annex 42 and to serve as a reference for other researchers in the field of residential cogeneration. The first part of the report focuses on existing performance assessment and evaluation studies that are mainly based on theoretical approaches, especially building simulation analysis. The second part focuses on existing laboratory and field tests of residential cogeneration units and systems. Here the focus is on references that give a link to available data from measurements, which might be of use for model validation.

CONTENTS

1 INTRODUCTION

The aim of this report is to give an overview of available studies and projects that cover the performance assessment and empirical evaluation of residential cogeneration systems in terms of environmental criteria, mainly primary energy demand and green house gas (GHG) emissions, in terms of technical criteria including the control and operation of cogeneration systems, and in terms of economic criteria.

The report comprises first a summary of the different systems analyzed and the different modelling techniques and assessment criteria applied.

The main body of the report is subdivided into two parts. The first part focuses on existing performance assessment and evaluation studies, which are mainly based on theoretical approaches, especially approaches that use dynamic building and plant modelling and simulation analysis. The second part focuses on existing laboratory and field tests of residential cogeneration units and systems. Here the focus is on references that provide a link to available data from measurements, which might be useful for model validation. Tests with propriety results, performed mainly by individual manufacturers and/or by energy utility companies, and results from field trials, are only briefly presented in this report.

This review was conducted to support the research of IEA Annex 42. However, it should also serve as a valuable reference for other researchers in the field of residential cogeneration.

2 SCOPE

The emphasis of Annex 42 was placed upon fuel cell, Stirling and ICE cogeneration systems suitable for use in new and existing single and low-rise-multi-family residential dwellings.

The report focuses on the scope and results of performance assessments and evaluations in terms of energy, environmental and economic criteria, as noted above, and on related performance tests.

Not covered in this report are the interactions between distributed electric power resources and the public electrical grid network, and related issues of electric power quality, safety and reliability. The report also does not address the specific national situations of energy supply, demand and market dynamics, such as standards and regulations that may affect residential co-generation policy and market adoption.

Covered in a separate IEA Annex 42 report are the topics of methodologies applied in the performance assessment studies, and the development and application of methods and procedures for the design and operational optimization of cogeneration systems. Also covered in separate IEA Annex 42 reports are the topics of available cogeneration technologies and heat demand profiles for space heating and domestic hot water.

3 TERMINOLOGY AND ABBREVIATIONS

BoP	Balance of plant
CCPP	Combined cycle (gas and steam turbine) power plant
CHP	Combined heat and power (cogeneration)
CCHP	Combined cooling, heat and power (tri- or poly-generation)
DG	Distributed generation
DHW	Domestic hot water
FC	Fuel cell
GHG	Green house gas
HP	Heat pump
HHV	Higher heating value (of fuel)
ICE	Internal combustion engine
LCA	Life cycle assessment/analysis
LHV	Lower heating value (of fuel)
MCHP	Micro cogeneration (or micro-CHP) (electric power capacity < approx. 15 kW)
MFH	Multi-family house
NG	Natural gas
NRPE	Non-renewable primary energy
PE	Primary energy
PEFC	Polymer electrolyte fuel cell (or proton exchange membrane fuel cell)
RE, RES	Renewable energy, renewable energy sources
SE	Stirling engine
SFH	Single-family house
SH	Space heating
SOFC	Solid oxide fuel cell

4 SUMMARY

This review summary focuses on the systems analyzed in existing micro-cogeneration (MCHP) performance assessment studies, on the methodologies and modelling techniques used, on the assessment criteria and metrics applied; and presents some results of the reviewed studies.

4.1 Performance assessment studies

4.1.1 Performance assessment criteria

The focus of most studies has been on the energy demand of the building in terms of delivered primary or renewable energy, and on the respective CO_2 or GHG emissions, calculated as annual or seasonal values. Exergy-based approaches were outlined but rarely used in the assessments.
A few assessments included a more comprehensive set of ecological criteria, considering additional environmental impact factors such as acidification and eutrophication, and extending into analyses of source-to-service and/or life cycle analysis (LCA).
The economic criterion used primarily was annual energy cost. When also considering fixed capital and installation costs, pay-back time and net present value analysis were the metrics most commonly used.

4.1.2 Performance analysis methodologies and models

<u>Comparisons</u>

Most studies included comparisons with benchmark or reference systems. Benchmark systems represented best available technology such as condensing gas boiler and grid electricity or commercially available MCHP systems. The assumed grid electricity generation mix dominates such energy and emission performance comparisons. Many studies considered marginal or best available central electricity generation scenarios that use combined cycle power plants (CCPP).
Comparisons were also made with other energy saving measures such as enhancing building fabric insulation, installing mechanical ventilation with heat recovery, or using biomass-based fuels.

<u>Design and dimensioning</u>

Decision processes and the respective incentives and barriers for the introduction of MCHP systems were analysed in many national contexts. Few articles focused on design procedures, but several articles concluded that systems should be dimensioned on the basis of the heat load of the building: Minimum heat load in order to achieve sufficient operation hours throughout the year, average or maximum heat load when considering energy or emissions.

<u>Optimization</u>

For performance optimizations, linearised system models were applied in certain cases. Multi-objective (energy-economic or energy-environmental) optimization techniques were also used to define sets of optimal configurations. Process flow models were combined with process integration methods and multi-objective optimization.

<u>Static vs. dynamic models</u>

Either static or dynamic models were applied, depending on the focus of the individual study. Dynamic models of the cogeneration system as well as of the building were used for some performance assessments, considering individual MCHP system components, namely heat storage devices, and the interaction of the system with the transient heat demands for building space heating and for domestic hot water (DHW).

Static models were used for design and dimensioning purposes and for more generic assessments of energy and cost savings potential, and for market studies.
For the assessment of control strategies and algorithms, dynamic models proved to be necessary in most cases.

4.1.3 Systems and configurations

Micro-cogeneration (MCHP) units and systems

Most performance studies dealt with emerging technologies such as fuel cell and Stirling engine driven MCHP units. ICE MCHP units were often studied based on results from laboratory tests.
Many systems also included an auxiliary or back-up heating system such as a gas boiler. The analysis of system configurations concerned storage type and size, and different configurations of storage devices. The combination of MCHP systems with solar thermal systems was analysed in several studies. Also combinations with heat pumps were analysed, mainly for larger buildings or for clusters of buildings.

Building

Many studies focused on individual building or building types. For instance, the application potential of MCHP to low energy houses according to the 3-liter home or the Passive House standards was assessed in Germany. Other work extrapolated the results for individual buildings to the national building stock. For local building clusters with small district heating networks, different MCHP configurations were compared to configurations with one larger CHP unit.

Loads

On the thermal side, the interaction of the MCHP system with the heat demand for space heating and for DHW was considered. For the determination of the space heat demand of the building two approaches were used: (i) specifying load profiles; and (ii) determining the space heating (and cooling) loads by dynamic building simulation.
The heat demand for DHW and the electricity demand for appliances and lighting were defined by specifying demand profiles. These demand profiles were based on measurements, were created on the basis of probabilistic distributions for occupancy and for the individual components, or were generated using stochastic methods. The topic of DHW and electric loads is covered in a separate report of IEA Annex 42.
An analysis of the impact of temporal precision in optimisation modelling for MCHP found that demand data must be at a maximum of 10 minute intervals to achieve reliable results.

Control and operation

Heat-following control modes were compared to electricity following control modes. Cost control methods that consider dynamic prices and emissions optimized control strategies were described and assessed. Predictive control was analyzed, especially for an SOFC system where on-off operation jeopardizes reliability and life-time due to thermal cycling degradation effects.

Fuel

In most studies natural gas was assumed as the fuel. Specific studies investigated the potential of biogas driven SOFC or wood pellet fired SE MCHP units. Hydrogen fuelled PEFC systems were analysed for remote locations or in combination with PV driven electrolysers.

Interaction with the electric grid

Many studies investigated the potential of MCHP to meet marginal electricity demand and to reduce peak loads. The assumed electricity generation mix and the interaction of the MCHP unit with the grid are important factors when comparing the MCHP system to different central electricity generation technologies and when discussing energy supply scenarios at the local (city), regional or national level. Many studies focused on resource management and electric grid quality; however, these topics are outside the scope of this review.

4.1.4 Results

On the level of individual buildings, many MCHP system studies showed reductions in non-renewable primary energy (NRPE) demand compared to conventional gas boiler systems and grid electricity as the benchmark. They confirmed the strong dependence of the achievable energy savings and, to an even greater extent, the resulting CO_2 emissions, on the grid electricity generation mix. Actual cost savings depended strongly upon factors such as transient heat and power demand variations, control modes, capacity and efficiency of the MCHP system, and upon electricity import/export conditions and modes. On the level of large-scale energy supply, MCHP systems with high electric efficiencies were required to be competitive with scenarios comprising central electricity generation with CCPP and heat production with building integrated heat pumps.

