Testing Residential Combined Heat and Power Systems at the Canadian Centre for Housing Technology

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ABSTRACT

A natural gas fired combined heat and power (CHP) system was tested under typical residential conditions at the Canadian Centre for Housing Technology (CCHT). This report describes the upgrades to the house for CHP testing, and the results for a particular Stirling engine CHP system. The upgrades include a thermal utilization module (TUM) that stores heat from the CHP and delivers it to space heat and domestic hot water on demand, and a grid connection that meets utility codes and supplies excess electricity to the grid. The TUM is fully instrumented, and records heat from the CHP, and to space heat and hot water, every minute. Control of the CHP and TUM are programmable. Electrical power to and from the CHP is monitored, and power quality is measured between the CHP, the house and the grid.

The CHP – which can deliver 6.5 kW of thermal power – easily met all house demands for space heating and hot water from late winter through summer. Although thermally driven, and with an electrical output of only 750 W, it supplied a significant percentage of the house electrical demand, and frequently supplied some electricity to the grid. The TUM is designed to work with any CHP that can supply heat as hot water, and the CCHT has a contract to test a solid oxide fuel cell in the near future.

Introduction

Combined heat and power (CHP) systems for communities or individual residences have the potential to greatly increase efficiency and reduce emissions through the recovery of co-generated heat for space heat and hot water. By decentralizing electrical generation, CHPs could also reduce the needs for increased grid capacity and more central power plants. CHPs are well suited for off grid locations, and can provide emergency or backup power during blackouts. CHP systems that are available or being developed include those based on diesel engines, Stirling engines, and fuel cells. Diesel is a proven technology, but creates noise, odors and pollution. Fuel cells have great promise but are in the prototype stage. We have tested a commercially available, natural gas fired, Stirling engine CHP that is sized for individual residences.

These tests demonstrated the characteristics of the Stirling CHP, and showed that the Canadian Centre for Housing Technology (CCHT) is now ready to test fuel cells. Several Canadian companies are now developing residential scale fuel cell CHP systems, and the CCHT has a contract to test a solid oxide fuel cell (SOFC) in the near future.

Powergen, a British Utility, has done laboratory testing and trials in occupied houses of the same CHP unit that was tested at the CCHT, and of three later versions by the same manufacturer. To date, they have installed 44 units in houses, and are in the process of installing another 400 (Harrison 2003). Powergen states that the installed cost is ₤3000 (US$5325), and consumer savings are typically ₤100 (US$180) per year, including the amortized extra cost of the CHP unit. The current model has a larger output (8 kW thermal and 1.2 kW electric vs. 5.8 kWth and 0.75 kWe) (Harrison, 2004). Despite the model changes, we believe that the results presented here are still relevant since we do not know of any other reports that give detailed results of testing CHP units under residential conditions.

Project Background

A residential CHP system must be integrated into the house's electrical, space heat and hot water system. This raises issues such as:

- Sizing the CHP system relative to average and peak electrical and thermal loads
- Whether the CHP system is controlled by demands for electricity (electrical lead), heat (thermal lead), or combinations of both.
- Dealing with the simultaneous production of heat and electricity.
- Optimization of CHP system operation and run time
- Need for and sizing of thermal and electrical storage (especially for off-grid systems)
- Handling and use of possible excess heat in summer
- Grid connection techniques and issues

The project described in this report involved making the houses at the Canadian Centre for Housing Technology (CCHT) CHP ready, and testing an early natural gas fired Stirling CHP system. Modifications were made to the electrical wiring, the HVAC, DHW, and monitoring systems of the CCHT Test House to allow residential CHP systems to be quickly connected, and to allow monitoring of all essential electrical and thermal CHP quantities. Once the house was modified, the CCHT's ability to test CHPs was demonstrated by installing and testing the Stirling CHP system.

At the present time, prototype Canadian fuel cell CHP plants are undergoing laboratory testing by the manufacturers. Discussions with several fuel cell companies have indicated that field-testing of first generation prototypes in a well-controlled but realistic residential setting such as the Canadian Centre for Housing Technology (CCHT) would significantly accelerate development and residential integration of these systems. The CCHT offers an intensively monitored real-world environment, with simulated occupancy to assess the performance of residential CHP systems in secure premises. This facility, which is jointly operated by the National Research Council (NRC), Natural Resources Canada (NRCan) and Canada Mortgage and Housing Corporation (CMHC) was designed to provide a stepping-stone for manufacturers of innovative technologies or systems prior to full field trials in occupied houses. The CCHT is open to projects from manufactures, utilities, government agencies, and others. For more information on the CCHT, see www.ccht-cctr.gc.ca.

Approach

The project consisted of designing and implementing the facility modifications in the following areas:

1. Electrical modifications to integrate the CHP system into the house electrical system, and to allow the CHP to export electricity to the grid.
2. Design and installation of the Thermal Utilization Module (TUM) to integrate the CHP system into the house's space and water heating system.
3. Design and installation of a combined monitoring and control system for the CHP and TUM
4. Installation and connection of the CHP unit.

