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Publisher's version / Version de l'éditeur:

Micro-Cogeneration 2008 [Proceedings], p. 8, 2008-04-29

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NRCC-50293

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A version of this document is published in / Une version de ce document se trouve dans:
Micro-Cogeneration 2008, Ottawa, Ontario, April 29-1 May 2008, pp. 1-8

INTEGRATION AND MONITORING OF MICROCHP SYSTEMS IN A RESIDENTIAL APPLICATION AT THE CANADIAN CENTRE FOR HOUSING TECHNOLOGY

Marianne Manning[1], Frank Szadkowski[2], John Gusdorf[2], Evgueniy Entchev[2], Mike Swinton[1], Mark Douglas[2]

[1]National Research Council Canada
Ottawa, Ontario, Canada
[2]Natural Resources Canada
Ottawa ,Ontario, Canada

ABSTRACT

The Canadian Centre for Housing Technology (CCHT) in Ottawa, Canada, has been host to a number of micro combined heat and power (microCHP) systems over the last five years. In order to meet the needs of advancements in CHP technology, the CCHT twin house facility was modified to allow for the installation and monitoring of microCHP systems, including the capture and storage of waste heat, and the export of electricity. Four different systems are highlighted in this paper: a 1kWe/6kWth (electrical/thermal) nominal Stirling engine from New Zealand, a solid oxide fuel cell (5kWe/5kWth nominal), a residential hybrid internal combustion engine/high efficiency furnace (1kWe/3.25-18kWth), and a 6kWe/11.7kWth Japanese cogeneration unit. Throughout these experiences, the CCHT research team has developed an expertise in the installation and operation of microCHP systems. This paper presents an overview of the modifications that were made to the facility to accommodate these different systems, and also presents some lessons learned from the integration of microCHP systems in an energy efficient R-2000 home.

INTRODUCTION

The integration of microCHP units into a home can take many forms. Installation requirements vary widely depending on the type and size of the CHP unit and the operating strategy (heat lead, electrical lead or constant output). Over the past 5 years, researchers at the Canadian Centre for Housing Technology (CCHT) have adapted their twin-house facility to allow for the installation and monitoring of four very different microCHP units ranging in size from 1kWe to 6kWe, and from 3.25kWth to 18kWth. While the installations did share a number of common elements, each presented its unique set of challenges. The purpose of this paper is to share a portion of the knowledge that has been acquired on the installation and monitoring of microCHP units in an R-2000 home.

BACKGROUND

CCHT. The Canadian Centre for Housing Technology is located in Ottawa, Canada. The centre features two identical twin houses that are the site of numerous side-by-side energy evaluations, and also an InfoCentre that houses a conference room and display area.

MICROCHP SYSTEMS. Four types of cogeneration systems have been assessed at the Canadian Centre for Housing Technology (CCHT). This section briefly describes the various technologies.

Figure 1. MicroCHP systems evaluated at CCHT. A) Stirling engine; B) solid oxide fuel cell; C) hybrid internal combustion engine with high efficiency furnace; D) 6kWe load following Japanese cogeneration unit

STIRLING ENGINE. Two Stirling engines were demonstrated at CCHT. This was the first type of microCHP system to be assessed at the centre. The system employs the Stirling cycle to generate heat and power from natural gas. The first demonstration occurred in early 2003, when a natural gas fired Stirling engine was installed in the Test House. This Stirling engine was capable of producing 736We, and 6.5kWth. A fourth generation of the engine was later installed in the InfoCentre to provide heating to the conference room and demonstration area in winter 2004/2005. This second engine had two power settings, nominally 850We and 6.0kWth at the low setting, and 1.2kWe and 8.0kWth at the high setting. This installation is pictured in Figure 1A. Both engines shared a similar setup and were operated on heating demand. Results from the evaluation of the Stirling engine appear in Entchev (2004) and Siemens (2005).

SOLID OXIDE FUEL CELL. The second cogeneration unit to be installed in the test house was a solid oxide fuel cell. This was a 5kWe/5kWth nominal unit, and was operated continually to produce 2.5kWe/2.3kWth. The fuel cell provided the heat and electrical needs of the house from March to May 2005. Figure 1B shows the fuel cell arriving at the facility. Results from the fuel cell project were published by Bell (2006) and Entchev (2007).

