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Synthetically derived profiles for representing occupant-driven electric loads in Canadian housing

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As one objective of the International Energy Agency's Energy Conservation in Buildings and Community Systems Programme Annex 42, detailed Canadian household electrical demand profiles were created using a bottom-up approach from available inputs, including a detailed appliance set, annual consumption targets and occupancy patterns. These profiles were created for use in the simulation of residential cogeneration devices to examine the issues of system performance, efficiency and emission reduction potential. This article describes the steps taken to generate these 5-min electrical consumption profiles for three target single-family detached households – low, medium and high consumers, a comparison of the generated output with measured data from Hydro Québec, and a demonstration of the use of the new profiles in building performance simulations of residential cogeneration devices.

Keywords: electric load profiles; demand modelling; residential electrical consumption; residential cogeneration; combined heat and power

1. Introduction

The combined production of heat and electricity from distributed generation technologies such as fuel cells, Stirling engines and internal combustion engines offers the potential for energy savings. Because these devices provide both electrical and thermal outputs, an accurate assessment of their performance requires a realistic prediction of the electrical and thermal loads demanded by the host building.

Building performance simulation is an ideal analysis method to assess these technologies. Well-developed methodologies exist to predict the temporal thermal demands for space heating and cooling. Models also exist to predict the temporal electrical demands of heating, ventilation and air conditioning (HVAC) equipment that operates in response to thermal demands (e.g. pumps and fans). Building performance simulation, however, lacks the predictive capabilities for occupant-driven or discretionary electrical loads (e.g. lighting and appliances). The creation of representative occupant-driven electric load profiles for residential buildings was one objective of Annex 42 of the International Energy Agency's Energy Conservation in Buildings and Community Systems Programme (IEA/ECBCS). This article treats the development of such profiles for Canadian housing.

A survey of existing electrical load profiles for Canada revealed that detailed measured data are limited (Aydinalp 2001). In most cases, data from only a small number of houses are available. A number of data sets were for the whole house, making it difficult to differentiate between HVAC and non-HVAC loads. Additionally, small communities of houses were often combined, creating an 'average' data set. By this aggregation of data, consumption peaks and valleys were rounded out. The data collection intervals were usually large – hourly data sets. As shown in Figure 1, these long sampling intervals result in a smoothing of the load profile, and overall lower magnitude of peaks. The impact of this smoothing can be highlighted by an example: if a grid-connected residential cogeneration system supplied a constant 800 W of electricity to the loads in Figure 1, by the hourly data we would predict that 24% of the electricity would be exported to the grid this day. However, if the higher resolution 5-min data are used for the same calculation, a much higher 30% export of the generated electricity is predicted. Depending on the shape of the consumption profile and the shape of the generated electricity profile, the difference could be even greater. This difference in exported electricity caused by the resolution of data has a direct impact on economic and emission calculations.

Rather than using the limited existing measured data, the objective of the current work was to

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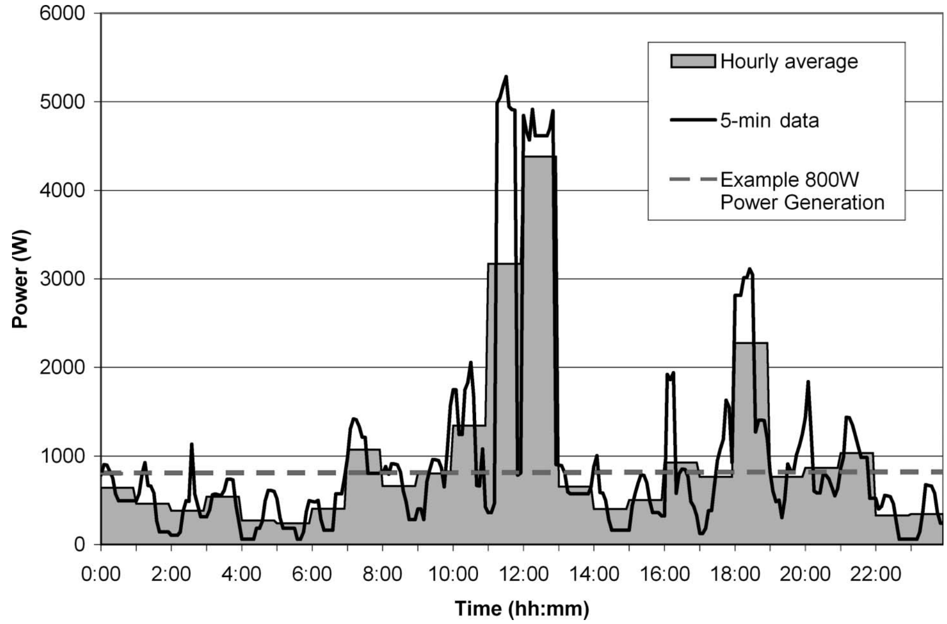

Figure 1. Generated load profile example – averaging the data hourly smoothes out peaks and valleys.

synthetically generate a new set of representative profiles at 5-min time resolution for the occupant-driven electrical loads in Canadian housing.

This article first reviews the previous efforts to synthetically generate the electric load profiles. This is followed by a description of the methodology employed in the current study. Following this, the new synthetically generated profiles are compared with measured data. The use of the new profiles in building performance simulations of residential cogeneration devices is then demonstrated. Finally, concluding remarks are provided.

2. Previous efforts to synthetically derive electric load profiles

Work has been performed by a number of researchers to develop detailed residential electrical load profiles from limited sources of data using a bottom-up approach: reconstructing the expected daily electrical loads of a household based on appliance sets, occupancy patterns and statistical data.

Walker and Pokoski (1985) constructed electric load profiles from individual appliance profiles. They introduced the concept of using 'availability' and 'proclivity' functions to predict whether someone is available (at home and awake) and their tendency to use an appliance at any given time. These functions were applied to predict individual appliance events, which were then aggregated into a load profile. Profiles were simulated and then compared with measured data from the Connecticut Light and Power Company. This preliminary modelling work was conducted for the purpose of predicting loads and load changes due to social and economic factors, in order for power generation planning.

Capasso *et al.* (1994) created household load profiles beginning with detailed information on human behaviour and also appliances. Functions in Capasso's model were based on such factors as occupant availability, activities, human resources (including number of hands, eyes, etc.), and also appliance ownership. The detailed data on occupant actions was readily available, thanks to an extensive time of use survey in Italy 1988–1989, which included activity diaries from 40,000 individuals. Although Capasso did generate profiles for individual houses, the goal was then to aggregate the profiles to predict the overall consumption of a group of households in a given area based on socioeconomics and demographics. This information could then be used to predict the response to rate policies and demand side management strategies.

Similarly, Paatero and Lund (2006) created electrical profiles to examine the demand side management strategies for Finland. However, they used a different bottom-up approach based on statistical consumption data, and not detailed occupant behaviour. Electrical data from hundreds of apartments in Finland formed the basis for the statistics used to fabricate these hourly demand profiles.

Yao and Steemers (2005) created a simple method of predicting household electrical loads for the design of renewable energy systems in UK. Their load prediction was based on detailed inputs including the number of occupants, occupied hours, the time period when each appliance will be used and the number of hours of use per day. This is a simpler method to the one described herein for creating the Canadian load profiles. Where Yao and Steemers' generator allows an appliance event to occur with equal probability at any time during a designated time period (an input that needs to be specified of each appliance and household), the Canadian synthetic profiles depend on statistical use curves to weigh the likelihood of appliance events occurring throughout the day.

The main thrust of recent work in load profile generation has been towards examining the grid effects of distributed generation systems including renewable energy technologies. For this, a large number (thousands) of diverse and detailed residential electrical load profiles are required. Because the collection of such a vast amount of data is costly, being able to predict these loads is essential.

