An Experimental and Simulation-Based Investigation of the Performance of Small-Scale Fuel Cell and Combustion-Based Cogeneration Devices Serving Residential Buildings

Final Report of Annex 42 of the International Energy Agency's Energy Conservation in Buildings and Community Systems Programme

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Ian Beausoleil-Morrison

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Report Editor & Annex 42 Operating Agent:
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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 to implement an international energy program. A basic aim of the IEA is to foster co-operation among the 24 IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration.

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 Energy Conservation for Building and Community Systems Programme (ECBCS), 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 commercialization. The objectives of collaborative work within the ECBCS research and development program are directly derived from the ongoing energy and environmental challenges facing IEA countries in the areas of construction, the energy market and research. The 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; and
- integration of building energy measures and tools to changes in lifestyle, work environment alternatives and business environment.

The Executive Committee

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

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 (*)

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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: Multizone 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 Toolkit 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 (*)

Preface

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 on 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 within 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	• Swiss Federal Laboratories for Materials Testing and Research (EMPA)/Building Technologies Laboratory • Swiss Federal Institute of Technology (EPFL)/Laboratory for Industrial Energy Systems • Hexis AG (Hexis) • Siemens Switzerland AG (Siemens)

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Ian Beausoleil-Morrison
Report Editor

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Summary

Residential cogeneration (also known as micro-cogeneration and small-scale combined heat and power) is an emerging technology with the potential to deliver energy efficiency and environmental benefits. The concurrent production of electrical and thermal energy from a single fuel source can, if designed and operated correctly, reduce primary energy consumption and associated greenhouse gas (GHG) emissions. The distributed nature of this generation technology also has the potential to reduce electrical transmission and distribution losses, and reduce peak demands on central power generation plants.

This booklet documents the research of Annex 42 of the International Energy Agency's Energy Conservation in Buildings and Community Systems Programme (IEA/ECBCS), which was established in 2003 to develop simulation models that advance the design, operation, and analysis of residential cogeneration systems, and to apply these models to assess their technical, environmental, and economic performance.

The models developed by the Annex were integrated into existing whole-building simulation tools to consider the coupling between the cogeneration device, other heating, ventilation and air conditioning components, and the buildings' thermal and electrical demands. This development work was complemented by extensive experimentation on 13 prototype and early-market, residential-scale cogeneration devices. Data were also collected and collated to characterize key loads on residential cogeneration: occupant-driven electrical loads and hot water usage patterns.

The new data and tools produced by Annex 42 were then applied to assess the performance of specific prototype, early-market, and in some cases hypothetical, cogeneration devices in four different national contexts. This analysis considered how fuel-cell-based and combustion-based cogeneration devices might perform under a wide range of operating conditions. These studies revealed that, in certain circumstances, residential cogeneration systems can significantly reduce primary energy consumption and GHG emissions relative to conventional means of supplying heat and power, despite the fact that many of the current prototypes considered have far from optimal performance.

This booklet provides a summary of the work and findings of Annex 42, the full details of which are contained in 1 400 pages of reports that are provided on the accompanying CD and are available from the IEA/ECBCS website (www.ecbcs.org).

Introduction

Annex 42 of the International Energy Agency's Energy Conservation in Buildings and Community Systems Programme (IEA/ECBCS) was established in 2003 to examine the emerging technology of residential cogeneration. Annex 42, whose working title was "FC+COGEN-SIM: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems," was a task-shared collaborative research project involving 26 organizations from 10 countries.

Residential cogeneration (also know as micro-cogeneration and small-scale combined heat and power) is an emerging technology with a high potential to deliver energy efficiency and environmental benefits. The concurrent production of electrical and thermal energy from a single fuel source can reduce primary energy (PE) consumption and associated greenhouse gas (GHG) emissions. Reductions in combustion by-products such as nitrogen oxides, sulphur dioxide, and hydrocarbons are also a possibility. The distributed generation nature of the technology also has the potential to reduce electrical transmission and distribution inefficiencies, and alleviate utility peak demand problems.

Annex 42 focused on natural-gas-fired cogeneration devices with electrical outputs that varied from under 1 kW to 15 kW. The following four technologies were considered:

- proton exchange membrane fuel cells (PEMFC), also referred to as polymer electrolyte membrane fuel cells;
- solid oxide fuel cells (SOFC);
- Stirling engines (SE); and
- internal combustion engines (ICE).

Annex 42 conducted a review of these four technologies for residential cogeneration. The principles of their operation were described and information on manufacturers and commercially available products was assembled based on existing published data as well as unpublished material derived from the Annex 42 participants. This review (Knight and Ugursal, eds. 2007) indicated a lack of detailed information on performance characteristics. In many sources, the reference point for efficiencies (lower or higher heating value of the fuel) was not mentioned, nor was information provided on part-load operation and parasitic energy losses. This underlined the need for further investigation of residential cogeneration technologies. The review clearly demonstrated that the residential cogeneration industry is in a rapid state of development and flux. Indeed, there were numerous acquisitions, business failures, and restructurings of companies within the industry over the four-year period of Annex 42's work. The market remains immature, but interest in the technologies by manufacturers, energy utilities, and government agencies remains strong.

Small-scale PEMFC, SOFC, SE, and ICE devices have only modest fuel-to-electrical conversion efficiencies: some existing prototypes have efficiencies as low as 5% (net AC electrical output relative to the source fuel's lower heating value, or LHV). Although SOFC technologies have the potential to deliver electrical efficiencies as high as 45%, these levels have not yet been realized in integrated small-scale cogeneration systems. Given that these electrical efficiencies are relatively low compared to combined-cycle central power plants (the state-of-the-art for fossil-fuel-fired central power generation), it is imperative that the thermal portion of the cogeneration device's output be well utilized for space heating, space cooling, and/or domestic hot water (DHW) heating. If this thermal output cannot be well utilized in the residence, then residential cogeneration technologies cannot be expected to deliver a net benefit relative to the best available central generation technologies.

However, the analysis of thermal energy utilization in buildings is complicated by strong coupling between the cogeneration unit, other heating, ventilation and air conditioning (HVAC) components, and the building's thermal and electrical demands. This complexity can be illustrated with a simple example that considers a cogeneration unit configured to follow a house's electrical loads. Lighting and appliance demands may peak late in the evening, resulting in substantial thermal output from the cogeneration unit. However, there may be little demand for space heating at this time as the house is allowed to cool slightly during the night. Similarly, there may be little demand for DHW. Consequently, the system will likely integrate some storage device to hold the thermal energy until a demand exists. The volume and thermal characteristics of the storage tank, the occupant electrical and hot water usage patterns, the house's thermal characteristics, and prevailing weather all influence whether this thermal energy will be exploited or wasted. The potential design and operational combinations of these factors are almost limitless. These system integration issues lead to the need to use whole-building simulation programs to facilitate the analysis of residential cogeneration.

These are the factors that motivated the formation of Annex 42, the specific objectives of which 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. These objectives were accomplished by developing and incorporating models of cogeneration devices (and associated plant components) within existing whole-building simulation programs. These models are more detailed than the simple performance map methods that have been previously applied to assess residential cogeneration and that cannot accurately treat the thermal coupling to the building and its HVAC system as outlined above. However, the Annex 42 models are more simplified than detailed process flow methods, which would be inappropriate for use in whole-building simulation as their computation burden precludes their application when using time-varying boundary conditions.

Annex 42 was structured into three subtasks:

- **Subtask A** – review current status of residential cogeneration technologies and characterize occupant-driven electrical and DHW usage patterns.
- **Subtask B** – develop models for residential SOFC, PEMFC, SE, and ICE devices and implement these into existing whole-building simulation programs. Experimental work was also conducted on prototype and early-market devices, and these data were used to calibrate the models (i.e., establish input data for them). In Subtask B, emphasis was placed on validating the models and verifying the accuracy of their implementations.
- **Subtask C** – assess the technical, environmental, and economic performance of selected cogeneration applications. This subtask focused on applying the models from Subtask B and the occupant-driven electrical and DHW usage patterns from Subtask A.

This booklet summarizes the research conducted by Annex 42 and provides some of its key findings. The accompanying CD includes detailed information on all aspects of Annex 42's research. All final reports and, in some cases, accompanying data files are included on the CD and are also available from the IEA/ECBCS website (www.ecbcs.org). Each of these reports is referenced and described in this booklet.

The remaining sections of this booklet are organized in the following way. Section II describes the Subtask A work on non-HVAC, occupant-driven electrical and DHW usage profiles. Sections III through V discuss the work of Subtask B. Section III provides an overview of the models and their implementation into existing whole-building simulation programs. Section IV addresses the calibration of these models using the experimental data gathered by Annex 42. Section V discusses the methods used to empirically validate the models and to verify their implementation into the whole-building simulation programs using comparative testing. Section VI discusses Subtask C work to assess the performance of residential cogeneration systems. It summarizes the existing literature, demonstrates how the Annex 42 models can be applied to examine the potential of residential cogeneration, and provides key findings from the simulation studies conducted by Annex 42. Readers interested in the performance of residential cogeneration systems could jump immediately to Section VI, although the information treated in sections II through V provide important context and methodology that form the basis of the results presented in Section VI. Finally, the booklet concludes with Section VII, which describes the lessons learned by Annex 42 and provides recommendations for future research.

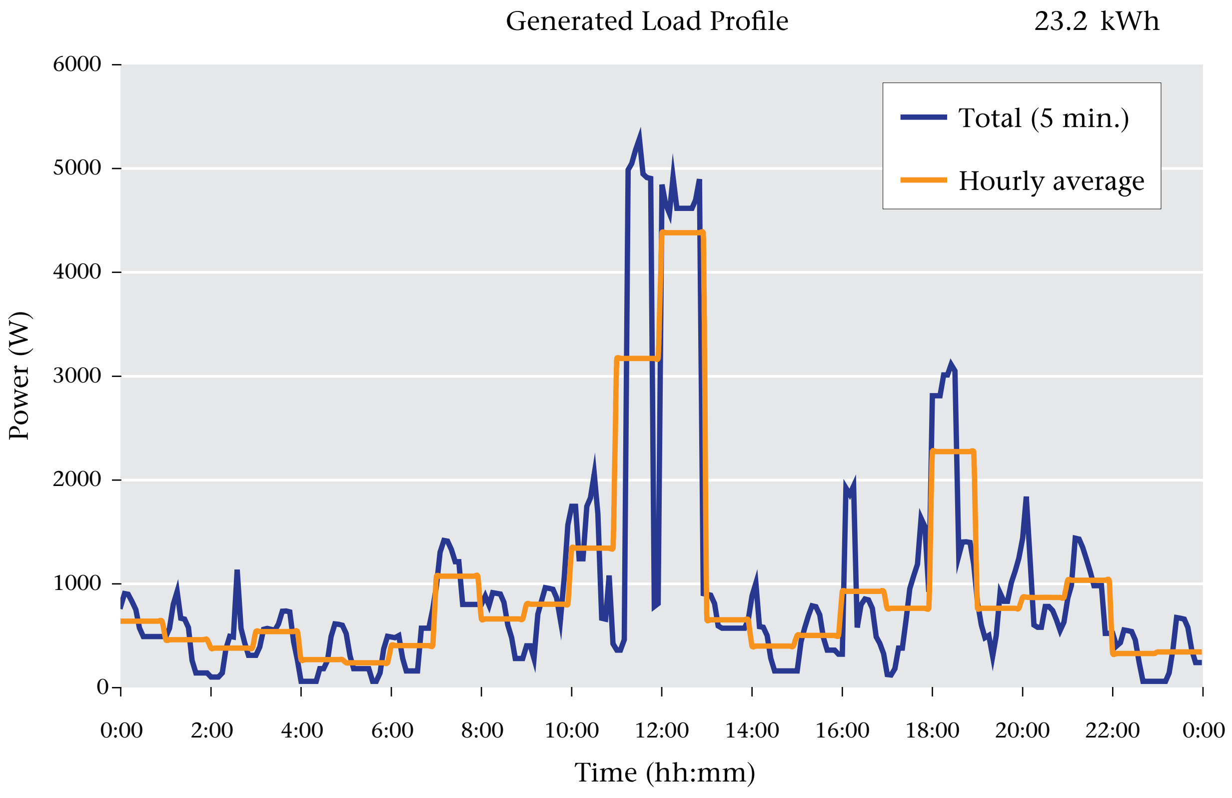
Electric and Hot Water Usage Profiles

"Profiles" describe how electricity and hot water are consumed over the course of time and are critical when analyzing residential cogeneration. Whole-building simulation programs model time-varying energy use for space heating, cooling, and ventilation, but their predictions for overall energy performance rely heavily on user input data for various end uses related to the activities and choices made by occupants. These activities and choices include things like electric appliances and domestic hot water for washing, and are referred to as non-HVAC electrical loads and DHW loads. Section II provides an overview of Annex 42 efforts to produce representative profiles; these profiles are applied in some of the performance assessment studies described in Section VI. A full report on this Subtask A activity is contained in Knight et al. (2007). Profile data sets are available on the CD as well as on the IEA/ECBCS website (www.ecbcs.org).

The importance of electric and DHW load profiles

The integrated design and performance assessment of fuel cells and other small cogeneration systems for residential buildings requires determining not only the thermal and electrical supply capabilities of the cogeneration system, but also the concurrent demand for the residential building under investigation. Whole-build-

Figure II-1 Electric load profile at 5-minute time intervals and averaged over 1-hour periods



ing simulation programs generally model the performance and operation of heating, cooling, and ventilation systems in the building, but non-HVAC electrical loads and DHW loads are inputs to the simulation (usually formulated as a power level combined with a schedule). These occupant-driven loads vary greatly but can be a relatively large portion of the total electrical and thermal energy use, especially in modern, high-performance building practice.

Residential draw patterns of electricity and DHW can generally be characterized by a small base load (or no base load for DHW) with short peaks of very high demand. Therefore, profiles for assessing a residential cogeneration system require a relatively high level of temporal resolution to realistically represent the actual context that the residential cogeneration unit would see. Fig II-1 illustrates the difference between an electric load profile at 5-minute time intervals and the hourly average values for the same profile. The latter profile has drastically reduced peaks, creating a false impression of the load to be met by the residential cogeneration system.

Selection and generation of load profiles

The methodology adopted for producing non-HVAC and DHW load profiles involved the following steps:

- review existing studies and data collections, and ascertain which consumption profiles or profile generators were available to the Annex;
- obtain real data from these existing studies where feasible;
- depending on the data availability, analyze these data against building and occupant characteristics; and
- produce standard datasets at as frequent a time interval as the data will allow, with supporting documentation for use within the Annex.

Table II-1 Non-HVAC electricity and domestic hot water (DHW) consumption datasets provided and used in Annex 42

	Non-HVAC Electricity		**DHW**	
Country	**No. of Profiles (used in the analysis)**	**Monitoring Interval (min.)**	**No. of Profiles (used in the analysis)**	**Monitoring Interval (min.)**
Canada	85 (57)	5, 15 and 60	12 (10)	5 and 60
USA	9 (1)	1, 5 and 60	4 (2)	1, 5 and 60
Switzerland	-	-	1 (1)	60
Finland	6 (6)	60	6 (6)	60
Belgium	2 (0)	15	2 (0)	15
UK	69 (69)	5	5	60
Germany	1	15	1	60
Portugal	1	10	-	-
EU	-	-	3 (1)	60

Review of existing data

Previous studies (Mansouri et al. 1996; Yao and Steemers 2005) have shown that the usage of non-HVAC electricity in residential buildings is primarily influenced by the following factors:

- floor area of the dwelling;
- number of occupants;
- geographical location;
- occupancy patterns;
- seasonal and daily factors;
- ownership level of appliances (number per household);
- fuel type for DHW, heating and cooking, etc.; and
- social status of occupants.

As the objective of Annex 42 was to produce profiles to assess residential cogeneration technologies rather than predict performance in specific buildings inhabited by specific occupants, a number of the above factors were not considered. Rather, focus was given to geographic location, house size, and temporal effects. In cases where profiles were generated for this Annex, the number of appliances per household and their use patterns were also taken into consideration.

Table II-1 lists the few monitored datasets that were found to meet the criteria and were available—many sources of data are proprietary and could not be used in the work of Annex 42.

These data sources were used to generate two distinct sets of non-HVAC electrical profiles: a set representative of Canadian conditions and a set representative of European conditions. The large differences in electricity consumption between households on the two continents prevented the use of just one set for both regions.

European non-HVAC electric profiles

The UK dataset was the most comprehensive and detailed (5-minute time interval) of the data sets available to the Annex. This dataset was used as a starting point for producing the European profiles. Fig II-2 shows examples of social housing measured for the UK data sets; this type of housing forms a significant part of the overall UK housing stock.

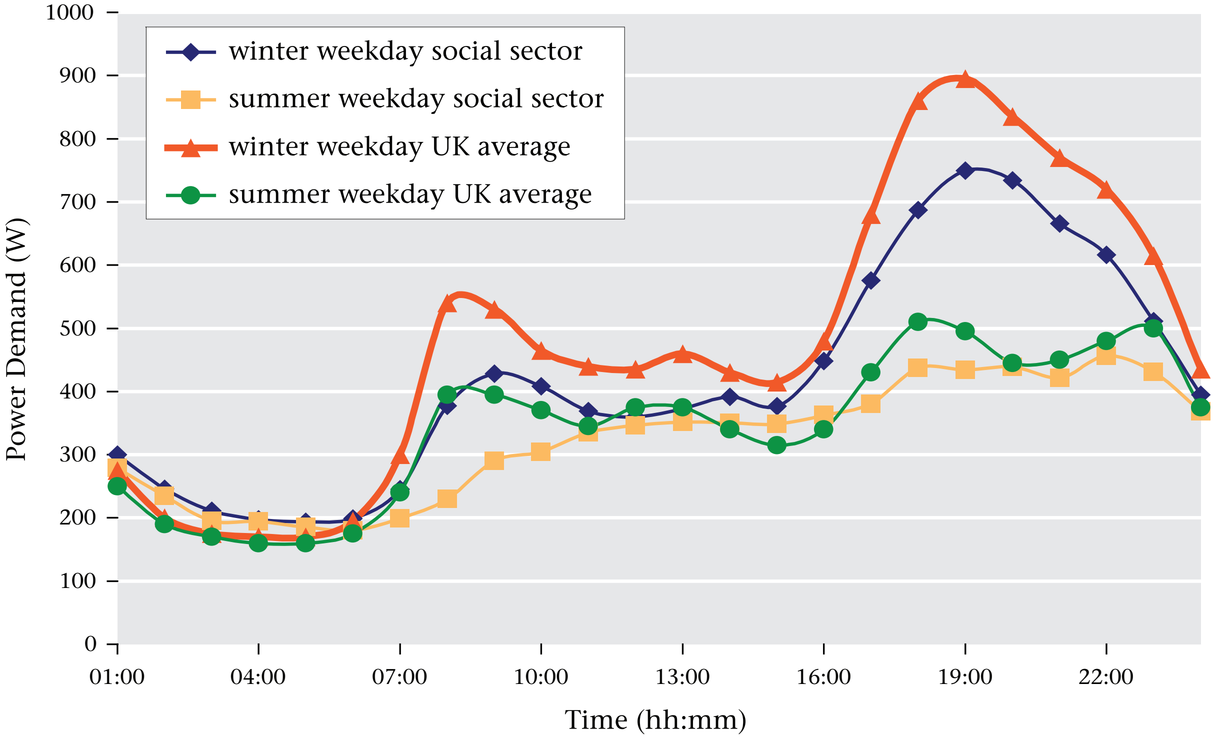
The datasets for the social sector were analyzed and compared to other data for average profiles for the entire UK residential sector. Fig II-3 is an example of analyses that indicate general lower consumption in the social sector.

