Project Summary Report

EBC

Energy in Buildings and
Communities Programme

EBC Annex 42

The Simulation of Building-Integrated Fuel Cell & Other Cogeneration Systems (COGEN-SIM)

Ian Beausoleil-Morrison

EBC

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Project Summary Report

Ian Beausoleil-Morrison

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About EBC

International Energy Agency

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

Energy in Buildings and Communities

The IEA co-ordinates research and development in a number of areas related to energy. The mission of one of those areas, the EBC - Energy in Buildings and Communities Programme, is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshop, held in April 2013. The R&D strategies represent a collective input of the Executive Committee members to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy conservation technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas of R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

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 in grey):

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
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Annex 9:	Minimum Ventilation Rates
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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
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Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings
Annex 48: Heat Pumping and Reversible Air Conditioning
Annex 49: Low Exergy Systems for High Performance Buildings and Communities
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings
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Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings
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Annex 57: Evaluation of Embodied Energy & CO2 Emissions for Building Construction
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements
Annex 59: High Temperature Cooling & Low Temperature Heating in Buildings
Annex 60: New Generation Computational Tools for Building & Community Energy Systems
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Annex 62: Ventilative Cooling
Annex 63: Implementation of Energy Strategies in Communities
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles
Annex 65: Long-Term Performance of Super-Insulation in Building Components and Systems

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

General Information

Project leader: **Dr Ian Beausoleil-Morrison, CANMET Energy Technology Centre, Natural Resources Canada, Canada**
Project duration: **2003- 2007**
Further information: **www.iea-ebc.org**

Small scale cogeneration systems for buildings locally generate electricity and heat from a single fuel source. They have potential to reduce the use of fossil fuels (and hence energy-related carbon dioxide emissions) as they distribute heat produced during the generation of electricity that would otherwise be wasted. Because the electricity produced is used close to where it has been generated, transmission losses are also avoided.

The EBC research project, "Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (COGEN-SIM)", has been carried out over a four year period between 2003 and 2007. The aim of the project was to generate a common approach to implementing models of residential scale cogeneration devices within building energy simulation tools.

While separate, 'freestanding' models have already been developed of the behaviour of residential cogeneration devices, this has not proved to be an adequate approach to sufficiently accurately model how such devices would operate in buildings. It has therefore now reached an appropriate point for the research community to investigate the implementation of cogeneration devices within building simulation tools. With this objective, this project undertook a joint international research effort that was conducted by 26 organizations from 10 countries (see Appendix A). This report summarises the work carried out during the project.

Target Audiences

There a number of principle target audiences for this report. The Project Overview is intended for:

1. Those active in or engaged with the buildings energy policy, design or construction communities, who wish to gain a brief understanding of how residential co-generation technologies may best be modelled during building thermal simulation. They may also be interested to learn about some initial results found when the tools developed have been applied.

Researchers in this field may wish to consult Beausoleil-Morrison (2008) directly. The remaining sections are intended to provide an introduction to the work carried out in the project, principally for the benefit of:

2. Building thermal simulation practitioners who wish to have an introduction to the approach used to implement co-generation devices in tools they are applying.

Participating Countries:

Belgium
Canada
Finland
Germany
Italy
Netherlands
Norway
Switzerland
United Kingdom
USA

Project Outcomes

Project leader: **Dr Ian Beausoleil-Morrison, CANMET Energy Technology Centre, Natural Resources Canada, Canad**

Project duration: **2003- 2007**

Further information: **www.iea-ebc.org**

Cogeneration devices have the potential to reduce the use of fossil fuels (and hence energy-related carbon dioxide emissions) as they distribute heat produced during the generation of electricity that would otherwise be wasted. Within the residential sector, the widespread use of cogeneration systems has been somewhat limited principally because of the lack of commercial devices available on the open market. Manufacturers are further developing such products and many technical barriers have been overcome to the extent that their more commonplace adoption seems likely.

Building thermal energy simulation tools have gained increasing importance in the past decade for building design and for producing 'asset ratings'. They are used for numerous purposes during building design, including for example, heating and cooling plant sizing, or optimising the design of control systems. Crucially, they may form the basis on which energy-related CO2 emissions may be calculated during building design, an example of asset rating.