Researchers in the UK have been generating UK-specific detailed load profiles to examine grid effects from the use of highly distributed power systems. The modelling of occupancy behaviour is key to creating the diversity of profiles required for assessing the grid impact of multiple residences with generation systems. This work relies on a bottom-up approach beginning with understanding occupancy patterns – predicting both the availability of occupants and activity levels. Jardine's (2008) occupancy model relies on identifying periods of activity where the electrical load is above the baseload, based on a sample of 100 measured domestic electricity load profiles. Richardson *et al.*'s (2008) occupancy model draws on a UK time-use survey from 2000, with thousands of participants keeping diaries of their activities every 10 minutes.

Despite this wealth of knowledge and the resulting high-resolution profiles for the UK, the UK electrical profiles are not of use for simulations of Canadian homes. The differences between Canadian and UK consumption patterns at the household level are large. Notwithstanding socioeconomic and demographical differences, the annual non-HVAC electrical consumption in the typical Canadian home is 6567 kWh/year, roughly twice that of the typical UK home (Knight *et al.* 2007).

The purpose of generating Canadian load profiles for the Annex 42 work is not to examine the grid effects or demand side management, but for the simulation of residential cogeneration technologies: to look at system performance in terms of ability to meet heating and electrical requirements of the house, and to examine the system efficiency and emission reduction potential. Instead of a large number of diverse profiles, a limited number of 'typical' Canadian load profiles are required. A single such profile needs to embody the characteristics of an average house, but also represent the variation of actions possible in a number of households. By achieving this, the set of profiles will be useful to compare the ability of different technologies and control strategies to meet a variety of demand scenarios.

3. Method for profile generation

The generated profiles described herein are not the first set of generated electrical profiles for Canadian homes. One set of non-HVAC electrical profiles was generated by Canadian company, Kinectrics, to simulate the occupant-driven loads. Annual electrical data sets were produced based on engineering assumptions as to the kind of appliances and lighting that are inside the home and when the occupants are expected to turn them on. Different annual profiles were created for combinations of two or four occupants, high/low energy users, and young/old occupants in an urban/rural setting. Each data set featured only a few different daily load profiles that were organized to form a full year of data: a weekday, Saturday, Sunday, laundry day and vacation days. The disadvantage to this approach is that this represents a limited number of scenarios, which may not necessarily challenge a system as in the real world. Also the profiles were produced at a 15-min resolution: a resolution of 5 min or lower is desirable for the simulation of residential cogeneration technologies.

To generate the load profiles for Canadian households, information was compiled on the expected annual consumption of the households, the appliance stock and characteristics and occupant usage patterns. Where no data were available, it was necessary to make educated assumptions. This section outlines the inputs for profile generation, and also the logic behind the generated profiles.

Detailed 5-min non-HVAC electrical load data were desired for three different typical families/households:

(1) Low electricity demand. An energy conscious family in an average detached house.
(2) Medium electricity demand. A regular family in an average detached house.
(3) High electricity demand. A large family with no interest in energy conservation, living in a large detached house.

3.1. Inputs

3.1.1. Annual consumption targets

Average 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 the Office of Energy Efficiency of Natural Resources Canada (NRCan 2005). 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, government surveys, 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 ones). Table 1 presents the electricity use for appliances and lighting for the average Canadian household, based on data for 2003 for the average stock of appliances.

These data for the average Canadian household formed the basis for setting electricity use targets. According to the 2006 Census of Canada (as reported by the Canada Mortgage and Housing Corporation 2008), the Canadian housing stock consists of 55.2% single-detached homes, 4.8% semi-detached and duplex, 5.6% row housing and 34.4% apartment and other dwellings. Because the average Canadian household as detailed in Table 1, includes all these dwelling types and the target household for profile generation is the single-detached home, adjustments to the targets were made. A separate set of targets was developed for each of the three households (low, medium and high energy) as follows.

The Energy Use Database tells us that the average Canadian household (including detached home, row houses and apartments) has 121 m^2 of floor area, whereas the average area for a detached house is 141 m^2. Because a detached house is larger than the average household (which includes a substantial amount of apartments), a detached house can also be assumed to have more occupants. Both the low and medium energy households assumed the average detached house size with a liveable space of 141 m^2, whereas 282 m^2 of floor space (twice the area of the average detached home) was chosen for the high-energy target household.

Table 1. Electricity use for appliances and lighting for the average Canadian household (average stock of appliances) (NRCan 2005).

	No. of appl.	KWh/year	KWh/appl.
Refrigerator	1.24	992	801
Freezer	0.56	346	614
Dishwasher	0.55	39	72
Clothes washer	0.81	62	76
Clothes dryer	0.79	780	988
Range	0.92	711	769
Other appliances	8.98	1896	
Lighting (/m^2)	121 m^2	1742	14.4
Total		6567	

The average number of appliances per household, as listed in Table 1, is less than one for most appliances. This again is due to the mix of households that make up the average Canadian household, including apartments with smaller appliance sets. It was assumed for the purposes of simulation that each of the three types of single-family detached households has a refrigerator, dishwasher, clothes washer, dryer and range. Because the average number of freezers per household was low, only the medium and high electricity demand households were assumed to have a freezer. The high demand household was assigned a second fridge, given that the average number of fridges per household exceeded one.

In addition to adjusting the number of appliances per household, the electricity consumption data for appliances and lighting have been adjusted to reflect the differences between households by the introduction of a 'use factor' for the appliances. The use factor presents the use of the appliance compared to average use. No data were available for the use factors, therefore they were assumed based upon common ideas about the differences between the average house and the average detached house. The use factors are not validated through any available data. The end result is a set of appliances and annual consumption targets for each of the three households, as listed in Table 2.

3.1.2. Appliance characteristics

To generate profiles, information was required on the size, duration and shape of the individual electrical loads. Each of the eight loads listed in Table 1 (refrigerator, freezer, dishwasher, clothes washer, clothes dryer, range, other appliances and lighting) were simulated individually and then combined to create daily 5-min non-HVAC load profiles.

For the dishwasher, washer, range and dryer, the electrical draw was calculated using the cycle duration, the cycles per year for the average house, and the target annual consumption (kWh/year) as described in Equation (1). The target annual consumption for the medium-energy house was chosen for this calculation, because the medium house is assumed to be an average single detached home. The average cycles per year were derived from standard appliance test methods of the Canadian Standards Association (CAN/CSA-C373-92, CAN/CSA-C361-92 and CAN/CSA-C360-98). Cycle duration was chosen based on measured data from the Canadian Centre for Housing Technology (CCHT) twin house research facility. At the CCHT, a simulated occupancy system triggers daily lighting and appliance events in a real single detached home.

Appliance consumption data are captured on a 5-min basis by individual electric meters with a resolution of 6 Wh/pulse (Swinton 2001).

$$\text{Average appliance electrical draw} = \frac{\text{annual consumption}}{\text{cycle duration} \times \text{cycles per year}} \quad (1)$$

The calculated electrical draw was compared with data from the Canadian Renewable Energy Network (Natural Resources Canada 2004), thus ensuring that the consumption targets, cycle duration, cycles per year and electrical draw were all realistic and properly related as in Equation (1). To match the target annual consumptions for the low and high electricity demand profiles, the number of cycles per year was varied. Details of appliance loads and cycles are presented in Table 3.

It was assumed that both the low and medium target houses were equipped with identical refrigerators, whereas the high-energy house contained two of the same model. The shape of the refrigerator and freezer profile was based on measured refrigerator data from the CCHT. The shape of the CCHT profile was scaled to match the target annual consumption. The same 70-min cycling sequence, as observed and measured in the CCHT refrigerator data, was repeated

Table 2. Energy targets for the profile generator.