Once the modifications were completed, the facility was commissioned and experiments were performed from March to June 2003, which included a range of conditions from late-winter space heating through water heating only. This report documents the changes to the CCHT facility, the experimental program and the results of the monitoring.

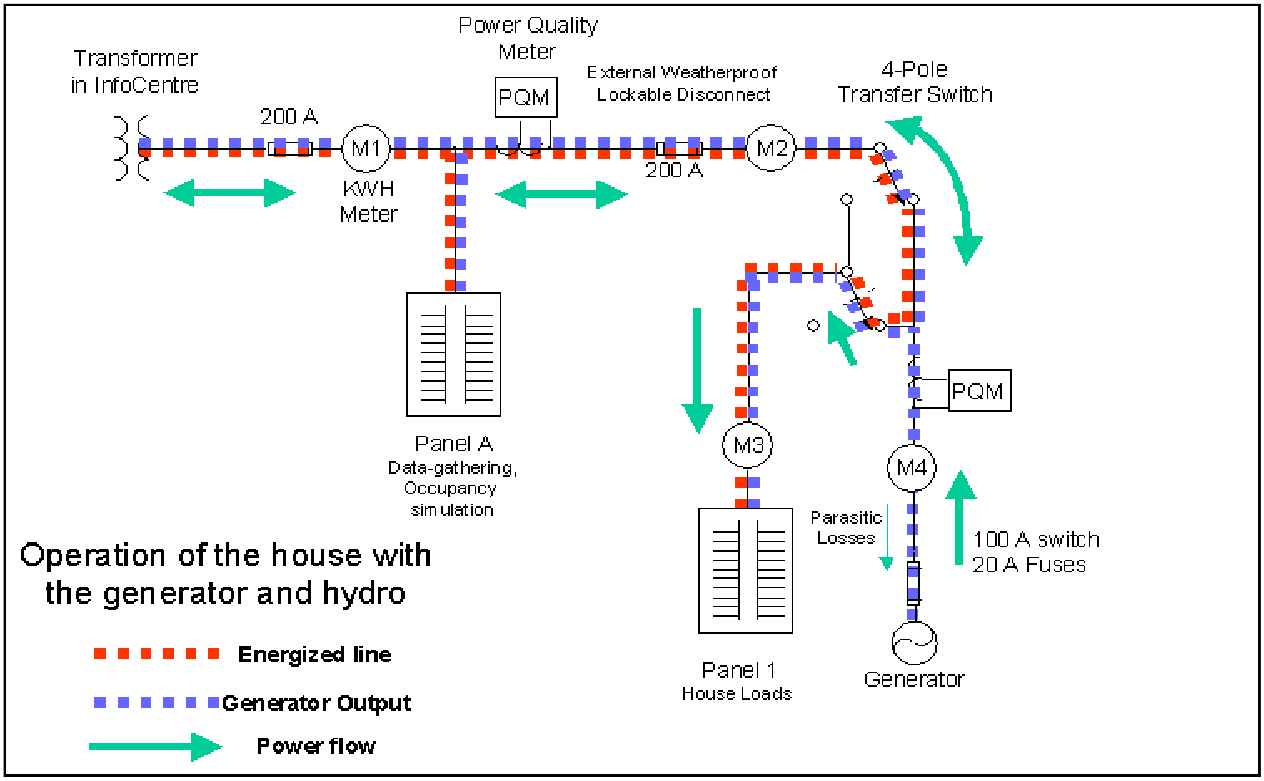
Electrical Modifications

The electrical modifications were designed by one of the authors with previous experience integrating the NRC's commercial-sized CHP system into the grid, and a good understanding and working relationship with local regulatory authorities. The modifications were made to accommodate the installation of CHP systems having a generating capacity up to 40 kWe, for either grid-dependent operation (this project) or stand-alone, grid-independent operation (possible future projects). Although only one of the two CCHT houses was used in this project, the following wiring changes were made to both of them, so in the future two CHP units can be tested simultaneously. The following items were added (see Figure 1).

1. Three bi-directional, pulse generating Kilowatt-hour meters (M1, M2 and M4), connected to the data collection system.
2. Two power quality meters.
3. A weatherproof, padlockable disconnect switch on the exterior of each house to meet requirements of rule 84-028 of the Canadian Electrical Code.
4. A four-pole transfer switch to allow various grid configurations without re-wiring.
5. A 100-amp disconnect / isolating switch to protect and isolate the CHP under test.

The cost of these wiring modifications was CA$6,540 for each house. Because these houses were modified to allow for various types of CHP systems, both connected and off-grid, and sized up to 40 kW, the wiring scheme is more elaborate than would be the case for a normal residential installation. It is estimated that the cost to retrofit a typical residence could be in the range of CA$2K to CA$3K (1.5 to 2.5K in US$). This cost could decrease if simpler installations were acceptable to electrical authorities (such as elimination of the external disconnect switch).