Past experience has shown over many years and in numerous countries that without a common approach, various types of discrepancies can arise between different simulation tools used for the same purpose. These can be caused by, for example, user interpretation, errors in computer codes, incorrect documentation, incorrect data handling by user interfaces or differences between physical modelling approaches.

This project has continued work in the IEA framework (within both the EBCS and Solar Heating and Cooling Programmes) and elsewhere in developing and enhancing the internationally renowned 'BESTEST' (Building Energy Simulation Test) procedures. The BESTEST procedures have helped to provide reassurance to building design teams and for national policy makers that the results generated by building thermal energy simulation tools are reliable.

The project has focused on natural gas fired cogeneration devices with electrical outputs varying from under 1 kWe up to 15 kWe. This range of outputs would be appropriate for dwellings as diverse as small one bedroom European apartments to large North American single family houses. 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);
- internal combustion engines (ICE).

Models of residential cogeneration systems were developed by the project team. These were then integrated into existing whole-building simulation tools to consider the coupling between the cogeneration device, other heating, ventilation and air conditioning components, and the building's 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 characterise key loads on residential cogeneration for occupant-driven electrical loads and hot water usage patterns.

The implementation of the cogeneration models within the thermal simulation tools has confirmed as anticipated that robust evaluation procedures must be followed to provide reassurance that the tools are providing accurate evaluations of the performance of cogeneration devices in buildings.

The accurate assessment of small cogeneration devices requires precise models of the type produced by this project to predict electrical and thermal performance with sufficient temporal resolution and accuracy.

It was found that current prototype and early-market, small scale fuel cell (SOFC and PEMFC) and combustion engine (SE and ICE) 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 energy conversion efficiencies (electrical plus thermal) range from 55% to as high as 100% (lower heating value basis) for some devices excluding ancillary power.

The new data and tools produced by the project were 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.

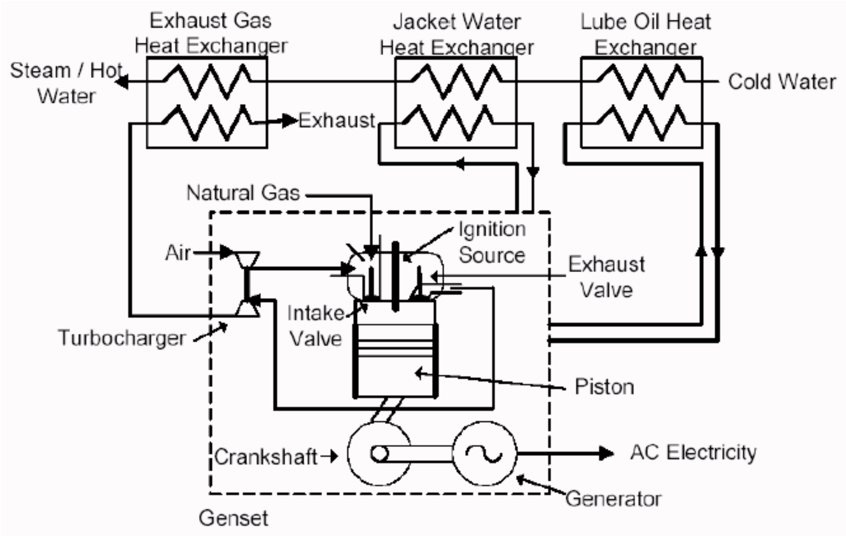
These studies revealed that, in certain circumstances, residential cogeneration systems can significantly reduce primary energy use and energy-related CO2 emissions relative to conventional means of supplying heat and power, despite the fact that many of the current prototypes considered have far from optimal performance. The basis of comparisons for small-scale cogeneration devices must be well-defined and should consider the current and future options for grid supplied electricity as well as current high performance and future options for space and domestic hot water heating.

Despite the lacklustre performance of some current prototype and early-market cogeneration devices, the detailed results for the building cases analysed show that when coupled to HVAC and domestic hot water (DHW) systems, the devices can reduce primary energy consumption by up to 33% and Greenhouse Gas (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% could be achieved, despite higher primary energy consumption.

However, when specifically compared with grid electricity where hydroelectric and nuclear power generation now form a significant portion of the mix (e.g., the Swiss electricity grid), some of the cogeneration cases analysed lead to reduced primary energy use of between 1% to 14%, while others show an increase of up to 9%. However, all cases lead to increased GHG emissions of between 5% to 43%.