	Medium-energy detached house			Low-energy detached house			High-energy detached house		
Load	Appliances per household	Factor	kWh per household	Appliances per household	Factor	kWh per household	Appliances per household	Factor	kWh per household
Refrigerator	1	1.0	801	1	1.0	801	2	1.0	1601
Freezer	1	1.0	614	0	0.0	0	1	1.3	798
Dishwasher	1	1.3	94	1	0.8	58	1	1.7	122
Clothes washer	1	1.3	99	1	0.8	61	1	2.0	152
Clothes dryer	1	1.3	1284	1	0.6	593	1	2.0	1976
Range	1	1.0	769	1	1.0	769	1	1.4	1077
Other appliances		1.3	2465		0.8	1517		1.7	3223
Lighting	141 m^2	1.0	2030	141 m^2	0.5	1015	282 m^2	1.0	4061
Total (kWh/year)			8156			4813			13,011
Average daily (kWh/day)			22.3			13.2			35.6

Table 3. Appliance characteristics for generated profiles.

Appliance	Power (W)	Cycle duration (min)	Cycles per year	Target annual consumption (kWh/year)
Dishwasher	467	30–45	200 (low) 322 (medium) 418 (high)	58 (low) 94 (medium) 122 (high)
Washer	505	30 (two 15-min cycles)	242 (low) 392 (medium) 601 (high)	61 (low) 99 (medium) 152 (high)
Dryer	4115	30–60	192 (low) 416 (medium) 640 (high)	593 (low) 1284 (medium) 1976 (high)
Range	1600	15–70	678 (low) 678 (medium) 950 (high)	769 (low) 769 (medium) 1077 (high)
Refrigerator	265 (peak)	–	–	801 (low) 801 (medium) 1602 (high: 2 fridges)
Freezer	 202 (peak) 263 (peak)	–	–	0 (low) 614 (medium) 798 (high)

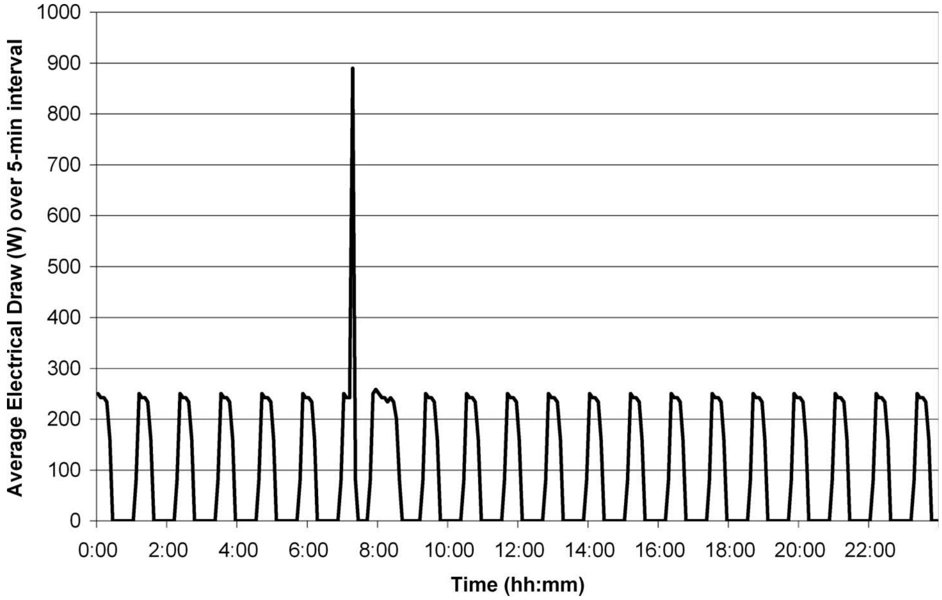

Figure 2. Sample daily refrigerator consumption profile.

throughout the day and randomly offset forward or backward to ensure a different starting point each day. A single 105-min defrost cycle was also added randomly during the day, matching the cycle sequence. A sample daily refrigerator consumption profile is shown in Figure 2.

A wide variety of loads fit in the category ‘other appliances’. To simulate these loads, a list was compiled from a series of buyer’s guides published by Natural Resources Canada (2002, 2004). This list of appliances with their power rating and expected hours of operation per month is presented in Table 4. Additionally, a constant baseload of 65 W was chosen based on Natural Resources Canada (2002) data and applied to account for standby loads from appliances such as microwaves, telephones, clocks and VCRs.

The list of lighting loads is presented in Table 5. These loads were assumed based on reasonable lighting loads, as measured at the CCHT. It was also assumed that the low-energy house would be using more efficient light bulbs, whereas the high-energy house would simply have more lighting loads based on its larger floor area.

3.1.3. *Time of use probability profiles*

To create realistic load profiles, knowledge of occupancy patterns is required. Canadian occupancy information was limited, so a simpler approach was taken to occupancy-driven control than the methods used by Jardine (2008) and Richardson *et al.* (2008).

Table 4. Other appliance loads (NRCan 2004).

	Appliance	Power rating (W)	Hours per month
Kitchen	Blender	350	3
	Coffee maker	900	12
	Deep fryer	1500	8
	Exhaust fan	250	30
	Electric kettle	1500	15
	Hot plate (one burner)	1250	14
	Microwave oven	1500	10
	Mixer	175	6
	Toaster	1200	4
Laundry	Iron	1000	12
Comfort and health	Electric blanket	180	180
	Fan	120	6
	Hair dryer	1000	5
Entertainment	Computer (desktop)	250	240
	Computer (laptop)	30	240
	Laptop charger	100	240
	Radio	5	120
	Stereo	120	120
	Television	100	125
	VCR	40	100
Outdoors	Lawn mower	1000	10
Tools	Drill	250	4
	Circular saw	1000	6
	Table saw	1000	4
	Lathe	460	2
Other	Sewing machine	100	10
	Vacuum cleaner	800	10

The range, dishwasher and washer events were guided using normalized energy use profiles from Pratt *et al.* (1989), as found in the Building America

Research Benchmark Definition (Hendron 2006); see Figure 3. These curves were applied to predict the occupants' actions, and to control the probability of an event occurring. The higher the fraction of total daily usage, the higher the probability that an event occurs. For example, a range event would be far more likely to occur at 17:00 than at 4:00. Because there is only one range, one dishwasher and one washer per house, only a single event from each appliance was allowed to occur at any one time: a new event could only be triggered if the appliance was in an 'off' state. The time of use curve for the dryer was not used to control its operation. Instead, since the time of use profile for the dryer was the same shape and offset from the time of use profile for the washer, dryer events were coupled to washer operation. Dryer cycles were allowed to trigger between 30 and 120 min following the end of the washer cycle.

The 'other appliance' time of use curve controlled the probability of a small appliance being activated. Events were allowed to overlap, and whenever an appliance was randomly activated, the load was chosen from the list in Table 4. The likelihood of a small appliance being chosen from the list is based on the listed hours of operation per month. For instance, an iron event – with only 12 h of operation per month, was four times more likely to occur than a mixer event – with only 3 h per month of operation. Each appliance event was assigned a random duration between 5 and 120 min.

Lights were controlled in a similar manner. Three different lighting profiles were implemented: one for winter, one for summer and one for the shoulder period (Figure 4). December through February were considered winter, and June through August were considered summer, with the remaining 6 months considered as the shoulder season. Lighting events were allowed to overlap, and the load for each event was chosen randomly from the lighting loads listed in Table 5. Each lighting event was assigned a random duration between 5 and 120 min.

Table 5. Lighting loads.