Figure II-2 Monitored residential buildings in the UK

Flats (Newcastle, England)

Town houses (Llanelli, Wales)

Figure II-3 Comparison of electric load profiles collected for the UK – social housing sector versus UK average



Key characteristics of the UK data profiles were then compared to data for residential electrical consumption from other European countries (Finland, Italy, the Netherlands, Germany, Portugal and Belgium). There was enough similarity to the other datasets to allow use of the UK profiles as representative examples of the European residential stock profiles.

Several variants of the non-HVAC electricity profiles for Europe were produced, including actual measured profiles of single households and average profiles over all monitored dwellings.

In the absence of further substantial datasets, the resulting European Electrical Consumption Profiles are a good first estimate of residential electrical energy consumption profiles for many European countries. They are an acceptable basis for assessing the potential performance of cogeneration systems when meeting this load.

Canadian non-HVAC electric profiles

Two types of electricity demand profiles were produced for assessing the potential performance of cogeneration systems when meeting the electrical energy demand profiles in single detached houses in Canada:

- generated profiles using a bottom-up analysis of electricity-using devices combined with a random generator developed by the National Research Council of Canada (NRC); and
- measured profiles using data from Hydro-Québec.

Target values for the total annual consumption as well as for major appliances and lighting in Canada were obtained from the Comprehensive Energy Use Database of Natural Resources Canada's Office of Energy Efficiency (Natural Resources Canada 2006). This database contains information on the electricity use of the average Canadian household based on data from surveys and other sources (manufacturers, electricity distribution companies, Statistics Canada, etc.). The database gives the type and average number of appliances per household, and the average electricity use for appliances and lighting (for average stock as well as for new stock).

The average detached house, however, is not the same as the average house. The average detached house is larger than the average house (141 m^2 compared to 121 m^2) and will have more people living in it than the average house. The electricity consumption data for appliances and lighting reflect these differences by adjusting the number of appliances per household and by introducing a "use factor" for the appliances.

A random profile generator was developed using a bottom-up approach based on counts of electrical devices in houses in Canada and patterns of use, to generate simulated electrical loads due to occupant actions. These data were generated for a full year in a much finer time resolution (5-minute intervals) than is generally available from most sets of monitored data (typically at 1-hour intervals). Having data at 5-minute intervals for a whole year assisted the modellers of the residential cogeneration systems in testing their simulations with realistic load variations associated with 5-minute load profiles. The gen-

Figure II-4 Example of generated electric load profile for 1 day

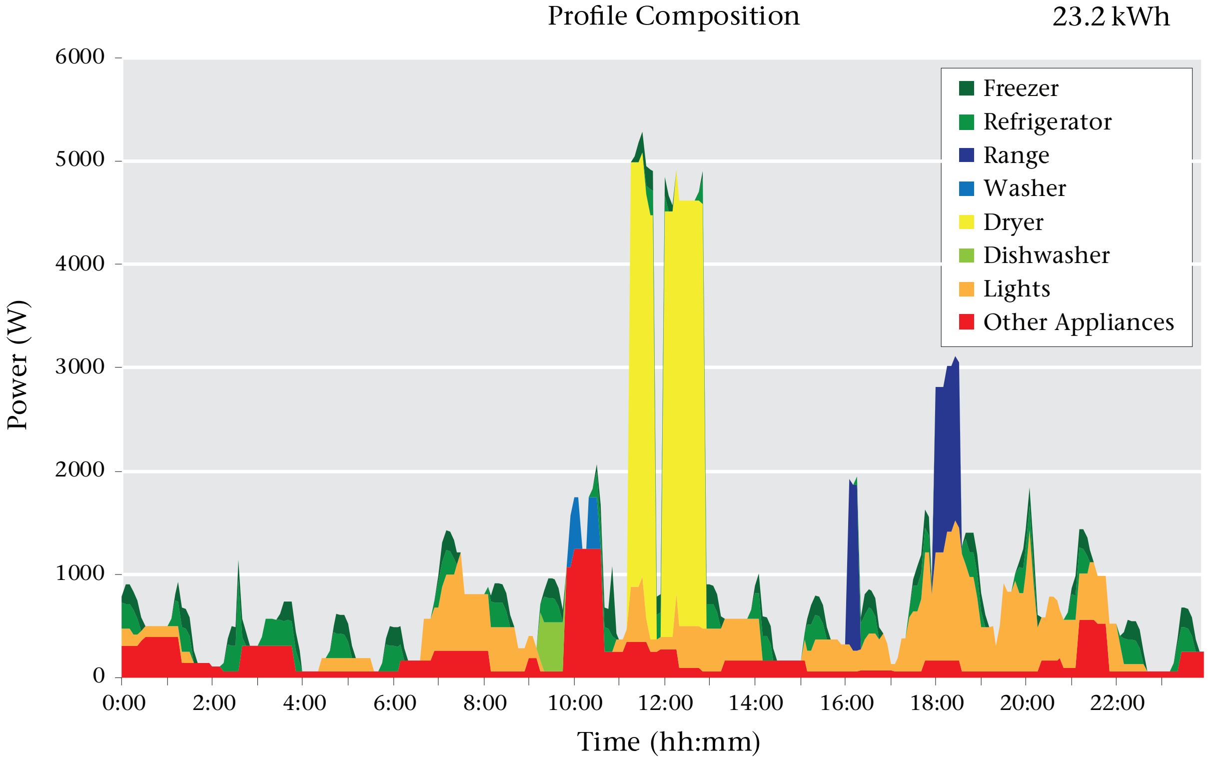
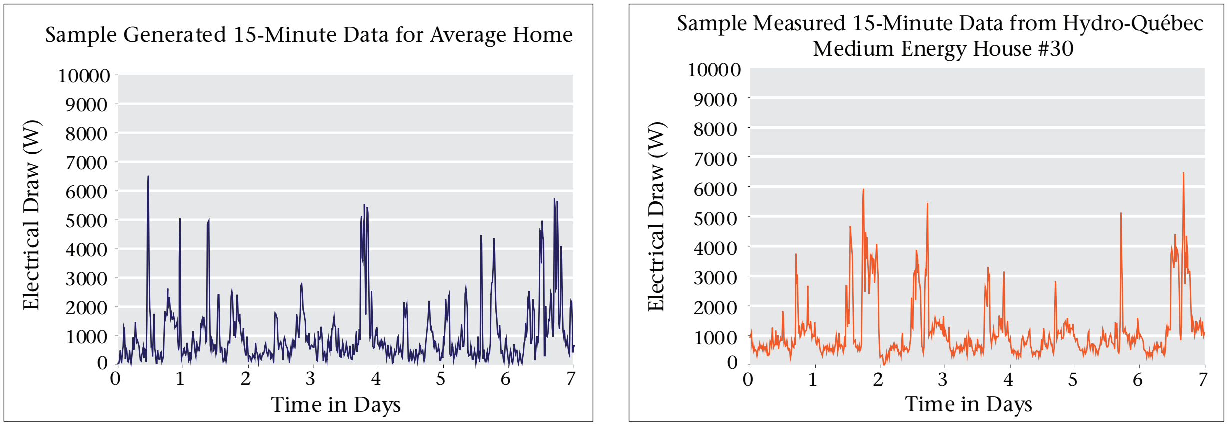


Figure II-5 Generated and monitored data at 15-minute intervals



erated profiles were developed in 3 sets to match the low, medium and high consumption targets.

Hydro-Québec measured the electricity demand at a 15-minute time step in 57 single detached houses during the period of January 1, 1994 to September 30, 1996 (Millette 2006). Total electricity demand, electricity for heating, and power consumption for DHW were measured, allowing the determination of non-HVAC profiles by subtracting the electricity consumption for heating and DHW from the total power consumption.

Finally, the generated load profiles were compared to the measured profiles (see Fig. II-5). (Note that the generated profiles cannot be expected to be identical to the measured ones.) Trial performance assessments were executed using both types of data and the results were found to be consistent, lending confidence to the use of generated profiles for the performance assessment studies reported in Section VI.

The European and Canadian non-HVAC electric profiles show clear similarities in the general shapes of the daily profiles: a morning peak, a reduction in the middle of the day, and a larger evening peak. However, the European and Canadian profiles also display large differences, for instance in the total annual consumption, which is due to a generally more modest electricity consumption in Europe and a difference in the type of house that the profiles represent. The European data were derived from direct measurement, mainly in flats and townhouses, whereas Canadian profiles were developed for detached housing. The user should consider the differences between the available profiles when deciding on the applicability of the profiles to a particular end use.

DHW profiles

It appeared difficult to produce appropriate DHW profiles for use in the Annex, based on the available measured consumption patterns, as high-resolution, measured DHW profiles were very limited in number (see Table II-1). However, a model to generate synthetic profiles had previously been produced by IEA Solar Heating and Cooling Programme (SHC) Task 26 (IEA/SHC Task 26 2006). This model can generate DHW load profiles using a probability-based approach to the occurrence of typical DHW draws for a bath, a shower, a dishwasher, and hand washing—these typical draws being based on monitored consumption rates. The model can generate annual DHW consumption profiles at time steps as small as 1 minute.

An example profile of variations in relative hot water consumption over one day was compared to the collected profiles from Table II-1 (as shown in Figure II-6). This comparison justified the use of load profiles generated by the DHW model from IEA SHC Task 26 for the performance assessment studies reported in Section VI.

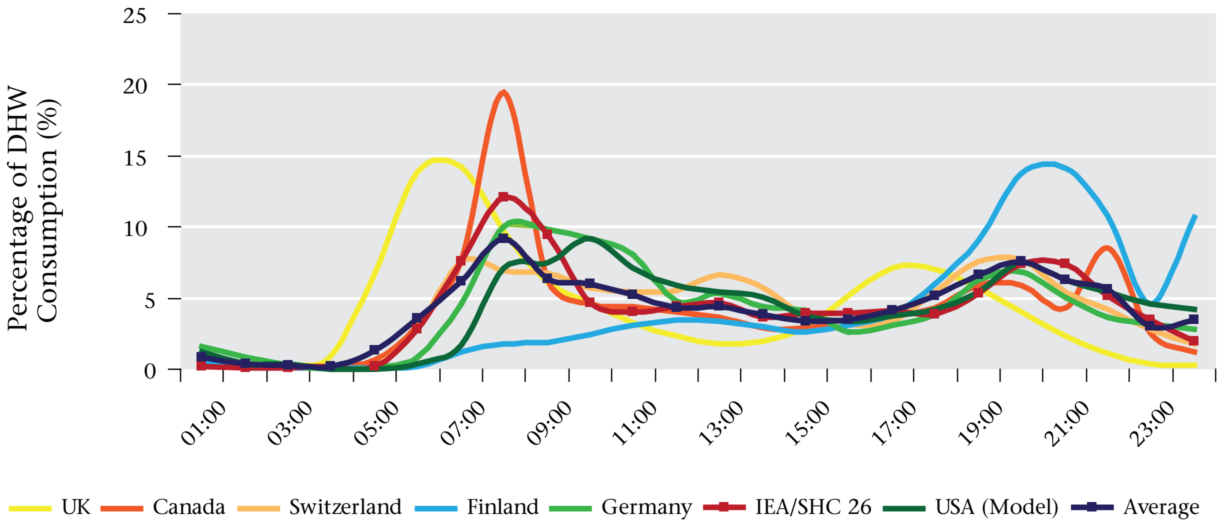
Analysis of the available profiles from Europe (see Table II-1) indicated that, for an average 45°C rise in DHW temperature, European countries would generally consume around 100 to 120 litres/day per household. Again, there is an apparent difference between the Canadian and European data, with the Canadian (and U.S.) data showing daily consumption rates of about 200 to 250 litres/day, twice as much as the reported European rates. Appropriate profiles were generated with the Task 26 DHW profile generator for use in assessing the economic, environmental, and energy performance impacts of cogeneration systems in residential buildings.

Non-HVAC electricity and DHW load profiles produced by Annex 42

The accompanying CD (and the IEA/ECBCS website www.ecbcs.org) contain detailed daily electrical consumption datasets for Europe at 5-minute intervals, and for Canada both generated profiles at 5-minute intervals and measured profiles at 15-minute intervals; as well as general set of generated daily DHW consumption profiles at intervals of 1, 5, 6, 15 and 60 minutes.

Although these profiles were developed specifically for the needs of Annex 42, it is felt that they are generally applicable in the modelling of buildings and their energy systems.

Figure II-6 Comparison of Annex 42 measured data and IEA/SHC Task 26 model data



Section III

Model Development

This section summarizes the models developed within IEA/ECBCS Annex 42 Subtask B for residential cogeneration devices. After an extensive review process, Kelly and Beausoleil-Morrison (2007) determined that there was a lack of cogeneration device models suitable for use in whole-building simulation programs, and Annex 42 then developed specifications for two generic models: one for fuel-cell-based cogeneration systems (SOFC and PEMFC) and a second for combustion-based systems (SE and ICE). Four specific device models were derived from these generic specifications

In order for the models to be available to as broad a user base as possible, one or more have been implemented within a variety of modelling platforms (TRNSYS, ESP-r, EnergyPlus and IDA-ICE; see page 21). This approach also enabled inter-model comparison to be conducted as a means of verifying the accuracy of each implementation (see Section IV).

The main requirement for the models was to accurately predict the thermal and electrical outputs from specific residential cogeneration devices. The models were required to operate within whole-building simulation programs operating at time steps ranging from less than 1 minute to up to 15 minutes.

Modelling approach

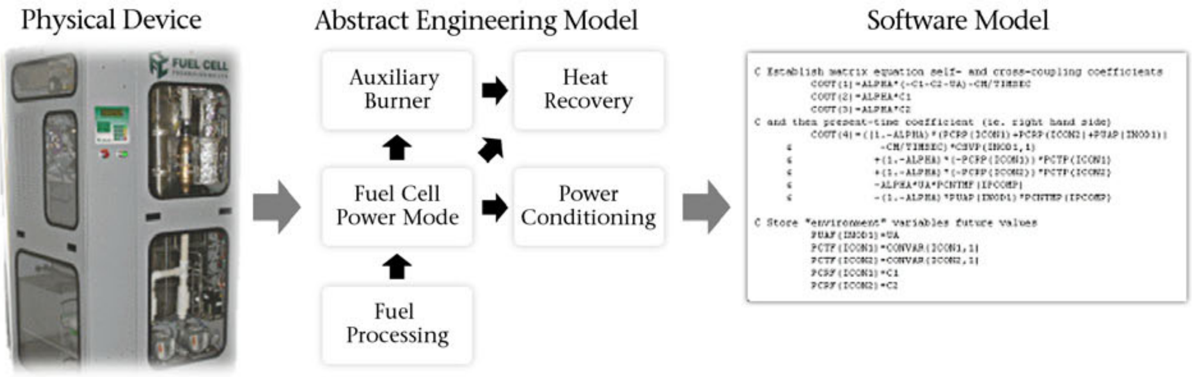
Developing a systems-level software model for a device is a three-stage process (Figure III-1):

- the physical characteristics of the device are identified;
- an abstracted engineering model is developed and verified; and
- the engineering model is then coded as a model within a building simulation tool.

The following sections provide a descriptive, non-mathematical overview of this model development process. More comprehensive descriptions (including the relevant equations) are available in the detailed model specifications report produced by the Annex (Kelly and Beausoleil-Morrison, eds. 2007).

The Annex 42 models use a pragmatic "grey box" approach, where the model structure partially reflects underlying physical processes and partially relies on empirical relations. Grey box modelling is used extensively in many engineering fields (e.g., Clarke 2001; Hrovat and

Figure III-1 Development of a systems-level device model

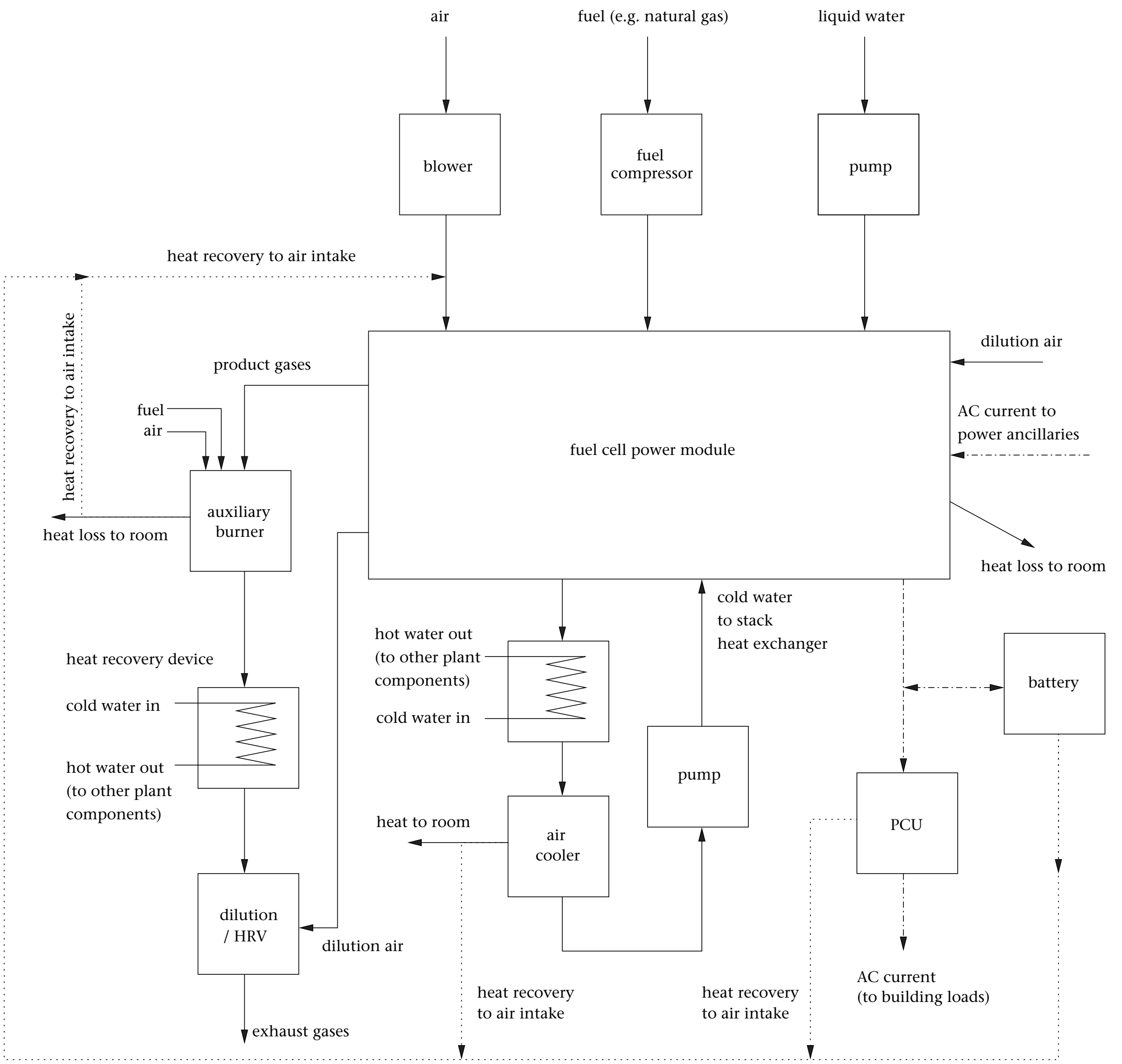


```
C Establish matrix equation self- and cross-coupling coefficients
         COUT(1)=ALPHA*(-C1-C2-UA)-CM/TIMSEC
         COUT(2)=ALPHA*C1
         COUT(3)=ALPHA*C2
C and then present-time coefficient (ie. right hand side)
         COUT(4)=((1.-ALPHA)*(PCRP(ICON1)+PCRP(ICON2)+PUAP(INOD1))
     &              -CM/TIMSEC)*CSVP(INOD1,1)
     &             +(1.-ALPHA)*(-PCRP(ICON1))*PCTP(ICON1)
     &             +(1.-ALPHA)*(-PCRP(ICON2))*PCTP(ICON2)
     &             -ALPHA*UA*PCNTMF(IPCOMP)
     &             -(1.-ALPHA)*PUAP(INOD1)*PCNTMP(IPCOMP)

C Store "environment" variables future values
         PUAF(INOD1)=UA
         PCTF(ICON1)=CONVAR(ICON1,1)
         PCTF(ICON2)=CONVAR(ICON2,1)
         PCRF(ICON1)=C1
         PCRF(ICON2)=C2
```