Figure 1. Schematic Diagram of the Updated Wiring and Metering in the CCHT Houses



Thermal Utilization Module Design and Installation

As shown in Figure 2, the Thermal utilization module consists of:

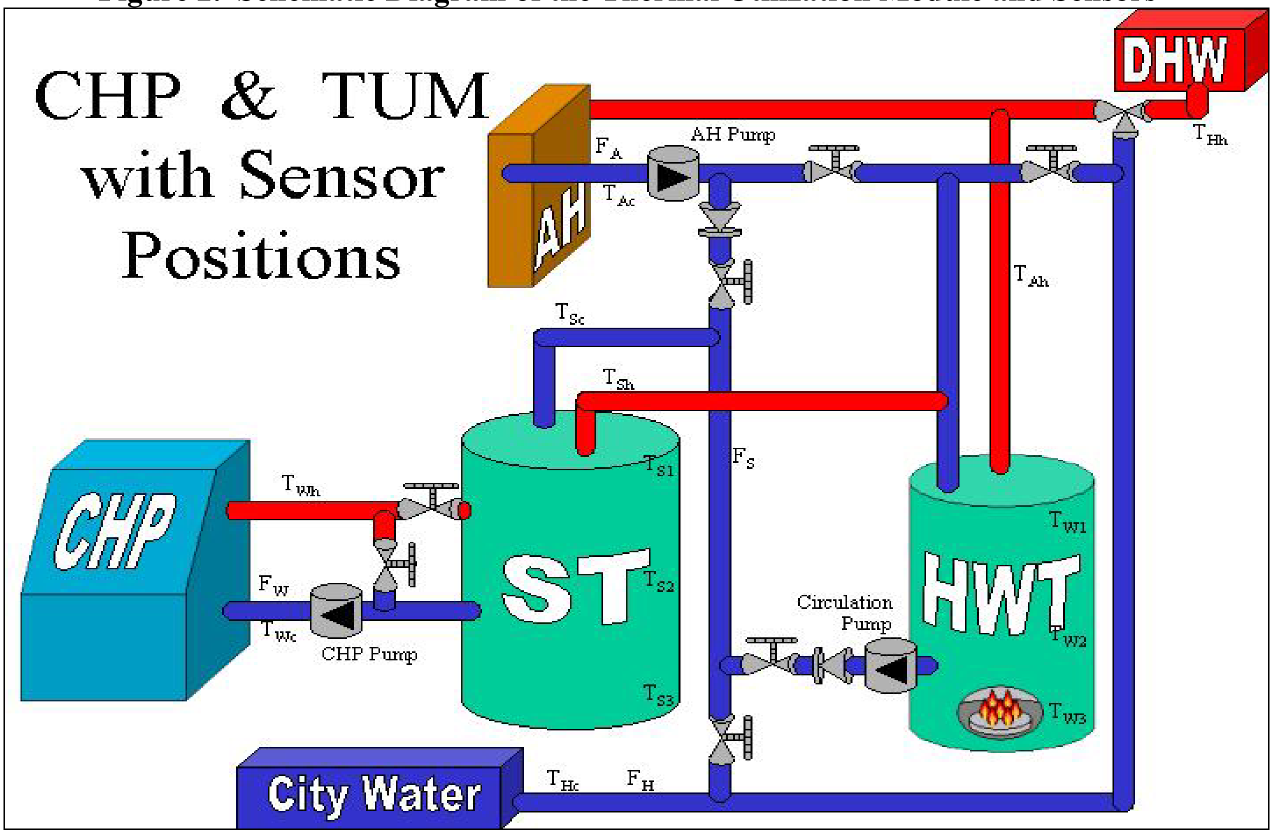
1. the Storage Tank (ST),
2. the Hot Water Tank (HWT),
3. the Air Handler (AH), and
4. Pumps and a Mixing Valve.

The burner on the HWT served as a backup or top-up burner in instances where the CHP unit could not supply all of the heat requirements, either due to heavy demand or shut down of the CHP unit. The TUM was designed so that it could be operated in two different setups by opening or closing the four valves between the ST and HWT. This allowed for the investigation of whether the strategy for directing heated water and cooler return water had an impact on the operating efficiency of the CHP and the TUM.

The Stirling Engine CHP

The commercially available, natural gas fired Stirling engine was purchased prior to the start of this project by NRCan for US$12K - current models are US$7.5K. A Stirling engine is an external combustion device and can burn many different fuels (diesel, NG, propane, biogas, kerosene, and solid fuels) providing the heat exchanger is specifically designed for the selected fuel. It has an induction motor/generator that automatically synchronizes the frequency of its alternating current output to the grid, and cannot operate unless it is connected to an active grid. The generator is used as a motor during start-up and shut-down. The manufacturer's specifications are 750We, 230V AC grid connected, continuous duty, with 20,000 Btu/hour (5.86 kW) of co-generated water heating. The unit was lab tested at the Natural Gas Technology Centre (NGTC) in Quebec, as a separate project preceding this one. It performed well in these tests, producing 750 We gross (with net output of 575 We once coolant pump consumption was subtracted), and 6.5 kW of heat at 80 °C (Natural Gas Technologies Centre 2001).

