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OPERATIONAL EXPERIENCE OF A RESIDENTIAL PHOTOVOLTAIC HYBRID SYSTEM

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Abstract—This paper reports on the operational experience acquired with a photovoltaic (PV) hybrid system installed as a line extension alternative at a residence located in northern New York State. The system includes an 850 W PV array, 25 kWh worth of battery storage, and a 4 kW propane generator. The paper features a detailed analysis of the energy flows through the system and quantifies all losses caused by battery storage round-trip, rectifier and inverter conversions, and non-optimum operation of the generator and of the PV array. The paper also analyzes the evolution of end-use electricity consumption since the installation of the PV hybrid system. © 1999 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

In the service territory of Niagara Mohawk, the electric utility servicing northern New York State, most residential homes are connected to the electric grid. However, there still exists several 'off-grid' or remote locations, which, for financial and/or environmental reasons related to their distance from an existing power line, are not connected to the utility grid (e.g., see Moore and Bigger, 1991). Most of these residences derive their electricity from gasoline or diesel generators, which can be noisy and unreliable. These systems are usually only capable of supplying electricity for basic needs such as essential lighting, water pumping and a limited number of plug loads (e.g., radio, TV).

In August 1994, Niagara Mohawk installed a prototype photovoltaic (PV)-generator hybrid system in Parishville, New York. The decision to select a PV-generator hybrid system rather than a pure PV system for the considered location is consistent with several studies on the subject (e.g., Kugele *et al.*, 1996). This system replaced an existing diesel powered electric generator and was sized to meet the residence's known lighting and plug loads, but not refrigeration, cooking or heating needs. The residence is located about 5 km from the utility grid. Parishville is located in northern New York State, near the Canadian border (see map in Fig. 1). This site is characterized by a yearly global irradiation of about 1350 kWh/m^2 (Marion and Wilcox, 1994), and by some of the coldest winter weather conditions in the US.

The first year of operation was a learning experience for both the residential user and the utility company. Several problems were encountered during the first year, linked to the unreliable operation of the initial generator and the inverter. The hybrid system underwent a major redesign in July 1995, with a new inverter and a new liquid propane generator (Bailey *et al.*, 1997). In this paper, we report on the second year operation of the hybrid system, after the system had achieved a reliable operational level (less than 1% unavailability).

2. SYSTEM DESCRIPTION

The redesigned system considered in this paper is illustrated in Fig. 2.

The system design philosophy was to maximize simplicity and use proven off-the-shelf components. The system was to be representative of the type of residential systems that were likely to be installed in the foreseeable future in the utility's service territory. Hence, the system was sized using conventional simulation tools (Menicucci and Fernandez, 1988) and representative insolation data, and did not involve any sophisticated hybrid design optimization (e.g. such as proposed by Seeling-Hochmuth, 1997, Samimi *et al.*, 1997, Borowy and Salameh, 1996 or Beyer and Langer, 1996) or sophisticated array field of view characterization (e.g., Van Schalkwijk *et al.*, 1997).