Analyses of the combination of MCHP systems with solar thermal systems confirmed that an overall increase in the contribution of renewable energy to meet energy demands was possible, but also identified conflicts between producing heat with the MCHP and with the solar thermal system.

The control mode was shown to have significant effects on the energy and environmental system performance. In many cases heat following modes showed the best energy efficiency while electricity following control modes reduced cost, but combined control modes were shown to be most effective in certain cases. In general base-load control offered better energy savings compared to a peak-load oriented control.

4.2 Experimental tests and evaluations

4.2.1 Laboratory test

Laboratory test results have been reported from all types of MCHP, although detailed results are not often given. Tests were conducted in steady-state mode for several load conditions, and for different supply and return temperature of the heat extraction circuit. Dynamic tests were made with MCHP systems including the storage components for typical space heating and DHW load profiles. Measurements have also been made in test or demonstration buildings with well monitored boundary conditions and fully controlled internal loads.

Many PEFC tests involved prototype systems and tests on individual components such as the stack or the reformer, while ICE and SE system tests were primarily conducted using pre-commercial or commercial integrated systems.

4.2.2 Field trials

Many field trials with MCHP units were conducted as a joint undertaking of MCHP manufacturers and energy service companies, however few results are reported. National programmes such as the Carbon Trust in the UK or the US DoD Residential PEM Fuel Cell Demonstration Program promote the development, installation and field testing of MCHP systems and publish respective results. In an European project, a cluster of PEFC systems was operated as a virtual power plant, remotely controlled by the energy supplier company. Extensive field trials with MCHP systems were also conducted in Japan, including PEFC, SOFC and ICE systems.

5 EXISTING COGEN PERFORMANCE ASSESSMENT STUDIES

5.1 Belgium

Voorspools & D'haeseleer (2001) report on studies on micro and mini CHP. Voorspools et al. (2001) and Voorspools & D'haeseleer (2002) concluded that heat following controlled residential cogeneration units taking over part of the electricity generation formerly produced by central power stations (partly coal-fired units with much higher emissions) is beneficial for energy savings and emission reduction. By reducing the size of the individual units to mainly carry thermal base load, the annual operation time of the cogeneration unit becomes larger, and the potential primary energy savings and emission reductions increase because central power generation, partly coal-fired, diminishes. For the specific context of electricity generation, the simulation tool PROMIX has been developed.

Lilien et al. (2004) and Pochet et al. (2004) report on the application of multi-objective optimisation in terms of GHG and cost for the system optimization for an installation of a 5 kWe SOFC in a Belgian home.

DePaepe et al. (2006) studied five different types of MCHP. All installations lead to a reduction in PE demand and CO_2 emissions. Stirling engines had the best PE demand and CO_2 emissions reduction performance. They also found that using a condensing boiler was often as good as installing a MCHP plant. Building loads were determined using DOE-2.

Voorspools & D'haeseleer (2006) considered the dynamic interaction between the cogeneration and the central power system. They found that both the reduced-scale sizing (smaller share of the total thermal energy but operation with a higher annual use) and the partial-heat-usage sizing (part of the MCHP heat cannot be used) of the cogeneration system can lead to significantly higher PE savings and emissions reductions than when applying current methods, which are largely based on simple static criteria for sizing the cogeneration unit on the basis of a maximum given or estimated heat-demand profile.

Haeseldonckx et al. (2007) showed that the impact of small thermal-storage devices on the net reduction of CO_2 emissions, in comparison to a reference scenario without cogeneration, is almost three times higher compared to the case without a heat buffer. It is also shown that, for the determination of the net reduction of CO_2 emissions, the operational behaviour of multiple small-scale cogeneration units can be approximated by the behaviour of one large fictitious unit.

5.2 Canada

In a report for Natural Resources Canada, Caneta Research (2001) assessed the potential for distributed cogeneration in multi-unit residential, commercial and institutional buildings in Canada, under a range of alternative control strategies and in applications with additional heat loads (e.g. desiccant cooling, absorption cooling), using DOE-2. They concluded that PE savings with a peak limiting control strategy are significantly lower than with base electric load control strategies in all locations and building types examined, making base load control the preferred operating control method. In terms of environmental impact they concluded that compared to marginal electricity production with a CCPP, distributed generation would reduce GHG emissions if electric efficiencies are high.

Iqbal (2003a,b) and Kahn et al. (2005) modelled and analysed a wind fuel cell hybrid energy system for stand-alone / remote residential scale applications, using Simulink.

Ferguson & Ugursal (2004) presented the results from a Canadian case study investigating the effect of varying PEM fuel cell size and operating strategy on the performance of a cogeneration system and demonstrated that these are critical factors that affect the performance of such systems. The simulations were made using ESP-r.

In Alanne et al. (2006) a financial analysis of a small 1-2 kWe SOFC system and a comparative assessment versus heating systems based on gas, oil and electricity was conducted using the simplified model for a single-family house located in Ottawa and Vancouver. The study shows that such an SOFC system is especially an attractive alternative to heating systems based on oil and electrical furnaces.

Onovwiona and Ugursal (2006) provide an up-to-date review of the various cogeneration technologies suitable for residential applications. Their paper considers the various technologies available and under development for residential, i.e. single-family (<10 kWe) and multi-family (10–30 kWt) applications, with focus on single-family applications. Technologies suitable for residential cogeneration systems include reciprocating internal combustion engine, micro-turbine, fuel cell, and reciprocating external combustion Stirling engine based cogeneration systems. The paper discusses the state of development and the performance, environmental benefits, and costs of these technologies. Onovwiona et al. (2007) also describe a parametric model for techno-economic evaluations of ICE based cogeneration systems and present results from energy sensitivity analysis for several controller types using the model in building simulations.

5.3 European Union

Two market oriented reports are listed here, as they also contain information gained from performance assessment simulations. The first is the Future cogen (2001) study. Secondly, the MicroMap (2002) study showed that between 5 million and 12.5 million MCHP systems could be installed and operating commercially in EU countries by the year 2020. This would result in CO_2 emissions savings of between 3.3 and 7.8 million tonnes per year. In addition, there is the potential to install 700,000 units in Central and Eastern European countries. These studies conclude that small SE MCHP systems producing around 1kWe of electricity are likely to take the largest market share, due to their widespread application, current advanced state of development and anticipated lower cost, compared to the alternatives.

Pilavachi (2002) gives a general overview on micro- and mini gas turbines, and outlines the potential for residential applications within the European Union.

Additional EU research projects dealing with MCHP include “MicroCHeaP,” where a comprehensive state-of-the-art and market review and an analysis of potential links between MCHP and other renewable energy sources are prepared, “FLAME SOFC” and “NextGenCell,” which deal with the development and the testing of new FC MCHP systems, and “Eclipse,” which produced life cycle inventories for energy systems, including ICE, SE, and SOFC MCHP systems.

5.4 Finland

Alanne developed decision methods for the evaluation of residential cogeneration systems. In Alanne & Sari (2004) issues are reviewed that can be supposed to influence decision making for CHP as an alternative energy source for buildings, highlighting the Finnish situation. In Alanne

& Saari (2006) this topic is expanded to political, economic, social, and technological dimensions and finally in the context of sustainability. In Alanne et al. (2006) a comparative economic assessment of a SOFC system is made (see Canada), and in Alanne et al. (2007) the selection of a residential energy supply system was considered as a multi-criteria decision-making problem that involves both economic and environmental issues.

5.5 France

Chevalier & Meunier (2005) performed an environmental assessment of biogas co- or tri-generation units, applying a life cycle analysis methodology.

5.6 Germany

In a study on municipal energy systems, Bruckner et al. (1997) show that, together with improved insulation in residential buildings, cogeneration offers considerable potential for energy savings and that the potential achieved by combining cogeneration and solar thermal systems is lower than the aggregate potential of the individual technologies. In a study on solar and hybrid district heating systems, Lindenberger et al. (2000) show gas internal combustion engine micro-cogeneration units to achieve cost savings and 20% (non-renewable primary) energy savings compared to a configuration with gas-fired condensing gas boiler and national grid electricity with the German electricity production mix. The micro-cogeneration units also surpass the solar thermal system in terms of both cost and energy savings. In a more recent study, Lindenberger et al. (2004) again single out cogeneration as a favourable option for supply-side reduction measures in local energy systems.