Sun 1997). In building simulation, cogeneration devices may be modelled using one of two approaches: subsystem and systems-level. Both are based on control volumes, which are arbitrary, bounded regions of space to which the laws of conservation of mass, momentum, species, and energy can be applied. One or more conservation, or balance, equations are formulated for each control volume and used to solve for time-varying energy and mass flows. With the subsystem approach, the device is broken down into separable functional elements (e.g., heat exchanger, fuel compressor, etc.) with each represented by a different control volume. With the systems-level approach, the device is represented as a single functional element. The physical processes in each control volume are considered when formulating the governing balance equations; however,

Figure III-2 Schematic of the FC-cogeneration device model[1]



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[1] Note that as the model is intended to be generic, not all of these control volumes need to be used; specific volumes can be activated or de-activated, as appropriate, for a particular fuel cell.

because the internal details of the devices are often not available, it is necessary to use one or more empirically derived expressions to represent these processes. The empirical coefficients of the equations are determined by testing the devices and calibrating inputs to the measured data. The subsystem approach requires more internal measurements during testing than the systems-level approach. Both approaches are applicable to the modelling of cogeneration devices. Within Annex 42, the subsystem approach was used in the modelling of fuel cell devices and an enhanced systems-level approach was deployed in the modelling of the combustion devices.

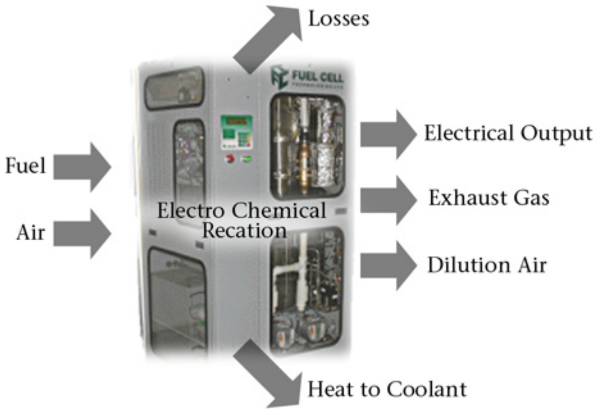
Fuel cell cogeneration model

The fuel cell model uses a subsystem approach with 12 control volumes to describe a generic fuel cell cogeneration device. Figure III-2 diagrams the model's different subsystems.

The core subsystem of the model is the fuel cell power module (FCPM). The FCPM control volume itself combines a number of sub-components, including fuel cell stack, fuel pre-heater, fuel de-sulphurizer, fuel reformer, pre-reformer, steam reformer, shift reactors, fuel control valves and actuators, air filter and pre-heater, downstream afterburner or combustor, water preparation system, and central controller. A large number of sub-components are grouped in the FCPM control volume to provide the model with sufficient flexibility to represent a wide variety of fuel cell devices; product-specific information regarding the arrangement of components such as afterburners and pre-heaters is not required.

The FCPM control volume gives rise to the main energy balance equation of the fuel cell device. This is represented in Figure III-3. Solution of this equation yields the basic performance characteristics of the device: fuel consumption, efficiency, etc.

Figure III-3 Energy balance for the FCPM control volume



Grouping the core components into a single control volume precludes an explicit treatment of the fuel cell's electrochemical behaviour. Consequently, this model does not attempt to simulate the electrochemical processes, but rather represents the performance of the FCPM using parametric relationships between the inputs and outputs, which also take into account the degradation in performance of the unit over time.

Modelling transient behaviour

Fuel cells for cogeneration, especially SOFCs, tend to have slow transient response characteristics because of their high operating temperatures, large thermal inertia, and internal controls that protect the stack from thermal stresses that would be induced by sudden temperature changes. Therefore, it is important to consider the transient behaviour of the FCPM. However, developing a fully transient model of the fuel cell (specifically the FCPM) is a non-trivial task and would require considerable access to data on the internal sub-components. Consequently, the model uses a pragmatic approach for dynamics that places limits on how quickly the FCPM can respond to control signal changes. The response during normal operation is characterized by input parameters that limit the change in operating point from one simulation time-step to the next. During start-up and cool-down periods, it is assumed that the rates of fuel and ancillary electricity consumption are constant. Note that the approach outlined here for treating transients approximates rather than explicitly calculates the transient performance. Therefore, it is not suitable for predicting phenomena such as the thermal stresses induced by non-steady-state operation or the impact of these stresses upon service life, as these would require more accurate calculation of temperatures and heat fluxes during transient conditions. However, the approach described is useful for studying the effects of transient performance on overall building behaviour over a long-term (e.g., annual) simulation.

Other fuel cell model constituents

The other subsystem elements of the fuel cell diagrammed in Figure III-2 comprise the balance of plant for the FCPM. These elements are also modelled using a mix of empirically derived equations and energy balances to describe relationships between inputs and outputs for each control volume. For example, the air blower control volume is used to calculate the electrical power consumed by that component and the resulting rise in temperature of the supply air. The heat added to the air is expressed as a fixed fraction of the blower's electrical consumption, which itself is a polynomial function of airflow rate.

Similarly, in the modelling of the integrated auxiliary burner (a double-chamber heat exchanger), the combustion gases from the FCPM are directed through one chamber of the heat exchanger and the exhaust gases from the auxiliary burner through the second chamber; water circulates through the heat exchanger to extract energy from both gas streams concurrently. The burner control volume incorporates energy balances, which describe two processes: the addition of heat from the burner and the mixing of the exhaust streams from the burner and fuel cell. The mathematical solution of the energy balances enables the temperature and flow rate of the resulting gas mixture to be calculated. This mixture then passes into the next control volume, a heat recovery device.

The PEMFC application of the model differs from the SOFC application by including the stack cooler subsystem that models direct cooling of the PEMFC stacks and heat rejection to the cooling water circuit or surrounding ambient air.

Modelling fuel and air supply

The model allows for virtually any input fuel mixture to the fuel cell component. The composition of the fuel supplied to the FCPM is defined in terms of molar fractions for each

Table III-1 Available fuel constituents

Fuels	
hydrogen (H_2)	
hydrocarbons	methane (CH_4), ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), pentane (C_5H_{12}) and hexane (C6H14)
alcohols	methanol (CH_3OH) and ethanol (C_2H_5OH)
inert constituents	carbon dioxide (CO_2) and nitrogen (N_2) and oxygen (O_2)

separate constituent. Table III-1 lists the possible fuel constituents. Similarly, the composition of the air stream has also been defined in terms of molar fractions of N_2, O_2, H_2O, Ar, and CO_2. The properties of the supply mixtures are calculated using correlations that are common for gas-phase thermochemistry. The model also gives the user the option of specifying liquid water supply for steam reformation; in the case of internally reforming SOFCs, this can be neglected.

Modelling electrical performance

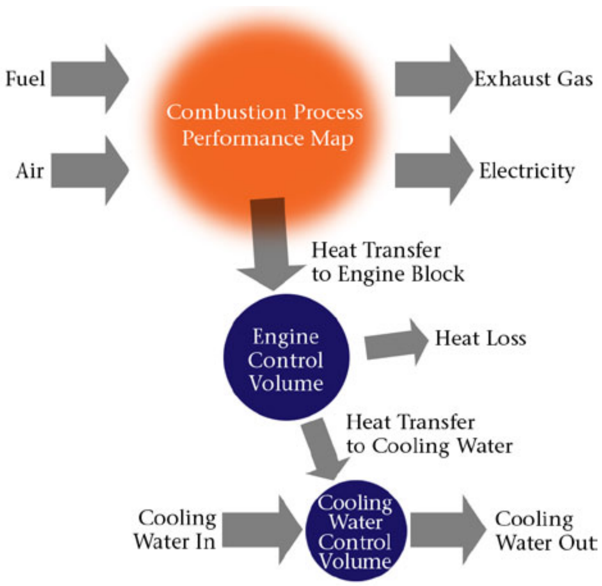
The operating point of the fuel cell is determined based on the gross power demand on it, and the system can be controlled to supply a specific power output. The total power required from the system can also be calculated; this includes the power drawn by auxiliary components and losses in the power conditioning system. The other operational parameters are then calculated based on the electrical load on the device.

The model is structured in this way to enable research on the sensitivity of system performance to DC-to-AC power conditioning unit (PCU) and battery characteristics. To facilitate this, a simple electrical storage model is included with the generic device: this is a quasi-static, state-of-charge (SOC) model that provides basic accounting of the electrical energy flows and losses to determine the SOC over time. A PCU model is also included, which converts direct current (DC) electricity produced by the FCPM into alternating current (AC) electricity used by most buildings and utility grids.

Generic ICE/Stirling engine model

This model has been developed to represent any combustion-based cogeneration device. The model comprises 3 basic control volumes (Figure III-4).

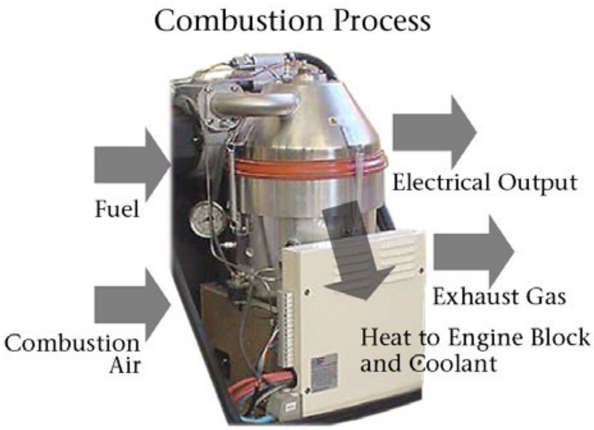
Figure III-4 The generic engine model control volumes



The energy conversion control volume represents the combustion processes taking place within (or outside in the case of Stirling engines) the cylinder or cylinders of the engine unit. Generic polynomial performance equations have been derived for this volume that relate the fuel heat release (to the exhaust gases and engine jacket) and fuel consumption to the electrical power production of the unit. The basic energy balance for this volume is depicted in Figure III-5.

The performance equations rely on two efficiencies that relate useful energy production to fuel energy consumption: one for the electrical efficiency and another for the thermal efficiency. These are both modelled as functions of the electrical output, coolant flow rate, and coolant temperature. This approach has significant advantages over a more detailed model: simplicity, ease of calibration, and reduced data collection burden. However, the model must be calibrated

Figure III-5 Energy balance for energy conversion control volume



using empirical data and so each set of model inputs is applicable to only one engine type, capacity, and fuel type.

Modelling of thermal transients in combustion engines

The model assumes that the dynamic thermal behaviour of the combustion cogeneration device is attributable to the thermal mass of the engine, exhaust-gas heat exchanger and, in Stirling engines, the external heater. The engine control volume includes the engine block and main drivetrain elements of the engine unit, which are the most thermally massive elements of the device. Consequently, the engine control volume energy balance is represented by a first order differential equation, which accounts for thermal storage in the engine itself along with skin losses and heat exchange between the engine block and the coolant heat exchanger control volume.

The energy balance for the heat exchanger control volume also includes heat storage and, as with the engine volume, is represented by a first order differential equation in the model. The coolant heat exchange with both the engine jacket and exhaust gases are accounted for within this volume. These multiple heat exchanges are represented using a single heat exchange equation, which utilizes the engine and this control volume's temperature difference and a constant heat exchange coefficient. Phenomena such as condensation of the exhaust gases are not explicitly modelled; however, their effect is implicitly accounted for in the engine performance equations.

Modelling of fuel for combustion engines

As for the fuel cell model, the fuel model for combustion engines has been developed to enable the simulation of virtually any input fuel mixture to the control volume component. Again, the composition of the fuel stream is defined in terms of molar fractions. The composition data is used to calculate the fuel LHV, which is in turn used to calculate the fuel input mass flow rate. The air stoichiometry is regulated to manage the combined heat and power (CHP) unit's combustion efficiency, operating temperature and emissions, and is calculated using a second order polynomial function based on the fuel mass flow rate.

Modelling of electrical performance and control in combustion engines

Electrical performance is modelled in a similar manner to the SOFC model: the electrical output of the device is treated in a basic manner in that the desired power output is used to determine the operating state. However, in the case of the Stirling engine model, the electrical output during warm-up can be calculated as a function of the engine control volume temperature.

Within the model, low-level controls manage the operation of subsystems within the unit to achieve optimum (and safe) performance for a given operating point. These controls can restrict the rates at which the power output and fuel flowing to the system can be increased or decreased[2]. To account for this, the model allows constraints on the maximum rates of change of both of these quantities. The model also includes an overheat-protection control that deactivates the unit when the coolant outlet temperature exceeds a specified value.

Typically, a CHP system will produce heat and power when in normal operation mode. However, CHP systems may exhibit three other operating modes with markedly different characteristics; these are the standby, warm-up and cool-down modes of operation. The model tracks which operating mode the CHP unit is currently in and switches the unit between modes depending on the prevailing system state, low-level control signals and system boundary conditions.

Summary of implementations

The models described previously have been implemented on the various modelling platforms shown below.

ESP-r

The device models have been integrated into the general release of the ESP-r platform. These models take the form of an algorithm (a coefficient generator which integrates the device within the ESP-r matrix-based plant systems solver) and corresponding database entry, which holds the data for the specific implementation of the device. ESP-r is available for download at www.esru.strath.ac.uk.

TRNSYS

The models have been developed as user-defined TRNSYS Types, based on the ESP-r coefficient generator subroutines. However, the use of these routines was adapted to the component-based solution approach prevalent within TRNSYS. The Types are available from Empa Building Technologies (www.empa.ch) upon request.

EnergyPlus

The fuel cell model (both SOFC and PEMFC) is accessed using the input object called GENERATOR:FUEL CELL. The combustion model (both ICE and SE) is accessed using the input object called GENERATOR:MICRO CHP. For more

Table III-2 Implementation of models on different platforms

Platform	Models Implemented
ESP-r	SOFC, PEMFC, ICE, SE
TRNSYS	SOFC, PEMFC, ICE, SE
EnergyPlus	SOFC, PEMFC, ICE, SE
IDA-ICE	SOFC

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[2] The fuel flow rate may be managed to optimize other engine performance criteria. For instance, in modulating Stirling CHP, the system's operating point is actually regulated by varying the pressure of the working fluid inside the engine. A low-level controller then regulates the fuel flow to ensure that the temperature at the hot end of the engine is maintained within an efficient operating range. Since the Stirling power system control volume does not provide sufficient resolution to model these effects, the fuel flow rate is used to uniquely describe the system operating point, and is defined as the system's principal control parameter.

information, refer to the EnergyPlus documentation. EnergyPlus is available for download at www.energyplus.gov.

IDA-ICE

The SOFC device model was developed for the IDA-ICE environment using the so-called NMF (neutral model format) modelling language, reported by Sahlin et al. (1989). The model follows the Annex 42 specification except that start-up and cool-down operation periods are not treated.

Closing remarks

The fuel cell and combustion cogeneration models can be applied to a wide variety of cogeneration devices and have been designed with considerable flexibility in mind (a feature inherent in the grey box modelling approach). The parameters required to calibrate governing equations can be determined from bench testing cogeneration devices. In the case of the combustion engine model, non-intrusive measurements (e.g., fuel flow rate, cooling water flow rates and temperature, electrical production) are sufficient to calibrate the model. However, due to its more detailed nature, some intrusive measurements (e.g., gas temperature flowing into gas-to-water heat exchanger, DC power flowing into power converter, air supply rate) are required to calibrate the fuel cell model.

While the combustion engine models account for thermal transient effects in cooling water outlet temperature, the SOFC and PEMFC models currently calculate only the steady-state performance at a particular simulation time step, with an approximation of the impact of transient performance. However, a similar approach to that adopted in the combustion engine models could equally be applied to the fuel cell models: where extra, massive thermal control volumes are associated with the cooling water heat exchangers. Finally, while all of the models calculate CO_2 emissions, other pollutant emissions such as SO_x and NO_x are not dealt with in detail. The combustion engine models incorporate a form of equation suitable for the modelling of time-varying non-CO_2 pollutant emissions. However, no attempt has been made to calibrate and validate these equations.

Finally, these models are intended for use at time steps ranging from 1 second to a few minutes. Half-hourly or hourly time steps are not recommended where transient issues are a concern, as their accuracy could be compromised.

Experimental Investigations and Model Calibration

As discussed in Section III, the Annex 42 models use a "grey box" approach, where the structure of the model is roughly related to the basic underlying physical processes. However, the models rely extensively on parametric equations describing the relationships between key input and output parameters. Each of these parametric equations requires empirical constants that characterize aspects of the performance of specific cogeneration devices. The establishment of these empirical constants is known as model calibration and requires data from experimental investigations.

Annex 42 developed and used an experimental protocol described in sections II–IV of Beausoleil-Morrison, ed. (2007) to calibrate the models. The Annex 42 experimental protocol and the experimental investigations conducted by Annex members are available on the CD accompanying this report and on the IEA/ECBCS website (www.ecbcs.org). This protocol outlines the data that should be measured, the required measurement frequency, and the situations that should be assessed.

Seven Annex 42 participants from 6 countries conducted experiments with prototype or early-market residential cogeneration devices. In total, 13 separate investigations were conducted on SOFC, PEMFC, SE, and ICE devices. These experimental investigations are summarized in Table IV-1. Photographs of 2 of the Annex 42 experimental facilities are shown in Figures IV-1 and IV-2.