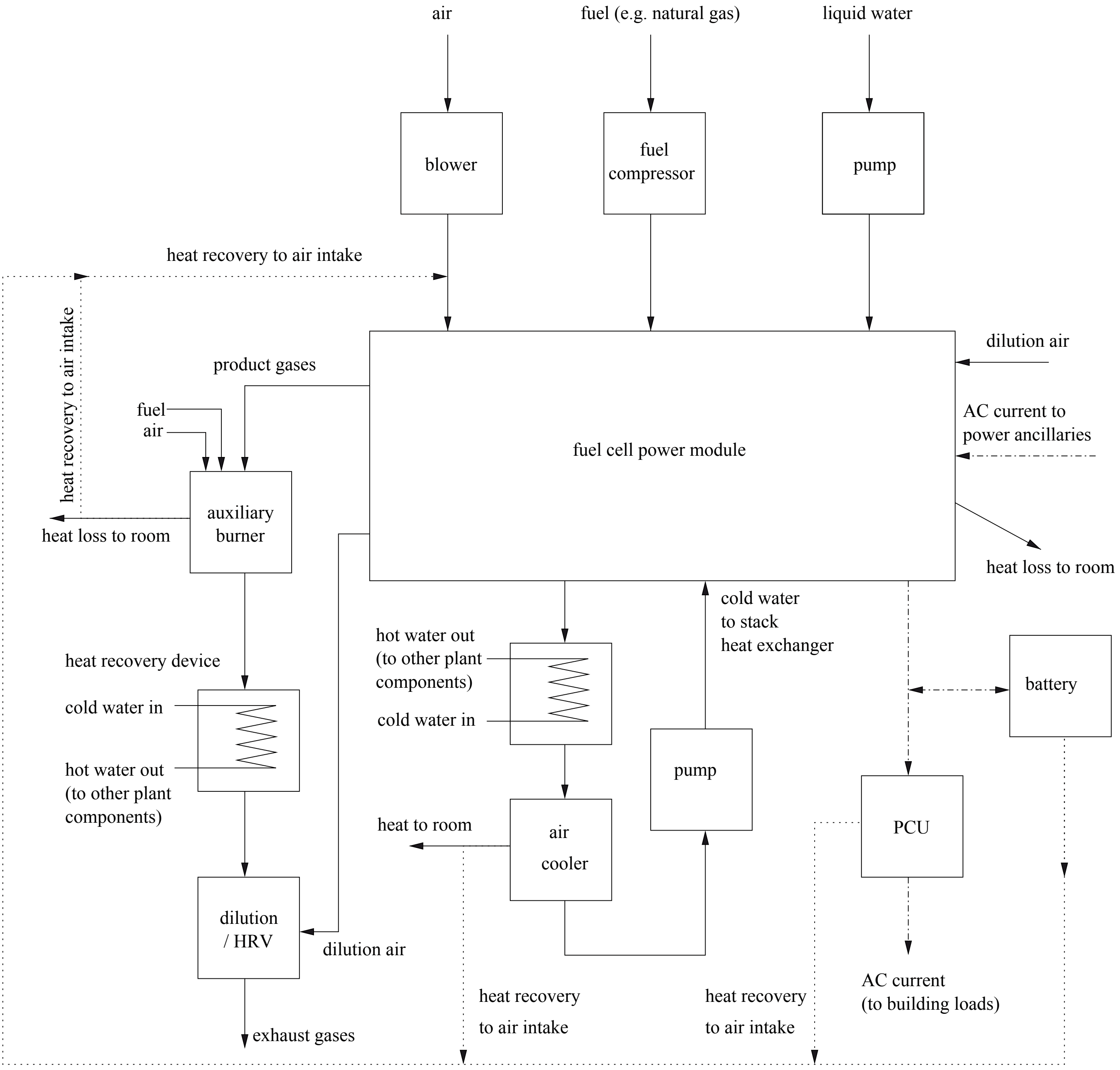
In general it was concluded that cogeneration devices with low electrical conversion efficiencies must have very high thermal conversion efficiencies (i.e., they must recover energy through condensing the water vapour in the exhaust gases) to compare favourably with conventional (condensing) heating technologies and grid electricity.

Figure 1. Schematic of the operation of a typical internal combustion engine based (spark ignited) cogeneration system.