Decentralized cogeneration with small district heating networks may be a valuable alternative to building-integrated micro-cogeneration units. The technological and environmental aspects of both approaches, also in combination with solar heat, are covered by Entress (1996, 1997). It is shown that the operation of the cogen unit should be limited to the winter period in order not to reduce the solar heat gains. Compared to individual central heating in each house, with combined cogeneration and solar district heat system, CO_2 emission savings in the range of > 50% are possible at the same cost (for the assumed German climate, electricity from coal fired power plant, fuel costs and revenues for provided electricity).

Krammer et al. (2000) and Krammer (2001) gave a detailed economic and ecological system comparison of residential fuel cell cogeneration and traditional technologies and outline market potential perspectives until 2025.

Schleitzer (2002) performed a holistic system analysis for the energetic use of biogenic gases in fuel cells.

Erdmann (2003) analysed what the market potential for this technology would be, what types of residential buildings might be most attractive, and what would be the quantitative changes in the fuel and the power market. The methodology of this paper differs from that of other studies in that he models the operation of stationary fuel cells on the basis of 15 min power load profiles of individual buildings. From these synthetic functions are drawn, describing the fuel cell power output/natural gas input, as a function of a number of specific properties of individual buildings. From this, the potential for the residential building stock in Germany is determined using a Monte Carlo simulation. The PhD thesis of Bokaemper (2002) is linked to these evaluations.

Pehnt (2002, 2003a, 2003b) and Pehnt et al. (2003) performed comprehensive source-to-service and life cycle analyses of fuel cells for both stationary power stations and transport applications. Similarly, building integrated cogeneration in residential applications was analyzed. In Pehnt et al. (2005) results are summarized of interdisciplinary investigations into the real benefits and barriers of micro CHP, and into the diverse consequences of a widespread introduction of micro CHP for the energy market, the customers, the environment and the economy. Reports by experts are given on the energy markets in Germany, Great Britain, the Netherlands, Japan, and the United States of America, and the respective peculiarities in these countries are highlighted.

In Arndt et al. (2003), the efficiency of various decentralized cogeneration technologies on an energy economic basis, their possible operating methods and their effects on the common electricity network were analysed. The analyses were based on heat demand load curves of the residential buildings with high resolution, generation load curves of the fuel cell plants and the ICE cogeneration plants respectively. To determine impacts of local input on the public grid, a detailed grid simulation of the electric low voltage grid was examined by means of the network tool SINCAL®.

Sander (2004) analysed the potential for stationary fuel cells systems in the German state Baden-Württemberg on the basis of experiences with the current demonstration plants. Industrial and housing demand and load structures of Baden-Württemberg in high temporal and structural resolution are derived by an elaborated methodology for the integration of different statistical databases. The fuel cell technology is economically compared to alternative supply options for representative application cases, and then integrated into the context of the overall energy economy of Baden-Württemberg for present and future energy and fuel scenarios.

Boehm (2004) developed a detailed PEFC model in TRNSYS and then comprehensively assessed the performance of such FC systems for a low energy SFH, considering high resolution load profiles and different configurations of auxiliary boiler, thermal storage and control. Compared to the reference system with condensing gas boiler and CCPP generated grid electricity, reductions of PE demand up to 21% resulted, when the FC is dimensioned for maximum heat load (space heating and DHW) and controlled following the heat demand.

Buildings complying with the Passive House Standard, Feist (2002), have a very low heating energy demand. The demand is focused on electrical appliances and domestic hot water. Compact multi-functional units (for heating/cooling, ventilation, hot water) with an integrated heat pump have been developed specifically for these applications, Buehring (2001). The suitability of micro-cogeneration systems integrated in Passive Houses, the interaction with active solar systems (solar collectors, photovoltaic panels) and with compact units, is a key issue which were studied e.g. by Buenger (2001) and by Vetter& Sicré (2003).

Sicré et al. (2004) investigated into the applicability of SOFC systems in residential buildings. In his PhD thesis, Sicré (2004) assessed SOFC and SE MCHP systems in relation with single-family very-low-energy buildings houses of different thermal insulation standards (according to 3 Liter House and Passive House standards), in combination with solar thermal and PV systems. Performance was compared to benchmarks with conventional energy supply systems, and computed allowable investment costs, based on simulations using TRNSYS and ColSim.
He concluded that the combination of cogen and solar thermal systems leads to lower PE demand, but lower operation hours and less income from electric supply to the grid result due to the reduced heat contribution from the cogen system. Therefore, combinations with PV seem to

be more attractive than solar thermal systems.

Vetter & Wittwer (2003) described the development of control strategies for residential fuel cell cogeneration plants, using the simulation environment ColSim [COLSIM-1]. A low energy house is simulated, including a fuel cell system fuelled with natural gas and a stratified storage with an internal gas burner, using measured electric and heat load data, with and without solar thermal system.

Wittwer et al. (2004) summarized the results of the study "Mini-KWK". Different MCHP system and control concepts were analyzed. With the present German grid electricity mix, MCHP offers reductions in PE demand; however, reductions may also be achieved by other measures like enhanced building insulation, mechanical ventilation with heat recovery, or by solar systems. For the reference building, due to the fast start-up and reaction time, the 1 kWe SE systems with 25% electric efficiency (LHV) showed lower PE demand than the SOFC and PEFC systems (>28% electric efficiency LHV). Operating costs are heavily governed by the electricity market conditions, by the number of on/off operations, and due to the system capacity limit, governed by the heat demand of the building.

Vetter (2005) treated this issue again in his PhD thesis, concluding that fuel savings with natural gas driven MCHP not only are dependant on the cogen system efficiencies, but also on the real heat demand of the building, namely for DHW. He also analysed the consequences of cost optimized control in relation with dynamic electricity prices and showed that the economic boundary conditions and the selected control modes have to be carefully specified in order not to evoke higher primary energy demands compared to the reference case.

Krewitt et al. (2004) summarized the result of several projects and PhD studies, performed in the context of the German study "Fuel cells in combined heat and power supply – ecological life cycle analysis, scenarios, market potential". The aim was to relate the present status of fuel cell development to the current energy-economic context, and to evaluate the possible role and the potential of decentralized stationary fuel cells in a future sustainable energy supply structure.

The study considers both building integrated MCHP, as well as decentralized fuel cell power plants, with and without CHP.
The study is concerned with the situation in Germany, but many data are of general nature and can be used or transferred to other situations.

The study focuses on ecologic benchmarking, comparing PEFC and SOFC systems with other innovative cogeneration technologies (SE and ICE), with heat pumps combined with central supply from advanced CCPP, and with traditional technology (oil and condensing gas boiler, and compact units for ventilation, space heating and DHW).

For the MCHP systems analyzed, the study gives detailed figures for a number of environmental impact parameters, such as acidification and eutrophication, non-renewable primary energy demand and global warming. The study considers materials used for the production and the impact of the operation of the energy supply systems. The ecological analysis was performed using the Umberto tool, Umberto (2003).
The MCHP systems were compared with a number of other systems with separate heating and electric supply from the grid. For the grid electricity supply, energy supply chains were derived for three future scenarios. Three building types are considered: Single family home (partially retrofitted), multi family house, 2 rows of terraced Passive Houses.

For single family houses all MCHP technologies are advantageous to condensing gas boiler and grid electricity (also from CC plant) in terms of NRPE and GHG emissions. However, best is the wood pellet stove with grid electricity. Heat pumps are equal to MCHP systems if the annual performance factor is > 3.3. Only fuel cell systems with high overall efficiencies are better than Stirling units. Therefore, one of the prime objectives of further fuel cell micro-cogeneration system development must be to improve the total efficiency. In terms of environmental pollution and health impacts, CHP technologies perform better than the reference technologies. For multi family houses, in addition, ICE MCHP units have been considered. These lead to higher pollutant emissions, however, the NRPE demand and the GHG emissions are on the same level as for fuel cell systems. This is mostly the effect of their higher total efficiency. For the rows of terraced Passive Houses, the low heat demand allows for low electricity production only. This leads to high demand of residual electricity supply from the grid. Such, the differences between the individual technologies analyzed are actually very small. In terms of pollutants, the impact of the production of the fuel cell system is of low overall significance in stationary applications, in contradiction to mobile applications, where the lower life-time of the vehicle leads to a much higher significance of the power train production.

5.7 Italy

Dentice d'Accadia et al. (2003) dealt with the application of micro-cogeneration (electrical power <15 kW) to small scale residential and light commercial application. An energetic analysis of micro-cogeneration systems was performed regarding its utilization in conjunction with domestic household appliances, namely electric storage water heater, domestic washing machines, and household dishwasher. These appliances consume a significant part of household electricity, mostly of it for the heating of the water. Replacing electric heating by heat from the cogeneration unit, great amounts of primary energy can be saved. Optimum operation modes for the CHP unit to match the user's thermal and electrical loads were identified.