Annex 42 participants adhered to the experimental protocol as closely as possible. Even so, the real-world limitations of their test facilities and restrictions in their test programs resulted in data that are not optimally suited for calibration work. For instance, the Canadian Centre for Housing Technology (CCHT) and Technical University of Munich (FfE) facilities are specifically designed to recreate the dynamic conditions actually experienced by a residential heating plant and do not impose a series of steady-state conditions which would be more straightforward to use when calibrating cogeneration device models. Moreover, the test programs at these centres precluded the invasive instrumentation suggested by the experimental protocol.

Not all of the data produced in the Annex were used to calibrate the models. Some data were judged to be unsuitable for the Annex 42 models (although they are clearly useful for other objectives), while others became available after completion of the Annex's working phase—too late to support the calibration efforts. Finally,

Table IV-1 Annex 42 experimental investigations with residential cogeneration devices

Country	Experimental Facility	Devices Tested
Germany	Technical University of Munich	SE, ICE(2), PEMFC
Belgium	Catholic University of Leuven	SE, ICE
Canada	Canadian Centre for Housing Technology	SE, SOFC
	Fuel Cell Technologies Ltd.	SOFC
USA	National Institute of Standards and Technology	PEMFC(2)
Italy	Napoletanagas	ICE
Switzerland	Swiss Federal Laboratories for Materials Testing and Research	ICE

Figure IV-1 Experimental facility at the Technical University of Munich

Figure IV-2 The Canadian Centre for Housing Technology

the calibration efforts were guided by the interests and resources of the participants. Whenever possible, the experimental data were included on the accompanying CD, and the Annex Participants may undertake further calibration efforts in the future.

Three detailed calibration exercises were undertaken in Annex 42:

- the combustion cogeneration model was calibrated to the WhisperGen SE device using data collected at the CCHT;
- the combustion cogeneration model was calibrated to the Senertec ICE device using data collected at FfE in Germany; and
- the fuel cell cogeneration model was calibrated to the FCT SOFC device, using data collected at the facilities of Fuel Cell Technologies (FCT) in Canada.

The scope of these experimental studies varied widely. The WhisperGen SE data were collected prior to establishment of the protocol, and are not optimally suited for model calibration. Both the Senertec ICE and FCT SOFC experiments adhered as closely as possible to the experimental protocol, but only the FCT SOFC tests included invasive instrumentation and measurements under steady-state conditions. The invasive instrumentation available in the FCT SOFC experiments permitted piecewise calibration of subsystems of the fuel cell model, and application of traditional uncertainty analysis to the derived model inputs.

In contrast, the WhisperGen SE and Senertec ICE datasets provide only a handful of global measurements taken outside of the device, from which numerous model inputs must be derived. Therefore, calibration with these datasets required unconventional parameter identification procedures.

For these reasons, the Annex 42 calibration exercises serve not just to derive inputs to the cogeneration models, but also to provide methods for calibrating the models using both invasive and global measurements.

A brief overview of these calibration activities follows. The calibration methodologies are outlined, principal sources of uncertainty identified, and sample results presented. A complete discussion of the calibration process is provided in sections V–VII of Beausoleil-Morrison, ed. (2007). This comprehensive report also presents the complete set of input data required to simulate the WhisperGen SE, Senertec ICE, and FCT SOFC devices using the Annex 42 models.

Combustion cogeneration model

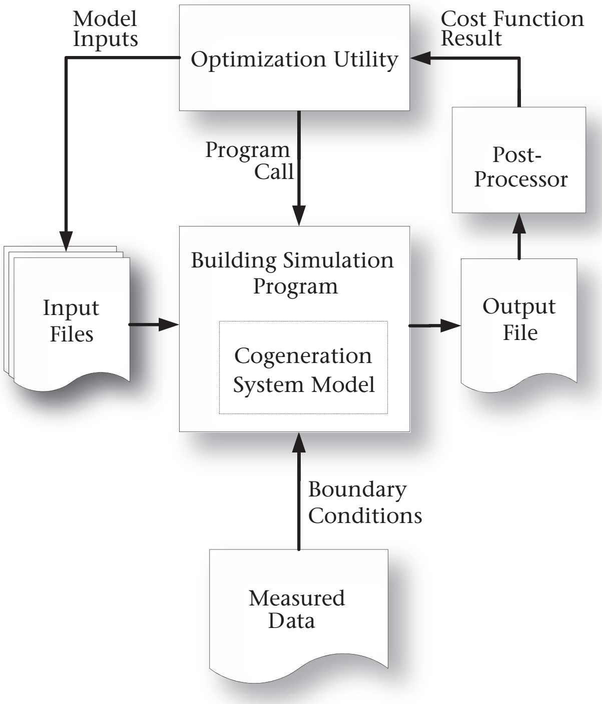
The WhisperGen SE and Senertec ICE experiments both sought to characterize the performance of the cogeneration device in response to real building loads—FfE installed the Senertec ICE unit on a test bench capable of recreating conditions inside a residential heating and hot water system, while the CCHT installed the WhisperGen SE unit inside a fully instrumented test house. Neither the CCHT nor FfE facilities were designed to impose steady-state conditions on the cogeneration device, and all of the measured data describe the system responses to changing conditions in the system. While they are not optimally suited for model calibration, the CCHT and FfE datasets both provide a rich description of the cogeneration units' performance, and were the most comprehensive combustion-based cogeneration performance datasets available to the Annex.

Both the CCHT and FfE tests restricted use of invasive instrumentation, and so measurements characterizing the cogeneration device's operation were limited to the following:

- the fuel flow rate;
- the cooling water flow rate;
- the cooling water inlet and outlet temperatures; and
- the net electrical output from the device.

While the combustion cogeneration model uses empirically derived relationships to represent some of the underlying physics inside the cogeneration device (e.g., heat transfer between the engine jacket and cooling water), these measurements provide only limited insight into the inner workings of the WhisperGen and Senertec cogeneration devices. Therefore, the calibration process required a methodology capable of deriving multiple model inputs from a limited set of measurements describing operation under dynamic conditions.

Figure IV-3 Coupling between optimization utility and Annex 42 combustion cogeneration model for parameter identification



Both the WhisperGen and Senertec calibration exercises first scrutinized manufacturers' literature and test documentation to identify as many model inputs as possible. Next, measurements that converged towards steady-state values during periods of extended operation were identified, and model inputs describing performance under these quasi-steady-state conditions were computed. Finally, the remaining uncalibrated model inputs were determined by comparing the model's predictions to the dynamic performance observed in the CCHT and FfE tests.

The last step in the calibration procedure was expedited with the assistance of third-party optimization utilities. These tools are designed to identify the inputs providing the minimum values for a given criteria (e.g., the difference between measurements and predicted values) and support problems in which the objective functions are calculated by an external program, such as a building simulation program.

The coupling between the optimization utility and the combustion cogeneration model is depicted in Figure IV-3. During each iteration, the utility writes the estimated model parameters to the simulation tool's input files. The utility then invokes the building simulation program, which performs a simulation using the parameters described in the input files and the boundary conditions described in the measured data. The building simulation program writes the results to an output file, which is post-processed. Finally, the utility interprets the post-processor's output and selects new values for the parameters based on the results of the simulation according to the selected optimization algorithm. As many as 5 000 such iterations were required to perform the WhisperGen SE and Senertec ICE calibrations.

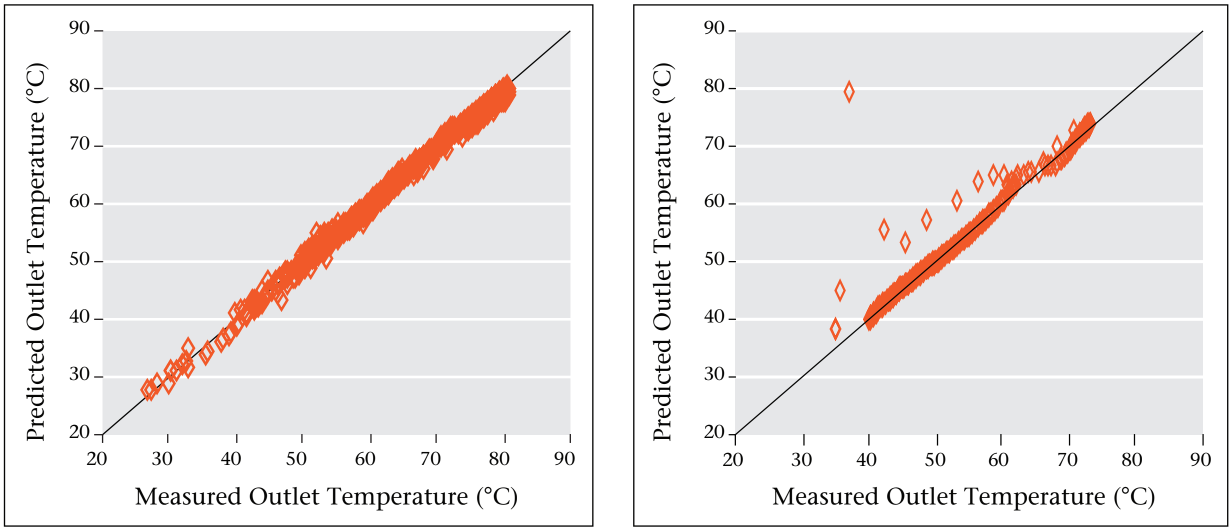
Assumptions and sources of uncertainty

The CCHT data were collected at varying time resolutions; the unit's net electrical output was averaged over 15-minute intervals, while the fuel and cooling water flow rates, and inlet and outlet temperatures were collected every minute. However, the resolution of the fuel flow meter proved too low to accurately characterize the unit's fuel consumption over 1-minute intervals. To reduce this uncertainty, the fuel flow measurements were averaged over 10-minute intervals. These measurements would still permit correlation of the unit's efficiencies to cooling water temperature, provided that steady-state measurements were available. But all of the CCHT data describe the WhisperGen unit's dynamic response to changing cooling water temperature, necessitating a dynamic parameter identification procedure.

Moreover, both the FfE and CCHT datasets contain few measurements reflecting cooling water temperatures below 50°C. In the remainder of the measurements, the cooling water was likely too warm to affect significant condensation in the cogeneration units' exhaust gas heat exchangers. Under these conditions, the units did not achieve the higher efficiencies possible with condensing heat transfer, and their performance appears insensitive to cooling water temperature. For these reasons, the equations describing the combustion cogeneration model's steady-state electrical and thermal efficiencies were assumed to be insensitive to the cooling water temperature in both the WhisperGen and Senertec calibration studies.

Even though the CCHT and FfE tests could not characterize an important part of the cogeneration operating regime, the results illustrate an important point—when integrated into forced-air and radiator-based heating systems, SE- and ICE-based cogeneration equipment may spend much of their time in non-condensing opera-

Figure IV-4 Comparison of predicted and measured outlet temperatures for
a) WhisperGen SE b) Senertec ICE devices



tion. In these applications, the CCHT and FfE data provide more realistic appraisals of performance.

When calibrated using the CCHT and FfE data, the combustion calibration model will provide reasonable predictions for cogeneration equipment integrated in applications that supply the device with cooling water at temperatures of approximately 50°C or greater. The calibrated model will under-predict heat recovery by as much as 10% in innovative applications that can supply the cogeneration device with much colder cooling water. Should additional measurements become available in the future, improved correlations using the functional forms proposed in the combustion cogeneration model specification would be welcome.

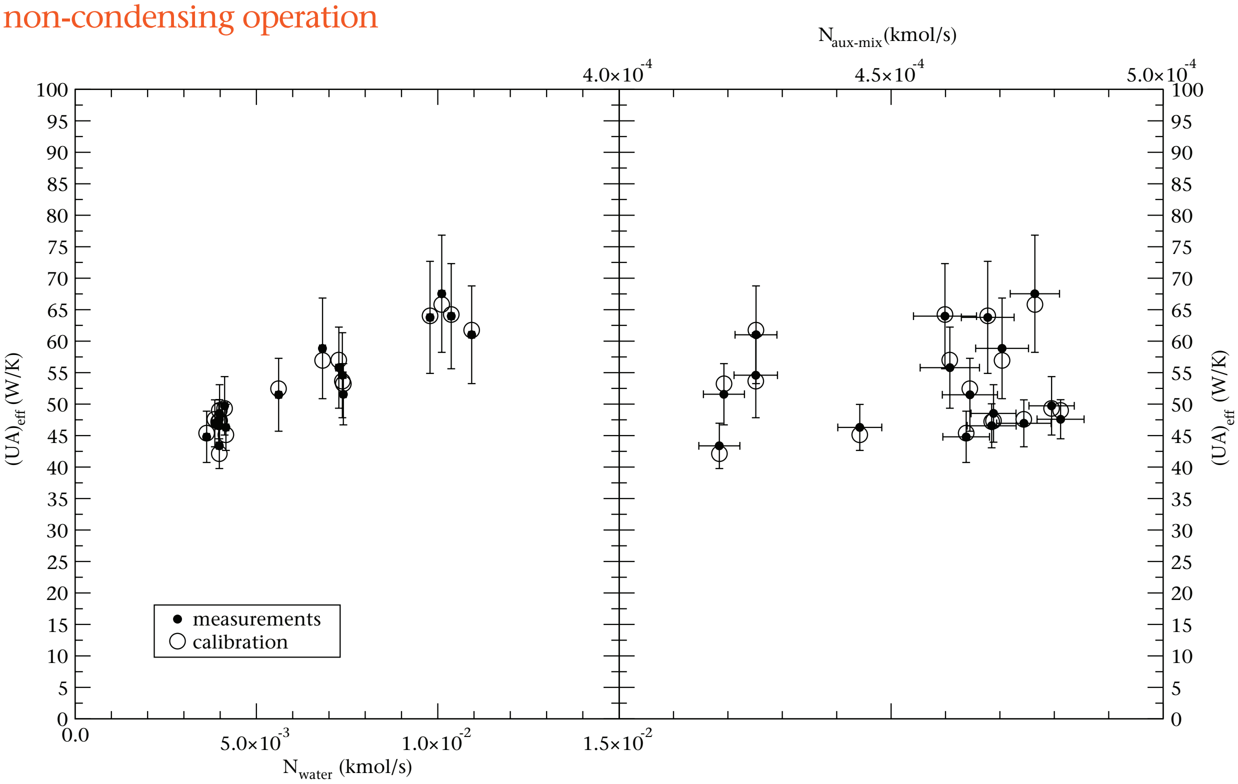
Sample calibration results

Figure IV-4 plots the agreement between the outlet temperatures predicted by the combustion cogeneration model, and those observed on the WhisperGen and Senertec devices. In both cases, the predictions agree very well with the measured values.

Fuel cell cogeneration model

The fuel cell cogeneration model was calibrated using data collected from an FCT SOFC unit at FCT's test facilities in Canada. Whereas the CCHT and FfE studies used test apparatus designed to recreate real-world conditions, the FCT test bench was designed specifically to adhere to the Annex 42 experimental protocol. The resulting data are optimally suited for the Annex's calibration activities, and support traditional uncertainty analysis of the derived inputs.

Figure IV-5 Measured and calibrated heat transfer coefficient (UAeff) during non-condensing operation



While the fuel cell cogeneration model provides 12 control volumes to support analysis of various SOFC and PEMFC cogeneration devices, only 4 of these are needed to represent the FCT SOFC unit:

- the fuel cell power module control volume;
- the exhaust gas-to-water heat exchanger control volume;
- the power conditioning unit control volume; and
- the dilution air system control volume.

The FCT test bench was configured to supply the SOFC cogeneration unit with cooling water at a specified temperature. This permitted testing the unit under steady-state conditions, in which all boundary conditions were held at reasonably constant values. Steady-state tests ensure that the unit's transient response does not contribute additional uncertainty to the measurements, and reduce precision error by permitting many measurements under reproducible conditions.

The FCT SOFC tests also included invasive instrumentation characterizing mass and energy flows into and out of these control volumes. This level of detail permitted each aspect of the model to be calibrated directly from measured data.

The FCT SOFC data comprise numerous measurements taken over a range of operating points. All of the data describing each operating point were first averaged, and the corresponding precision index computed. The average values describing the range of operating points were then regressed using the functional form of the relevant correlation from the model specification. In this way, the fuel cell model inputs were derived.

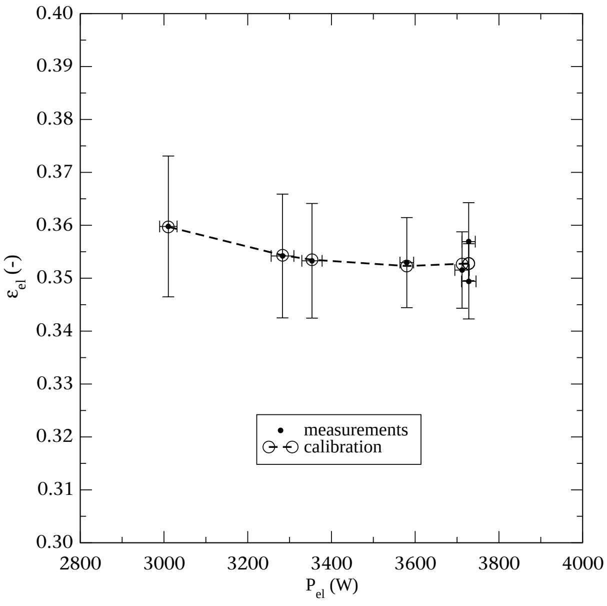
Sources of uncertainty

Bias error data for all instrumentation were recorded to support uncertainty analysis. The test configuration introduced further measurement uncertainties, some of which were accounted for by assigning additional bias error to the measurements. Most notably, physical restrictions on instrument placement prevented measurement of the exhaust gas velocity in a region of fully developed flow. And the condensate from the gas-to-water heat exchanger was first collected in an internal reservoir before being pumped out into the external tilt-bucket gauge, introducing time lag between the occurrence of condensation and its measurement. Measurement uncertainties were computed using the standard method proposed by the American Society of Mechanical Engineers (Abernethy et al. 1985), which considers bias and precision errors and their propagation into derived quantities.

Calibration results

Each control volume was characterized using numerous measurements taken at a range of operating points. Data describing each operating

Figure IV-6 Measured and calibrated electrical efficiency (ε_{el})



point were averaged, and the resulting averaged data were regressed using the relevant functional form given in the model specification.

Figure IV-5 compares the calibrated exhaust gas heat exchanger coefficient, (UAeff), with the values derived from measurements. The left side of the figure plots the heat transfer coefficient as a function of the exhaust gas flow rate, while the right side plots the coefficient as a function of the cooling water flow rate. The error bars indicate the measurement uncertainty at the 95% confidence level. As shown, the calibrated model well represents the dependency of the heat transfer coefficient on the two flow rates.

Similarly, Figure IV-6 plots the predicted and measured power module electrical efficiency as a function of the unit's rate of net electric output. Again, the results agree well.

Closing remarks

Annex 42 developed an experimental protocol to guide experimental measurements of residential cogeneration devices, and participants adhered to this protocol as closely as possible when testing cogeneration equipment. Even so, the real-world limitations of the test facilities and restrictions in the test programs resulted in data that are not optimally suitable for calibration. Nevertheless, the data provide rich descriptions of cogeneration system performance (that go well beyond what is available from manufacturers), and the results from three experimental studies were used to calibrate input data for Annex 42 models.