Project Outcomes

Figure 3. Schematic of the FC-cogeneration device model (note that as the model is intended to be generic, not all of those control volumes need to be used, specific volumes can be activated od de-activated, as appropriate, for a particular fuel cell.



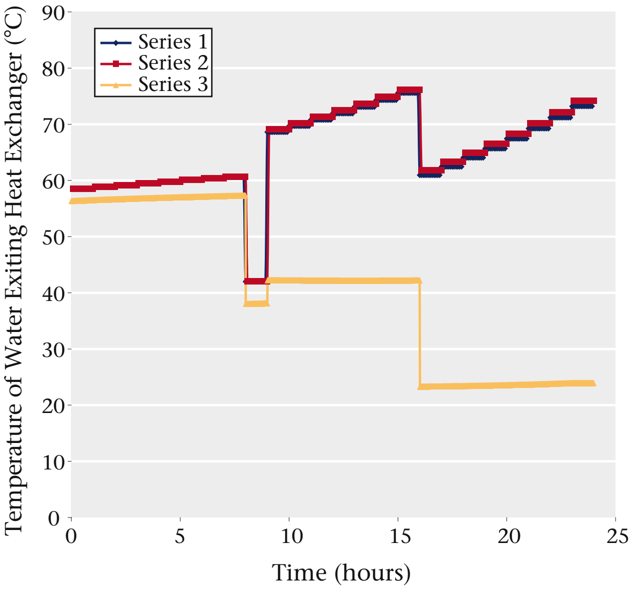


Figure 2. Fuel cell cogeneration model: predicted heat exchanger outlet temperature with heat capacity bug.

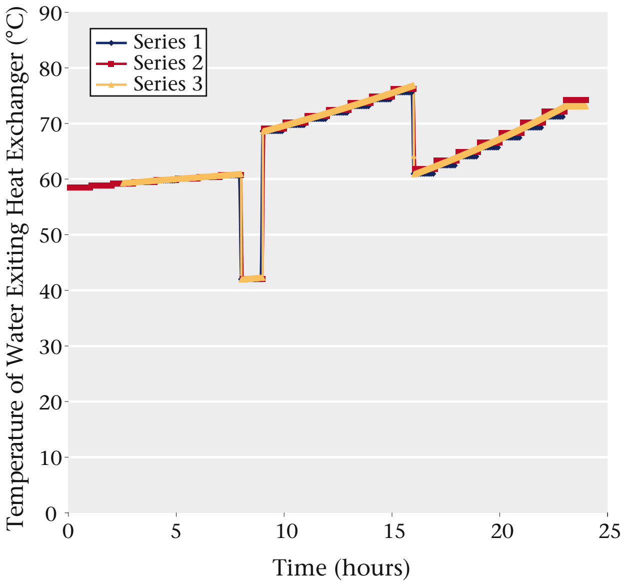


Figure 3. Fuel cell cogeneration model: predicted heat exchanger outlet temperature with heat capacity bug corrected.

Cogeneration Technologies for Residential Application

The project has examined four types of natural gas fired cogeneration devices with electrical outputs varying from under 1 kWe up to 15 kWe. This range of outputs would be appropriate for dwellings as diverse as small one bedroom apartments to very large single family houses. The following four technologies were considered:

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

Combustion engine based cogeneration systems

The basic elements of a reciprocating internal combustion engine based cogeneration system are the engine, generator, heat recovery system, exhaust system, controls and acoustic enclosure. The generator is driven by the engine, and the useful heat is recovered from the engine exhaust and cooling systems. The key components of a typical internal combustion engine based cogeneration system are shown in Figure 1.

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

Fuel cell based cogeneration systems

In a fuel cell, the chemical reaction of oxidation (in place of combustion) is made using an electrochemical reaction where the reactants are separated by a membrane that only allows ions to cross. To complete the electrical balance, electrons have to move through a circuit, which produces a current. Depending on the type of membranes, the ions able to cross will be differ: H+ (hydrogen ions, which are single protons) for

PEMFC or O_2- (oxygen ions) in SOFC. In both cases, the heat produced as a product of the electrochemical reaction is used to produce hot water.

PEMFC technology involves the reaction of hydrogen with oxygen in the presence of an electrolyte (a medium in which an electric current may be established) to produce electricity without combustion and mechanical work. Water and heat are produced as by-products. PEMFCs are classified as low temperature fuel cells due to their relatively low operating temperature of under 100°C, typically 80°C, which is well suited to residential applications.