Sasso et al. (2003) discussed a domestic scale cogeneration plant incorporating heat pump (CHP/EHP). Starting from the experimental results of a MCHP prototype, an energetic and environmental analysis of the whole plant is employed to compare the CHP/EHP with the conventional systems to supply heat and/or power.

Cardona & Piacentino (2004) compared a medium size CCHP pilot plant for two office buildings (situated in a Mediterranean area, Palermo, Sicily) with other plant configurations, varying both for machine sizes and management criterion, in order to affirm whether or not the plant selected by the designer in a simplified manner was or not an appropriate solution. The comparison was performed from an energetic and economic viewpoint.

Possidente et al. (2006) compared three ICE residential MCHP systems in an exergetic, economic and environmental analysis to a conventional system with separate production of heat and electricity. The micro-cogeneration obtained primary energy savings up to 25% and a pollution emissions reduction up to 40%.

Annunziato et al. (2006) described the models of a micro-turbine, developed in Matlab/Simulink, and models of thermal network and building, implemented in TRNSYS and demonstrated their application for PE saving and CO_2 emission analysis.

Bertini et al. (2006) presented a methodology for design optimization of a CHP plant for eco-buildings. The optimization process investigated different configurations of the system in terms of component sizes and nominal powers and it was conducted by artificial life ("ALIFE") software developed by ENEA. The thermal network and the eco- building were modelled in TRNSYS while the CHP system was implemented in Matlab/Simulink.

Sibilio et al. (2007) investigated the potential of micro-cogeneration units in residential trigeneration applications. The state of art of this technology was considered, a test facility designed and built to evaluate the performances of MCHP- Electric Heat Pump (EHP) systems, and the Energetic, Economic and Environmental (3-E) analysis in some operation mode to match the users loads was proposed. Compared to the best available reference system and economically justifiable technology for separate production of electricity based on gas fuelled combined cycle with electrical efficiency of 55% (Italy), at the best conditions, corresponding to full recovery of MCHP waste heat, the primary energy savings factor PES is 14%, and the avoided CO_2 emissions are 17%.

5.8 Japan

Aki et al. (2005) analyzed the residential market penetration of fuel cells in Japanese markets over the next 30 years under a number of scenarios: two scenarios with and without energy interchange, and seven scenarios examining future uncertainties in fuel prices, fuel cell costs, and product lifetimes, using a multi-objective model of cost reduction and CO_2 emission mitigation. The study suggested that sharing of fuel cells and related equipment and energy interchange via a web of electricity (micro-grid), heat, and hydrogen networks can enable flexible and cooperative operation, which increases the load factor of the equipment and provides additional advantages such as cost reduction and CO_2 mitigation. The study concluded that this interconnection and energy interchange can provide an early and gradual market penetration of fuel cells, and contribute to the realization of the governmental target of CO_2 mitigation. The study also concluded that a reduction in gas prices and government subsidies for fuel cell residential systems can accelerate their market penetration and result in further cost reductions and CO_2 mitigation. In Aki et al. (2006) this topic is further treated.

Nagata (2005) uses a the optimal generation mix model (OPTIGEN) to evaluate 0.7 kWe PEFC cogen systems in terms of CO_2 reduction potential. The results suggest that PEFC systems do not always contribute to mitigating CO_2 emissions, even if the technological target for efficiencies of PEFC systems are achieved in the future. The operating patterns of PEFC systems will change markedly according to grid electricity rates.

Obara (2006) studied the dynamic characteristics and generation efficiency of a micro-grid structured from 17 houses with a 3 kWe gas ICE generator installed in one house and 1 kWe PEFCs installed in 16 houses. In Obara (2006b) the heat network of residential fuel cell CHP systems was studied and shown how the hot-water piping can be optimized on the basis of the analysis.

Weber et al. (2006) explored the integration and optimization of a SOFC in a polygeneration system with two absorption-chillers for an office-building in Tokyo. A two-level optimization was introduced to minimise the CO_2 emissions and to compute the associated costs. At the first level the design parameters of the system were optimised using an evolutionary algorithm, and the second level optimised the daily operation of the system using a linear programming algorithm. The fully decentralized SOFC-based energy system could result in a potential CO_2 reduction of 45% compared to the conventional system with electric cooler/heater system from the central power grid, however at an estimated cost increase of about 290%. The methods applied could also be used for the optimization of residential systems.

Inada et al. (2007) developed an optimization model in order to evaluate the MCHP based on daily-basis demand data. Using actually monitored energy demand data in four households, the differences between using daily-basis data and using the monthly average data were evaluated from viewpoints of economic and environmental performance of MCHP systems. By adding the penalty factor to disposal heat of MCHP, CO_2 reduction and energy conservation as well as cost reductions were achieved.

5.9 Netherlands

Laag et al. (2002) conducted system assessment studies within the framework of the technology development program for residential micro-cogeneration applications in the Netherlands. They describe typical residential electricity and heat demand levels and patterns for individual households in the Netherlands. By installing natural gas fuelled co-generation equipment, based on SE, gas ICE or FC technologies, to fulfil the residential energy demands, PE savings of 12% (SE) to 24% (FC) are expected for applications in an average Dutch household. The CO_2 emission reduction is even stronger by a change in the fuel mix, favouring natural gas. For the average household the reduction varies from 1.0 (SE) to 2.7 (SOFC) tons CO_2 per year. The annual NO_x reduction is expected to be 1.3 to 2.2 kg per household. Design considerations are given in order to utilize the savings potential to a high degree, together with a SWOT (strengths, weaknesses, opportunities and threats) analysis.
The DHW demands are based on Dutch national averages, space heating demand profiles (15 min interval) are simulated with TRNSYS, and the electricity demand profile (1 min interval) are based on average and measured typical profiles of household appliances. Using this data, a simple stochastic profile generator was built using @Risk (an add-in for MS Excel).

Ruijg & Ribberink (2004) assessed profitability of PEFC, SOFC and SE residential cogeneration systems, heat and electricity storage, with various control strategies. Electricity demand following control showed higher profits than heat following modes due to an expected (too) low feedback tariff. The optimal control strategy provided ample profits to balance the additional investment compared to a high-efficiency boiler. Transforming the surplus of electricity produced by the cogen system into heat led to a significant reduction of the energy savings.

Houwing & Bouwmans (2006) researched the impact of the application of residential MCHP on operational energy flows to and from households, energy costs and CO_2 emissions. These operational impacts were shown to be significantly dependent on the adopted control mode applied in the total MCHP system. However, nearly every control mode showed cost and emission reductions in different seasons. The design of the heat-following, electricity-following and least-cost control modes was presented and their implementation in an agent-based model was discussed.

5.10 Sweden

Hedstroem et al. (2004) describe a solar–hydrogen–biogas-fuel cell system installation in the GlashusEtt building. The energy system consists of a 4 KWe/6.5kWth PEFC, a photovoltaic (PV) cell array, an electrolyser, hydrogen storage tanks, a biogas burner, dc/ac inverters, heat exchangers and an accumulator tank. The fuel cell stack can be operated with reformed biogas, or directly using hydrogen produced by the electrolyser. To evaluate different automatic control strategies for the system, a simplified dynamic model has been developed in MATLAB Simulink. Wallmark & Alfors (2002a, 2002b, 2003) further analysed this system by exergetic, technical and economic evaluations. Wallmark (2004) constructed and simulated exemplifying energy systems a basis for the technical and economic evaluations. Fuel cell system installations are predicted to be economically unviable for probable near-term conditions in Sweden. The main factor in the economic evaluations is the fuel price. However, fuel cell system installations are shown to have a higher fuel utilisation than the conventional method of energy supply.

5.11 Switzerland

For low temperature space heat production, Zogg (1998) compared different combinations of micro-cogeneration systems, heat pump systems, condensing gas boiler and grid electricity supply by a modern CC power plant in terms of primary energy, CO_2 and other pollutant emissions. Low temperature heat covers more than 50% of the space heat demand in Switzerland. Low temperature heat produced by medium size cogen units and by compressor heat pumps can reach fuel utilization factors of more than 150%. The basic assumption for his evaluation was that all electricity produced and considered is used by the heat pumps for space heating. The additional household electricity demand was not considered. However in an additional paper of Zogg (2002), the electricity demand is also considered. Derived from the total non-renewable (fossil and nuclear) energy consumption values for Switzerland, a ratio of low energy heat to electricity demand of 0.23 was estimated. In the study, this ratio was varied from 0 (all electricity generated is used for heat production by heat pump) to 0.25. It was concluded that heat pumps are inevitable for low temperature heat generation, MCHP system must reach electric efficiencies above 40% (LHV) to be competitive with CCPP solutions, and combustion CHP systems must comply with more stringent emission standards.