HYBRID INTERNAL COMBUSTION ENGINE INTEGRATED WITH HIGH EFFICIENCY FURNACE. In winter 2007, a hybrid system consisting of a natural gas fed internal combustion engine with a high efficiency condensing gas furnace was evaluated. The hybrid system had a small electrical capacity of 1kWe and a thermal output of 3.25 or 18kWth. It was designed to be 'heat lead' as it was controlled according to heat demand of the residence. The hybrid system is designed to act as a two-stage furnace where the first stage utilizes the heat generated by the engine operation with output of 3.25kWth. The second stage features both the engine and furnace operation with a total output of 18kWth. The system is pictured during lab tests in Figure 1C. Results from this project are confidential to the client.

6KWE COGENERATION UNIT COUPLED TO GROUND LOOP. A Japanese cogeneration unit was operated in 2007 as part of a project to explore its performance in combination with a residential total energy system. The cogeneration unit is a natural gas fuelled engine with a maximum output of 6kWe and 11.7kWth. It has electrical load following capabilities. In the installation at the CCHT Reference House, the unit was coupled to a system consisting of two 1-ton ground-source heat pumps, and a backup air handler and storage tank. The heat pumps were sized to meet peak cooling loads in the house, but undersized for heating loads – allowing the opportunity for heat input from the cogen unit. The cogen unit was also connected to a ground storage loop. Preliminary results of this residential total energy system are discussed by Gusdorf (2007) and Yang (2007).

COMMON REQUIREMENTS

Although the four CHP units differ by size, technology involved and control strategies, they shared some common installation features. In all cases, methods were needed for managing electrical and heat outputs. Depending on the mode of operation – electrical lead, heat lead, or constant output – and the size of the unit, the management methods were adjusted. This section addresses the commonalities in the integration of the systems into a single family house with forced air heating.

ELECTRICAL. Electrical system modifications were made in both research houses in 2003 in anticipation of industry requirements. As CHP systems were advancing, a facility was required to bridge the gap between laboratory tests and real-world installations. Electrical modifications were needed to allow the microCHP unit to provide power to the house, to export to the grid, or to run in "island" mode (isolated from the grid), while still ensuring that the facility's data acquisition and simulated occupancy systems remained operational. A schematic of the electrical system upgrades are provided in Figure 2. All electrical system components including wires and switches were sized for 200 Amps. Local electrical inspections were performed before each unit was operated. Some important features of the electrical system include:

- An external lockable disconnect was required as a safety precaution, to allow the local utility to shut down the CHP unit. With the exception of the fuel cell, the remaining CHP systems tested required excitation from the grid to operate. In the event of a power outage, these systems would shut down automatically.
- Two power quality meters. One power quality meter monitored the line from the utility, the second meter monitored the generated supply.
- Separate electrical panels. One panel is dedicated to the monitoring system and simulated occupancy and receives a constant supply from the utility. The main house loads on a second panel can be supplied by either the utility, the CHP unit (in island mode) or by both. A third panel of loads (the pony panel) was installed to ensure that the CHP unit would have a constant minimum baseload in case of a power outage – this was necessary for the fuel cell.
- Bi-directional electric meters. These meters were necessary to monitor the amount of electricity being supplied to the house or exported. A total of

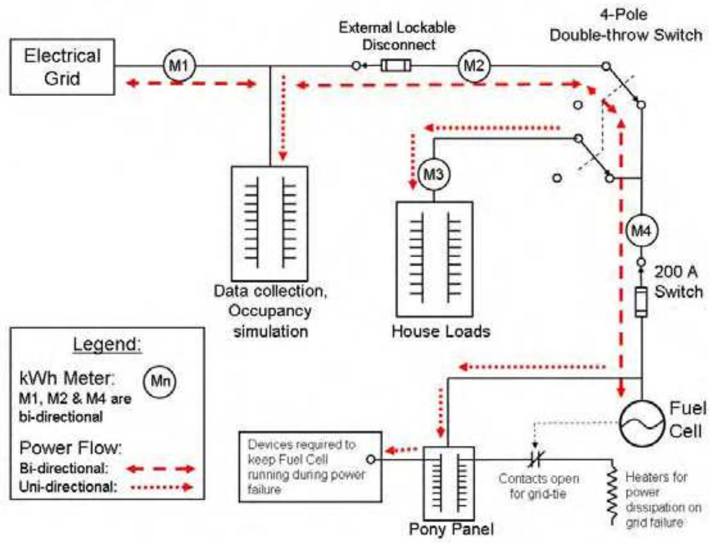

Figure 2. Electrical modifications for the fuel cell

3 bi-directional meters were required, shown in Figure 2 as M1, M2 and M4. Meter M3 is uni-directional for monitoring the house loads. The resolution of these meters was 0.0006 kWh/pulse, and data was collected on a 5-minute basis.