Name	Average house load (W)	High-energy house load (W)	Low-energy house load (W)
Lighting load 1	60	120	30
Lighting load 2	100	200	50
Lighting load 3	120	240	60
Lighting load 4	410	820	205
Lighting load 5	200	400	100
Target annual consumption (kWh/year)	2030	4061	1015

3.2. *Logic*

By combining the appliance characteristics, the time of use probability curves and the annual consumption targets, realistic 5-min non-HVAC load profiles can be created. The control logic for generating load profiles allowed an appliance to come on by chance at any time throughout the day. The probability of any event happening in any 5-min period is controlled by the fraction of total daily usage for that hour (from the time of use curves) and a variable arbitrarily named the 'chance factor' c, as shown in Equation (2). As c is increased, the probability of the event occurring decreases. Thus, by varying c the total number of annual events changes, and thus the desired annual

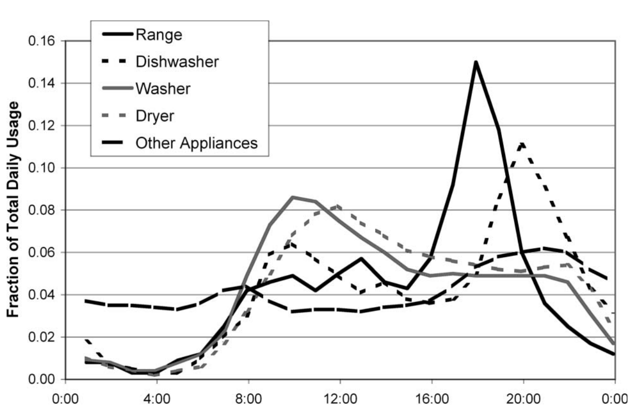

Figure 3. Time of use curves for different loads (Pratt *et al.* 1989).

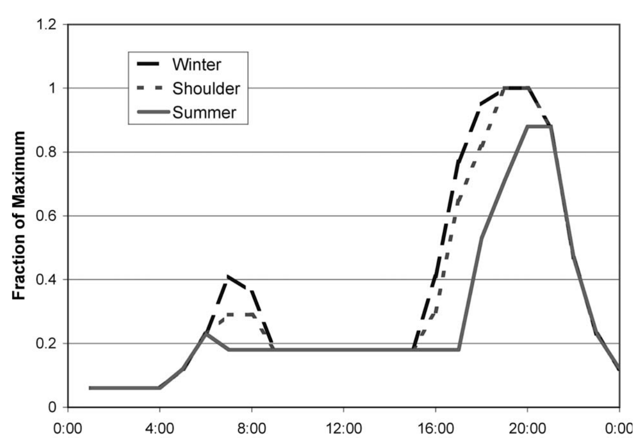

Figure 4. Lighting time of use curves for winter, summer and shoulder seasons (Pratt *et al.* 1989).

consumption target can be attained. For each appliance, c was sought through iteration, as outlined in Figure 5.

$$\text{Probability} = f/c \tag{2}$$

where f is the fraction of total daily usage – from the time of use curves, c is the chance factor – chosen to attain the desired annual consumption target.

When controlled in this manner, the average electrical draw of an appliance over a large number of days will tend towards the shape of the time of use curve. Figure 6 illustrates the result from applying the washer time of use curve to generate data for the high energy, average energy and low energy target households. Although an identical washer is operated in each of the three households, the number of events is adjusted to meet the target annual appliance consumption by changing the chance factor.

3.3. Output

The eight loads were generated individually and then combined on a daily basis to create a random 5-min daily load profile for the house. Although there is no change in the controlling assumptions of the profile generator for weekend and weekday operation, the stochastic variations produced through the generation process create a wide range of daily profiles. When used in simulation, these profiles will expose CHP devices to a variety of test conditions.

A sample of the generated daily profiles from Year 1 of the medium-energy house is represented in Figure 7. These figures present the minimum (Figure 7a), average (Figure 7b) and maximum (Figure 7c) daily profiles from a constant set of inputs. In these figures, individual loads are presented stacked one upon another, accumulating to the total 5-min electrical draw shown on the y-axis.

A total of 365 days were produced from each set of the three sets of inputs (low, medium and high energy households), with seasonal variations for lighting. These generated days were strung together to produce an annual set of 5-min data. Three yearly profiles were created for each household type. The resulting annual profiles are compared in Table 6.

Figure 8 presents the average hourly load from the yearly profiles in graphic form. Note the small variation between the 3 years of data for each

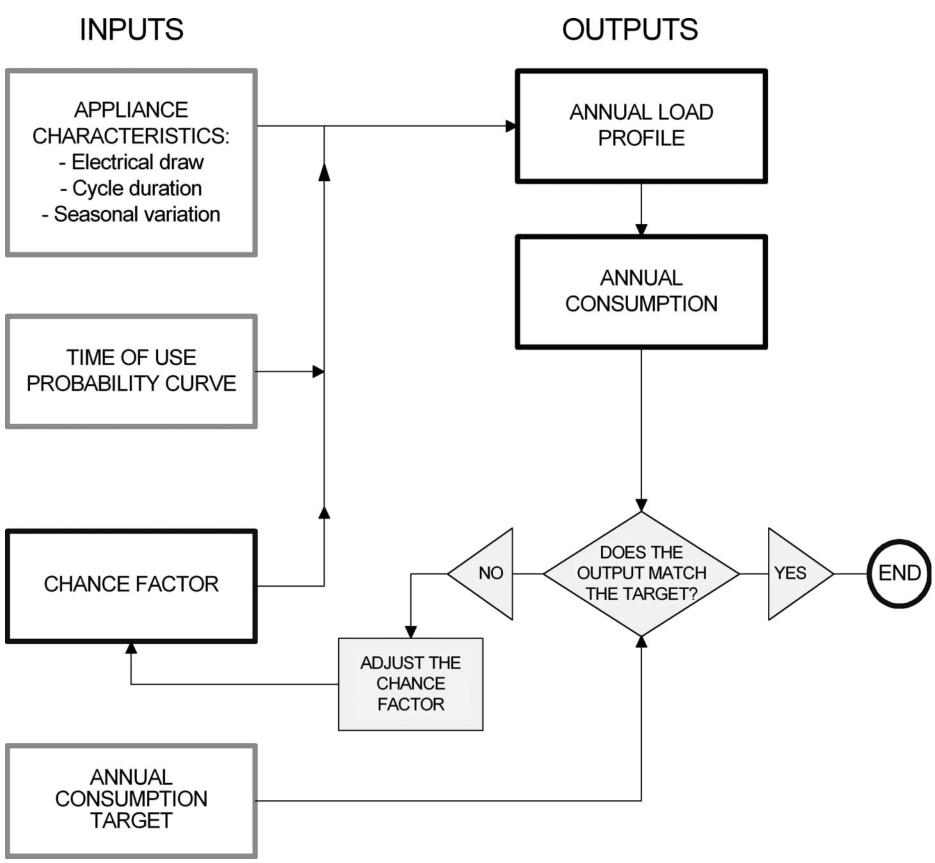

Figure 5. Flow chart for selecting the chance factor.

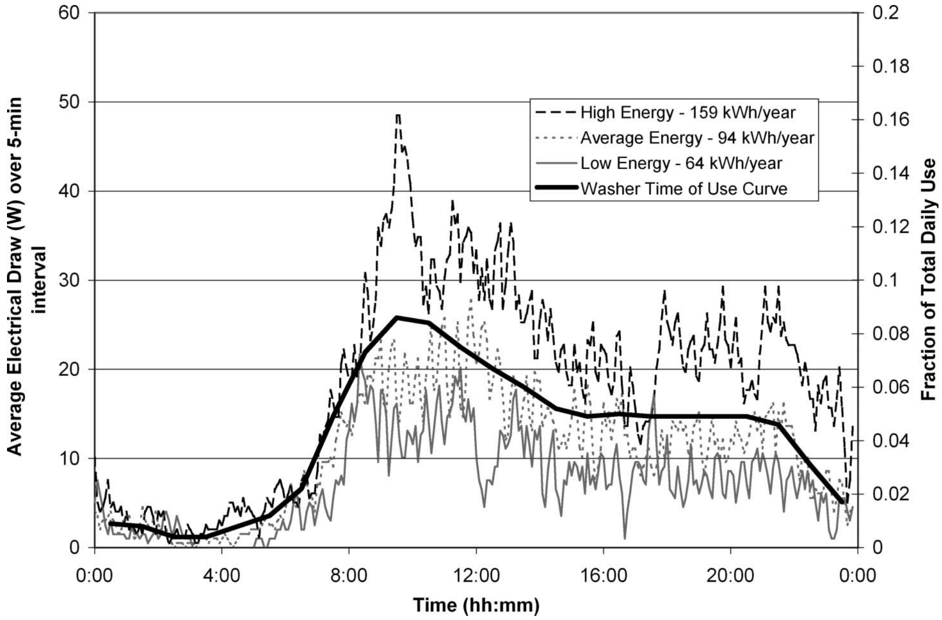

Figure 6. Average daily washer consumption – based on 1000 randomly generated daily profiles.

household. This is a result of the stochastic generation process and the degrees of freedom available during the profile generation.