Figure 2. Schematic Diagram of the Thermal Utilization Module and Sensors



Control Strategy

CHP unit control. The Stirling CHP unit is a heat-driven device that is turned on when there is a need for heat in the TUM. The following is the CCHT's control strategy for the CHP unit:

- The CHP unit and its pump are turned on if:
  - The CHP unit is in stand-by mode (ready to start), and
  - The top of the ST is < 60 C.
- The CHP unit is turned off if its output is > 80 C.
- The CHP circulation pump is turned off 25 minutes after the CHP unit is turned off.

Thermal utilization module control. The TUM controls turn the circulation pump on and off according to temperatures in the Storage Tank (ST) and the Hot Water Tank (HWT):

- The pump is turned on if the Hot Water tank needs heat and can get it from the Storage tank:
  - The bottom of the HWT is between 47 and 70 C, and
  - The Del T between ST top and HWT bottom is > 7 C.
- The pump is turned off if:
  - The bottom of the HWT is not between 47 and 70 C, or
  - The Del T is < 2 C.

The house thermostat controls the operation of the Air Handler (AH) pump and fan, and the demand for hot water is controlled by the house simulated occupancy system.

Instrumentation of the TUM. Each heat transfer loop of the TUM has 2 thermocouples and a flow meter. As shown in Figure 2, the loops are:

- from the CHP unit to the Storage Tank (ST),
- from the ST to the Hot Water Tank (HWT),
- from the HWT to the Air Handler (AH), and
- from the HWT to Hot Water Taps.

Data were collected, and heat flows were calculated, every 10 seconds. These were averaged and saved every minute. Two existing natural gas meters were used to monitor the gas consumption of the CHP unit and that of the HWT back-up burner.

Monitoring and Results

Monitoring took place between March 13 and June 10, 2003. For analysis purposes, the overall monitoring period was split up into 27 individual "runs" for which energy balances and system efficiencies were calculated. In essence, each run can be viewed as an individual experiment. Some of the characteristics of these runs include:

1. The duration of each run ranged from 23 to 65 hours, and averaged 40 hours. Run duration varied due to CHP unit problems and changes from one setup to the other.
2. 3 additional runs during which the CHP unit failed were not analysed with the others. These "failed" runs demonstrated that the gas burner in the HWT serves as a backup, supplying all space heat and HW demands when the CHP fails.
3. In all runs, the house space heat and hot water demands were met.
4. 8 runs used additional heat from the HWT gas burner. This was due to the control strategy and HWT setting, not to lack of available heat from the CHP. For these cases, the gas use by the HWT was 6% or less of total gas use.

Outdoor temperatures during the 27 runs ranged from -15.6 to 32 °C (4 to 90 °F), and can be considered representative of late winter to summer conditions in Ottawa.

Analysis – Calculation of Efficiencies from Energy Balances

The performances of the CHP and TUM for each run are analysed in terms of several efficiencies. In the following definitions of efficiency, Net CHP Electricity is the amount that the unit generated during a run minus the amount that it used during start-ups and shut-downs.

CHP Electrical Efficiency = Net CHP Electricity / CHP Natural Gas Consumption

CHP Thermal Efficiency = Heat to TUM / CHP Natural Gas Consumption

CHP Total Efficiency = Electrical Efficiency + Thermal Efficiency
= (Net CHP Electricity + Heat to TUM) / CHP Nat Gas

$$\text{TUM Efficiency} = \frac{\text{(Heat to Space Heat + Heat to Hot Water + Positive Storage)}}{\text{(Heat from CHP + HWT Nat Gas + Pump Energy)}}$$

$$\text{System Efficiency} = \frac{\text{(Net CHP Electricity + Heat to Space Heat + Heat to Hot Water + Positive Storage)}}{\text{(CHP Nat Gas + HWT Nat Gas + Pump Energy)}}$$

Tables 1 and 2 present the minimums, means and maximums of these efficiencies for the 27 runs.