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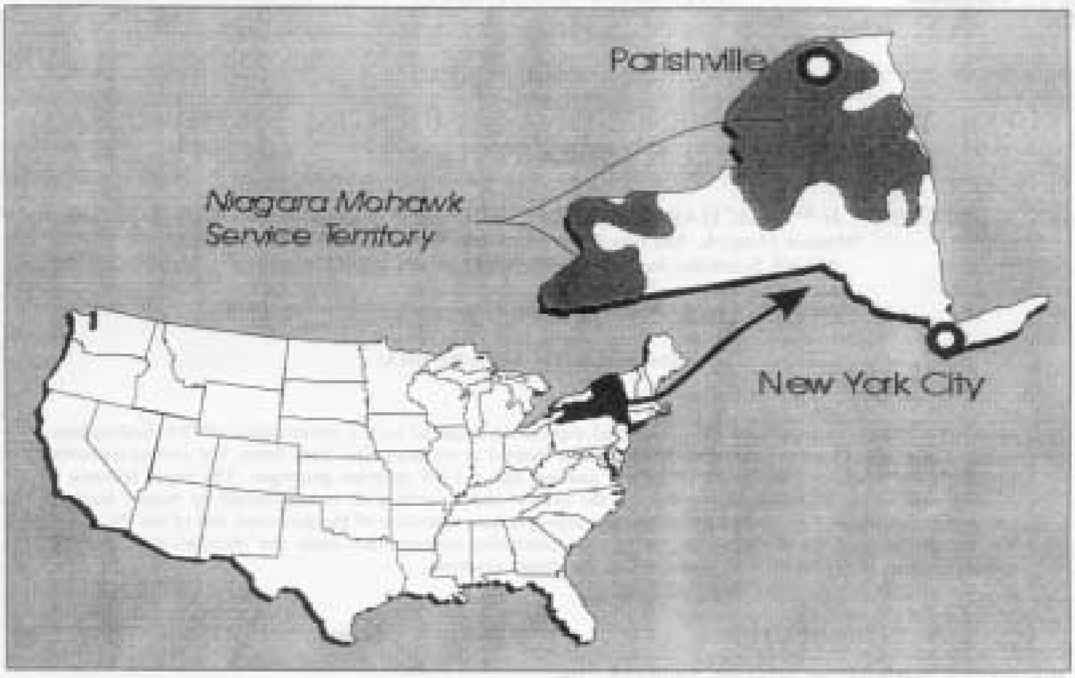

Fig. 1. Geographic location of the test PV hybrid site and service territory of Niagara Mohawk.

The loads, generator, PV array and battery bank are interconnected through an Ananda 5-404 Power Center built around a Trace 4024 inverter. The inverter has a capacity of 4 kWac.

The PV array is composed of sixteen Siemens M55 modules rated at 53 W[1] each, installed in eight parallel two-module strings. The array is south-facing and can be manually set to a winter or a summer tilt, i.e. 60 and 30°, respectively. No major obstructions are present within the array's field of view.

The battery bank consists of four GNB Absolyte IIp deep cycling lead–acid batteries, providing a rated storage capacity of 24 V/1055 Ah at a 7-h discharge rate.

The propane powered generator is a Kohler 6.5 RMY with a stand-by rating of 6.5 kWac at 120 V.

3. EXPERIMENTAL DATA

An extensive data acquisition system was installed to monitor energy production, energy flows and energy consumption. The parameters monitored are listed in Table 1. There are many redundant current and voltage data points, allowing for systematic quality control of the data. For instance, the array DC output was measured directly and could be verified by adding the battery power in(out)flow and the inverter DC input power. All sensor points were scanned at a 10-s frequency and were archived on a 15-min basis. Table 1 lists all recorded parameters along with the type of sensors used. Similar monitoring systems have been used elsewhere (e.g., Durand *et al.*, 1996).

4. RESULTS

4.1. Overall energy production and utilization

Remote residential loads in northern climates generally do not provide the best possible match with PV output since these loads typically peak in winter and during early morning and evening hours (Niagara Mohawk, 1997). The residence in Parishville, New York is no exception, as can be seen in Figs. 3 and 4.

Fig. 3 illustrates the residence's monthly energy consumption from August 1995 to July 1996, along with the respective end-use contributions of the PV and of the generator. The residential loads primarily consisted of lighting, a 250-W water pump and various small household appliances. Heating, refrigeration and cooking were not included.

The winter electrical energy consumption, of the order of 7 kWh per day, is almost twice as high in the winter as in the summer, driven by

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[1] 20°C 100 W/m2 @ AM 1.5.