The combustion cogeneration model was calibrated using data provided by FfE for a Senertec ICE unit, as well as data provided by the CCHT for a WhisperGen SE unit. The fuel cell cogeneration model was calibrated using data provided by FCT for an FCT SOFC unit.

These data differ widely in their scope and resolution. For instance, the CCHT and FfE facilities were originally designed to recreate real-world conditions inside a residential heating system, and cannot impose steady-state conditions on the cogeneration equipment. Moreover, the test programs at these centres precluded invasive measurement. On the other hand, the FCT test program was specifically designed to impose steady-state conditions and incorporate invasive measurements.

For these reasons, the combustion and fuel cell cogeneration models required different calibration methodologies. The combustion cogeneration model was calibrated using an iterative parameter identification procedure that fit its predictions to the dynamic performance data, while the fuel cell cogeneration model was calibrated using steady-state data and traditional uncertainty analysis.

Preliminary review of the results suggests that the derived inputs accurately reflect the calibration data; complete validation of the calibrated models is presented in Section V. However, the diverse approaches used in these studies serve not only to derive model inputs, but are also instructive for future calibration efforts burdened with less-than-optimal data.

Validation of Annex 42 Models

The validity of the Annex 42 models and their calibration to represent specific cogeneration devices is critical given that these models will be widely distributed. Consequently, considerable effort was expended to verify the implementations of the models into the whole-building simulation tools and to compare model predictions with measurements.

The validation of building simulation programs is a complex and challenging field that has existed almost as long as building simulation itself. Extensive activities have been conducted under the auspices of the IEA, the American Society for Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), the European Committee for Standardization (CEN), and others to create methodologies, tests, and standards to verify the accuracy and reliability of building simulation programs. Notable examples include ANSI/ASHRAE (2004), CEN (2004), and Judkoff and Neymark (1995).

In addition to providing consistent methods for comparing predicted results by simulation programs, these initiatives have proven effective at diagnosing internal sources of errors. Judkoff et al. (1983) classify these errors in three groups:

- differences between the actual thermal transfer mechanisms taking place and the simplified model of those physical processes;
- errors or inaccuracies in the mathematical solution of the models; and
- coding errors.

Judkoff and Neymark (1995) proposed a pragmatic approach composed of three primary validation constructs to check for internal errors. These are:

- analytical verification;
- empirical validation; and
- comparative testing.

During analytical verification, the program output is compared to a well-known analytical solution for a problem that isolates a single heat transfer mechanism. Typically, this necessitates very simple boundary conditions. Although analytical verification is limited to simple cases for which analytic solutions are known, it provides an exact standard for comparison.

Program outputs are compared to monitored data during empirical validation. The measurements can be made in real buildings, controlled test cells, or a laboratory. The design and operation of experiments leading to high-quality datasets is complex and expensive, thus restricting this approach to a limited number of cases. The characterization of some of the more complex physical processes treated by building simulation programs (such as heat transfer with the ground, infiltration, indoor air motion, and convection) is often excluded due to measurement difficulties and uncertainty.

A program is compared to itself or other programs during comparative testing. This process includes both sensitivity testing and inter-model comparisons, enabling inexpensive comparisons to be made at many levels of complexity. However, in practice, the difficulties in equivalencing program inputs and outputs can lead to significant uncertainty in performing inter-model comparisons. Comparative testing also provides no absolute measurement of program accuracy; while different programs may make similar predictions, all of these predictions may be incorrect.

A general principle applies to all three validation constructs—the simpler and more controlled the test case, the easier it is to identify and diagnose sources of error. Realistic cases are suitable for testing the interactions between algorithms, but are less useful for identifying and diagnosing errors. Although comparing actual long-term energy usage of a building with simulation results is perhaps the most convincing evidence of validity from the building designer's perspective, this is actually the least conclusive approach. Because whole-building simulation requires the simultaneous operation of all possible error sources (which may produce offsetting errors), good or bad agreement with long-term measurements cannot be attributed to program validity.

A validation program following the accepted methodology outlined above was designed and executed for the Annex 42 models. Since each model was independently implemented into a number of building simulation programs, emphasis was first placed on inter-model comparative testing to identify coding errors and inaccuracies in the mathematical solution of the models. Empirical validation was then used to assess the validity of the mathematical models to simulate the performance of actual cogeneration devices. This process not only verified the mathematical model but also the accuracy of its calibration using the empirical data gathered from the validation experiments. The third validation construct, analytical validation, was not used in Annex 42 because of the complex nature of these devices and the lack of appropriate analytic solutions for the relevant thermodynamic processes.

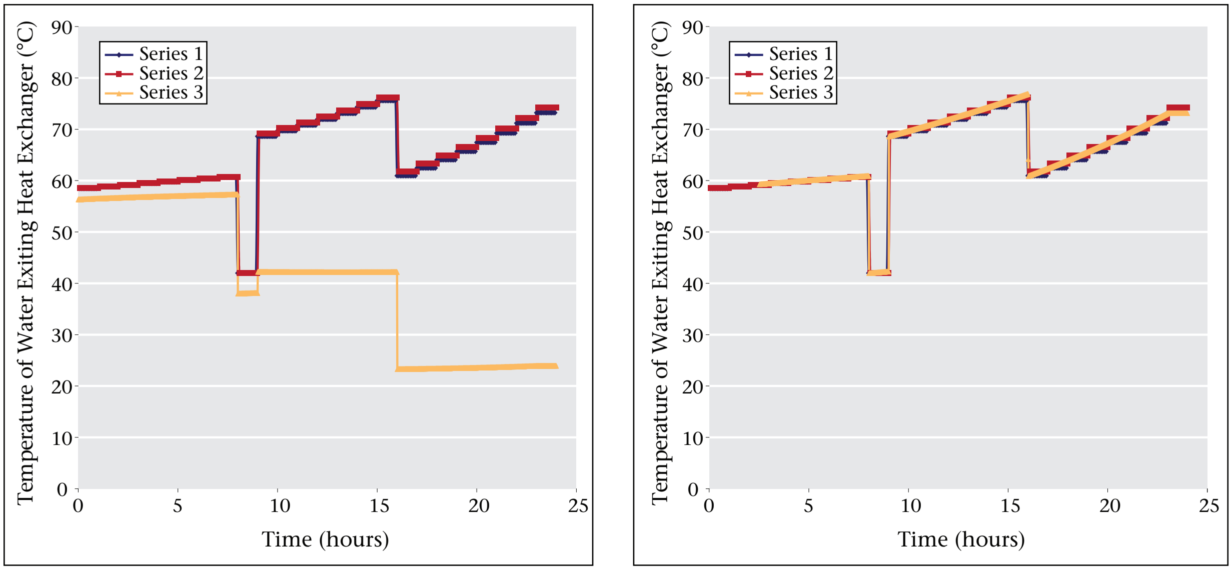
Comparative testing

Inter-model comparative test suites were devised for the Annex 42 cogeneration models. The fuel cell cogeneration model test suite comprises 50 test cases, each carefully constructed to isolate a specific aspect of the model. Similarly, 44 such cases were devised for the combustion cogeneration model. Collectively, these test cases examine every aspect of the Annex 42 models, and exercise each line of source code in their building simulation program implementations. By design, the test cases make no attempt to represent realistic cogeneration systems or operational configurations. Rather, they are designed to exercise specific aspects of the model and to exaggerate differences between implementations for the purposes of diagnosing errors.

The comparative testing program initially uncovered numerous differences between the predictions made by the various model implementations. Not all of these stemmed from source code errors (bugs); several aspects of the model specifications were misinterpreted by the implementation authors, and in some cases, the solution philosophies used in the respective simulation programs prohibited exact agreement between the various implementations. Over the course of the comparative testing program, numerous errors were identified in every one of the implementations. These errors have been corrected, and the implementations now reliably produce comparable predictions. The resulting test suites with the accompanying results from the building simulation tools are a valuable resource for others who wish to implement the Annex 42 models into other simulation platforms.

An example of a coding error that was detected and corrected through this comparative testing process is illustrated in Figure V-1. This test case isolates the heat-exchanger component of the fuel cell model, which characterizes the transfer of heat from the fuel cell's hot product gases to a cooling water stream. In this particular configuration, the heat exchanger's performance is characterized using the log mean temperature difference method. The fuel cell's electrical output was made to increase in 100 W increments over a 24-hour period, while the cooling water temperature was reduced from 50°C to 30°C

Figure V-1 Fuel cell cogeneration model: predicted heat exchanger outlet temperature with



(a) heat capacity bug

(b) heat capacity bug corrected

eight hours into the test, and again to 10°C eight hours later. The cooling water flow rate was also reduced from 0.01 kg/s to 0.0028 kg/s nine hours into the test.

The results of this test, depicted in Figure V-1(a), revealed a disagreement between the predictions of the model implementations. Subsequent examination of the source code identified a coding error in one of the tools; the heat capacity of the cooling water stream was expressed on a mass rather than molar basis (that is, J/kg K instead of J/kmol K). This error went undetected in initial testing because it manifested itself only under certain operating conditions which were encountered in this test case. Following a simple correction to the source code, the predictions from all three programs agreed well, as shown in Figure V-1(b).

Interested readers and those developers wishing to implement the Annex 42 models into other simulation platforms are referred to a comprehensive presentation of the comparative testing program, test suites, and results in sections II and III of Beausoleil-Morrison and Ferguson (2007).

Empirical validation

The Annex 42 fuel cell and combustion cogeneration models were validated using empirical data collected during the Annex's experimental testing efforts:

- The fuel cell cogeneration model was validated using data collected from an FCT SOFC unit at their facilities.
- The combustion cogeneration model was validated using data collected from a WhisperGen Stirling engine device at the CCHT.

The empirical data derived from each of these experiments were divided into two sets: a calibration dataset and a validation dataset. The calibration dataset was used exclusively to calibrate the model, while the validation dataset was used to quantify the model's accuracy. An example of how these experimental data were used to validate the Annex 42 combustion cogeneration model is provided here. Interested readers are referred to sections IV and V of Beausoleil-Morrison and Ferguson (2007), for a more complete treatment of this topic.

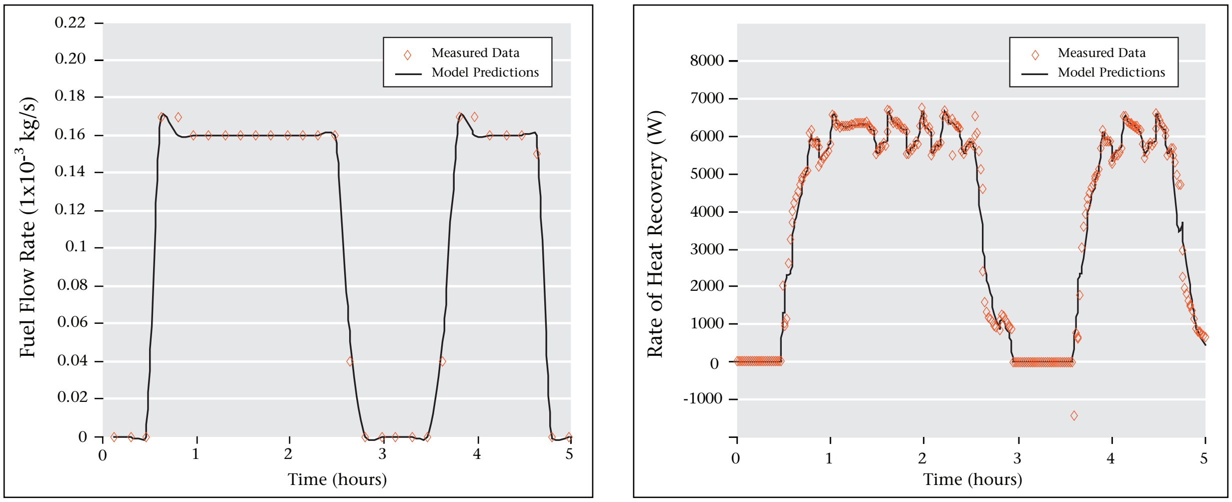
The same sources of uncertainty encountered during calibration of the combustion CHP model also burdened the validation effort. Most significantly, the 10-minute fuel flow data and the 15-minute electrical data permit validation of the combustion cogeneration model's predictions at these time scales only, and not at 5- or 1-minute intervals. But another important source of uncertainty was introduced by the method used to calibrate the model; since only a limited set of measurements were available to calibrate the model's many inputs, an optimization tool was used to select the inputs providing the best agreement with the experimental data.

While the resulting predictions accurately reflect the experimental observations, the model inputs selected by the optimization tool may not represent the WhisperGen unit's physical attributes. Indeed, if there are errors in the model's theoretical basis, the optimization tool will select input values that reduce or eliminate their effect on the model's predictions.
For this reason, empirical validation of the model using the CCHT data cannot rigorously test the model's theoretical basis. But the accuracy of the calibrated model can be quantitatively assessed with experimental data to ensure that the model can be used with confidence with the inputs derived during the calibration phase.

The combustion cogeneration model was validated by subjecting the model to the same boundary conditions (cooling water inlet temperature and flow rate; ambient temperature; and control signal) observed in the two validation datasets. The predicted fuel flow rate, rate of heat recovery and rate of electrical generation were then compared with the observations.

The model's predictions agree well with the experimental results. In both validation datas-

Figure V-2 Comparison between combustion cogeneration model predictions and measured data over a 5-hour period:



(a) fuel flow rate

(b) rate of heat recovery

ets, the estimated cumulative fuel usage differed from observations by less than 0.5%, while the estimated cumulative heat recovered differed by less than 2.4%. And the estimated cumulative electricity generation differed by less than 3.4%.

The model also demonstrated acceptable agreement with the WhisperGen data when its predictions were compared on a time-step by time-step basis. Figure V-2 plots the 10-minute averaged fuel flow rate and 1-minute averaged rate of heat recovery predicted by the model alongside the corresponding experimental results. Clearly, the model reflects the WhisperGen unit's behaviour.

Closing remarks

The Annex 42 fuel cell and combustion cogeneration models have been extensively validated through both inter-program comparative testing and comparison to empirical data. In comparative testing, participants devised comprehensive test suites that exercised every aspect of the Annex models. The EnergyPlus, ESP-r, IDA-ICE and TRNSYS implementations of the models were each exercised over these test suites, and their results compared. Over the course of this testing program, numerous errors in all of the implementations were remedied. Therefore, the participants are confident that all four simulation platforms correctly implement the Annex models.

After completion of the comparative testing, the model predictions were compared to empirical data collected for a WhisperGen SE device and an FCT SOFC device. In both cases, the separate datasets were used during the calibration and validation efforts to ensure the calibrated models were not biased towards a particular dataset. The results strongly suggest that the calibrated models accurately reflect the performance of these devices. Both the fuel cell and combustion cogeneration models demonstrated acceptable-to-excellent agreement with the experimental observations. Therefore, they can be used with confidence.

Performance Assessments of Residential Cogeneration Systems

Literature review

Annex 42 reviewed the literature on the systems analyzed in existing residential cogeneration performance assessment studies, on the methodologies and modelling techniques used, and on the assessment criteria and metrics applied. This section presents some results of the reviewed studies. The full contents of this literature review can be found in Dorer (2007).

On the level of individual buildings, many residential cogeneration 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 on factors such as heat and power demand variations, control modes, the capacity and efficiency of the residential cogeneration system, and electricity import/export conditions and modes. On the level of large-scale energy supply, residential cogeneration systems with high electric efficiencies (above 40%, LHV basis) were required to be competitive with scenarios comprising central electricity generation with natural-gas-fired combined cycle power plants (CCPP) and heat production with building-integrated and ground-coupled heat pumps.

Analyses of the combination of residential cogeneration 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 residential cogeneration system 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 load following modes showed the best energy efficiency, while electricity load following control modes reduced cost. In general, base-load control offered better energy savings compared to a peak-load oriented control.

Annex 42 performance assessment methodologies

Annex 42 developed a set of methodologies that could be consistently applied by all participants for the performance assessment studies of Subtask C. These methodologies are documented in Dorer and Weber (2007a). The report covers the general aim and purpose of such performance assessment studies, describes concepts and approaches, gives definitions and nomenclature, specifies the performance assessment criteria used, outlines the framework for the description of the system parameters and the boundary conditions, and gives guidance on the selection of standard and reference systems.

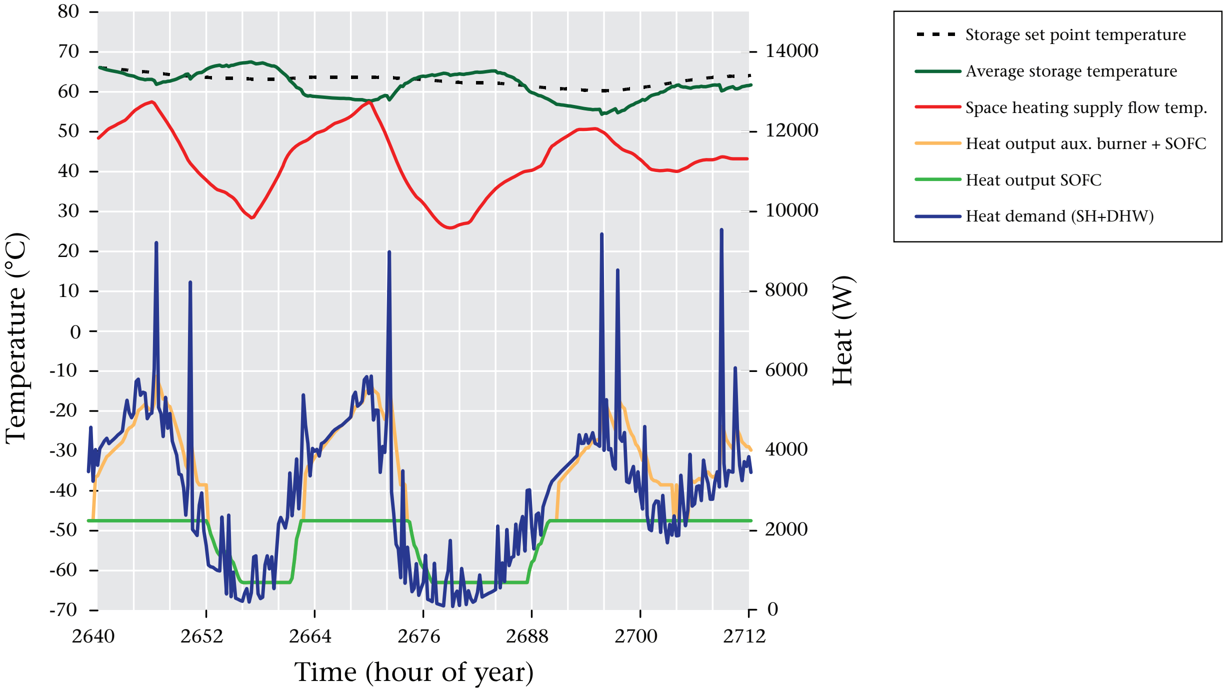
The following criteria were applied in the Annex 42 performance assessment studies:

- energy demand (delivered energies and primary energies, considering one or several generation scenarios for the grid electricity);
- energy efficiencies on different levels (cogeneration device, cogeneration system including storage, building level);
- CO_2 or GHG emissions; and
- economic factors.