Table 1. CHP Unit Efficiencies

	Heat	Electric	Total
Minimum	73.1%	4.0%	77.5%
Mean	75.5%	6.4%	81.7%
Maximum	80.5%	9.0%	88.7%
Mean, Setup 1	76.2%	6.1%	81.9%
Mean, Setup 2	75.1%	6.6%	81.6%

Table 2. TUM and Total System Efficiencies

	TUM	System
Minimum	44.2%	38.9%
Mean	56.8%	49.8%
Maximum	75.1%	66.4%
Mean, Setup 1	57.4%	50.3%
Mean, Setup 2	56.4%	49.5%

During the review and analysis of results, it was realized that the quantity of heat required by the house for space and water heating would have an influence on each component of the CHP system. Accordingly, each of the efficiencies was plotted against the thermal output of the TUM (total space and water heating demand). Those functional relationships are shown in Figures 3 & 4. As can be observed, both the CHP unit and the TUM performance are dependent on the TUM output, to varying degrees. The same daily pattern of hot water demand (260 L/day) was used for all 27 runs. When there is no demand for space heat (hot water demand only), the average demand on the TUM is 0.48 kW. For the 10 runs with no space heating, TUM output varied from 0.39 to 0.62 kW, due to different start and end times (different HW demands), and different CHP unit run time patterns. All three curves in Figures 3 and 4 are projected to reach close to the TUM output capacity of 4.40 kW. Some of the trends emerging from this analysis are described below.

CHP Unit Efficiency

The CHP unit efficiency increased only slightly with the thermal load. This is probably due to lower inlet temperatures of the cooling system to the CHP, associated with higher space heating loads. According to the regressions in Figure 3:

- The CHP unit heating efficiency varied from 74% for hot water only to about 79% at system capacity.
- The CHP unit electrical efficiency varied from 5.5% to about 9% at system capacity.
- The CHP unit total efficiency varied from 79.5% to about 88% at system capacity.

System Efficiency

Observations on the system efficiency (Figure 4) include:

- The energy efficiency of the System shows significant dependence on thermal load. This is due to the fact that the stand-by losses from the TUM are relatively constant, while the useful heat varies mainly with space heat load.
- According to the regressions, the system efficiency varies from 41% for HW only to over 70% at CHP capacity.

The system efficiency compares favourably with the efficiency (energy factor) of domestic water heaters, while generating by-product electricity. These efficiencies could be improved with optimized thermal utilization module design. As shown in Tables 1 & 3, there were only small differences between the two setups investigated, although setup #2 appeared to generate a slightly better electrical efficiency.

Improvements to the TUM efficiency could be based on modelling to determine whether two tanks are needed, or whether one (larger) one would do. If two are needed for some applications, then one tank could be left unheated during non-space heating seasons, thus reducing heat losses by approximately one half. Similarly, a single stratified tank could have only its top half heated during warm seasons. Control of the HWT burner should be integrated into the TUM control rather than left to the original tank aquastat.

Parasitic Pump Losses

The TUM includes 3 pumps that consume between 73 and 86 W each. The CHP pump uses an average of 1.19 kWh per run, or 7.8% of the CHP net electrical output in each run. All three pumps together average 1.95 kWh per run, which is 12.4% of the CHP net output, or 0.4%.