Godat & Maréchal (2003) showed the application of modelling and process integration techniques to identify the optimal operating conditions and the optimal process structure of a PEFC the system.

Dorer et al. (2004, 2005) demonstrated a methodology for assessing the performance in terms of primary energy demand and the CO_2 emissions for SOFC and, to a lesser extent, PEFC natural gas driven home cogeneration systems. Using TRNSYS, the systems were evaluated for Swiss and European grid electricity generation mix types and compared to traditional gas boiler systems. Typical heat and electricity demand load profiles for different types of Swiss residential buildings and occupancy were considered. Compared to gas boiler systems as the benchmark, the fuel cell systems studied achieved a reduction of 6 to 48 % in NRPE demand for the building types and electricity mixes considered, but the strong dependence of the achievable savings and, to an even greater extent, the resulting CO_2 emissions on the grid electricity generation mix was confirmed. The interaction with hot water storage and solar thermal collectors, and the impact of storage size and predictive control was analyzed. The potential of the fuel cell systems to achieve primary energy reductions declined when used in combination with solar thermal systems. The most significant reductions in NRPE demand resulted for cases where the thermal energy output of the fuel cell matches the building heat energy demand (SH and DHW).

Pfeiffer et al. (2005) examined the energy-saving potential of various combinations of available and future residential building and building energy systems technologies, including SOFC cogeneration, and showed that with the considered implementation scenarios and building stock projections the requirements of the 2000 W society as a vision for sustainable development can be met.

Maréchal et al. (2005) give a methodology for the thermo-economic evaluation of fuel cell systems, based on a process flow model (using VALI), an energy integration model (in EASY), a multi-objective optimisation tool (MOO by EPFL) and a MATLAB based interface. The application is illustrated for a hybrid PEFC model.

Rognon (2005) showed that with electricity from combined heat and power, the use of combustibles in Switzerland would be halved, as are CO_2 emissions. Measured against Switzerland's total volume of emissions from combustibles, the reduction of CO_2 emissions would be 21% of the present-day level. The required power could also be obtained from new co-generation plants, without heat utilisation. In this case, the reduction of combustibles and pollutants would be greater than with conventional combined heat and power, and the results would be even better with partial or full heat utilisation from co-generation systems.

Primas A. (2007) outlined in a holistic approach, which types of small and medium size cogeneration and trigeneration systems and system combinations perform best for which applications (heating and cooling load demand profiles and temperature levels). The evaluation investigated the technical/economic viability, the ecological advantages based on LCA, and estimated the efficiency potential, in a time perspective to the year 2010.

5.12 UK

Few et al. (1997) and Smith (1999) modelled a domestic sized combined heat and power (CHP) system incorporating a heat pump and conclude that the incorporation of the heat pump gives a CHP/HP plant very high effective efficiency, hence significantly reducing carbon dioxide emissions and fuel costs. The incorporated heat pump gives a high degree of flexibility in meeting domestic energy requirements, including cooling applications, as the heat to power ratio of a CHP/HP plant can be varied over a wide range. In Smith & Few (2001) the respective prototype plant was analyzed.

Newborough (2004) discussed the application of cogeneration systems to individual homes, with particular reference to the transient variations that occur in domestic requirements for heat and power. Predicted energy-cost savings, based on simulations employing 1 min demand profiles, are presented for several prospective MCHP systems. The effects upon energy-cost savings of prime mover capacity and efficiency, heat-recovery efficiency, central-heating boiler efficiency, and the unit price for exporting electricity are assessed. For various configurations of a nominally 1 kWe MCHP system, reductions of 16-39 % in annual energy expenditure are identified. Savings per average home of around 1 tonne of CO_2 per annum are predicted, but actual savings will depend strongly upon factors such as transient heat-and-power demand variations, the operating mode, capacity and efficiency of the MCHP system, and upon electricity import/export conditions and modes.

Peacock & Newborough (2005, 2006) investigated the effects of applying SE and FC MCHP systems to single UK dwellings, and to various dwellings within a group, by using heat and power demand data recorded on a 1-min time base across a full year. FC and SE MCHP systems are predicted to supply 25–46% of the single dwelling's annual electricity demand. Compared to a non-CHP base case of employing a condensing boiler and network electricity, savings represent 9% and 16% of emissions attributable to the single UK dwelling, which is highly significant relative to other individual measures that can be deployed in the domestic sector. In Peacock & Newborough (2007) a 50 dwelling data set of heat and power demands was employed to investigate the implementation of various penetrations of MCHP system on the resultant electrical load profile using two control methodologies: heat-led and a proposed method for modulating the aggregate electrical load. The first caused the daily load factor of the net load profile to decrease from 42.5% to 28.6% on a January day and the after diversity maximum demand to decrease from 2.0 to 1.2 kW. The second caused the daily load factor to increase from 42.5% to 48.6% and the after diversity maximum demand to decrease from 2.0 to 0.9 kW. Further maximum resultant load factor values were identified for a day in January, April and July.

Hawkes et al. (2006a) developed techno-economic modelling of MCHP to determine the minimum annual cost of meeting a given residential electricity and heat demand profile through optimal sizing of MCHP electrical generation capacity. This modelling approach was applied to investigate key economic factors for SOFC MCHP systems in the UK in Hawkes and Leach (2005a), to investigate least cost operating strategies for a variety of MCHP technologies in Hawkes & Leach (2007a), and to examine the influence of various options for meeting residential space heating and DHW demand using SOFC-based MCHP in Hawkes et al. (2007b). It was found that MCHP can represent and economic proposition with environmental benefits in some UK situations. The least cost operating strategy for MCHP in winter was found be to follow both heat and electricity demand rather than simply to follow heat demand, and that "slow" heating of dwellings is desirable for SOFC MCHP technology from an economic, environmental, and technical point of view. In Hawkes and Leach (2007c) the techno-economic modelling was also applied to examine future economic and environmental scenarios for various MCHP technologies in the UK as building insulation improves. Hawkes and Leach (2005b, 2006b) also assessed the performance of aggregate sets of MCHP units in the context of capacity credit and comparison with district heating networks. In an earlier paper Hawkes and Leach (2005c) assessed the impact of temporal precision in optimisation modelling for MCHP, and found that demand data must be at a maximum of 10 minute intervals to achieve a reliable result.

Cockroft & Kelly (2006) made a comparative CO_2 savings assessment of FC, SE and ICE MCHP and heat pumps for the UK domestic sector against a common datum of energy supply from condensing gas boilers and grid electricity for a number of scenarios. The main finding of the work is that air source heat pumps yield significantly more CO_2 savings than any of the other technologies examined.

Boait et al. (2006) modelled the time distribution and use of the electricity output from microCHP, based on trials with a Stirling 1 kWe MCHP unit in a typical English detached four bedroom house. Coupling the model with a stochastic model of domestic electrical load, they predicted the proportion of output that would be consumed locally, for six household scenarios comprising three different types of house and two levels of occupation and appliance use.

Abu-Sharkh et al. (2006) focused on a microgrid of domestic UK users powered by small CHP. It was found that the optimum combination of the generators in the microgrid - consisting of around 1.4 kWp PV array per household and 45% household ownership of MCHP generators - will maintain energy balance on a yearly basis if supplemented by energy storage of 2.7 kWh per household.

Watson et al. (2006) investigated how PV, wind and micro-cogeneration might be deployed in the UK in pervasive local energy systems based on micro-grids. Technical and environmental performances were analysed with consumer-, company- and community-led models and policies were explored to support investment by consumers and energy companies.

5.13 USA

Krist & Gleason (1999) analyzed the feasibility of fuel cell CHP systems for residences based on the load requirements of the residence as measured on peak summer and winter days. The study results suggested that fuel cell based CHP systems are suitable for residential applications.

In earlier studies, Darrow & Smit (1993) evaluated the economic performance and potential market application for a 5 kilowatt ICE based cogeneration package. The analysis identified limited segments in both residential and commercial markets where a 5-kW unit would provide economic value under the high first cost scenario. In the residential market, space heating and water heating loads were found to be not sufficient to provide attractive paybacks, but, applications with pool and spa heaters were highlighted as more attractive. The combined market potential for the CHP unit at an installed cost of $1800 per kilowatt was estimated at 3500 units per year.