4. Comparison of the generated profiles with measured data

During the mid 1990s, Hydro Québec performed an experimental programme to assess the impact of energy saving measures in electrically heated houses in Quebec. For 2.5 years, the total cumulative electricity consumption over 15-min periods was measured, as well as the separate amounts for space heating and for domestic water heating. The balance between the total electric consumption and the latter two quantities provided suitable non-HVAC electricity demand profiles for use in building simulation.

These measured demand profiles contained data samples at 15-min intervals between 1994 and 1996. Houses were selected for comparison to the generated data based on their total annual consumption and the annual targets already established. Low energy and medium energy measured profiles were chosen as listed in Table 7. Although two houses from the survey had annual consumptions in the range of the low electricity demand target, and two survey houses were in the range of the medium electricity demand target, there was no house in the survey that showed consumption comparable to the high electricity demand target.

A comparison of the generated data to real-life consumption curves provided by Hydro Québec (15-min data) has shown that they are similar in terms of peaks, averages and total yearly consumption. A visual comparison of 1 week of measured and generated profile data for a medium-energy house is presented in Figure 9. In this figure, the 5-min generated data has been aggregated to create 15-min data for a better comparison. Generally, real-life curves (Figure 9b) tend to be more repetitive than the generated data (Figure 9a). This is, however, not considered a fault, because the generated profiles are designed to expose CHP units to a variety of conditions in a single year.

A statistical comparison using probability curves with 100 W bins shows that there are some differences between the measured data and the generated data. In this comparison, the 5-min generated data were first converted to 15-min averaged data – to match the time step of the measured data.

For the low-energy use households (Figure 10), the measured data show a concentration of loads around 400 W and a lack of loads below 200 W, whereas the generated data has a significant amount of small loads below 200 W. This suggests that the generated data should likely have a higher constant baseload to match these particular measured profiles.

In the comparison of measured data to generated data for the medium-energy households (Figure 11), the generated data resembles the probability curve of Houses 30 and 48. Once again, a higher baseload would help to improve the fit of the generated data to the measured data. Interestingly, there are two 'dead zones' in the measured data, at 800 and 1600 W.

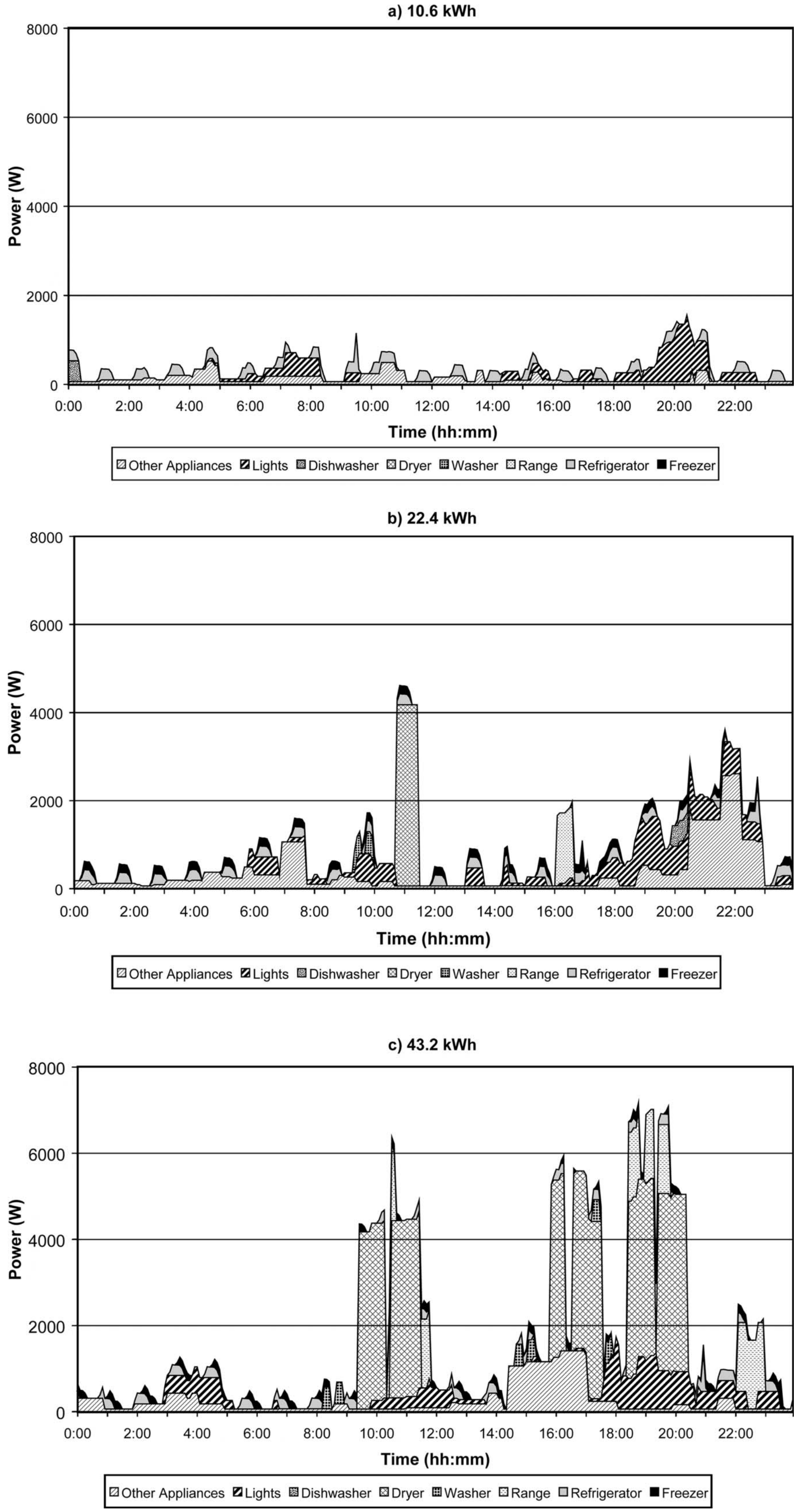

Figure 7. Sample daily profiles from Year 1 of the medium-energy house, for (a) minimum daily consumption (b) average daily consumption (c) maximum daily consumption.

Table 6. Comparison of annual profiles.