Solid oxide fuel cells are a solid-state power system that uses a ceramic material as the electrolyte layer. With SOFC, oxygen ions cross the membranes. They are classified as high temperature fuel cells with an operating temperature of 750°C - 1000°C. The fuel used to produce hydrogen or a mixture of H_2 and CO can be derived from internal reforming of hydrocarbons or coal gasification. Their high operating temperature and the high-grade residual heat produced can be used for space heating and water heating loads for residential, commercial or industrial applications.

Implementation, Measurements and Testing for Building Simulation Models

The cogeneration models developed were independently implemented into 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 the project were used to 'empirically validate' the models. As a result, it can be stated with a high degree of confidence that the models within the project can accurately represent the performance of residential cogeneration devices when properly calibrated.

The project successfully developed a model with sufficient precision and resolution for simulating SOFC and PEMFC cogeneration devices within the context of whole-building thermal simulation programs. A similar, but less detailed model was developed and verified for SE and ICE cogeneration devices.

It is necessary to systematically evaluate tools using a number of parallel approaches. These include:

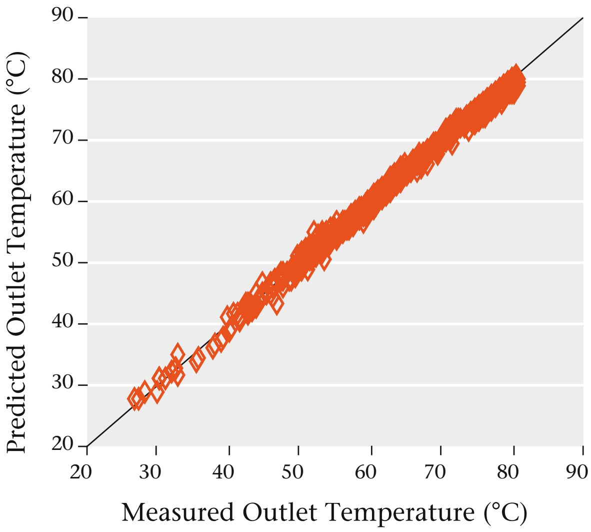
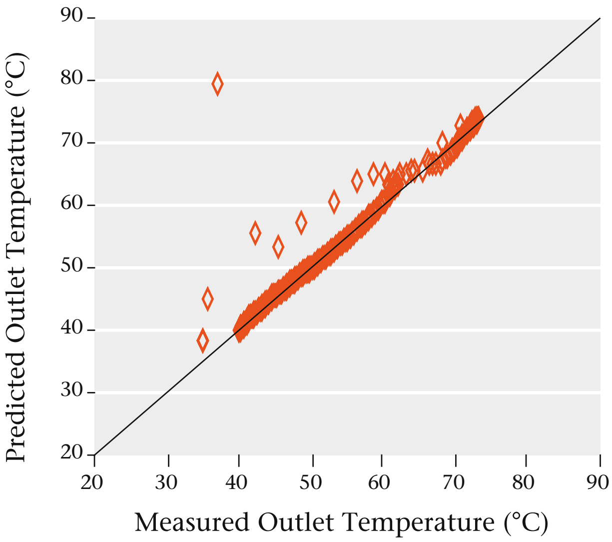


Figure 4. Comparison of predicted and measured outlet temperatures for a) a Sterling engine, and



b) an internal combustion engine device

- comparison of simulation tool results with exact known solutions (‘analytic evaluation’),
- inter-model comparisons between the results of different simulation tools (‘comparative evaluation’), and
- comparison of simulation tool results with measured results from experiments (‘empirical evaluation’).
- It was not possible to carry out comparisons with exact solutions in this project due to the complexity of the systems being considered. For this reason, emphasis was placed on comparative testing between models and with measured data.

A series of inter-model comparative tests were devised for the fuel cell cogeneration (FC-cogeneration) model developed. This is composed of 50 test cases, each carefully constructed to isolate a specific aspect of the model. Collectively these test cases examine every aspect of the model and exercise each line of a source code implementation of the model. By design, these test cases make no attempt to represent realistic situations or FC-cogeneration systems. Rather, they are designed to exercise specific aspects of the model and to exaggerate differences between programs for the purposes of diagnosing errors. Figure 4 2 illustrates of an example of where a programming bug was detected by means of comparative testing.