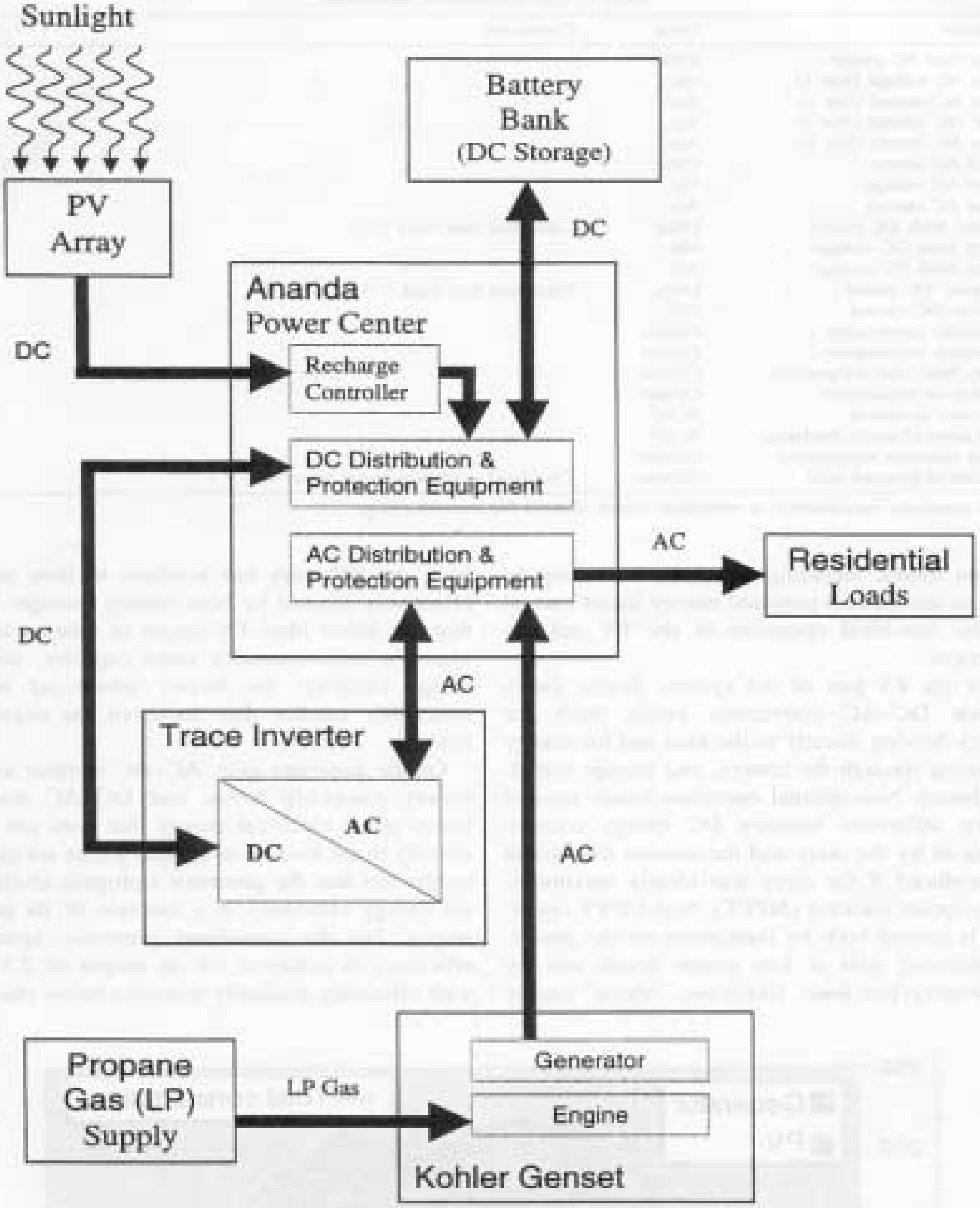

Fig. 2. Hybrid system block diagram.

higher lighting requirements and more activities inside the home. Overall PV contribution to the load is 27%. Fig. 4 illustrates the residence's average daily load profile superimposed over the PV array's average output.

Overall energy consumption is about half that of typical grid-connected Niagara Mohawk residential customers without electrical heating or cooling loads. However, the daily/monthly load patterns observed at the residence in question is typical of these customers (Niagara Mohawk, 1997).