	Low-energy detached house			Average detached house			High-energy detached house		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Annual consumption target (kWh/year)	4813	4813	4813	8156	8156	8156	13,011	13,011	13,011
Annual consumption (kWh/year)	4762	4672	4837	8159	8218	8112	12,956	13,140	13,044
Average daily consumption (kWh/day)	13.1	12.8	13.3	22.4	22.5	22.2	35.5	36.0	35.7
Maximum daily consumption (kWh/day)	28.0	24.8	26.2	43.2	39.2	42.3	53.1	58.4	55.4
Minimum daily consumption (kWh/day)	6.4	6.9	6.9	10.7	10.4	11.7	21.2	19.9	20.6
Average daily draw (W)	544	533	552	931	938	926	1479	1500	1489
Maximum yearly 5-min peak (W)	8099	7432	6973	8808	8313	8760	10,480	10,927	10,047

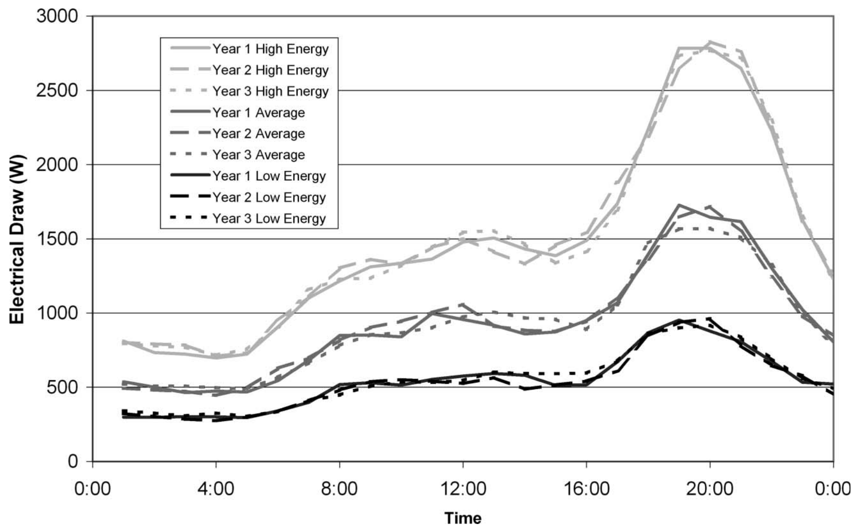

Figure 8. Yearly average profiles for low, average and high energy houses, hourly data.

Apparently, loads from 701 to 800, and 1501 to 1600 W are not attainable with the lighting and appliance set in this home.

These measured data represent a very small subset of houses. The lack of detailed measured data is the reason that generated profiles were created – to simulate the large variation of possible daily loads in current housing stock. There is a need for greater understanding of the appliance sets and loads found in houses as well as occupancy patterns. With updated information, the simulated profiles could be improved.

5. Sensitivity analysis on the use of generated profiles *versus* measured profiles

A performance assessment study of a Stirling engine residential cogeneration system was performed as part of the work for IEA/ECBCS Annex 42. In this study, a comparison was made between a new technology for the combined production of heat and power at the scale of a single residence (a prototype Stirling engine system) and the conventional way of separate production of heat (in a natural gas-fired furnace) and electricity (using large-scale power plants). The generated electricity demand profiles presented in Section 3.3 had been used as inputs to the simulations in this study. The availability of the set of measured 15-min electricity consumption profiles from Hydro Québec (see Section 4) now allowed the comparison of the simulation results for generated electricity demand profiles to those using measured profiles. All simulations were conducted using ESP-r, a whole-building simulation program (Clarke 2001). Further details on the simulated systems can be found in the Annex 42 report (Ribberink *et al.* 2007).

For this comparison between the use of generated and measured profiles, the three medium energy-use generated profiles (5-min time basis) were selected together with four measured non-HVAC simulation profiles (15-min time basis), which had annual electricity consumption close to that of the selected

Table 7. Comparison of characteristics of generated and measured profiles.

Profile	Dates	Annual consumption (kWh/year)	5-min peak load (W)	15-min peak load (W)	Average load (W)
Low energy					
Generated Y1	–	4762	8099	7834	544
Generated Y2	–	4672	7432	7065	533
Generated Y3	–	4837	6973	6549	552
House #21 Y1	1 January–31 December 1994	4460	–	5620	532
House #21 Y2	1 January–31 December 1995	4750	–	5080	542
House #40 Y1	1 January–31 July 1995 + 1 August–31 December 1994	5223	–	8100	596
Medium energy					
Generated Y1	–	8159	8808	8070	931
Generated Y2	–	8218	8313	8038	938
Generated Y3	–	8112	8760	8328	926
House #30 Y1	1 January–28 February 1996 + 1 March–31 December 1994	8265	–	8080	943
House #30 Y2	1 January–31 December 1995	8426	–	7020	962
House #45 Y1	1 January–28 February 1996 + 1 March–31 December 1994	7425	–	6568	848
House #45 Y2	1 January–31 December 1995	7713	–	7028	881
High energy					
Generated Y1	–	12,956	10,480	10,313	1479
Generated Y2	–	13,140	10,927	9910	1500
Generated Y3	–	13,044	10,047	9292	1489

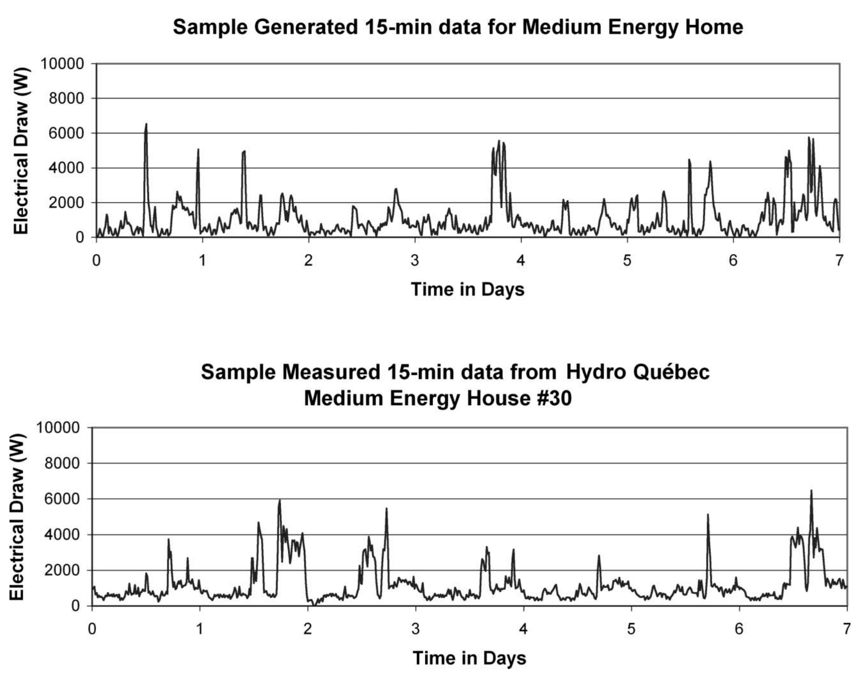

Figure 9. Sample generated and measured non-HVAC loads for a medium energy home.

generated profiles. Table 8 presents the most important characteristics of the seven selected profiles.

The three generated and four measured electricity demand profiles were used as inputs to annual simulations of the prototype Stirling engine residential cogeneration system and the conventional reference system of separate production of heat and power. For these seven cases, the difference in performance between the Stirling engine system and the conventional alternative was expressed in the reduction of GHG emissions due to the application of the Stirling engine system and in the increase in overall efficiency

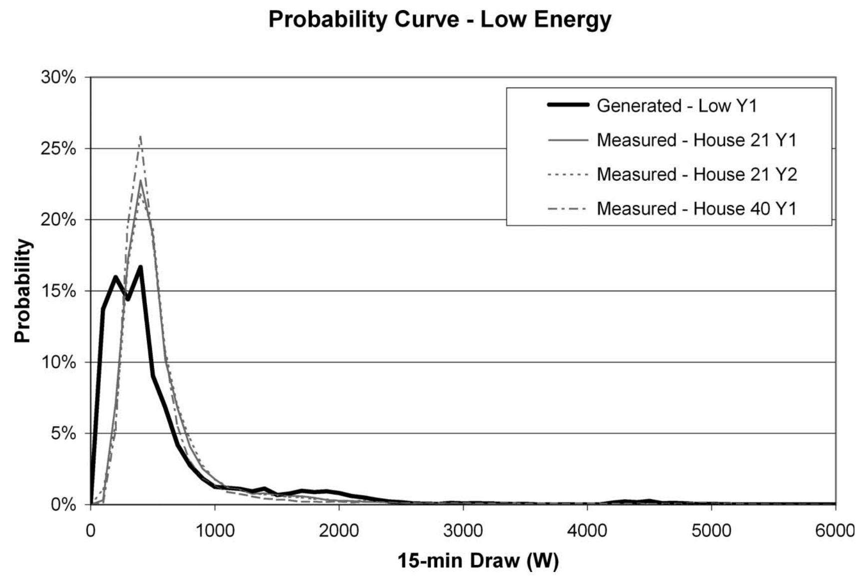

Figure 10. Statistical comparison of generated and measured data for low-energy homes, 100 W bins.