Little (2000) estimated the performance and cost requirements for distributed generators in residential US markets to be: 1) capacity of 1-5 kW, 2) efficiency > 35%, 3) life time > 10 years, 4) O&M time > 4000 hours, and 5) NO_x emissions levels < 20 ppm. Heat recovery, cycle-ability, and start-up time were also considered important requirements for this market. A detailed economic model was then used to estimate the allowable cost of distributed power technologies in a variety of applications including residential applications. For residential applications, the study concluded that the typical capacity for distributed generation technologies would be in the range of 0.5 – 10 kW, while the allowable system costs would be in the range of $1,000 - $ 2,500 for market entry, to be reduced to $800 - $1,000 to sustain the market. The study concluded that residential applications have potential "mass markets," but pose unique technical and cost challenges. These challenges include the high variability of residential electrical load profiles. Additional challenges include the need for minimal installation and service requirements (a maximum of once per year), and a long operating life. The study suggested that CHP will be difficult in US residential markets because of the lack of coincidence between thermal and electric loads. The study also concluded that the most cost-effective on-site generators will be small, base-loaded systems, operating in parallel with the utility grid.

In an assessment of fuel cell technologies for building applications, Ellis & Gunes (2002) reviewed the market potential of fuel cell cogeneration systems in US residential applications on the basis of both the match between system characteristics and the US residential electrical and thermal load profiles and the system economics. Two methods for estimating the economic potential of a cogeneration system were presented: 1) a simplified cost of electricity analysis, and 2) an hourly system modelling method. They concluded that residential systems will likely require some type of thermal storage to be economical and that fuel cell system costs must drop to less than roughly $1,000/kWe before they can be compete with utility power in most US regions. The Northeast region was identified as having the largest market potential. Ellis also concluded that increasing the load factor of the cogeneration system, which requires using thermal storage or thermally activated cooling systems, will improve the economics of these systems considerably.

Gunes (2001), Gunes & Ellis (2003) studied a 4.1 kWe and a 5 kWe PEFC cogeneration system in an US average SFH, with a vapour compression heat pump for cooling and heating, and a thermal storage tank. These studies evaluated the performance of the CHP system in order to determine the system design parameters, the energy use patterns, the environmental effects, and the life cycle cost. System design parameters included the thermal storage tank size, the heat pump size and coefficient of performance, and the design power output of the fuel cell system. These studies showed that the performance of the CHP system for two climates can result in a reduction in primary energy use of 34 to 55% compared with conventional all-electric or gas-electric systems. This reduction, coupled with the lower carbon and sulphur content of natural gas and the reduced emissions of NOx leads to a much lower environmental impact for the fuel cell CHP system. The study, however, showed that the CHP system can only be economically attractive if the initial system costs are reduced to below $500/kWe, which is at the low end of the typical cost projections for stationary fuel cell systems.

Karady et al. (2002) from the Power Systems Engineering Research Center (PSERC) at the University of Wisconsin provide fundamental information and a detailed technical description of an economic decision-making model for a fuel cell system.

In a study conducted by TIAX (2002) the performance and manufactured cost of a stand-alone residential natural gas fuelled SOFC cogeneration system was characterized and compared to grid-connected alternatives for a typical US single family, detached house with conventional construction and typical energy loads. The effects of different energy storage options, heat recovery options, and cogeneration vs. power-only systems were examined. The study concludes that with the load profiles for typical homes including the highly variable electrical load, achieving attractive efficiency and cost for stand-alone residential SOFC system will likely be challenging. This study also suggests a need to increase part-load power electronics efficiency.

Fischer (2003) investigated the economic viability of three MCHP technologies (SE, FC and Steam Generator Topping Cycles) in terms of pay-back times for a SFH with average US consumption data in 50 US states and some locations in the UK. For the SE and the steam topping cycle systems the modelling results were consistent with references and the simple payback period was less than 10 years only in New England, New York, and Alaska. For the FC system the simple payback was less than 12 years only in Alaska and less than 25 years in Alaska, New York, Vermont, and Michigan. The long payback times were primarily associated with high capital and installation costs.

Tsay (2003) assessed a 5kWe PEFC system versus a 10kWe hybrid SOFC-GT technology in terms of market viability, competitiveness and sustainability.

Oyarzabal et al. (2004) developed thermodynamic, geometric, and economic models for use in the optimal synthesis/design of PEM fuel cell cogeneration systems for multi-unit residential applications. The results of the study indicate that the optimal system life cycle costs are significantly impacted by the number of residences served by the system (i.e., the system size) with a system serving one unit costing $30,000/kW life cycle cost compared with $2,800 & $2,300 for systems serving 50 units and 100 units respectively. The system efficiency, however, did not change significantly with the change in system size. The study concluded that the energy and economic characteristics of the most promising syntheses/designs are presented for fuel cell cogeneration systems serving 50 residences. The study concluded that fuel cell cogeneration systems are likely to be economical in clusters of homes or apartment complexes first and then may become applicable to single family homes as the manufacturing volume increases.

Reporting on The National Rural Electric Cooperative Association (NRECA) Cooperative Research Network (CRN) residential fuel cell program, Torrero & McClelland (2004) addressed issues of electrical interconnection with the grid and suggest that grid-parallel units can provide an added dispersed generation grid resource while enhancing customer appeal if they can automatically disconnect from the grid and run in a grid-independent mode during a grid outage. Torerro and McClelland also suggest a potential exists for residential FC systems to be concurrent, load-levelling, on-grid electric storage systems. With regard to thermal recovery, the study also concludes that economically accomplished, thermal recovery provides energy cost savings offsets that are vital to paying for the fuel cell power plant and its fuel. The study finds that using thermal recovery to offset electric water heating can be particularly economic in grid-connected DG scenarios. The study also concludes that although space heating is not normally considered for fuel cell thermal recovery, when carefully combined with pre-existing water heating thermal recovery, the incremental cost of providing residential space heating with the DG system may be attractive.

Yi et al. (2004) also investigated the fuel flexibility of a 25 kW SOFC reformer system and concluded that although the SOFC can tolerate a wide variety in fuel composition, the performance of integrated SOFC reformer systems may require significant operating condition changes and/or system design changes in order to operate well on this variety of fuels.

Braun et al. (2006) evaluated a SOFC system for residential applications in terms of fuel supply and concludes that the efficiency performance advantages of methane-fuelled SOFC systems compared to hydrogen-based SOFC systems can be as high as 6%. Earlier, Braun (2002) studied the design and optimisation of SOFC systems.

Maclay et al. (2006) developed a model of a solar-hydrogen powered residence, in both stand-alone and grid parallel configurations, using Matlab/Simulink. The model assesses the viability of employing a regenerative fuel cell (RFC) as an energy storage device to be used with photovoltaic (PV) electrical generation. Other modes of energy storage such as batteries and hybrid storage were also evaluated. Analyses of various operating conditions, system configurations, and control strategies were performed. Design requirements investigated included RFC sizing, battery sizing, charge/discharge rates, and state of charge limitations. Dynamic load demand was found to be challenging to meet, requiring RFC and or battery sizes significantly larger than those required to meet average power demand. Batteries in a hybrid configuration increased PV utilization and both battery efficiency and power density. Grid parallel configurations were found to alleviate many of the difficulties associated with energy storage costs and meeting peak demand. While these configurations were attractive from the residential demand and cost perspectives, they required that the utility grid meet significant dynamic power demands.

Rodriguez et al. (2006, 2007) characterized distributed generation (DG) installations in urban air basins, and simulated the potential air quality impacts using a state-of-the-art three-dimensional computational model of the South Coast Air Basin (SoCAB) of California. Realistic implementations of DG in the SoCAB result in small differences in ozone and particulate matter concentrations in the basin compared to the baseline simulations. The baseline accounts for population increase, but does not consider any future emissions control measures or new in-basin central power plants. If distributed generation were used to meet up to 20 percent of the increased power demand in Southern California by 2010, the basin-wide peak ozone level would increase by no more than three parts per billion, and the peak concentration of particulate matter would increase by no more than two micrograms per cubic meter.

A performance rating system for residential fuel cells has been developed at the US National Institute of Standards & Technology by Davis et al. (2006). For four types of fuel cell systems, steady-state and simulated dynamic use models are combined to predict the performance of the system in response to typical residential electrical and thermal loads for various representative climates.

For a PEFC unit as a combined source of heat, power and hydrogen (CHP&H), El-Sharkh et al. (2006) presented a hybrid evolutionary programming and hill–climbing based control approach for the system. This study evaluated the impact of changes in the cost parameters, such as tariff rates for purchasing or selling electricity, the fuel cost for the PEFC plant, and hydrogen selling price, on the optimal operational strategy for the PEFC unit. Results show the importance of optimizing system cost parameters in order to minimize overall operating cost.

6 EXISTING COGENERATION EXPERIMENTAL TESTS AND EVALUATIONS

6.1 Belgium

For the evaluations mentioned in Section 5, DePaepe et al. (2006) also made measurements on ICE-MCHP. Results from tests on a SenerTec ICE-MCHP unit at the TME laboratory at K.U. Leuven are described by Voorspools et al. (2001c).