4.2. Energy flows

One of the main objectives of this project was to produce a detailed experimental accounting of energy flows through the hybrid system. In particular, we were interested in quantifying all

Table 1. List of monitored parameters

Parameter	Units	Comments
House total AC power	kWac	
House AC voltage (line 1)	Vac	
House AC current (line 1)	Aac	
House AC voltage (line 2)	Vac	
House AC current (line 2)	Aac	
Genset AC power	kWac	
Genset AC voltage	Vac	
Genset AC current	Aac	
*Battery bank DC power	kWdc	Calculated batt. bank $V \cdot I$
Battery bank DC voltage	Vdc	
Battery bank DC current	Adc	
*PV array DC power	kWdc	Calculated batt. bank $V \cdot$ PV array I
PV array DC current	Adc	
PV module temperature 1	Celsius	
PV module temperature 2	Celsius	
Battery bank case temperature	Celsius	
Ambient air temperature	Celsius	
Horizontal insolation	W/m^2	
POA (plane of array) insolation	W/m^2	
Logger reference temperature	Celsius	
*Gallons of propane used	Gallons	Calculated using Genset AC power

Some parameter measurement is redundant, which allowed for cross-checking.

system losses, including actual device losses, as well as uncollected potential energy losses caused by the non-ideal operation of the PV and the generator.

For the PV part of the system, device losses include DC–AC conversion losses, both for energy flowing directly to the load and for energy transiting through the battery, and storage round-trip losses. Non-optimal operation losses amount to the difference between DC energy actually produced by the array and the amount that would be produced if the array was ideally maximum-power-point tracking (MPPT). Non-MPPT operation is caused both by limitations on the power-conditioning unit at low power levels and by full-battery/low-load situations, where energy from the PV array has nowhere to flow and is effectively limited by high battery voltage. Note that we define ideal PV output in relation to the system's experimentally rated capacity, not its design capacity; the former turned out to be noticeably smaller than expected, as explained below.

On the generator side, AC–DC rectifier losses, battery round-trip losses and DC–AC inverter losses affect electrical energy that does not flow directly to the load. Non-optimal losses are caused by the fact that the generator's propane-to-electrical energy efficiency is a function of its power output. For the considered generator, optimum efficiency is achieved for an output of 2.5 kW, with efficiency gradually dropping below that. We

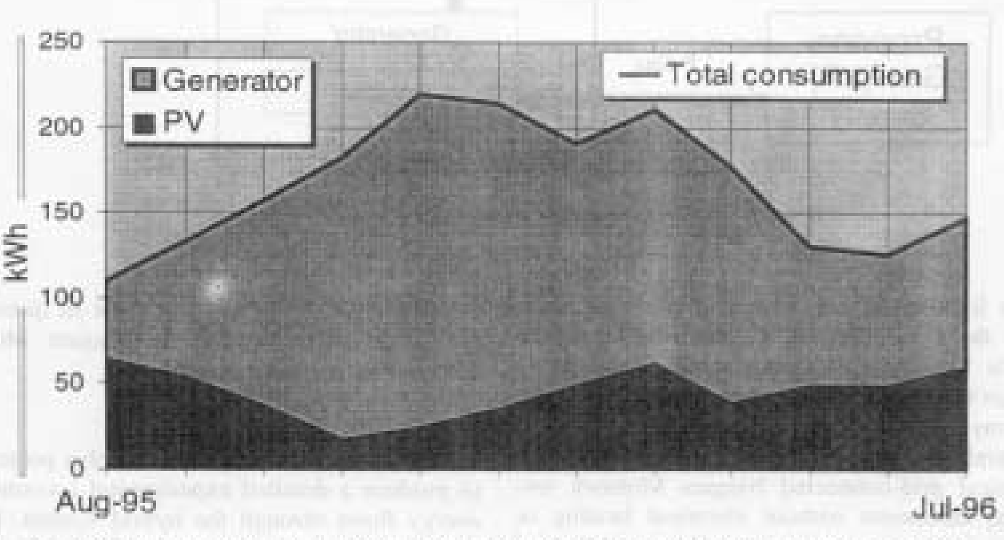

Fig. 3. Residence's energy consumption and respective contribution of PV array and propane generator.