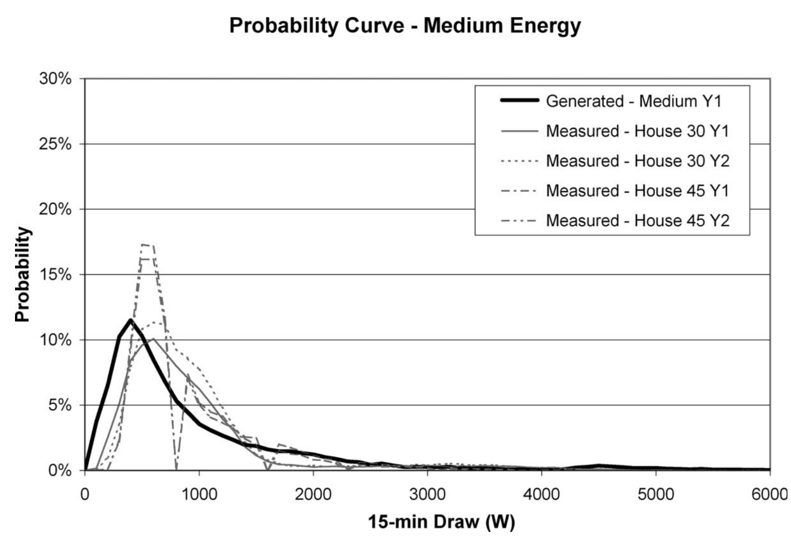

Figure 11. Statistical comparison of generated and measured data for medium energy homes, 100 W bins.

of providing heat and electricity to the house (the net house efficiency). Because the Stirling engine system used was an early prototype that had not been optimized, all cases actually showed an increase in GHG emissions and a decrease in net house efficiency when the Stirling engine system was applied. For this article, however, the focus was not the performance of the prototype Stirling engine system in comparison to the reference system, but the difference in the results between the simulation cases using the three generated profiles and those of the four measured profiles.

Figure 12 displays for all seven simulation cases the (negative) reduction of GHG emissions due to the application of the Stirling engine system compared to the reference cases using the same electric load profiles. The results for the seven cases are very similar. All cases show an increase in GHG emissions by around 1.3%. The small variation in the GHG emission reduction for the seven cases is most likely caused by the differences in emission intensity of displaced on-the-margin grid power (Mottillo *et al.* 2006).

Figure 13 presents the results indicating the (also negative) improvement of the net house efficiency when compared with the reference cases, assuming electricity imports to come from coal- or natural gas-based electricity production. Again, the annual simulations

Table 8. Characteristics of generated profiles and measured profiles.

Profile name	Annual electricity consumption (kWh)	Peak electricity consumption (W)	Heating season[a] electricity consumption (kWh)
Generated profiles (5 min)			
Medium Y1	8159	8808	4861
Medium Y2	8218	8313	4790
Medium Y3	8112	8760	4802
Measured profiles (15 min)			
House #30 Y1	8265	8080	4957
House #30 Y2	8426	7020	5147
House #45 Y1	7425	6568	4494
House #45 Y2	7713	7028	4687

[a]Heating season is defined here as the period October through April.

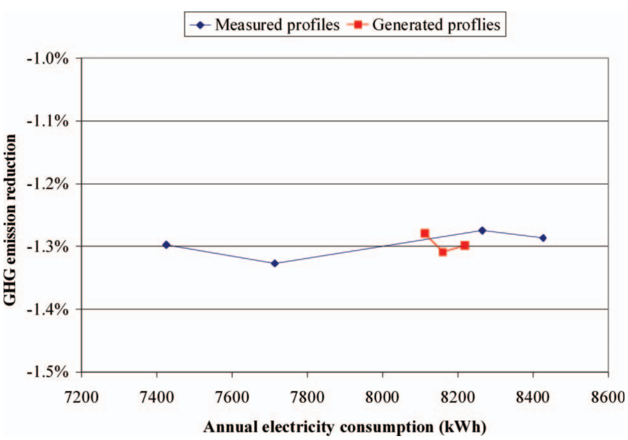

Figure 12. Comparison of GHG emission reduction of a Stirling engine-based residential cogeneration system using measured profiles and generated profiles (negative values indicate actual emissions increases).

of the Stirling engine system using the generated and measured electricity profiles show very similar results in their comparison to the reference cases. The decrease in net house efficiency for the cases using the generated profiles are very close ($\leq$0.1%-point) to the trend for the cases using measured profiles for both electricity from coal and for natural gas-fired power plants as source of grid electricity. A potential cause for these differences is displayed in Figure 14: the cases using the generated profiles appear to benefit less from the casual gain from electricity consumption during winter than the cases with the measured profiles. However, more detailed investigation is required to explain this difference based on, e.g., the difference in 'peakiness' between the two sets of profiles and/or the different time bases of the generated and measured profiles. These investigations may result in general conclusions on the use of these sets of generated and measured profiles in building the simulation studies. This work, however, is outside the scope of the current study.

It should also be noted that the more negative results for the system using natural gas-based electricity in Figure 13 are caused by the fact that natural gas-based system in itself was more efficient than the coal-based system. The decrease in performance due to the use of the prototype Stirling engine system therefore has a more pronounced effect on the net house efficiency for the cases using natural gas-based power production.

6. Conclusions

A set of three annual non-HVAC load profiles was created successfully for each of three target Canadian households (low, medium and high energy detached), based on a limited amount of available information. These profiles were applied successfully in the simulation of a Stirling engine residential cogeneration system, and compared favourably to simulation results using measured non-HVAC profiles from Quebec homes.

Despite the lack of planned variations for weekdays, weekends and holidays, the current load profile generator generates a large variety of days – incorporating greater day-to-day variety than a measured profile. This variety of days is well suited to test a residential cogeneration system by exposing it to a wide range of consumption profiles. If it is still desired, the days from a year's worth of generated data could be selected to represent weekdays, weekends and holidays, and arranged accordingly.

This method of profile generation could be readily adapted to provide not only an electrical output but also a water draw profile. Already, the performance of individual appliances such as the dishwasher and clothes washer is recorded. Thus, water consumption profiles for these individual appliances could be included at the appropriate times. More data for time of use of other water draws, not associated with appliances, would be required in order to add tap draws, shower draws, bath draws, etc.

Although the synthetic Canadian profiles proved useful in simulating a residential cogeneration system, and compared favourably to simulation results with measured data, there is still room for improving the realism of the synthetic profiles. The largest limiting factor to these improvements is the availability of input data. Lighting and small appliance loads together make up over half the non-HVAC energy requirements of the average Canadian home. Unfortunately, these

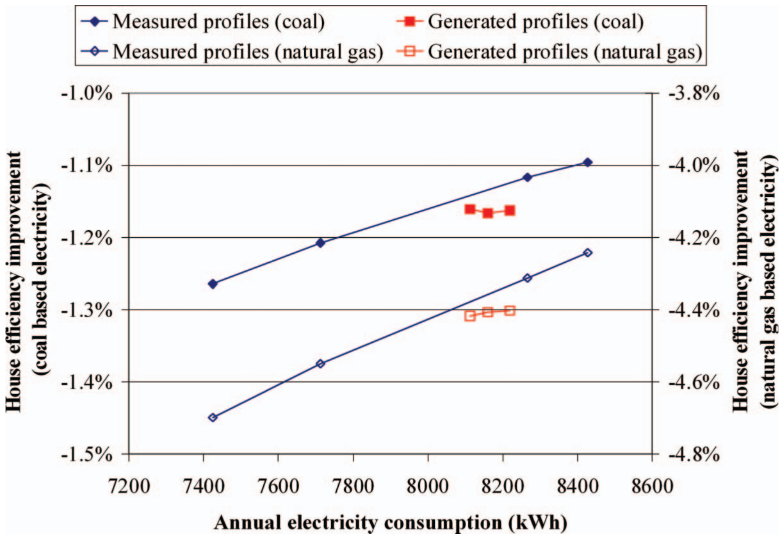

Figure 13. Comparison of net house efficiency improvement for a Stirling engine-based residential cogeneration system using measured profiles and generated profiles.