6.2 Canada

Entchev et al. (2004) described the experimental evaluation of a 736We and 6.5kWth SE MCHP unit in the demonstration houses at the Canadian Centre for Housing Technology in two different setups and scenarios that were tested over the 2003winter/spring seasons. The unit was fuelled by natural gas, was connected in parallel to the grid and the residual heat from the engine was utilized through a specifically designed heat utilization module. Data showed that the micro-generation unit was able to satisfy all of the space and water heating loads to the house during the testing period. For the detailed report see Bell et al. (2003).

6.3 European Union

Burton (2003) reported on the installation and monitoring of two “Whispergen” stirling engine microCHP systems in France and the Netherlands in the context of the EU-DEO project.

In the EU FP5 Project “Virtual Fuel Cell Power Plant”, 58 Vaillant 4.5 kWe PEFC MHP systems representing two design iterations are installed in MFH and small commercial buildings, located in 7 European countries. The systems are natural gas fuelled, grid parallel operated. Per Dec. 2004 the fleet achieved a total of > 200.000 operating hours and > 600 MWh electrical energy production.

In the EU FP5 project “Hybrid Fuel Cell/Heat Pump System FUEL-SAVE”, a novel integrated PE fuel cell/heat pump system intended for use in buildings to provide heating, cooling and electricity.

In the EU FP 5 project “Fuel Cell Testing and Standardisation Network FCTESTNET” a network of research and industrial organisations involved in development and testing of FC and FC systems was created. This network produced proposals for harmonisation of test procedures at the level of FC systems down to stacks and cells.

The Institute of Materials for Electrical Engineering (IWE) at the University of Karlsruhe (TH) is co-partner of a fuel cell test laboratory (FC-TestLab) since October 2003, in which fuel cell systems and components are tested. The FC-TestLab is operated in cooperation with the European Institute for Energy Research (EIfER), an institute at the University Karlsruhe (TH) supported by the Electricité de France (EdF). In the FC-TestLab fuel cell systems for stationary applications (fuel cell heating systems, CHP-systems) are examined in terms of ability, efficiency and stability in the context of national and international research projects. Main focus is the investigation of the dynamic behaviour (start up, load changes, shut down) and the coupling to the electrical grid. Beside complete systems also single components like fuel cell stacks can be electrically characterised. Furthermore fuel cell systems are tested in the FC-TestLab in terms of operation behaviour and reliability before the installation at the customer by the EdF.

Further projects deal with the development and the testing of new MCHP systems, namely a 2kWe SOFC unit in the “FLAME-SOFC” project, and a 5KWe high temperature PEFC unit in the “NextGenCell” project.

6.4 Finland

Fontell et al. (2005) presented the design and construction of a 1 - 5 kWe SOFC test system together with initial test results obtained during the first 1080 hours of operation. The main purpose of the test system is to analyse and demonstrate a complete SOFC system including fuel and air supply systems, heat exchangers, fuel processing units, power electronics etc., as well as be a platform for testing and evaluation of individual BoP components. The study describes basic design criteria and properties of the test system. Characteristics of major sub-systems such as fuel and air supply, steam supply, purge gas, exhaust heat-recovery, power electronics and control system are also explained. The system will be used for system testing and modelling purposes for several years to come. It will also support product development and designing of an upcoming alpha-prototype and other prototype units.

6.5 France

Hubert et al. (2006) studied a micro-cogenerator based on a natural gas reformer and a PEFC in its entirety, pointing out the links between different sub-systems. The study was conducted within the EPACOP project, which aimed at testing PEFC systems on user sites to evaluate development and acceptance of this technology for small stationary applications. Five units were installed from November 2002 to May 2003 and have been operated since then in real life conditions. They deliver up to 4kW of AC power and about 6 kW of heat. The Centre for Energy and Processes (CEP), one of the scientific partners, processed and analysed the experimental data from the five units, running in different regions of France. This database and the study of the flow sheet enable to propose changes to enhance the efficiency of the system composed of a steam reforming, a shift and a preferential oxidation reactor, a fuel cell stack and heat exchangers. The steady state modelling and optimisation of the system is done with Thermoptim®, a software developed within CEP for applied thermodynamics.

6.6 Germany

At the Research Institute for Energy Economy (FfE), the project Innovative CHP-Systems Metrological Analysis, Economical Evaluation, System-Benchmark and Optimization is conducted as contribution to Annex 42. This work is documented in the Annex 42 report on experimental validation.

At the Fraunhofer Institute for Solar Energy Systems (FhG-ISE), the system developed and analyzed in the frame of the NEGEV (Neue Gesamtenergieversorgungskonzepte für Gebäude) comprises a 1 kWe PEFC, solar thermal collectors and a 750 litre stratified storage tank, Vetter & Wittwer (2002).

Koening et al. (2005) from TU Karlsruhe present measured steady state and dynamic operation characteristics of a prototype 2 kWe PEFC CHP system, installed in the FC-TestLab at the University of Karlsruhe, see § 6.3 The system, which was developed at the ZSW in Ulm (FC-stack) and the FhG-ISE Freiburg (reformer) is operated and tested in close cooperation with the Stadtwerke Karlsruhe.

Thomas (2002, 2003) and Thomas & Wyndorps (2004, 2005) reported on the tests performed at the HS Reutlingen on Senertec ICE- and Solo SE MCHP units. The laboratory is specifically equipped to also test part-load configurations, and to comply with the requirements for certifications for the label „Der Blaue Engel". More recently, Thomas (2006) reported on a small SE CHP unit running on bio mine and sewage gas.

6.7 Italy

Dentice d'Accadia et al. (2000) described a test facility designed and built to evaluate the performance of MCHP modules in different operation modes. This test facility is divided in two sections: the first contains the MCHP module (< 5 kW electric output) and permits its performance evaluation, the second contains specific systems in order to evaluate both their energetic efficiency and their matching with cogeneration units. To find a better energy saving configuration, domestic appliances (dishwasher, clothes-washer) and water heater are both electricity or thermal and electricity driven; furthermore pure thermal and electrical loads can be introduced too..

Gigliucci et al. (2004) report on the results of an beta-version PEFC CHP system, supplied by H-Power, installed at the Enel Produzione experimental area sited in Livorno (Italy). Results show that the prototype behaved as expected by a first "proof of concept" system and outline improvements to be achieved in order to satisfy the energy needs of Italian small residential applications.

Possidente et. al (2004) reported on the energetic analysis of a natural gas fuelled micro-cogeneration system for applications in residential and small commercial (MCHP) sector combined with an electric heat pump (EHP) obtained by experimental tests made in a simulation station. Two operating modes in stationary MCHP/EHP system conditions were simulated: first, winter operation with co-production of electric and thermal energy, and second summer operation with co-production of electric, thermal and cooling energy (trigeneration). The results showed that the efficiency of this system is high when the MCHP works at full regime and in summer working mode, but part-load performance was also very satisfactory.

Sasso et al. (2006) further outlined this topic and found that at the best conditions corresponding to full recovery of MCHP waste heat the Primary Energy Savings (PES) is about 20%, and the avoided CO_2 emissions are about 30%, compared to traditional gas boiler/electric grid system.

Possidente et al. (2006) reported the results of an intense experimental activity on three different ICE MCHP units, one of them made in Japan and in a pre-selling phase. The description of the test facility, with the equipments and the data acquisition systems, can be found in Dentice d'Accadia et al. (2003) and in Dentice d'Accadia et al. (2000), see above.

6.8 Japan

Hamada et al. (2004) described the performance evaluation of a 1 kWe PEFC for application to a hybrid utilization experiment involving renewable energy and a fuel cell for a residential energy system. The study included experiments on electrical efficiency and heat recovery efficiency as well as experiments of the characteristics of partial load, water temperature for heat recovery, start-up time, load following and exhaust gas, and hot water tank. The DC electrical, the net AC electrical and the heat recovery efficiencies (LHV) were 42.5%, 28.3% and 49.2%. An overall energy efficiency of 77.9% was reached. The study also found no difference in overall energy efficiency under part load conditions. The study concluded that the system can obtain stable performance with regard to the characteristics of heat and power generation for each load factor under continuous operation over 24 h. The system efficiency was reduced by 5% of the initial value after a cumulative operation time of about 600 h.

Higashiguchi (2004) gave an overview on the development of residential PEFC cogeneration systems at Osaka Gas. The PEFC cogeneration systems had been operated since 1999 to evaluate the system's reliability and durability. In order to achieve the target energy savings, system operation mode and system power control are also very important. Extensive field testing of prototype units started in April, 2002, evaluating system reliability and durability at real customers' houses. The total accumulated system operating hours exceeds 100,000 hours as of July 30, 2004.