Cogeneration system and building interaction

The performance of the cogeneration device depends on how it is integrated to serve the building's thermal and electrical demands.

Figure VI-1 Temporal evolution of single-family house heat demand for space heating and domestic hot water (SH+DHW), the heat outputs of the 1-kWe SOFC device and the auxiliary gas burner, and the related storage and space heating supply flow temperatures

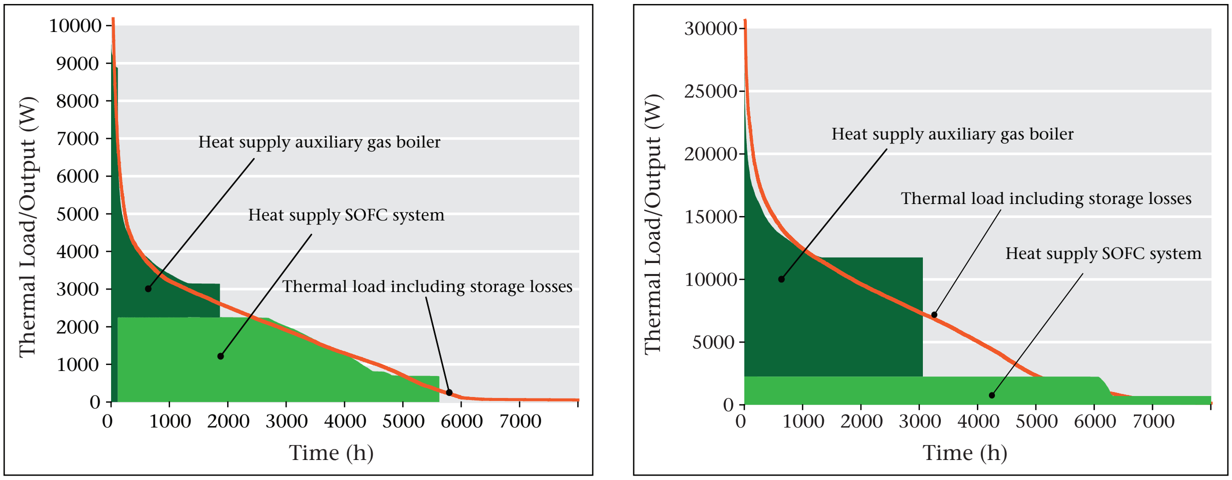


The effective utilization of the cogeneration device's thermal output for space heating and for heating DHW is crucial to realizing high levels of overall energy efficiency and the associated environmental benefits. The Annex 42 models consider this transient behaviour of the cogeneration devices, and the incorporation into whole-building simulation tools makes it possible to account for the interactions with the building and its environment, the occupants, the thermal and electrical production and distribution systems, and energy management and control systems. Results of the performance assessment studies showed that the actual temperature level of the return flow from the space heating system may have a significant impact on the system performance, and that large discrepancies may occur between the nominal efficiencies of the cogeneration device and the overall efficiency of the cogeneration system if the heat for starting up and cooling down the cogeneration device is not well recovered.

Examples of typical simulation results using the Annex 42 models are given below for buildings equipped with a 1-kWe SOFC device, thermal storage and auxiliary gas burner (Dorer and Weber, 2007b). Figure VI-1 shows the temporal evolution of building heat demand (for space heating and DHW) of a single-family house (SFH), the system heat outputs, and the related temperatures for a 3-day period. The time periods with part-load operation on the one hand, and the need for additional heat from the auxiliary burner on the other hand, both affecting system efficiency, are clearly demonstrated. Figure VI-2 shows the annual duration curves (graphs that present which part of the thermal

Figure VI-2 Annual duration curves of the thermal building load (space heating and domestic hot water) and of the heat output of the 1-kWe SOFC system, for

a) Single-Family House (SFH) b) Multi-Family House (MFH)



load plus storage losses was met by which heat source capacity for what number of hours per year) of the building heat load for space heating and DHW, and the respective curves of the heat supply of the cogeneration and the auxiliary gas burner device, both for a single-family house (SFH) and a multi-family house (MFH). The graphs in Figure VI-2 show how much the different heat sources are utilized over the year. These graphs contain valuable information on how the separate heat sources contribute to the operation of the total system, and therefore, to its overall efficiency.

Performance assessment studies

Basically, Annex 42 did not plan to carry out exhaustive performance assessments, but rather to develop the models (and methodologies) as a basis for such assessments. Nevertheless, 5 performance assessment studies were made on the application of residential cogeneration systems with prototype and commercially available cogeneration devices. Whole-building simulation programs (ESP-r and TRNSYS) incorporating the models described in Section III, and applying the calibration parameters described in Section IV and the electrical and DHW load profiles presented in Section II were used in some of these studies. In some cases, hypothetical cogeneration systems were simulated. It is felt that these studies realistically forecast the energy and emission reduction and efficiency improvements of these systems in comparison to reference systems consisting of traditional or best available technologies. Three studies fully applied the performance assessment methodology referred to above, while the fourth study (Germany) extrapolated results from extensive experimental tests, and the fifth study (Italy 2) is based on test results and a simplified modelling approach. Tables VI-1 and VI-2 give an overview of the buildings and systems analyzed, and the modelling approaches applied. The studies are then individually summarized below, followed by a discussion of the results. Each of the performance assessment studies listed is documented in detail in separate reports contained on the accompanying CD and is available from the IEA/ECBCS website (www.ecbcs.org).

Table VI-1 Overview of the performance assessment studies conducted: buildings, cogeneration technologies and reference systems

Study	Building Load Profiles	Systems	Reference Heating Systems	Reference Electricity Grid
Canada	SFH detached	SOFC and SE	Condensing furnace and high-efficiency water heater	On-the-margin mix according to several Canadian provinces, CCPP
Switzerland	SFH, MFH; 3 energy levels	SOFC, PEMFC, SE, ICE	Condensing gas boiler, ground-coupled heat pump	European mix, Swiss mix, CCPP
Germany	10- & 20-apartment MFH	PEMFC, SE, ICE	Non-condensing and condensing boiler	Average German mix, mix replaced by CHP, CCPP
Italy 1	Italian average and new MFH;	ICE	Non-condensing and condensing boiler	European mix
Italy 2	MFH of variable sizes	ICE	Non-condensing and condensing boiler	Italian mix, CCPP

Table VI-2 Overview of the performance assessment studies conducted: load profiles and modelling approaches

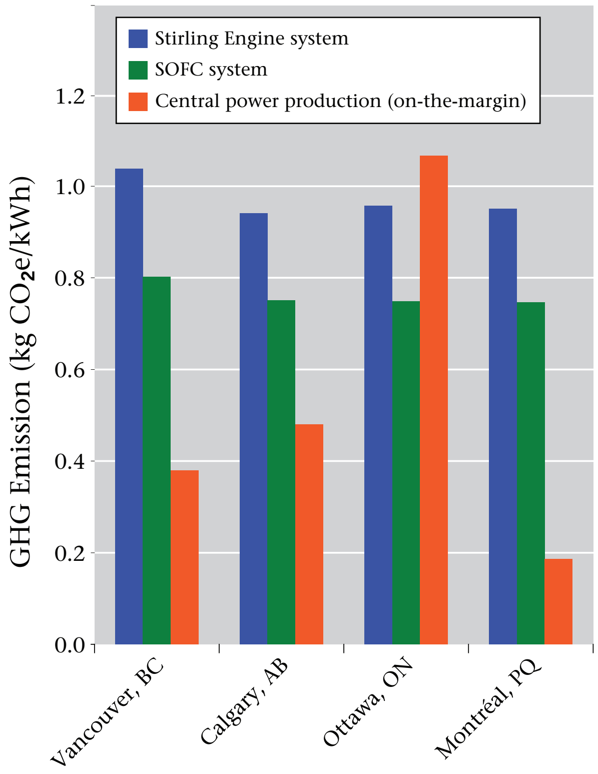
Study	Load Profiles Electric/DHW	Modelling (Simulation Tool)
Canada	Annex 42 Canadian profiles	Annex 42 models (ESP-r) with Annex 42 calibrated input data
Switzerland	Annex 42 European profiles	Annex 42 models (TRNSYS) with Annex 42 calibrated input data and with assumed input data; and performance map models based on test data and manufacturers' data.
Germany	German load profiles Similar to tests	Extrapolation of measured results to annual energies and emissions (Matlab)
Italy 1	Electric: Italian profile DHW: Annex 42 profiles	Annex 42 model (TRNSYS) with input data partially calibrated with test data
Italy 2	Measured load profiles similar to tests	Simplified modelling (spreadsheet tool based)

Canadian study

This study examined the performance of prototype SE and SOFC devices in single-family detached houses in Canada (Ribberink et al. 2007). The objectives of this study were to realistically forecast the GHG emission reduction and efficiency improvement of these prototype systems in comparison to a reference system consisting of a condensing furnace, a high-efficiency water heater, and on-the-margin grid electricity.

The results of this analysis show that the GHG emission reduction potential is mainly determined by the displaced emissions of grid electricity (Figure VI-3). Application in Ontario of the prototype SOFC system, which has a

Figure VI-3 Greenhouse gas emission factors for electricity



relatively high electricity production, would substantially reduce the GHG emissions of the house, despite a very low net cogeneration system efficiency (conversion of fuel to net AC power + useful heat, higher heating value or HHV basis) of 37%. The prototype SE system has a higher system efficiency but low electrical power output and negligible GHG emission reduction when applied in heat load following operation in Ontario. The prototype cogeneration devices in this study would cause GHG emissions to increase when applied in Quebec, Alberta, and British Columbia.

SE systems operated in heat load following mode consume between 5% and 10% more natural gas than the reference system (assuming grid power from a natural-gas-fired CCPP), a difference that may already be bridged by relatively easy measures like reducing heat storage losses (more and/or better insulation) and balance of plant power consumption (using high-efficiency DC-motor pumps). The SOFC, which was operated continuously with a three-month summer stop, needs 50% to 150% more natural gas input compared to the same reference system, partly due to the necessity to dump excess heat. Improvements to both SE and SOFC prototype systems are possible that will allow the systems to reduce the primary energy input to the house and have substantial GHG emission reductions.

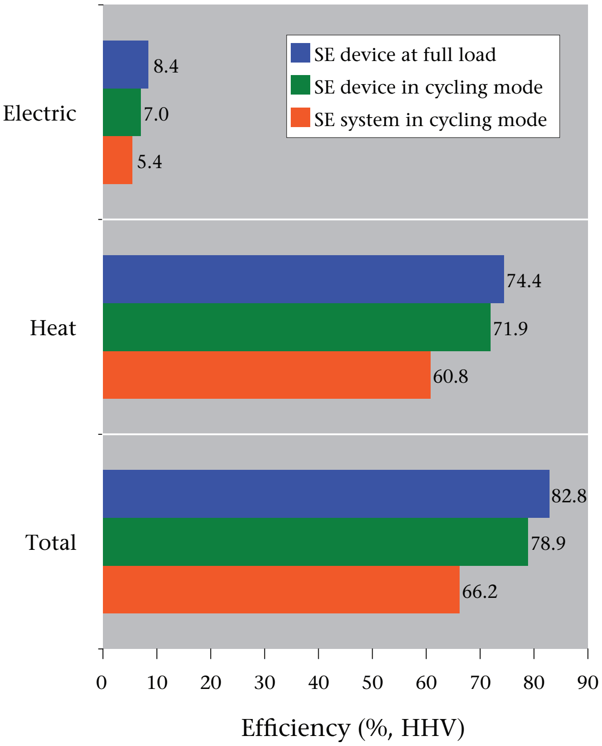
This study also demonstrated the importance of using detailed models of the residential cogeneration systems. The efficiencies of the prototype SE system (consisting of an SE device, a heat storage device, and an auxiliary burner) under real operating conditions were considerably lower than those of the SE device alone when operating at full load. This is due to losses associated with the start-up and shut-down cycles of the SE device as well as thermal losses from the heat storage (see Figure VI-4).

The current study has focused on the measured performance of prototype residential cogeneration systems. These prototypes

- had efficiencies well below those expected for mature technology;
- had unsophisticated operating strategies that could be vastly improved (SOFC); and
- had inappropriate electrical capacities (SE was too small, SOFC too large).

The results of this study provide a “snapshot” of the development of residential cogeneration systems based on the performance of early prototypes, which is certainly not representative of the potential of these technologies. The report

Figure VI-4 Efficiencies of prototype Stirling engine residential cogeneration device and system for various operating modes



contains valuable information for designers of residential cogeneration systems regarding the optimization of their systems, but should not be used to form an opinion on the potential impact of these technologies. Further investigation into the future potential of residential cogeneration technologies in Canada is necessary and recommended.

Swiss study

This study examined a number of residential cogeneration systems in residential buildings in Switzerland (Dorer and Weber 2007b). The performance in terms of NRPE demand and of CO_2-eq emissions was analyzed for different cogeneration technologies, and compared to the reference system with gas boiler and electricity supply from the grid. An earth-coupled heat pump system was also analyzed for comparison. The cogeneration devices were integrated into SFHs and MFHs of different energy standards: Swiss average, the target values of which are in the present building code of the Swiss Engineers and Architects Association (SIA target); and the low-energy Passive House (PH) standard. Standard DHW and electric demand profiles specified within Annex 42 (Knight et al. 2007) were used. Three different electricity generation mixes were considered (European, Swiss, and CCPP). The simulations were made for one Swiss geographic location (Basle) using the whole-building simulation program TRNSYS.

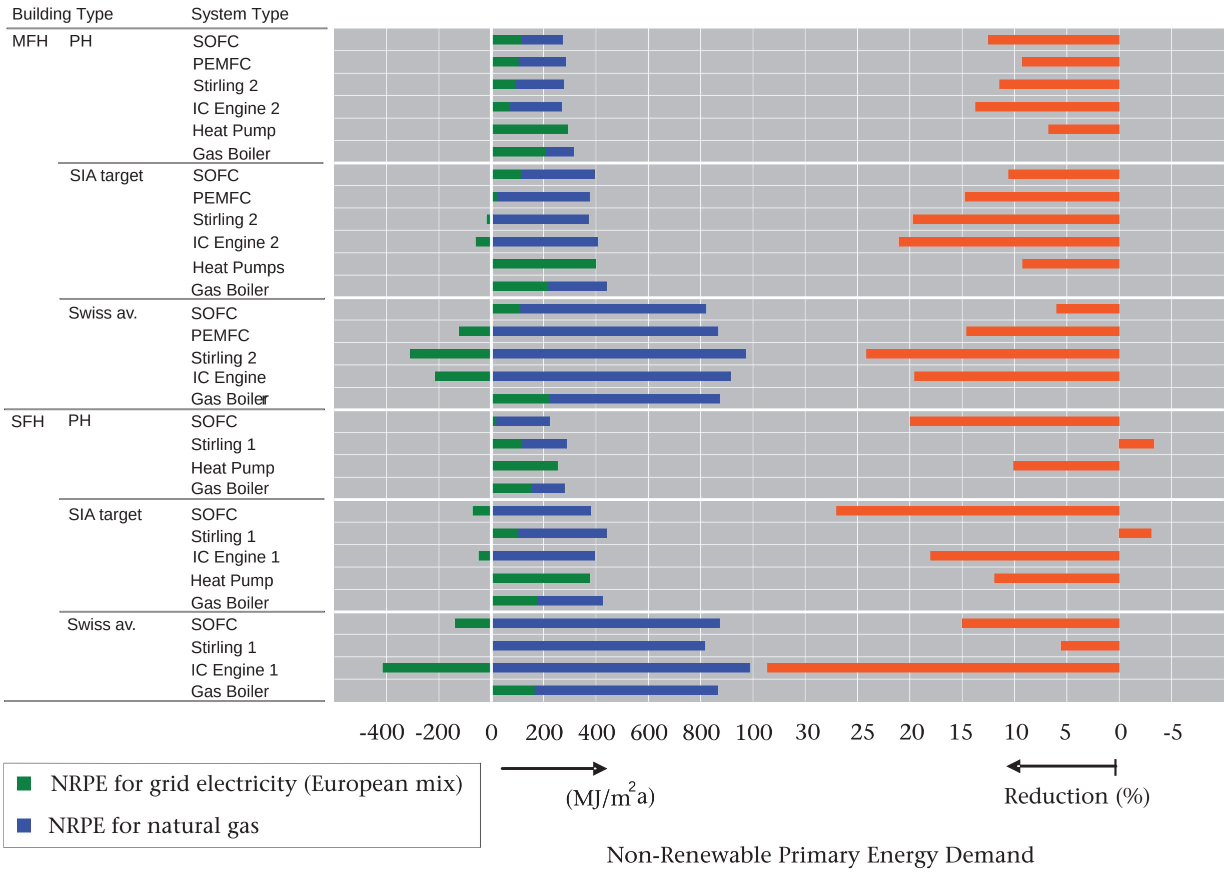
For the cogeneration systems, the detailed dynamic component models and calibration data described in sections III and IV were used in cases where enough detailed performance data regarding the residential cogeneration device were available. For the other cases, simplified performance map models had to be employed, partially calibrated with results from laboratory experiments conducted within Annex 42 (Beausoleil-Morrison, ed. 2007), with manufacturers' data, or with assumed performance data. Thus, for the latter cases, the dynamic effects of start-up and shutdown were not considered. The cogeneration devices considered included the following: (1) a natural-gas-fuelled SOFC (Annex 42 model with assumed performance data); (2) a PEMFC (performance map model with measured data from stationary laboratory tests); (3) two different SEs (Annex 42 model with calibrated data and performance map model with manufacturer's data, respectively); and (4) two different internal combustion (IC) engines (calibrated Annex 42 model and performance map model with measured data, respectively).

Concerning NRPE demand for the European electricity mix, most residential cogeneration systems offered reductions of up to 33% compared to the reference system (Figure VI-5). For the Swiss and the CCPP electricity generation mixes (not shown in Figure VI-5), the ground-coupled heat pump systems resulted in the largest NRPE reductions (up to 29%). The maximum reduction with a cogeneration system was 14%.

With regard to emissions in terms of CO_2-eq, most cogeneration systems offered reductions for the European electricity mix (up to 23%). However, maximum reductions resulted for the heat pump system (24%). For the Swiss mix, only the heat pump system led to emission reductions; all the residential cogeneration systems resulted in higher emissions. For the CCPP mix, maximum reductions resulted again by far with the heat pump systems (up to 29%). The maximum reduction with a cogeneration system was achieved with the SOFC system in the SFH (12%).