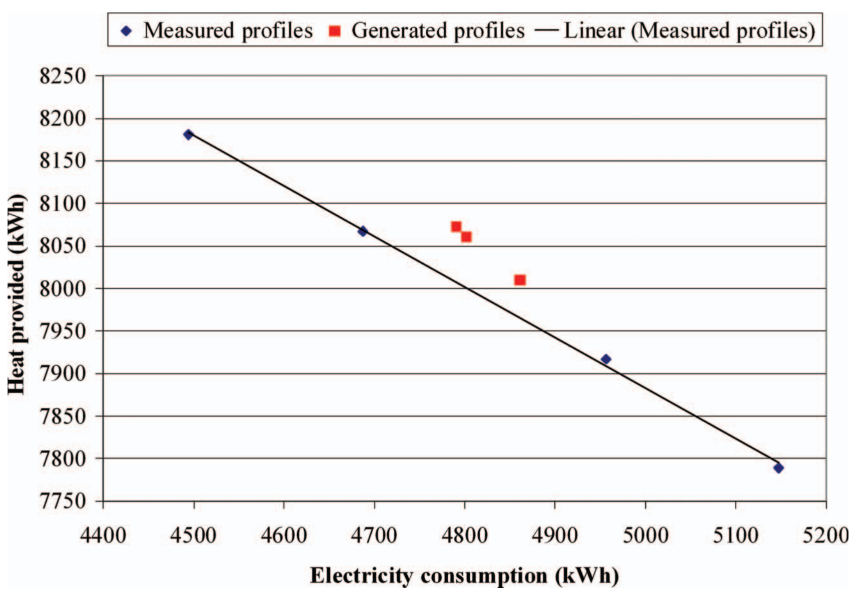

Figure 14. Relation between electricity consumption and heat provided for space heating during the heating season using measured and generated electricity consumption profiles.

loads are the least understood, and required many assumptions during the profile generation process. More detail is needed on the type of small appliance and lighting loads in houses and particularly their usage patterns. Baseloads are also a factor – as indicated by the statistical comparison of the generated profiles to a few measured houses – the baseload appears to be underestimated. Again, a better understanding of baseloads in houses would lead to improvements in profile generation.

The current generated profiles include only seasonal variations for lighting. Other seasonal variations could be added to improve the realism. For instance, less dryer use in the summer due to drying of clothes outside, and lower refrigeration loads in winter due to increased efficiency at cooler indoor temperatures could be incorporated.

Improvements could also be made to increase the resolution of the profiles to 1 min or even less. This would help to create the profiles that show the same frequent variations as real-time loads, and would be particularly useful for examining the interaction of residential renewable energy sources (particularly wind and solar), house loads and the grid.

The method of generating non-HVAC domestic load profiles could easily be applied for different target households, or even different countries. The limiting factor of applying this method is the availability of the inputs: knowledge of what are typical appliance sets, occupancy usage patterns and ranges of annual consumption is essential.

Acknowledgements

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References

Aydinalp, M., *et al.*, 2001. *Characterization of energy load profiles in housing literature review*. Halifax: Canadian Residential Energy End Use Data and Analysis Centre, Dalhousie University.

Canada Mortgage and Housing Corporation, 2008. *Housing market information: CHS-demography 2007* [online]. Available from: http://www.cmhc-schl.gc.ca/odpub/esub/64693/64693_2008_A01.pdf [Accessed 12 September 2008].

Capasso, A., *et al.*, 1994. A bottom-up approach to residential load modeling. *IEEE Transactions on Power Systems*, 9, 2.

Clarke, J.A., 2001. *Energy simulation in building design*. 2nd ed. Oxford: Heineman. ISBN 0750650826.

CSA, 1992. *Energy consumption test methods for household dishwashers*. CSA Standard CAN/CSA-C373-92.

CSA, 1992. *Test method for measuring energy consumption and drum volume of electrically heated household tumble-type clothes dryers*. CSA Standard CAN/CSA-C361-92.

CSA, 1998. *Energy performance, water consumption and capacity of automatic household clothes washers*. CSA Standard CAN/CSA-C360-98.

Hendron, R., 2006. *Building America research benchmark definition, Version 3.1* [online]. Available from: http://www.nrel.gov/docs/fy05osti/37529.pdf [Accessed 14 August 2006].

Jardine, C., 2008. Synthesis of high resolution domestic electricity load profiles. *In*: 1st *international conference and workshop on micro-cogeneration and applications*. 29 April–1 May 2008 Canada. Ottawa.

Knight, I., *et al.*, 2007. *European and Canadian non-HVAC electric and DHW load profiles for use in simulating the performance of residential cogeneration systems*. A report of subtask A of FC+COGEN-SIM: the simulation of building-integrated fuel cell and other cogeneration systems. Annex 42 of the International Energy Agency, Ottawa, Canada.

Mottillo, M., *et al.*, 2006. *Examining the feasibility of a hydrogen-based renewable energy-powered residential co-generation system for grid-connected houses*. Natural Resources Canada Internal Report.

Natural Resources Canada, 2002. *Photovoltaic systems – a buyer's guide*. Appendix B. ISBN 0-662-31120-5. Available from: http://www.canren.gc.ca/prod_serv/index.asp?CaId=101&PgId=551 [Accessed 9 September 2008].

Natural Resources Canada, 2004. *Micro-hydropower systems – a buyer's guide*. Appendix C. ISBN 0-662-35880-5. Available from: http://www.canren.gc.ca/app/filerepository/buyersguidehydroeng.pdf [Accessed 9 September 2008].

Natural Resources Canada, 2005. *Energy use data handbook, 1990 and 1997 to 2003*. Gatineau, QC, Canada: NRCan Office of Energy Efficiency. ISBN 0-662-3909-X.

Paatero, J.V. and Lund, P.D., 2006. A model for generating household electricity load profiles. *International Journal of Energy Research*, 30, 273–290.

Pratt, R., *et al.*, 1989. *Description of electric energy use in single-family residences in the Pacific Northwest – end-use load and consumer assessment program (ELCAP)*. DOE/BP-13795-21. Richland, WA: Pacific Northwest National Laboratory.

Ribberink, H., Motilla, M., and Bourgeois, D., 2007. *Performance assessment of prototype residential cogeneration systems in single detached houses in Canada*. A report of subtask C of FC+COGEN-SIM: the simulation of building-integrated fuel cell and other cogeneration systems. Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme, Ottawa, Canada.

Richardson, I., Thomson, M., and Infield, D., 2008. A high-resolution domestic building occupancy model for energy demand simulations. *Energy and Buildings*, 40, 1560–1566.

Swinton, M.C., Moussa, H., and Marchand, R.G., 2001. Commissioning twin houses for assessing the performance of energy conserving technologies. *Performance of exterior envelopes of whole buildings viii integration of building envelopes*. clearwater, Florida, 2 December 2001, 1–10. (NRCC-44995).

Walker, C.F. and Pokoski, J.L., 1985. Residential load shape modeling based on customer behavior. *IEEE Transactions on Power Apparatus and Systems*, PAS-104, 7.

Yao, R. and Steemers, K., 2005. A method of formulating energy load profile for domestic buildings in the UK. *Energy and Buildings*, 37, 663–671.