THERMAL STORAGE. In order to use the outputs of the CHP units to their full potential, some means of thermal storage was required. A number of different approaches were used:

Stirling Engine. The Stirling engines were heat lead. In order to reduce the engine cycling time, the first engine tested was connected to a 150L water storage tank, and a 189L gas-fired hot water tank. The tanks had a provision to be connected either in sequence - with total volume of 339L or in parallel- where the storage tank acts as a preheat tank to the gas fired one. Both options were explored and assessed during the field trial. A larger tank enables longer ON times, and longer operation at steady state results in better efficiency. The tanks were coupled together by means of a circulation pump. In the second field trial, the Stirling engine was connected directly to a single 189L gas-fired hot water tank– causing shorter cycling times, but reducing the requirement for a second circulation pump.

Fuel Cell. The fuel cell was operated at a continuous electrical output. Heat produced was stored in a gas-fired hot water tank (200L) in the house basement. Since the fuel cell was located in the garage, long lines were required to move heat from the garage into the basement.

Hybrid Internal Combustion Engine integrated with High Efficiency Furnace. The hybrid system was directly in line with the furnace, with no hot water connections. The system was sized to produce a small amount of heat continuously, with the furnace providing backup heat. When there was no heat needed in the house, the system shut down, so no storage was required.

6kWe Cogeneration Unit. The cogeneration unit was located outside the house, and was connected both to a 189L hot water tank and a 300L water storage tank in the house basement, and also to a 75m deep vertical ground loop. Different possible modes of operation were examined including delivering heat to both the water tanks and ground loop in sequence. A diagram of the system is presented in Figure 3.

HEAT UTILIZATION. Three of the CHP systems operated similarly to deliver heat to the house. For the Stirling engine, fuel cell and 6kWe cogeneration unit, the heat utilization portion of the setup closely resembled a typical hot water combo system: the hot water storage tank was connected to the domestic hot water supply of the house, and to a water coil in an air handler. An example of the thermal connections of a CHP system, in this case the fuel cell, is shown in Figure 4 (TUM refers to “Thermal Utilization Module”). The hybrid system was different from the other systems in that it was connected directly to the ductwork, and a heating coil internal to the CHP unit provided heat to the air passing through the furnace.

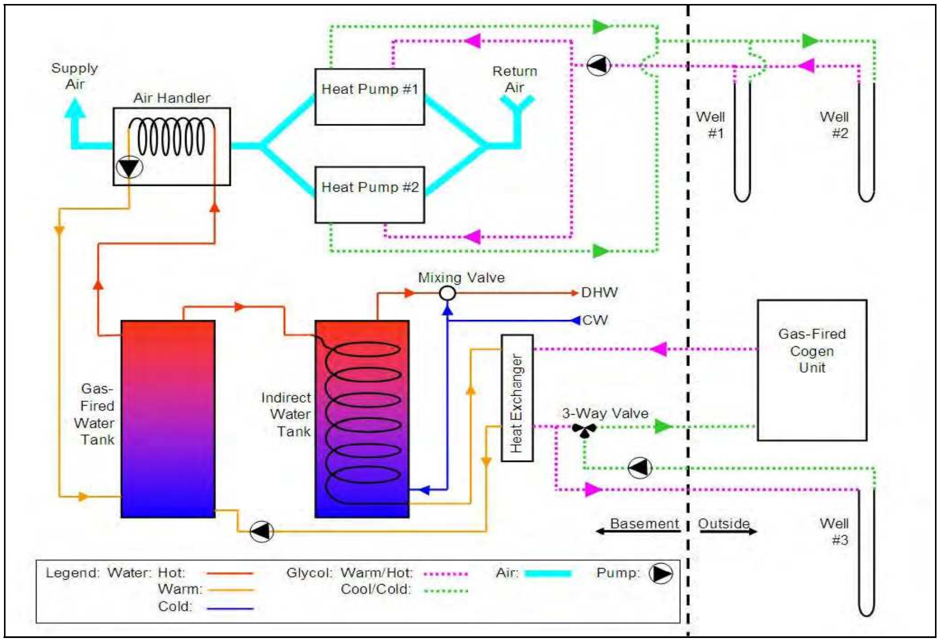

Figure 3. Schematic of the residential total energy system: 6kWe cogeneration unit with 2 stage ground source heat pump.