For one type of MFH building, the size of the SOFC and PEMFC devices were varied by scaling

Figure VI-5 Annual non-renewable primary energy (NRPE) demand (MJ/m².a) (for natural gas and for grid electricity) of the basic building and system types analyzed, and reductions of NRPE demand (%), compared to the "condensing gas boiler/ electricity from grid" reference system (European grid electricity mix):

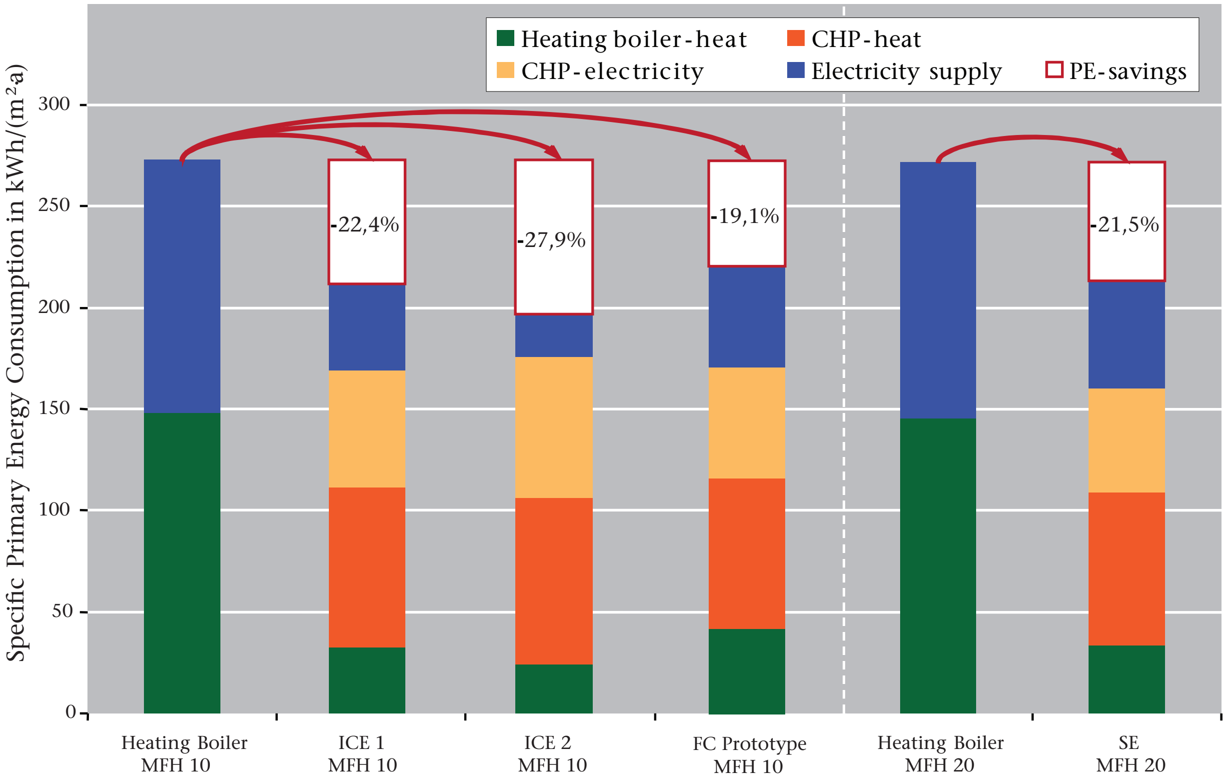


the performance characteristics of the original fuel cell device up and down, and the cases were analyzed in terms of annual NRPE demand. The optimal ratio of thermal output of the fuel cell device to building heat demand was dependant on the electricity mix and the characteristics of the electric efficiency curve of the fuel cell device. The results show that for minimizing overall NRPE demand, the annual heat output of the device should be dimensioned to about 80% to 90% of the annual building heat demand. In general, the size of thermal storage had little influence on the NRPE demand.

German study

The aim of the research project “Innovative residential cogeneration systems for energy supply in houses” was to analyze whether residential cogeneration systems are a reasonable (in terms of energy and emissions) and economically viable option for the energy supply of residential buildings in Germany. First, experimental measurements were conducted in the laboratory of the Institute for Energy Economy and Application Technology of the Technical University of Munich, including the following residential cogeneration devices: a 4.7-kWe modulating ICE device (ICE 1), a 5.0-kWe ICE device (ICE 2), a modulating 9.5-kWe Stirling device (SE) (all commercially available); and a prototype 4.6-kWe polymer electrolyte membrane fuel cell device (FC Prototype or PEMFC). Typical daily profiles of the demand for space heating and DHW preparation were used for the experiments of these systems

Figure VI-6 Specific primary energy consumption of the energy supply of the reference system and the residential cogeneration (CHP) systems (combination “Average building stock heating system, German electricity grid”)



on a dynamic test apparatus. Second, daily energy balances of the CHP systems were determined from these tests by considering typical daily profiles and characteristics of the heating period. Third, a projection from these daily values to annual values was done, and the energetic quality was expressed by characteristic parameters. The essential results of the tested CHP systems and their comparisons can be found in Mühlbacher and Geiger (2007). The results formed the data basis for a comparison of systems and profitability analysis (Arndt et al. 2007). Two building loads were considered: a 10-apartment multi-amily house (MFH10) for the ICE and the PEMFC devices, and a 20-apartment building (MFH20) for the SE device.

In the first part of the system comparison, primary energy and emissions comparisons were made for a number of combinations in terms of heat and grid electricity supply: heat supply according to (i) the heating technology used in the current German building stock and (ii) the best available technology (condensing gas boiler); grid electricity according to (i) the fuel mix of central power production that is substituted by residential cogeneration, (ii) the average German mix, and (iii) the best available technology (CCPP). In the second part of the system comparison, in order to allow a cross-comparison of the residential cogeneration systems, the results were adjusted to cogeneration devices with an equal thermal power rating, thus eliminating the influence of differences in thermal power capacities. Additionally, a profitability analysis was performed.

Figure VI-6 shows the specific primary energy consumption of the cogeneration systems analyzed (assuming the German electricity mix), and the comparison to the reference system “stock” (average building stock heating system, German electricity grid). Figure VI-7 shows the corresponding CO_2 emissions. Compared to the conventional reference systems, reductions from 19.1% to 27.9 % in primary energy consumption and from 21.8% to 31.3 % in CO_2 emissions are possible using the tested cogeneration devices. Even compared to the reference system with the “best available technology,” the primary energy consumptions were reduced by 5.2% to 12.7% and CO_2 emissions by 5.9% to 13.5 % (not shown).

The system comparison confirmed that implementing residential cogeneration, in comparison to separate generation of electricity and heat, can reduce the primary energy demand and CO_2 emissions. The profitability analyses, based on current economic conditions in Germany, indicated that the electricity generated by the residential cogeneration system should be used as far as possible within the building itself, based on current general conditions.

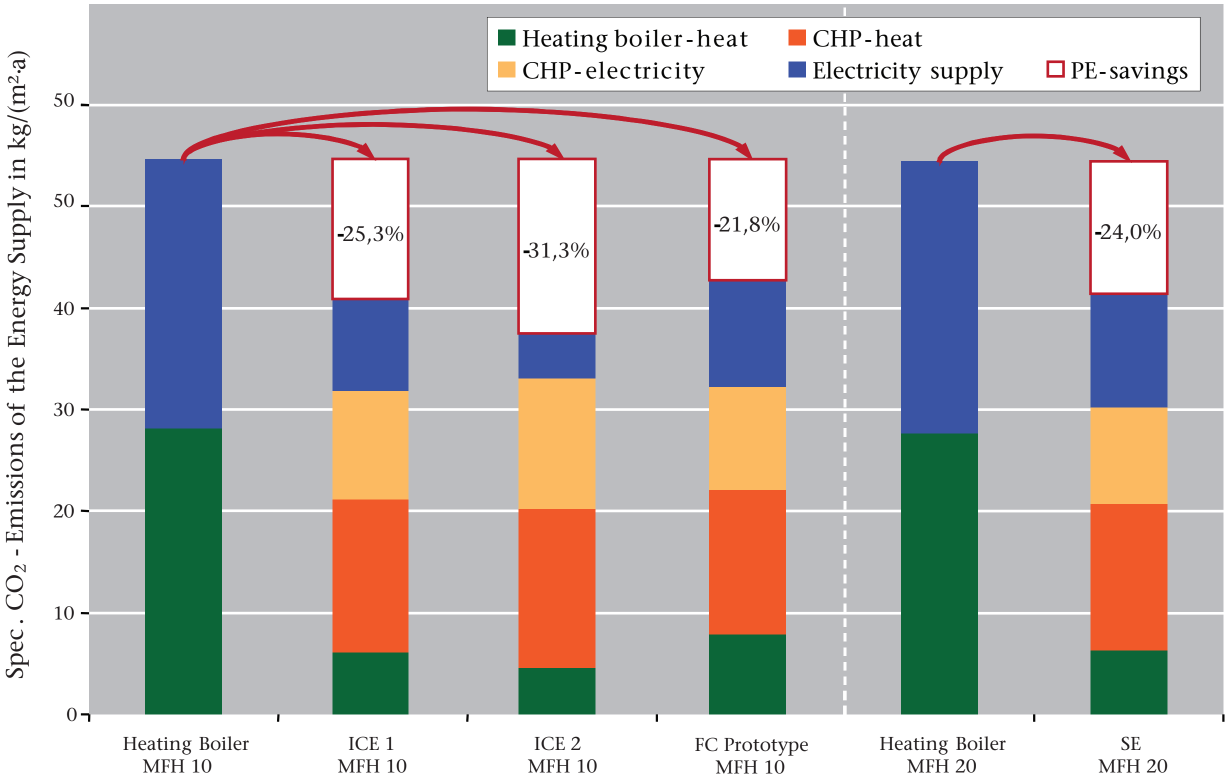
Using detailed simulations (based on the Matlab model), analyses were conducted of the dynamical processes concerning the interaction of individual elements of the cogeneration systems, and the reaction of the cogeneration systems on heating, DHW and electrical loads.

Experimental tests of additional cogeneration devices could strengthen the results of this study, as smaller residential cogeneration systems have entered the market in the meantime. Further research and optimization work should focus on cogeneration control.

First Italian study

The aim of this study (Di Pietra 2007) was the energy, environmental and economic performance assessment of an ICE residential cogeneration device for average social multi-family houses representative of the Italian building stock (built between 1976 and 1985). Four Italian climatic zones were considered. The results

Figure VI-7 Specific CO$_2$ emissions of the energy supply of the reference system and the residential cogeneration (CHP) systems (combination "Average building stock heating system, German electricity grid")

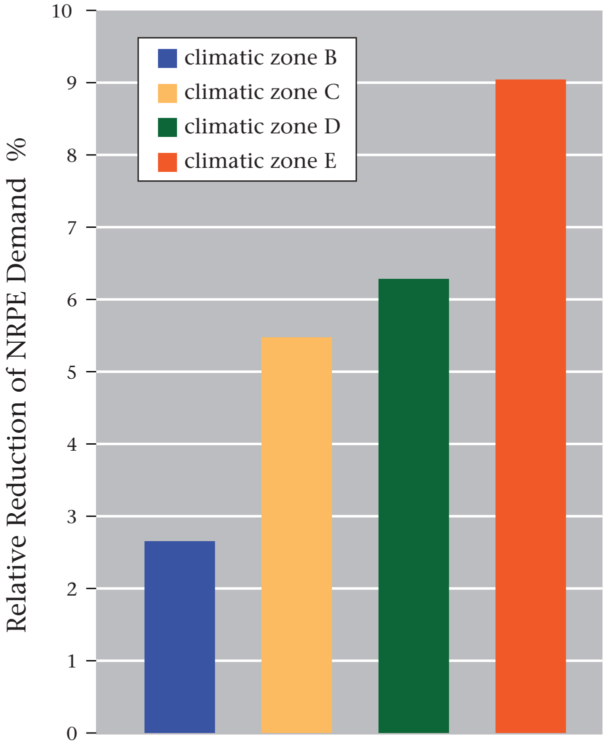


were compared to traditional energy supply systems for residential buildings (standard gas boiler). The TRNSYS program was used to simulate building-integrated generation systems, and the amounts of primary, thermal and electric energy delivered to the building were determined. The internal combustion engine was modelled using the Annex 42 model, developed and partially calibrated with commercially available residential cogeneration devices.

Electricity demand load profiles for a typical multi-family house and occupant types were considered in regard to the geographic allocation of each simulated building. The DHW profiles for the multi-family houses simulated have been produced directly using IEA SHC Task 26 profiles. European electricity generation mixes were considered.

Figure VI-8 shows results for NRPE savings for the different climate zones. The percentage reductions of CO$_2$ emissions and NRPE demand were higher in cold climates (climate zone E, Biella) than in warmer areas (climate zone B, Palermo). Nevertheless, the primary energy saving (PES) index was almost constant at around 20%. The electricity costs with cogeneration plant were lower in colder areas, where the system operates longer during the heating period, thus generating more electric energy, reducing delivered grid electricity and increasing exported electricity to the grid. Unitary thermal cost for space heating and DHW of the cogeneration system were almost equal in each climatic zone.

Figure VI-8 Reductions of NRPE demand (%) for the ICE residential cogeneration system, compared to the “standard gas boiler/electricity from grid” reference system (European grid electricity mix)



New buildings showed a substantially different performance in terms of NRPE reduction in warmer areas. Residential cogeneration systems lead to higher primary energy reduction in the social buildings with a high energy demand level than in the new buildings with a lower energy demand level.

Second Italian study

The aim of this study (Sasso et al. 2007) was to analyze the energetic, economic and environmental implications related to the use of residential cogeneration (≤ 15 kWe). The potential PES and the environmental benefits of small-scale, on-site energy conversion devices were analyzed for a number of dwellings, operating modes and electricity grid reference systems, assuming electrical loads from 0 to 10 kW, and thermal loads from 0 to 30 kW. As the aim was to evaluate only the most important parameters affecting cogeneration in the residential sector, a simplified spreadsheet-based tool was developed which did not include the Annex 42 models, but was based on measured performance and load data.

To test small residential cogeneration devices in actual operating conditions, a test facility has been built with some residential appliances, such as a dishwasher, washing machine, and water heaters, that are used both in their traditional configuration (electricity-driven) and in more efficient configurations (thermal- and electricity-driven). Detailed investigations were performed on ICE residential cogeneration devices (1.67, 3 and 6 kWe), one of which is available on the Japanese and European markets. Furthermore, a trigeneration system has been tested, consisting of a residential cogeneration device driving an electric air-to-water vapor compression heat pump and providing 4 kWe, 12.5 kWth in heating and 6 kWth in cooling.

The study showed that, with some limitations, cogeneration is promising for powering both domestic appliances and whole building loads. To supply the energy demand related to a cycle of the dishwasher, a cycle of the washing machine and the production of 80 litres of hot water at 60°C, the cogeneration system obtained a PES factor of 51.7% with respect to the Italian electricity generation mix, and of 36.2% with respect to the best available technology (CCPP). The respective values for the CO_2 emission reduction were 64.4% (Italian mix) and 38.1% (CCPP).

For a simple pay-back period (SPB) of less than 5 years, 8 dwellings constituted the minimum building size for the application of a 6-kWe residential cogeneration device in the south of Italy (Figure VI-9). The operating strategy had little influence on the SPB in buildings with 8 or more dwellings, but influenced energy savings when deployed in such a building (Figure VI-10). The equivalent CO_2 emissions reduction was not influenced by the operating strategy, and the related increase with the number of dwellings is negligible (not shown).

Discussion

A plurality of factors influence the performance of the residential cogeneration systems analyzed. Many of the cases investigated demonstrated the potential for primary energy savings compared to traditional energy supply technologies. However, all studies showed that the potential for reductions in primary energy consumption and greenhouse gas emissions is mainly determined by the primary energy and emission rates of the grid electricity displaced by cogeneration. Energy and emission savings can also be achieved in comparison to electricity generation by a CCHP; however, earth-coupled heat pump systems are superior in such cases. Results repeatedly showed that the low electric efficiency and low thermal efficiency (e.g., due to a non-condensing heat exchanger) of the cogeneration device may lead to increased energy consumption and emissions in comparison to traditional systems with condensing gas boiler and grid electricity.

The availability of detailed models and simulation tools in the field of building-integrated cogeneration has provided valuable informa-

Figure VI-9 SPB period for varying number of dwellings

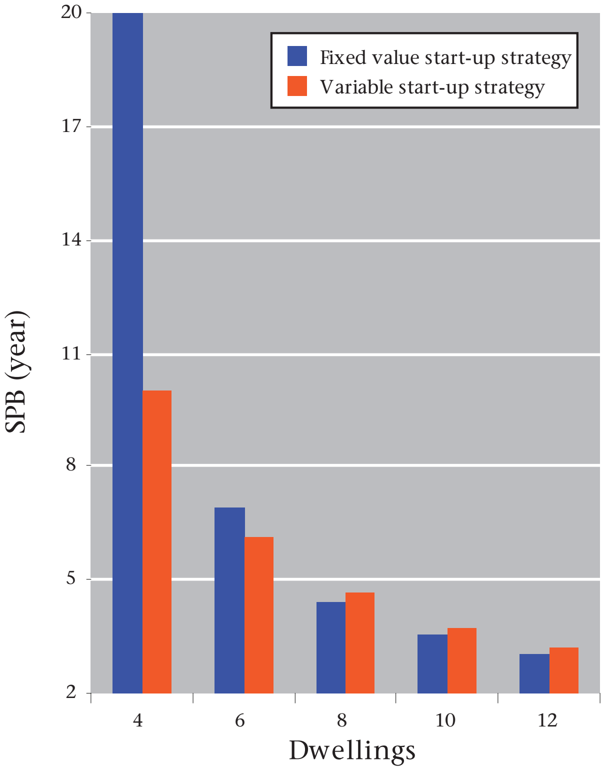
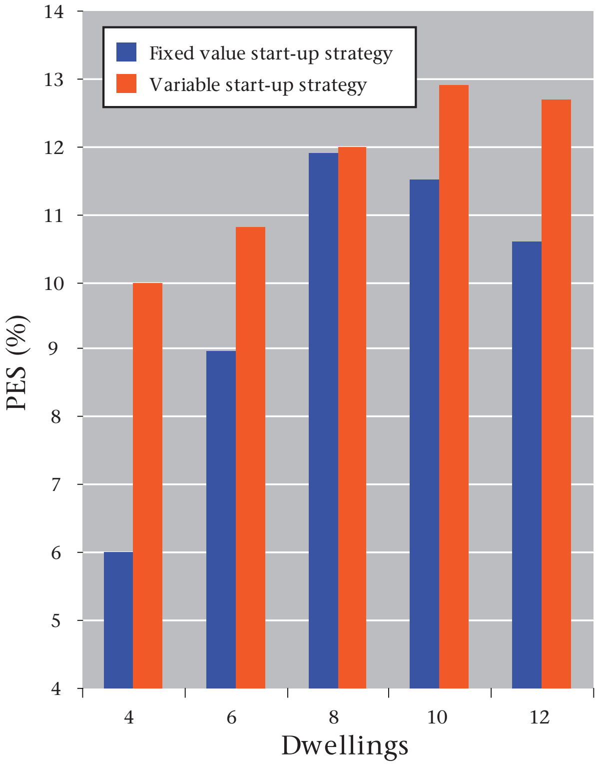


Figure VI-10 Annual PES index as a function of number of dwellings



tion on the performance and operation of such systems. The importance of performing detailed simulations with small time steps was demonstrated, showing in certain cases significant reductions of electric and thermal system efficiencies compared to the nominal (full-load) efficiencies of the cogeneration device. Therefore, system efficiencies must be determined by considering in detail the load-supply interaction and the influence of heat storage and system control. In the studies presented, this has been done by applying the Annex 42 models, or by considering measured data from integrated laboratory tests comprising the cogeneration system and the building and appliance load side.