Figure 3. CHP Unit Efficiencies vs. Thermal Utilization Module Output

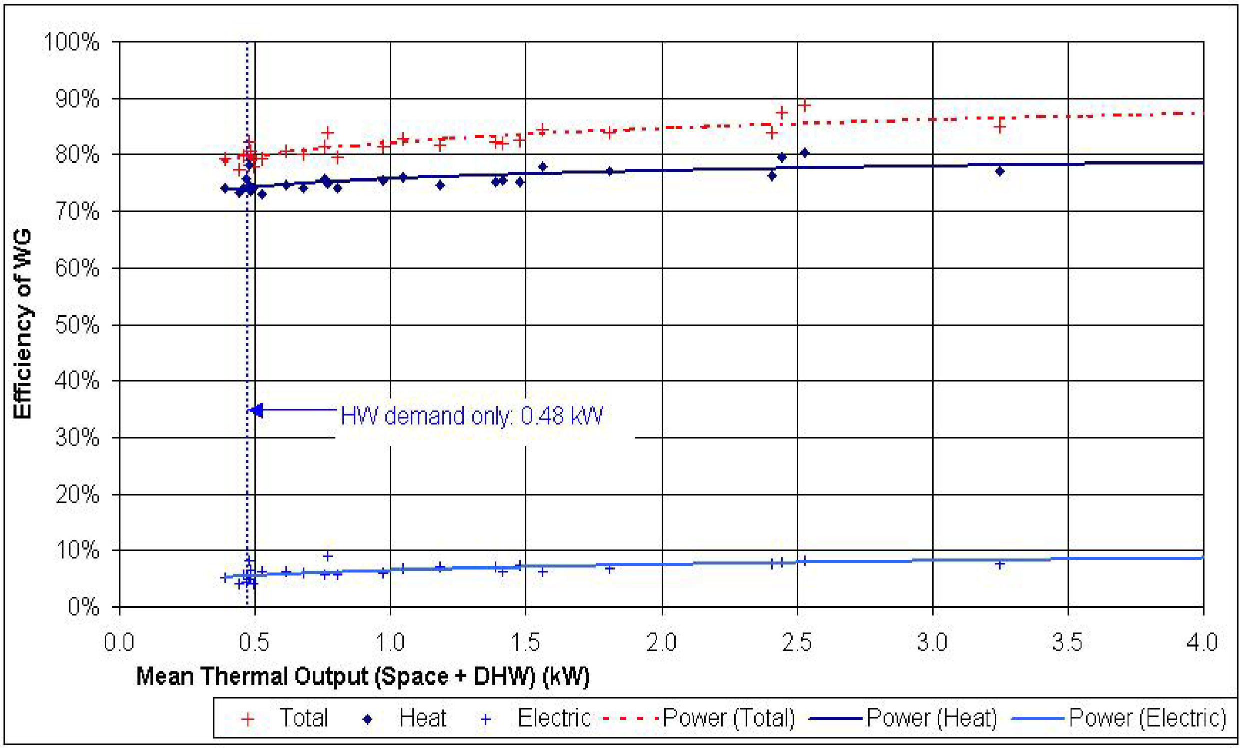
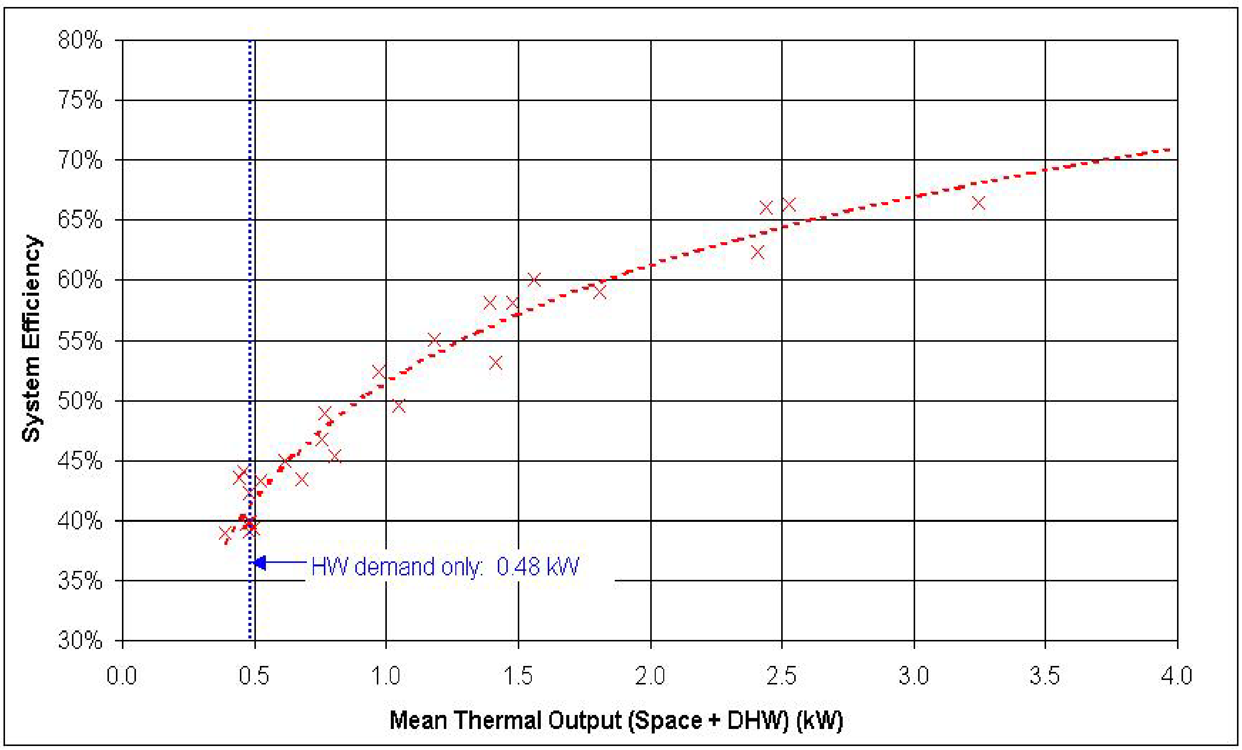


Figure 4. System Efficiency vs. TUM Output



of the System output (heat plus net CHP electric). The pump energy is therefore low in comparison with CHP electrical generation, and insignificant compared to total output

Furthermore, pump energy could be reduced if the pumps were optimized in terms of size, efficiency and control, and would be even less significant if the electrical output of the CHP were higher, as it would be with a fuel cell sized for a house.

Potential for Electrical Savings and Exports to the Grid

Two examples were selected to highlight how much electricity is generated by the CHP in proportion to house electricity demand, and where that electricity goes. The first example, shown in Figure 5a and Table 3 represents one of the colder periods of testing, while the second run in Table 3 is for a milder day. The figure shows house demand, supply by the CHP unit, and net house demand from the grid. The reduction in electrical requirements from the grid due to the CHP unit is apparent, as are periods of electricity being exported to the grid (negative grid supply). Table 3 summarizes the electricity balance for these two runs. While most of the electricity produced by the CHP unit goes to the house (94 and 98% in these examples), there were still instances of export to the grid (6 and 2%), even with this small heat led generator. The CHP unit supplies important percentages of the house's electricity requirement (43 and 25% in these examples).