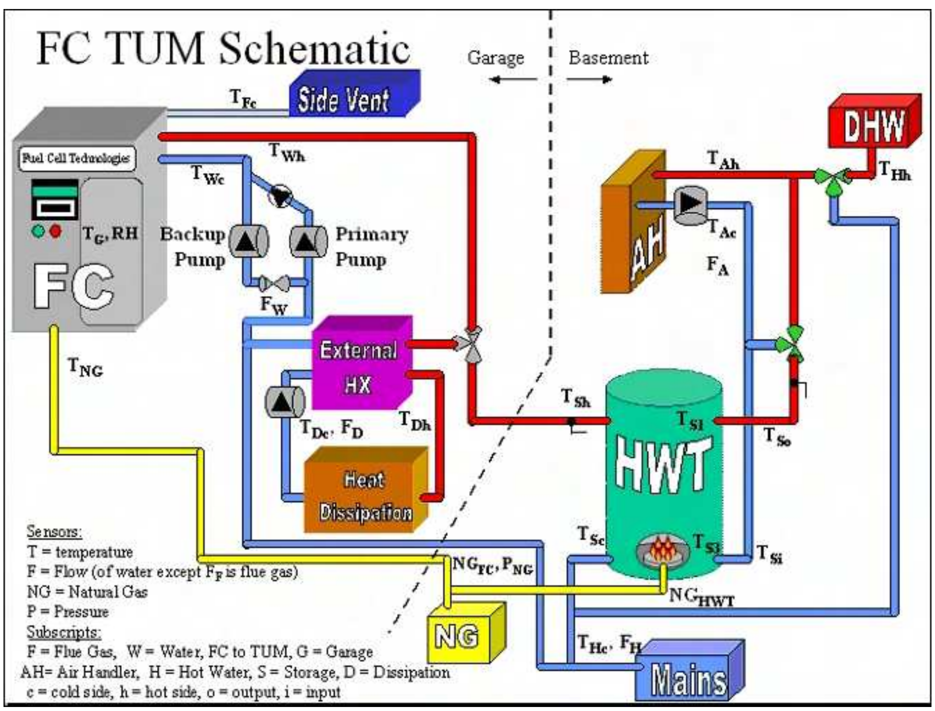

Figure 4. Thermal connections of the fuel cell

HEAT DISSIPATION. Half of the systems tested required a method of heat dissipation, for when the heat produced by the CHP exceeded the thermal requirements of the home. Since the Stirling engines and the hybrid system engine were heat lead and were shut off whenever heat requirements were met, no dissipation was required. However, the fuel cell was operated in a constant state, and thus excess heat had to be managed. Similarly, the 6kWe cogeneration unit engine was operated either at full electrical output or electrical load following, and so at times produced more heat than was needed for the house.

Heat dissipation took different forms for the fuel cell and 6Kwe cogeneration unit. For the fuel cell, whenever the water tank inside the house reached a threshold temperature, valves redirected the hot fluid to a dedicated air handler in the garage. It dissipated the excess heat to the outdoors. The 6kWe cogeneration unit is equipped with an internal radiator system to accomplish the same feat. Alternatively, researchers connected this cogen unit to a loop in the ground, to allow excess heat to be stored underground and potentially retrieved at a later time.

While waste heat was dissipated in these studies, storage would be by far a more effective use of energy and would contribute to a higher efficiency. By accurately measuring the amount of heat that goes to the atmosphere, improvements can be made on the sizing of future systems and the information can be used to design a proper storage system. When monitoring a system, researchers found that a fluid loop was the most precise way to determine the amount of excess heat that is dissipated. The temperature of the fluid entering and leaving the air handler coil, as well as the flow rate, were monitored.

BACKUP HEAT. In order to guarantee that all the space heating needs of the house were met, provisions were made to provide backup heat to the cogeneration system.