Many studies have focused on the performance assessment of typical prototype and commercially available residential cogeneration systems. Therefore, the results provide only a present-day picture of the development of residential cogeneration systems and do not reflect the full potential of the technologies. Notwithstanding, many cases showed that prototype technologies can provide positive results in terms of the performance assessment methodology applied. The studies also identified where, how and why systems can be improved, which is invaluable for future technology development.

Summary, Conclusions and Recommendations

Summary

Annex 42 was established in 2003 to develop precise and non-proprietary tools and information for evaluating the performance of small-scale cogeneration devices for residential buildings. The rigorous evaluation of primary energy savings and GHG emission reductions relative to conventional technologies was desired because previous analyses were based on simplified performance map approaches that decoupled the performance of the cogeneration unit from that of the building and were often conducted at coarse temporal resolutions.

Annex 42 successfully developed a model with sufficient precision and resolution for simulating SOFC and PEMFC cogeneration devices within the context of whole-building simulation programs. The model contains discrete control volumes and input parameters that can be adjusted to simulate a variety of particular devices. A similar model, without subsystem characterization, was developed and verified for SE and ICE cogeneration devices.

Annex 42 worked with numerous manufacturers to obtain data for model development and evaluation (13 devices were tested in 6 participating countries). Experimental investigations of at least one prototype or early-market example of the four technologies (SOFC, PEMFC, SE, ICE) were accomplished. These experimental investigations revealed electrical and thermal performance of current devices that was below expectations, and start-up and shutdown operating characteristics that can significantly impact overall performance.

Instances of Annex 42 models were independently implemented into source code for four widely used building simulation tools (ESP-r, EnergyPlus, TRNSYS, and IDA-ICE). Extensive efforts were made to apply widely accepted comparative testing techniques to verify the independent implementations of the models. Furthermore, some of the measured data gathered by Annex 42 were used to empirically validate the models. As a result, it can be stated with a high degree of confidence that the Annex 42 models can accurately represent the performance of residential cogeneration devices when properly calibrated.

Evaluating the performance of cogeneration devices serving residential buildings requires both accurate models and accurate, temporally resolved, discretionary occupant-driven electricity and DHW consumption profiles. Annex 42 successfully acquired extensive end-use profile data and information by examining existing measured datasets and models, developing and using a synthetic electric load profile generator, and making detailed measurements. The results of this effort include representative usage profiles for non-HVAC electricity and DHW that are suitable for Europe and Canada.

The new models—calibrated using the experimental data—along with the new non-HVAC electrical and DHW usage profiles were exercised in the building simulation tools to assess the performance of specific prototype, early-market, and in some cases, hypothetical cogeneration devices and applications. The GHG emissions and primary energy consumption of the small-scale cogeneration devices were compared to the GHG emissions and primary energy consumption that would be associated with servicing the houses with electricity from the central grid and with natural gas boilers and furnaces in four countries for a wide range of conditions: climate, house thermal characteristics, occupant behaviour, integration with HVAC, control strategies, etc.

Conclusions

The major conclusions of this four-year, multinational study are as follows:

- The accurate assessment of small cogeneration devices requires precise models of the type produced by Annex 42 to predict electrical and thermal performance with sufficient temporal resolution and accuracy. This includes the consideration of the start-up and shutdown cycles, off-design performance, and the explicit coupling with building HVAC systems.
- The assessment of particular small cogeneration devices should be accompanied by a detailed set of performance measurements for calibration of the models, which can be subsequently used to assess performance for a range of operating conditions and circumstances.
- A detailed understanding of discretionary, occupant-driven electrical and DHW usage profiles with sufficient resolution for use in a whole-building simulation are required for accurate performance evaluations.
- Residential-scale profiles must be garnered with higher temporal resolution than that used for larger systems (e.g., utility grid, industrial site, commercial building) due to the relatively high magnitude of temporal variations and relatively non-coincidence of electrical and thermal loads.
- The basis of comparison for small-scale cogeneration devices must be well-defined and should consider: (1) current local marginal electricity generation, transmission and distribution technology, and/or (2) advanced technology likely to be installed in the future local electrical grid; (3) current DHW boiler technology, and/or (4) advanced DHW boiler technology likely to be used in the future; (5) current space heating technology, and/or (6) advanced space heating technology likely to be used in the future. Detailed, temporally resolved emissions and efficiency performance should be well documented for all options.
- Current prototype and early-market, small-scale SOFC, PEMFC, SE, and ICE cogeneration devices have steady-state electrical conversion efficiencies in the range of 9% to 28% (net AC power relative to the lower heating value of natural gas). Overall (electrical plus thermal) energy conversion efficiencies range from 55% to as high as 100% (lower heating value basis) for some devices. These efficiencies do not consider the power draws of ancillary components that are required to couple the thermal output of the cogeneration devices with the building's HVAC and/or DHW system.
- Despite the lacklustre performance of some current prototype and early-market cogeneration devices, the current detailed analyses for the building cases analyzed show that when coupled to HVAC and DHW systems, the devices can reduce primary energy consumption by up to 33% and GHG emissions by up to 23% relative to conventional heating technologies (condensing boilers, furnaces, DHW heaters) and grid electricity in Europe. In one region of Canada, GHG emission reductions of up to 22% can be achieved, despite higher primary energy consumption.
- When specifically compared with grid electricity where hydroelectric and nuclear power generation form a significant portion of the grid mix (e.g., Swiss grid), some of the cogeneration cases analyzed lead to reduced primary energy consumption of 1% to 14%, while others show an increase of up to 9%. However, all cases lead to increased GHG emissions of 5% to 43%.

- Although one current prototype SOFC cogeneration device leads to a 22% reduction in GHG emissions in one region of Canada, current prototype SOFC and SE cogeneration devices lead to increased GHG emissions in three other Canadian regions that have high hydroelectric power generation.
- When compared with grid electricity provided by a natural-gas-fired combined cycle power plant, current prototype SOFC and SE cogeneration devices lead to increased energy consumption in Canada.
- Cogeneration devices with low electrical conversion efficiencies must have very high thermal conversion efficiencies (i.e., they must recover energy through condensing the water vapour in the exhaust gases) to compare favourably with conventional (condensing) heating technologies and grid electricity. Also high-efficient technologies should be applied for balance of plant equipment (for instance, pumps) to minimize the internal power consumption of residential cogeneration systems.
- Another crucial issue in terms of overall annual system energy efficiency is the appropriate sizing of the residential cogeneration device. Preliminary analysis indicates that for maximum efficiency and GHG emission reduction, the annual heat output of the cogeneration device should be in the range of 80% to 90% of the annual building heat demand (the remainder being supplied by a back-up heating device). The ratio is dependant on the grid mix and on the characteristics of the electric efficiency curve of the cogeneration device. If the optimum electrical efficiency of the cogeneration devices is at part load, a larger device, operating longer times at part load, might be favourable.

Recommendations

Annex 42 has contributed to the performance assessment and the understanding of residential cogeneration technologies and has produced new data and tools that can be applied by researchers, manufacturers, energy utilities, and governments to further assess and guide the development of these emerging technologies. However, much research remains to improve performance analyses and the residential cogeneration technologies themselves in order to reach the full potential benefits offered by residential cogeneration. Recommendations emanating from the work of Annex 42 include the following:

- As manufacturers continue to refine their designs, the Annex 42 models should be calibrated for the next generation of cogeneration devices.
- The models should be further exercised to establish optimal configurations and control strategies for the balance of the HVAC plant and to provide guidance on the sizing of cogeneration devices and other components (e.g., thermal storage capacities).
- Work should be extended to examine novel applications of cogeneration, such as the integration with solar thermal and solar electric devices and the adaptation of cogeneration systems for biofuels.
- Further model development is warranted to improve critical aspects of the model, such as the start-up and shutdown phases of SE and ICE systems.
- Further model development to include additional governing physics and chemistry to improve understanding and enable the more accurate modelling of systems is desired.
- Future work should examine the use of thermal output from cogeneration devices to drive thermally activated cooling systems.

- Alternative electrical and thermal storage strategies should be examined to exploit the energy produced by cogeneration devices more fully.
- The work of Annex 42 should be extended to examine cogeneration devices serving the electrical and thermal demands of small communities or clusters of houses, larger buildings, and non-residential applications.
- Study of the impact of exporting power over low-voltage networks is also warranted.
- Further experimental work is recommended to gather more representative data for discretionary, occupant-driven electrical and DHW usage profiles, including providing data for additional countries and projecting demands in the future in response to technology improvements (e.g., lighting and appliances).
- The technical models, techniques, and understanding of Annex 42 should be applied to investigate significant socio-economic, policy, and commercialization issues that might affect adoption and market penetration of the technologies in various countries under various scenarios.

References

References indicated with an asterisk (*) are available on the CD that accompanies the printed version of this report and from the ECBCS website at www.ecbcs.org/annexes/annex42.htm.

Abernethy R.B., Benedict R.P., Dowdell R.B. (1985). ASME Measurement Uncertainty. Journal of Fluids Engineering, 107:161–164.

ANSI/ASHRAE (2004). Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. Standard 140-2004, Atlanta, USA.

Arndt U., Mauch W., Mühlbacher H., Tzscheutschler P., Geiger B. (2007). Performance of Residential Cogeneration Systems in Germany. IEA/ECBCS Annex 42 Report. *

Beausoleil-Morrison I. [ed] (2007). Experimental Investigation of Residential Cogeneration Devices and Calibration of Annex 42 Models. IEA/ECBCS Annex 42 Report. *

Beausoleil-Morrison I., Ferguson A. [ed] (2007). Inter-model Comparative Testing and Empirical Validation of Annex 42 Models for Residential Cogeneration Devices. IEA/ECBCS Annex 42 Report. *

CEN (2004). prEN ISO 13791: Thermal Performance of Buildings Calculation of Internal Temperatures of a Room in Summer without Mechanical Cooling—General Criteria and Validation Procedures. ISO/FDIS 13791:2004, Brussels, Belgium.

Clarke J. A. (2001). Energy Simulation in Building Design. Butterworth Heineman, 2nd Edition.

Di Pietra B. (2007). Performance Assessment of Residential Cogeneration Systems in Different Italian Climatic Zones. IEA/ECBCS Annex 42 Report. *

Dorer V. (2007). Review of Existing Residential Cogeneration Systems Performance Assessments and Evaluations. IEA/ECBCS Annex 42 Report. *

Dorer V., Weber A. (2007a). Methodology for the Performance Assessment of Residential Cogeneration Systems. IEA/ECBCS Annex 42 Report. *

Dorer V., Weber A. (2007b). Performance Assessment of Residential Cogeneration Systems in Switzerland. IEA/ECBCS Annex 42 Report. *

Dorer V., Weber R., Weber A. (2005). Performance Assessment of Fuel Cell Micro-Cogeneration Systems for Residential Buildings. Energy and Buildings 37 (11), 1132-1146.

Hrovat D., Sun J. (1997), Models and Control Methodologies for IC Engine Idle Speed Control Design, Control Engineering Practice, 5 (8), 1093-1100.

IEA/SHC Task 26 (2006). http://www.iea-shc.org/task26/.

Judkoff R., Neymark J. (1985). International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method. IEA/ECBCS Annex 21 Subtask C and IEA/SHC Task 12 Subtask B Report.

Judkoff R., Wortman D., O'Doherty B., Burch J. (1983). A Methodology for Validating Building Energy Analysis Simulations. Technical Report TR-254-1508, Solar Energy Research Institute, Golden, USA.

Kelly N., Beausoleil-Morrison I. [eds] (2007). Specifications for Modelling Fuel Cell and Combustion-Based Residential Cogeneration Devices within Whole-Building Simulation Programs. IEA/ECBCS Annex 42 Report. *

Knight I., Kreutzer N., Manning M., Swinton M., Ribberink H. (2007). Residential Cogeneration Systems: European and Canadian Residential non-HVAC Electric and DHW Load Profiles. IEA/ECBCS Annex 42 Report. *

Knight I., Ugursal I. [ed] (2005). Residential Cogeneration Systems: A Review of the Current Technologies. IEA/ECBCS Annex 42 Report. *

Mansouri I., Newborough M., Probert D. (1996). Energy Consumption in UK Households: Impact of Domestic Electrical Appliances, Applied Energy 54 (3), 211-285.

Millette J. (2006). Hydro-Québec, Shawinigan, Canada. Personal Communications.

Mühlbacher H., Geiger B. (2007). Innovative KWK-Systeme zur Hausenergieversorgung - Endbericht Phase II (Messtechnische Untersuchungen), Lehrstuhl für Energiewirtschaft und Anwendungstechnik. TU München, Germany.

Natural Resources Canada (2006). http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/comprehensive_tables.

Ribberink H., Bourgeois D., Mottillo M. (2007). Performance Assessment of Prototype Residential Cogeneration Systems in Single Detached Houses in Canada. IEA/ECBCS Annex 42 Report. *

Sahlin P., Sowell E. F. (1989). A Neutral Model Format for Building Simulation Models. Conference Proc. Building Simulation 1989, IBPSA, Vancouver, Canada.

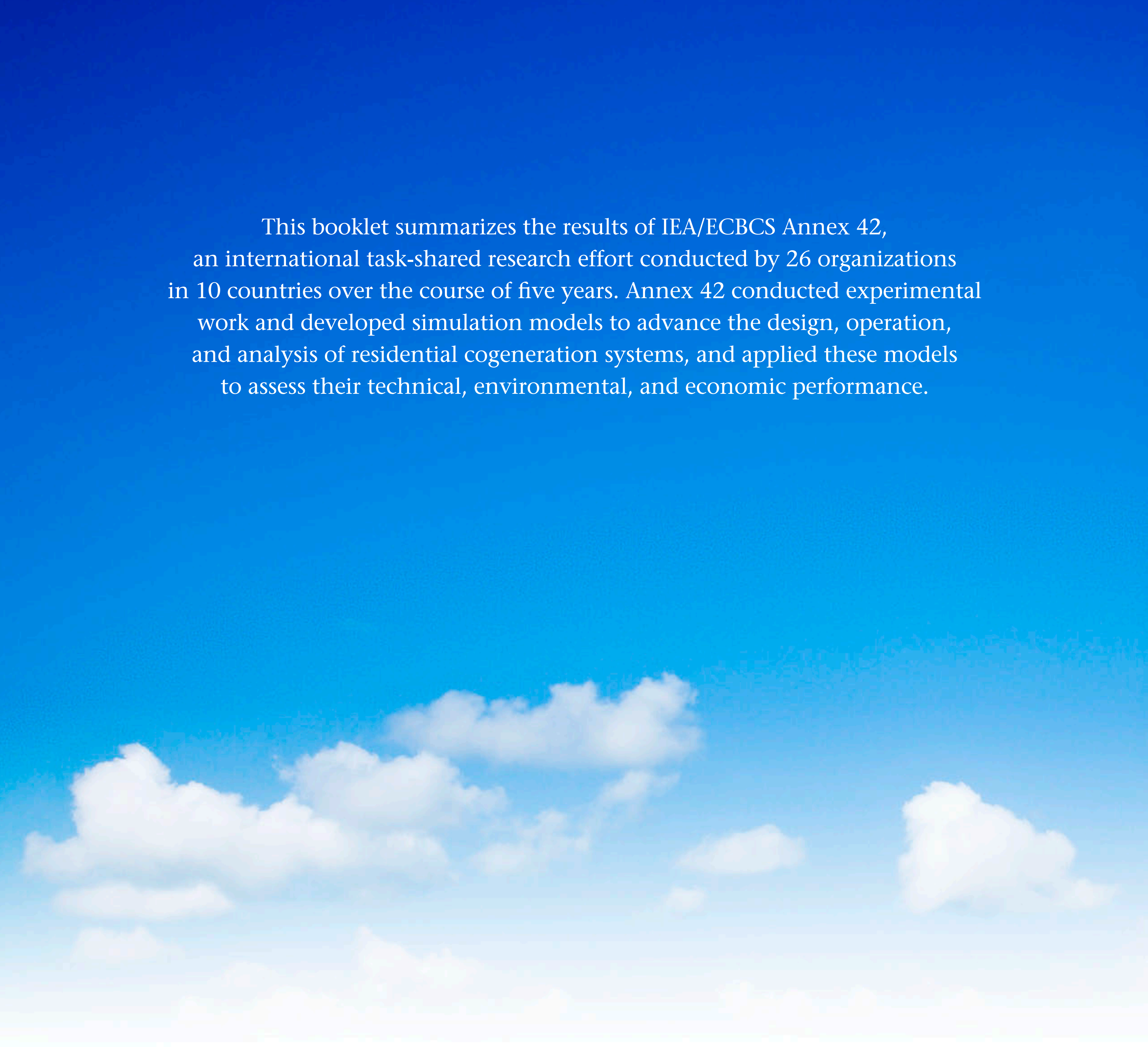
Sasso M., Roselli C., Sibilio S., Possidente R. (2007). Performance Assessment of Residential Cogeneration Systems in Italy. IEA/ECBCS Annex 42 Report. *

Yao R., Steemers K.A. (2005). A Method of Formulating Energy Load Profiles for Domestic Buildings in the UK. Energy and Buildings 37 (6), 663-671.

Abbreviations

AC	Alternating Current
ANSI	American National Standards Institute
ASHRAE	American Society for Heating, Refrigeration and Air-Conditioning Engineers
CCHT	Canadian Centre for Housing Technology
CCPP	Combined Cycle Power Plant
CEN	European Committee for Standardization
CHP	Combined Heat and Power
DC	Direct Current
DHW	Domestic Hot Water
ECBCS	Energy Conservation in Buildings and Community Systems
EHP	Electric Heat Pump
EMPA	Swiss Federal Laboratories for Materials Testing and Research
ENEA	National Agency for New Technologies, Energy and the Environment
EU	European Union
FC	Fuel Cell
FCPM	Fuel Cell Power Module
FCT	Fuel Cell Technologies
FfE	Forschungsstelle für Energiewirtschaft (Research Institute for Energy Economy)
GHG	Greenhouse Gas
HHV	Higher Heating Value
HVAC	Heating, Ventilation and Air Conditioning
IC	Internal Combustion
ICE	Internal Combustion Engine
IEA	International Energy Agency
LHV	Lower Heating Value
MFH	Multi-Family House
NMF	Neutral Model Format
NRC	National Research Council of Canada
NRPE	Non-Renewable Primary Energy
PCU	Power Conditioning Unit
PE	Primary Energy
PEMFC	Proton Exchange Membrane Fuel Cell
PES	Primary Energy Savings
PH	Passive House
SE	Stirling Engine
SFH	Single-Family House

SH	Space Heating
SHC	Solar Heating and Cooling
SIA	Swiss Engineers and Architects Association
SOC	State of Charge
SOFC	Solid Oxide Fuel Cell
SPB	Simple Pay Back
UK	United Kingdom
USA	United States of America



This booklet summarizes the results of IEA/ECBCS Annex 42, an international task-shared research effort conducted by 26 organizations in 10 countries over the course of five years. Annex 42 conducted experimental work and developed simulation models to advance the design, operation, and analysis of residential cogeneration systems, and applied these models to assess their technical, environmental, and economic performance.

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