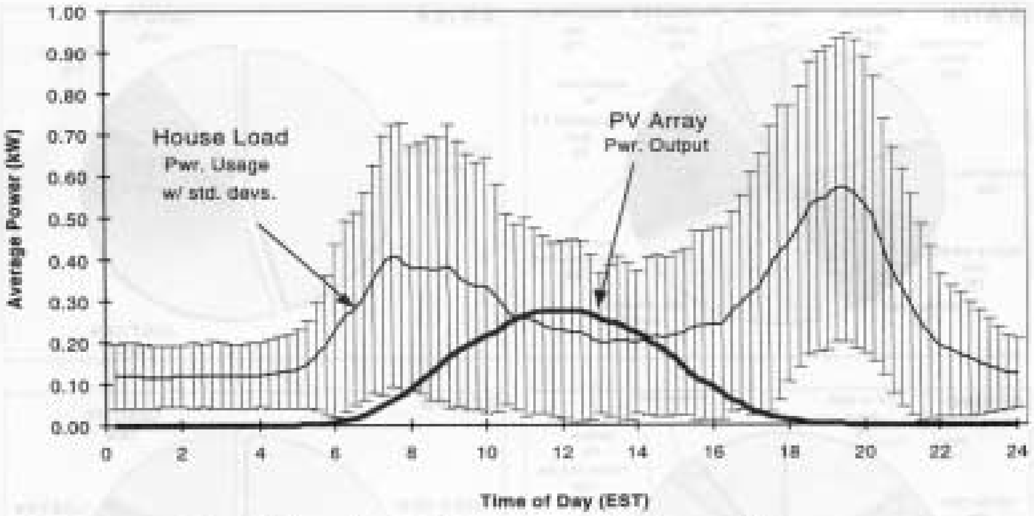

Fig. 4. Daily residence load pattern contrasted with average PV output.

define non-ideal losses as the difference between the energy actually produced by the generator and the energy that would have been produced had the generator operated at optimum efficiency.

4.2.1. Experimental results. System energy flows are illustrated in Fig. 5. For each season, there are two pie charts, one identifying all flows and the other summarizing the proportion of energy used and lost by the PV and the generator. It is interesting to note that almost half of the energy produced by the hybrid system is wasted. Device inefficiencies account for 65% of this lost energy.

On the PV side, 60% of the losses are device-related and 40% are non-optimal losses. It is important to remark here that these non-optimal losses are gauged with respect to the actual, not the expected, system peak rating (see comparison with simulations below).

On the generator side, 67% of the losses are device-related since much of the energy produced by the generator has to transit through the battery and be subjected to AC–DC, storage and DC–AC inefficiencies. Generator losses may have been enhanced by a desire by the homeowner to minimize noise by limiting the permissible times when the generator could operate.

While PV contributions in the winter are the smallest, there is a better utilization of PV. A larger proportion of direct PV-to-load transfer (higher loads plus lower PV output) results in smaller device losses.

4.2.2. Comparison with simulations. The hybrid system did not perform as well as initially anticipated in three respects: (1) the PV contribution to the total load was smaller than expected, (2) maximum PV output fell short of design expectations and (3) losses and inefficiencies were slightly larger than predicted from simulation.

The actual PV contribution to the load (27%) was less than initially projected (over 75%) because the residence's energy consumption grew substantially since the installation of the hybrid system (see load growth discussion in Section 4.3).

Based upon the individual module nameplate ratings, the PV array's peak power output should have been 848 W-DC (at a module temperature of 20°C and irradiance of 1000 W/m^2). The actual rating of the array under these conditions was estimated at 725 W-DC by determining the upper envelope of the actual DC output and accounting for temperature efficiency degradation. The factors responsible for this difference are: slightly optimistic individual module rating, module mismatch, line losses and a non-optimum IV curve power point, even under the most favorable insolation and load conditions set by the voltage of the battery bank.

Concerning actual versus simulated inefficiencies and losses, we performed an a-posteriori simulation of the hybrid system accounting for the 1995 load patterns and actual system rating (i.e. 725 W-DC), using typical meteorological conditions and a validated PV simulation program, PVFORM-4 (Perez *et al.*, 1994). As seen in Fig. 6, plane of array irradiance estimated from local typical meteorological year (TMY) data are quite comparable to 1995–1996 readings in Parishville.