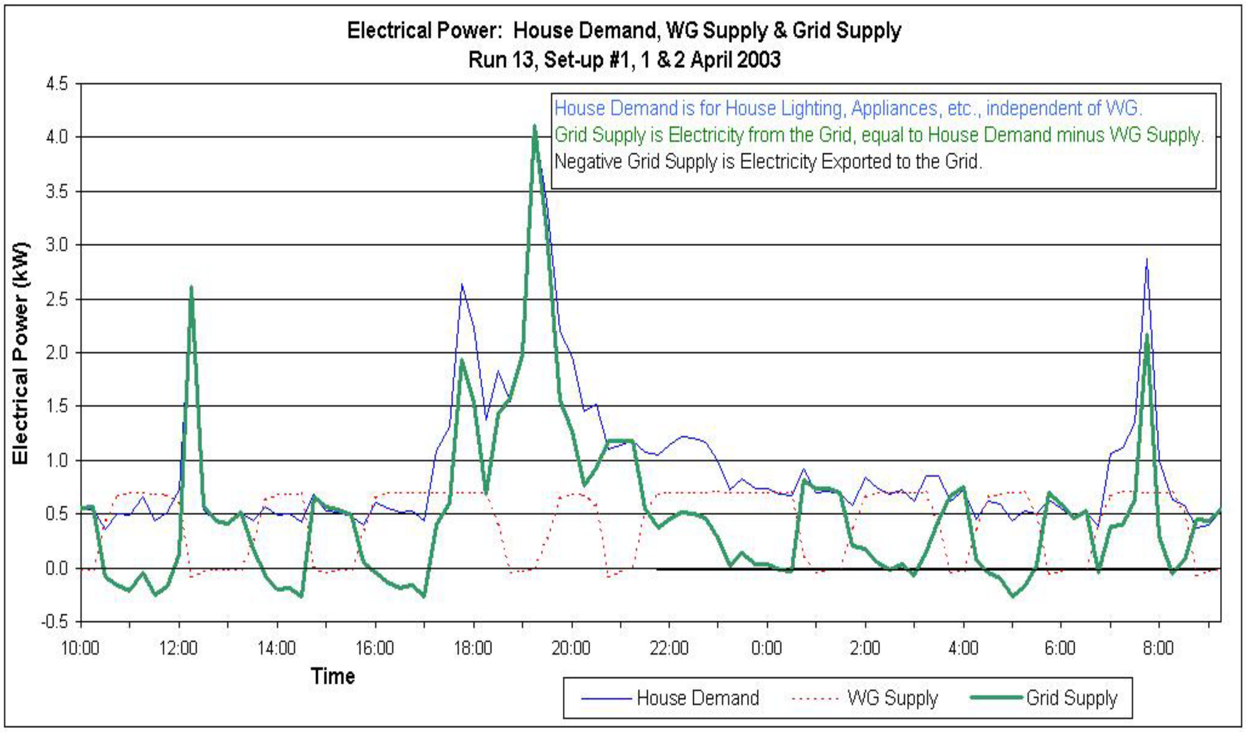
Role of Thermal Storage Interfacing Between CHP and House