As Ballard (2006) reports, 102 Ebara Ballard residential fuel cell cogeneration systems were installed in 2005, out of a program total of 480 units, under sponsorship of METI's Large Scale Monitoring Program. The Ebara Ballard units led the field in overall efficiency at 74.9% (HHV), primary energy savings of 21.8%, and a 35.7% reduction in carbon dioxide emissions.

The domestic 1 kWe SOFC-based cogeneration system of Osaka Gas/ Kyocera has been installed in a research home at Osaka Gas's NEXT 21 experimental housing complex (1 home of 4 persons and 108 m2 floor area), Kyocera (2006a). In May 2006 operating test results from the end of November in 2005 to the beginning of March in 2006 were published, Kyocera (2006b).The electric efficiency was over the development target and it was 49% (AC output LHV), while the efficiency of recovering exhausted heat was 34% (LHV). The electric power was generated following the demand in the home and the one-day average electric efficiency achieved is 44.1% (AC output LHV) and the heat recovery efficiency averaged for one day was 34%. Comparing with electric supply by a thermal power station and heat supply using town gas by a gas company, reduction of 31% in primary energy and reduction of 45% in CO_2 exhaustion were made.

Honda has installed a few thousand of its 1kW IC engine Micro-CHP units in Japan but little data from their experience has been published to date.

6.9 Netherlands

A prototype PEFC system with an experimental 2 kWe PEFC stack developed at ECN, and a commercially available reformer and power conditioner unit, was operated for an extended period of time. The gross electrical efficiency (LHV) of this system of 28 % has potential to increase to 35 % by adopting a dedicated reformer size and optimizing the stack performance. The PEFC system is capable to operate in a dynamic mode of operation. van der Oosterkamp & van der Laag (2003) note that the intent of this study was not to develop a highly-integrated cogeneration system, and the thermal output of this test unit may not be representative of the cogeneration systems being developed by manufacturers today.
A pre-commercial residential Sulzer Hexis HXS 1000 Premiere SOFC system was tested in a heat following mode. The HXS 1000 Premiere system was operated in a heat following mode. The system electrical efficiency (AC output, LHV) was found to be 25-32 % at full load, the thermal efficiency around 60-53 %, and the total efficiency therefore 85 % (LHV).

ECN also conducted field trials using the Enatec Stirling CHP unit, Van der Woude et al. (2004). At present, little has been published about these tests.

6.10 Switzerland

At Empa laboratories, tests were made on a Senertec ICE unit, for stationary conditions as well as for cold and warm start-up, Schreiber (2002).

An EcoPower ICE unit was measured in a low energy building demonstration project of the Swiss Federal Office of Energy in Unteraegeri, Frei et al. (2003). It is concluded that the combination with the solar thermal system is critical, and that in reference to a condensing gas boiler and grid electricity no significant PE savings could be realized.

Van Herle et al. (2004) at EPFL have completed extensive testing of a biogas-fueled Sulzer Hexis SOFC system, producing 1 kWe, 2.5 kWt while coupled to a biogas processing system. The SOFC system was field-tested using fermented biogas on a farm in Switzerland. Over 5000 hours of steady-state operation were accumulated.

Schlegel et al. (2006) reported on results from field tests with a Stirling MCHP unit, installed in a SFH.

Field test with several Hexis SOFC systems are ongoing, however no results have been published so far.

6.11 UK

Veitch (2006) reported about the experimental performance evaluation of a WhisperGen Mk III unit at Durham University. Electric and gas utility E.ON-UK offered Whisper Tech's WhisperGen MCHP unit to households and housing developers, and about 100 systems are installed by 2006, Slowe (2006).

The Carbon Trust is running a major field trial of small and micro-CHP devices. An update on these trials was given in Carbon Trust (2005). A total of 100 Micro CHP test sites are planned of which 79 sites are currently (March 2007) operating. Apart from Micro CHP devices, also 30 condensing boilers are being tested to more accurately set the benchmark for the Micro CHP units. Each test site is aimed to yield at least 12 months of good quality data on a 5 minute time basis. It is the intention of the Carbon Trust to make all non confidential data (e.g. the electric demand data) publicly available, but this is probably some time off and exactly how it will be done has not yet been decided.

A report by E.ON UK PLC (2006) discussed the performance of the Whispergen micro CHP, based on data from the Carbon Trust micro CHP Field Trial and complementary test work. It is concluded that (i) in all homes significant Carbon savings were demonstrated; (ii) the average CO_2 savings for the sample homes were 16% and up to 19%; (iii) family homes, typical of target market, save 1.1-1.5 tonnes of CO_2 annually; (iv) the value of electricity generated can pay for the marginal investment in as little as 3 years in the typical family home.

Yagoub et al. (2006) presented typical test results from operation of a hybrid solar-gas driven CHP system with a Rankine cycle based 1.5 kW electrical micro-turbine generator unit and a of the solar collector system with a thermal capacity of 25 kW.

6.12 USA

Ten Hoven (1994) documented the development of a natural gas powered cogeneration system for residential and light commercial use. The unit produced 5 kW of electrical energy and 45,800 BTUs of thermal energy. Several prototype systems were produced and three were installed at various field test sites. The study reports that further work on this project has been discontinued due to market limitations linked to the excessive installed costs of the system.

Technical reports have been published by White et al. (2004, 2005), PlugPower (2004), and SwRI (2004), describing the overall PEM Fuel Cell Demonstration Fleet to demonstrate domestically-produced, residential-scale, stationary PEFC at military facilities, managed by the Fuel Cell Team at the US Army ERDC/CERL. This DoD Residential PEM Fuel Cell Demonstration Program installed, operated, and monitored PEFC systems with and without cogeneration. The electricity and thermal energy produced by these systems was used to power both residential and industrial loads. The study focused on the energy and economic performance of the PEFC systems including total operating hours, total electricity production, total fuel usage, total waste heat recovery, availability, electrical efficiency, and thermal efficiency.

The requirements for the DoD Residential PEM Fuel Cell Demonstration Program included: 1) all PEFC system must be produced in the United States, and 2) the units must be installed at U.S. military facilities. In 2001 22 fuel cell systems were installed at 10 military installations, in 2002 17 fuel cell systems were installed at 15 military and DOD installations, and in 2003 30 fuel cell systems were installed at 20 military and DOD installations. An overview on the demonstration programme is given by Lux et al. (2003). In general, the study describes the program as a success because the first sites to complete the 1-year program both met and surpassed the minimum 90 percent availability requirement assumed by the study to be necessary to demonstrate PEM fuel cell systems as a viable technology for various building applications and other small-scale stationary demands. The study, however, identifies a number of difficulties and challenges facing the industry.

acing the industry.

Torrero & McClelland (2004) report on the evaluation of the field performance of residential fuel cells.

The Center for Fuel Cell Research and Applications (CFCRA) was established at the Houston (USA) Advanced Research Center (HARC) in 1999, and is funded by a group of private energy suppliers. The centre's primary objective is to provide fuel cell testing services for private corporations. To-date, HARC has tested four different PEFC systems ranging from 3-5kW electrical output, and at least one of these systems was configured for cogeneration operation using natural gas, Bullock (2003) , Houston Advanced Research Center (2004). Each system was treated as a single control volume, and only the system's inputs and outputs were instrumented. HARC evaluated the system's performance when new and over extended periods to assess the effects of long term use.

A Siemens 25 kW SOFC system was initially installed at the Highgrove Generating Station of Southern California Edison in California in 1994. It operated approximately 6500 hours on its first stack before being replaced in mid-1995 with a new air electrode supported (AES) tubular SOFC design. Testing of SOFC operation on logistic fuels began in October 1995 with approximately 750 hours of operation on jet fuel, 1500 hours on diesel fuel, and 650 hours on natural gas during transitions. In February 1996, the system was shut down after 11,500 hours of system testing (5,000 hours on the new stack). The system was then relocated to the National Fuel Cell

Research Center and restarted January 1998 where it has operated on natural gas. As of June 2002, the system has operated for a total of 19,750 hours with 13,250 hours on the current stack.

At the National Institute of Standards and Technology (NIST), several FC MCHP units were laboratory tested. A summary of this work is included in the Annex 42 report on experimental validation. NIST has also proposed test methodologies and performance rating standards for residential fuel cell systems, Davis (2002, 2006)

The Solid State Energy Conversion Alliance (SECA) was formed to accelerate the commercial readiness of SOFC modular units in the 3 kWe to 10 kWe power range for use in stationary, transportation, and military applications. Overviews on the program are given by Williams et al. (2006a, 2006b).

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