The advantage of storing hot water from the CHP unit in a hot water tank is that the heater can provide backup heat to the tank during periods of high heating demands. For both the Stirling engines and the fuel cell, backup heat was provided in this manner. Simply, the aquastat temperature on the water heater was set to maintain the tank at an adequate temperature (e.g. >50°C) throughout the trials.

The backup heat for the engine in the hybrid system was provided by the high efficiency furnace. While the engine provided the first stage of heating, the furnace provided a second stage. Since the CHP unit was installed upstream of the furnace, both the CHP unit and furnace operated at the same time when heating demands were high.

The 6kWe cogeneration unit setup was designed to allow backup heat to be provided by either the hot water storage tank, or by two ground source heat pumps installed vertically beside the ground storage loop. The intention was to store excess heat in the ground when electrical demands are high, and to recover the heat at a later time, when required. The two ground source heat pumps were installed in parallel, upstream of the air handler and hot water coil from the storage tank.

PROJECT-SPECIFIC FACILITY MODIFICATIONS

Each microCHP unit is unique, and so changes were made to adapt the facility accordingly. This section outlines these individual modifications.

STRLING ENGINE. The very first modifications were made to the CCHT twin-houses for the Stirling engine. Since the electrical system was designed for larger power generation, smaller fuses were put in place. The Stirling engine required a specific coolant with corrosion inhibiters to operate. Since the same potable water was being used both in the air handler coil and for domestic use, the system was not a closed loop, and a flat plate double wall heat exchanger was required.

The most significant modifications required for the installation of the Stirling engine were a direct result of it being designed for the UK and New Zealand and not North America. First, the engine required 240 VAC, so two 120 V lines were combined with no neutral to provide the proper voltage for the machine to run. Also, the engine and controls were designed to provide heating through a typical UK-style cast-iron radiator heating system – and not a forced air system. Thus, researchers had to provide new controls for the engine and pump operation, basing the control logic on storage tank temperatures and outdoor temperature.

Finally, while the earlier generation of the Stirling engine had taken combustion air from the room, the later generation that was tested in the InfoCentre field trial took air from outside via a concentric intake/exhaust duct. Researchers noted that the minimum temperature for combustion air was –10°C. During a cold snap, outdoor temperatures in Ottawa can drop below –25°C. In consultation with the manufacturer, the engine's intake was changed from exterior to interior air.

SOLID OXIDE FUEL CELL. The fuel cell required a number of specific changes to the facility for its operation. First, the fuel cell required a gas supply between 14.4 to 34.5 kPa (2.1 and 5.0 psi). This is higher than the normal residential natural gas pressure of 1.7 kPa (0.25 psi). Thus, a separate high pressure natural gas line at 15.5 kPa (2.25 psi) was installed with a high-pressure gas meter. A 200A disconnect with 45A fuses was installed to protect the system.

The fuel cell was cooled by potable water, since it was housed inside the garage in a heated enclosure and there was no danger of freezing. The loop to the dissipation air handler, in the garage outside of the heated enclosure, contained food grade antifreeze. Heat was exchanged between the two loops at a double-walled flat plate heat exchanger.

The fuel cell was different from the tested internal combustion engines in that it could not be easily turned on or off. Due to the fragile nature of the fuel cell's ceramic stack, energy production had to be very slowly ramped up and ramped down to avoid rapid temperature changes. A panel containing approximately 2 kW of loads – 2 heaters, circulation pumps and the dissipation air hander - was connected directly to the fuel cell. In the case of a power outage, the emergency load would help to dissipate excess electricity produced by the fuel cell, and allow it to complete its shutdown procedure safely.

Due to the high internal temperatures of the fuel cell itself, and the uniqueness of the installation, several safety precautions were also taken. Aside from remote monitoring by the manufacturer, CCHT monitored surface temperatures of the unit and installed a security system with high temperature and smoke sensors in the garage. The CCHT data acquisition system was also connected to an alert system that would call researchers in the case of high temperatures, pump failure or power failure. A secondary pump and emergency cooling circuit were put in place, in case of failure of the primary cooling loop.

HYBRID SYSTEM. Since the hybrid cogen/furnace system was already North American approved upon its arrival at CCHT, little to no additional modifications to the facility were required. The system was already fully integrated with a control system for a forced air distribution system.