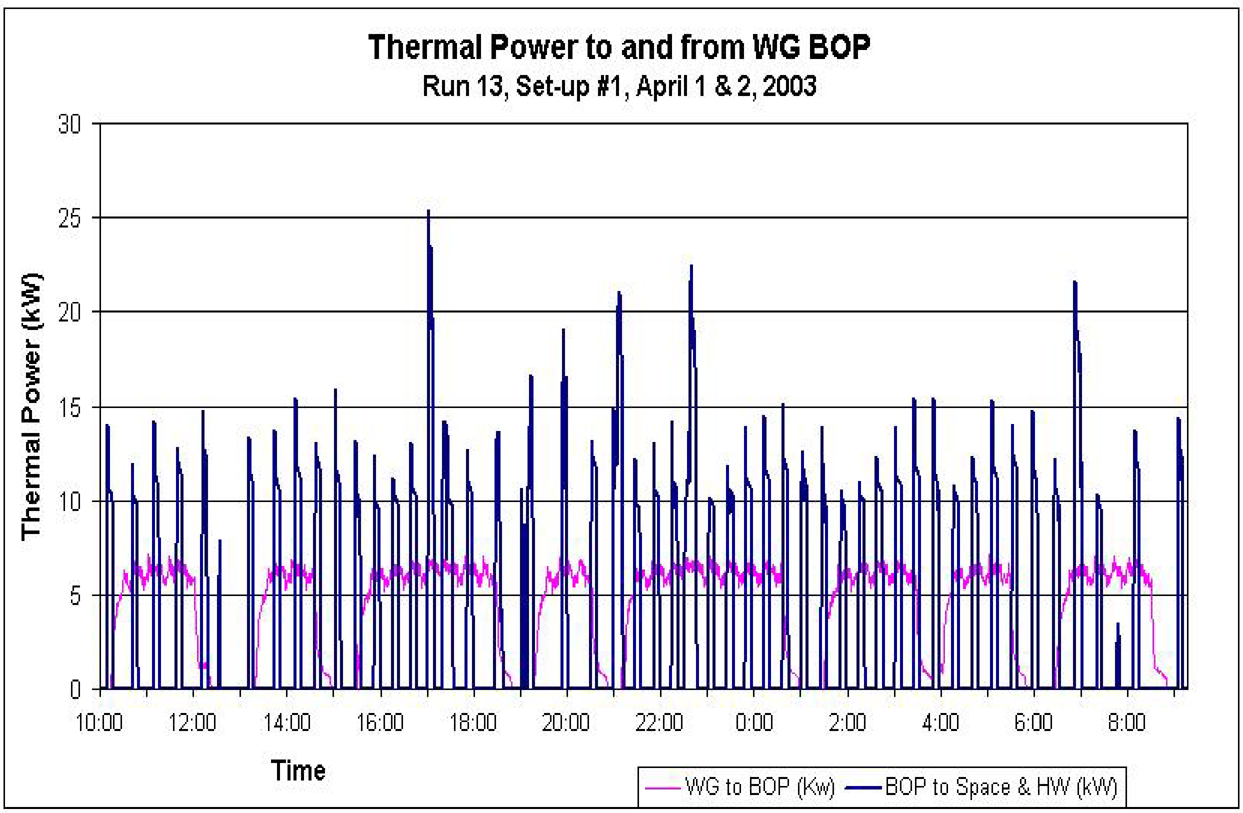
Figure 6b shows how the thermal storage of the TUM receives heat from the CHP unit over longer periods but in small quantities, and delivers that heat to the air handler and hot water devices in shorter but more heat intensive bursts. It is these characteristics that highlight the importance of the storage design. An optimized storage system could probably stretch the operation of the CHP unit into even longer runs, reducing standby losses, while satisfying the needs of the air handler and hot water system on their own demand schedules.

Table 3. Example Electricity Balance for the CHP Supply and the House Demand

	Run 13 (April 1 & 2)		Run 23 (April 24)	
	kWh	%	kWh	%
CHP Unit:				
CHP electricity generation	9.95	100%	5.34	100%
CHP electricity used by the house	9.36	94%	5.23	98%
CHP electricity exported to the grid	0.60	6%	0.11	2%
House:				
Total house electricity consumption	21.74	100%	20.72	100%
Electricity supplied by the grid	12.38	57%	15.49	75%
Electricity supplied by the CHP	9.36	43%	5.23	25%

Figure 5a & b. Electrical and Thermal Power Profiles for the CHP & TUM, Run 13.





Future Work

NRCan is working on a project to test the current version of the Stirling engine CHP in an occupied house. The CCHT has a contract with a Canadian fuel cell manufacturer to demonstrate the first residential fuel cell in a house in Canada. This solid oxide fuel cell (SOFC) will generate 5 kW of electricity and 6 kW of heat. Tests should begin in the near future, and the SOFC will be monitored intensively during winter, summer and shoulder seasons.

Conclusions

The primary objective of this project was to develop and demonstrate a test facility at the CCHT that can assess residential CHP systems, and their integration into houses, under real-world conditions. This objective has been met: with the modifications to its electrical and thermal installations, combined with the monitoring and data analysis techniques demonstrated in this project, the CCHT now has a proven track record that clearly demonstrates that it is ready to test a range of combined heat and power systems – including fuel cells – in residential applications. The proven features include the bi-directional grid connection with the ability to switch between grid-connected and independent units, power meters and power quality meters, and the thermal utilization module that stores CHP generated heat, and releases it on demand.

The second objective was to quantify the performance of an early residential CHP system (Stirling engine based) and to begin to examine building integration issues such as HVAC interface, storage, control, and CHP system sizing. This objective has also been met over the course of the project. The TUM, controls and data collection have performed as expected and provided a good base for tests and evaluations of the CHP. The efficiencies of the CHP unit, the TUM, and the system were all quantified for a range of operating conditions and good functional relationships were developed that describe the performance of this system over a broad range of such conditions. The complementary analytic techniques developed over the course of the study shed some light on the role of system sizing and storage size. Both of these factors were shown to affect duty cycle and standby times, the latter being identified as a major component of the TUM efficiency.

The CHP system was shown to compare favourably with the efficiency of domestic water heaters, while generating by-product electricity. This efficiency could be improved by optimized TUM design.

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