The project interacted 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 expectation,expectation and start-up and shut-down operating characteristics that can significantly impact overall performance.

Both the fuel cell and combustion cogeneration models were validated using empirical data collected during the project’s experimental testing efforts:

Figure 4. Electric load profile at 5-minute time intervals and averaged over 1-hour periods.

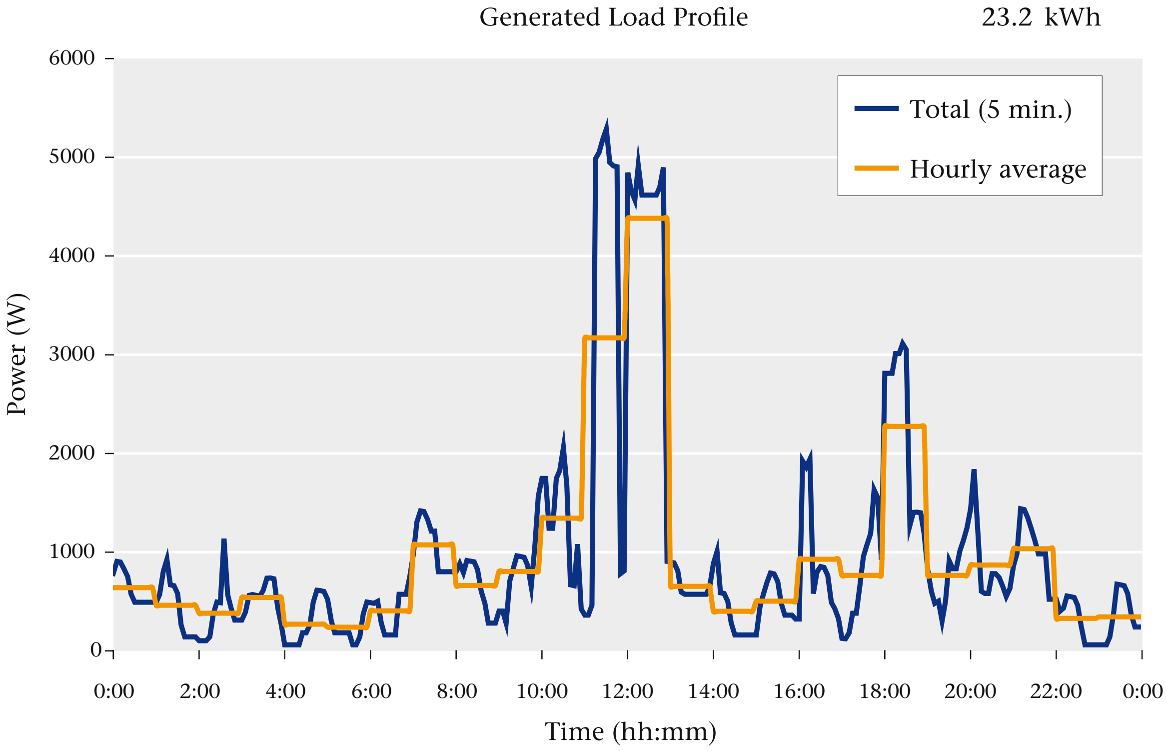


Table 1. Essential data for model calibration.

Static Measurements	Time-varying Measurements
1. Mass of cogeneration device, not including the balance of plant components (e.g. pumps, storage). 2. Empty and charged mass of heat exchanger (exhaust-gas-to-air or water-to-water) used for capturing thermal output. 3. Total mass of cogeneration device. 4. Composition of fuel (molar fractions of CH_4, $C_2H_6C_3H_8$, higher hydrocarbons, N_2, CO_2).	1. Electrical demand placed upon cogeneration device (W) 2. Net AC electrical output from cogeneration device (after parasitic losses, battery losses, and losses from power conditioning unit) (W). 3. Natural gas consumption rate (m^3/s at standard temperature and pressure). 4. Air supply rate to cogeneration device (kg/s). 5. Temperature of air supplied to cogeneration device (^{o}C). 6. Humidity of air supplied to cogeneration device (RH or Tdp) 7. Flow rate of liquid water supplied to cogeneration device (kg/s) 8. Flow rate of exhaust gases through gas-to-water heat exchanger or flow rate of water on cogeneration side of water-to-water heat exchanger (kg/s). 9. Temperature of exhaust gases as they enter gas-to-water heat exchanger or temperature of entering water on cogeneration side of water-to-water heat exchanger (^{o}C). 10. Temperature of exhaust gases as they exit gas-to-water heat exchanger or temperature of exiting water on cogeneration side of water-to-water heat exchanger (^{o}C). 11. Flow rate of water on plant side of gas-to-water or water-to-water heat exchanger (kg/s) 12. Temperature of entering water on plant side of gas-to-water or water-to-water heat exchanger (^{o}C). 13. Temperature of exiting water on plant side of gas-to-water or water-to-water heat exchanger (^{o}C). 14. Exhaust gas composition (molar fractions of CO_2, N_2, Ar, O_2, H_2O, CH_4, H_2, CO, etc). 15. Ambient air temperature $^{(o}$C). 16. Ambient air humidity (RH or Tdp).