6KWE COGENERATION UNIT. Electrical modifications were required to accommodate the 6kWe cogeneration unit. Two transformers were installed - one to convert 120V to 100V upstream of the cogeneration unit, and the second to convert the generated 100V back to 120V for supply to the house (see Figure 5). The engine also required the installation of 2 current transformers (CTs) to permit it to see the amount of electricity being imported from the grid, enabling it to load follow. The cogeneration unit also required a 40A fused disconnect.

A food grade glycol solution was used in the cooling loop to prevent freezing of the pipes. The glycol was isolated from the hot water by a double-walled flat plate heat exchanged. While this antifreeze may not have been the best performing product available, it was chosen to minimize the impact on the environment in the case of a leak in the ground loop.

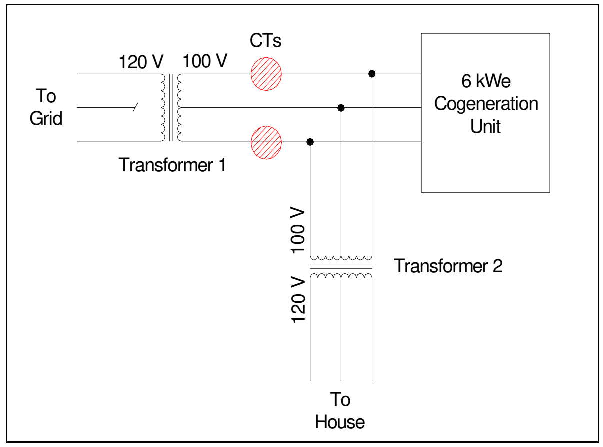

Figure 5. Simplified Schematic of the Existing Transformer setup for the 6kWe Cogeneration Unit

LESSONS LEARNED

LOCATION. The location of the CHP unit plays a large role in installation requirements and performance. For the Stirling engine and hybrid system, the chosen location was the house basement. Both these systems were small, so they could be moved down the basement stairs for the installation. By being in the basement, the heat from the systems was dissipated inside the house. Since both systems only ran when heat was needed, the added heat simply contributed to meeting the heating demands of the house. In warm weather, where only hot water heating for domestic use is required, these additional heat loads in the house may exceed the house heating requirements. In cooling season, this addition of heat to the basement would require additional operation of the air conditioning system to keep the house at a desired setpoint. One advantage of having the CHP unit inside the home is that the house's control system will maintain the house at a set temperature – so no additional cooling or heating systems are required uniquely for the CHP system.

Due to the fuel cell's large size and weight, it was not a candidate for basement installation. Instead, the fuel cell was installed in the garage. The house's garage is outside the house envelope, and is not heated or cooled. For the fuel cell installation, a small enclosed room was created in the garage. This space was heated in winter by a small electric space heater to ensure that the air entering the fuel cell was at an acceptable temperature, and to avoid freezing the pipes in the enclosure. When the fuel cell continued to operate into spring and conditions changed, the fuel cell enclosure began to overheat. Forced ventilation of the fuel cell enclosure was required to keep temperatures to acceptable levels.

Installing a CHP unit outdoors also poses its own set of challenges. The 6kWe cogeneration unit was installed beside the house. In addition to being exposed to the elements and vulnerable to potential vandalism, the engine and coolant lines are exposed to the Ottawa climate. In winter, power had to be provided to the engine to run internal heaters when not operational. Additionally, a heating cable was wrapped around the coolant lines to prevent freezing.

ADAPTING CHPs for NORTH AMERICAN RESIDENTIAL INSTALLATION. A couple of the products tested at CCHT were not manufactured for installation in Canada. While control strategies can be changed to adapt a system to a water storage tank and forced air system, there are inflexible constraints imposed by the existing nature of the utility supply. For example: electricity had to be transformed from 120V to 100V for the 6kWe cogeneration unit – a device from Japan. Two lines of 120V were combined to provide the Stirling engine from New Zealand with its desired 240V electrical supply. The resultant voltage was still not identical to the requirement. The engine did run, however, there were difficulties with the low voltage controls and flame ionization detector, which resulted in numerous "no flame" faults and failure to start. The natural gas line pressure in the house was also at the low end of the required supply.

While the fuel cell was manufactured in Canada, it was not optimized for a residential installation. Apart from the large size of the fuel cell, it required a high pressure of natural gas. A second high pressure line with gas meter was installed in the Test House to accommodate this requirement.

Only temporary approvals were sought to install foreign technologies in a research house. For actual installation in a home, Canadian certifications would be required.

OPTIMIZATION. For most of these systems, the installation was a first in a Canadian home. For this reason, the experiments were mainly centered on demonstrating the integration of the unit in the home, and not on performance optimization. For example, the storage tank used in the Stirling engine field trial was chosen based on availability. The larger the tank, the longer the run-time of the engine and the higher the efficiency. Often two or more separate pumps were required to circulate water and coolant between storage tanks, to the air handler, and from the CHP. Reducing the number of pumps necessary will decrease electrical consumption.

Long lengths of pipe were also necessary at times due to existing positions of equipment. The fuel cell was located in the garage, in order for hot water to reach the storage tank it had to run across the garage ceiling, down to the basement, and across a few meters of the basement.

The electrical modifications to the house were made for 200 Amps to manage any potential future house load. In many instances switches and wires were larger than what would be required in a normal installation. Sizes could be optimized for an individual house and cogen unit, which would result in substantial installation cost savings.

The use of two transformers for the conversion of electricity to and from the 6kWe Japanese cogen unit resulted in substantial losses – approximately 4.7 kWh/day. However, these transformers were only required in order to do early testing on a model designed for use in Japan. Any manufacturer who is interested in selling to the North American market would produce cogeneration units with generators or inverters for North American electrical system characteristics.

REMOTE MONITORING. A line for high-speed communication and data transfer is invaluable, particularly with prototype systems. It allows the manufacturer to monitor their system regularly and diagnose problems remotely. In the case of the fuel cell, the manufacturer was able to monitor and control the inner workings of the fuel cell remotely, while researchers monitored external systems. The demonstration was called to an end due to the premature failure of thermocouples inside the fuel cell core, as detected remotely.

COOLANT AND DOUBLE PLATE HEAT EXCHANGERS. Because the CHP units were set up in conjunction with a combo system to provide both space heating and hot water for domestic use, with the exception of the hybrid engine/furnace system, the system was not a closed loop. In order to prevent coolant from passing to the potable water supply, a double plate heat exchanger was required. One way of eliminating this requirement is to supply hot water for domestic use from a separate system – allowing the CHP system heating loop to be closed. However, without hot water heating demands, CHP operation would be limited to the heating season.

CONTROL OF THE HOT WATER TANK. Optimization of a residential system with a CHP unit would include minimizing the amount of back-up fuel used by the hot water tank, while insuring that hot water and space heat are always available, and maximizing CHP run times. This would involve changing the HWT temperature set-points according to outside temperature and time of day. This control was not attempted during any of these tests due to safety concerns (need for pre- and post purging), but should be considered for future systems.

CONCLUSIONS

Since the initial facility modifications in 2003 to make the CCHT twin houses cogen-ready, researchers have successfully demonstrated and assessed 4 different microCHP technologies: two generations of a Stirling engine, a solid oxide fuel cell, a hybrid internal combustion engine/high efficiency furnace, and a 6kWe cogeneration unit capable of load following.

Throughout these efforts, expertise has been gained in installation and monitoring of microCHP units including electrical connections and heat management. The most important lesson from these installations is that every system is unique and comes with its own set of challenges. Accommodations for electrical generation, thermal storage, heat utilization, and backup heat all need to be carefully designed.

Ideally, CHP units need to be designed by the manufacturer to suit the market. Accommodating systems designed for foreign locations often requires substantial modifications that lead to lower efficiency and less-than optimal performance. For a Canadian home, systems need to be sized for ease of installation, be designed for 120/240 VAC 60 Hz electricity, 1.7 kPa (0.25 psi) natural gas pressure, and for a range of climate conditions. The controls need to be designed to accommodate forced air systems.

ACKNOWLEGEMENTS

Thanks are extended to Luc Saint-Martin who had the vision to make CCHT microCogen ready; to Mike Bell for initiating the first successful cogen project at CCHT and the first residential fuel cell project in Canada; to Walter Kalbfleisch for his electrical design; to Gilles Joanisse and Stephane Diotte for their help in electrical installations; to Advanced Engine Technology Ltd. for their help with the 6kWe cogeneration unit; to our past students Véronique Fournier, Chloé Leban and Edouard Limouse for their diligence in documenting the installations; and to Kathleen Siemens for her ongoing efforts with the Stirling engine.

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