- The fuel cell cogeneration model was validated using data collected from an ‘FCT’ SOFC unit.

- The combustion cogeneration model was validated using data collected from a ‘WhisperGen’ Stirling engine device.

An overview of the minimum measured data required for model calibration purposes for fuel cells are presented in Table 1.

Demand Profiles

Accurate demand profiles for heat for space heating and for domestic hot water and electricity are critical for understanding the performance of residential cogeneration technologies. For the characteristics of such systems to be properly understood, it is necessary to match up the behaviour of particular devices with the demands made on them.

While space heating demand profiles can be calculated by building thermal energy simulation tools, profiles for electricity use or domestic hot water production cannot. So, data must be obtained about these from a source other than modelling. The project consequently obtained measurement results for such demand profiles. These included data for North America (from Canada) and from Europe (from the UK).

Evaluating the performance of cogeneration devices serving residential buildings requires both accurate models and accurate, occupant-driven consumption profiles for electricity and domestic hot water (DHW). The project successfully obtained extensive end-use profile data and information by examining existing measured datasets and models, developing and using an artificial electrical load profile generator, and making detailed measurements. The results of this effort include representative usage profiles for non-HVAC (heating, ventilation and air conditioning) electricity and DHW that are suitable for Europe and Canada. A typical artificially generated electric load profile is shown in Figure 4.

Project Conclusions

The conclusions from the model implementation phase of the project are as follows:

- The implementation of the cogeneration models within the thermal simulation tools has confirmed as anticipated that robust evaluation procedures must be followed to provide reassurance that the tools are providing accurate evaluations of the performance of cogeneration devices in buildings.

- A detailed understanding of occupant-driven electrical and DHW usage profiles with sufficient resolution for use in a whole-building simulation tool are required for accurate performance evaluations.

- The assessment by manufacturers 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.

- Current prototype and early-market, small scale fuel cell (SOFC and PEMFC) and combustion engine (SE and ICE) 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 energy conversion efficiencies (electrical plus thermal) range from 55% to as high as 100% (lower heating value basis) for some devices excluding ancillary power.

- The accurate assessment of small cogeneration devices requires precise models of the type produced by this project to predict electrical and thermal performance with sufficient temporal resolution and accuracy.

- Typically for individual dwellings, all measured data should be recorded at 5 minutes intervals, which is generally more frequent than that required for larger systems.

Project Outcomes

- The new models, along with the new non-HVAC electrical and DHW usage profiles, were applied in the modified building simulation tools to assess the performance of specific prototype, early market, and in some cases, hypothetical cogeneration devices and applications. The energy-related CO2 emissions and primary energy use of the small-scale cogeneration devices were compared to the energy-related CO2 emissions and primary energy use 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. The findings from these initial assessments are:

- The basis of comparisons for small-scale cogeneration devices must be well-defined and should consider the current and future options for grid supplied electricity as well as current high performance and future options for space and domestic hot water heating.

- 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 domestic hot water 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.

- However, when specifically compared with grid electricity where hydroelectric and nuclear power generation now form a significant portion of the mix (e.g., the Swiss electricity 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 between 5% to 43%.

- 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.

- 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).

Further Information

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Project Reports

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Project Participants

Category	Organisation
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
The Netherlands	Energy Research Centre Netherlands (ECN) / Renewable Energy in the Built Environment
Norway	Norwegian Building Research Institute (NBRI) Telemark University College
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)
United Kingdom	Norwegian Building Research Institute (NBRI) Telemark University College
USA	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

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