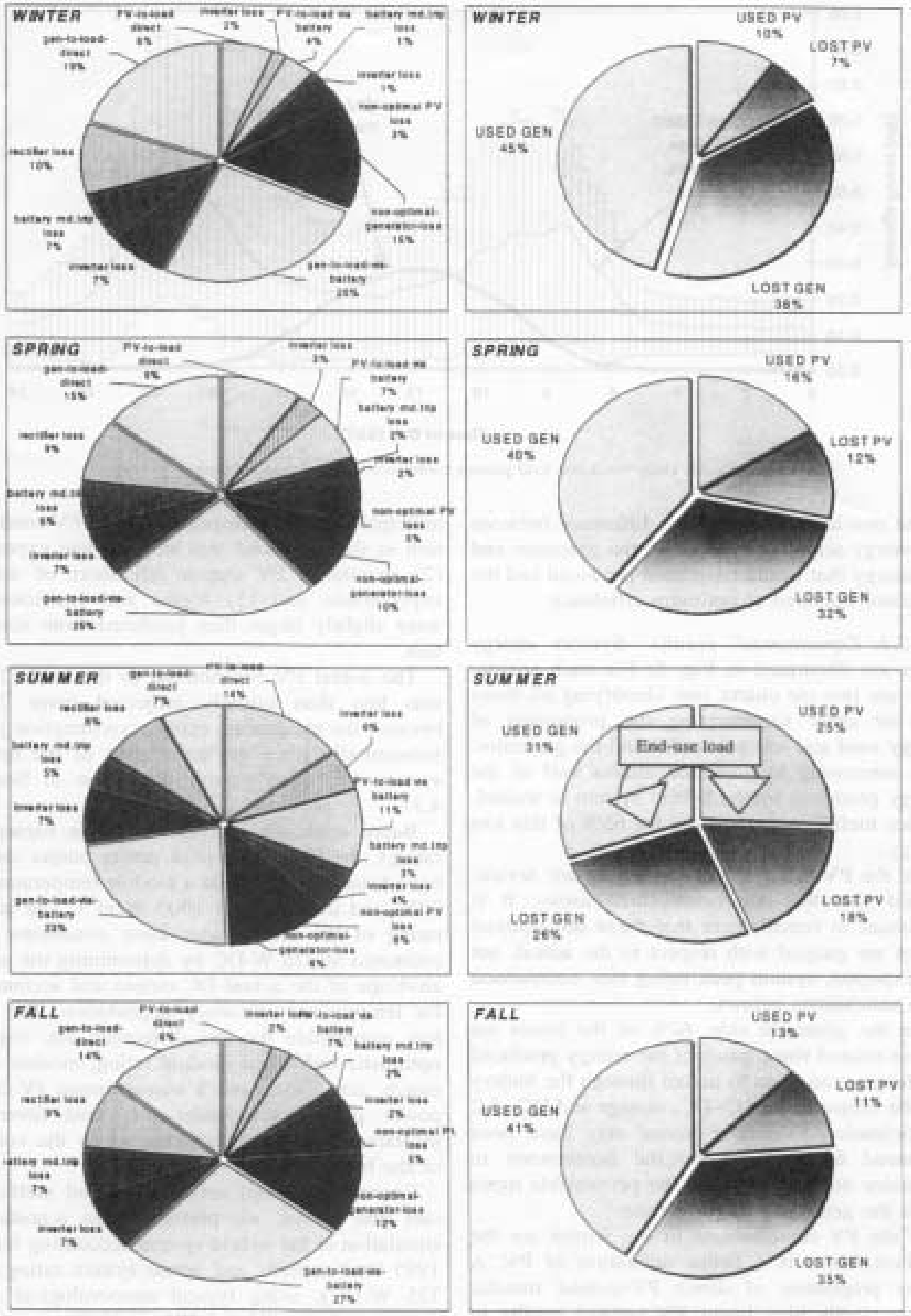

Fig. 5. Seasonal energy flows through the hybrid system, quantified relative to the total energy input to the system.

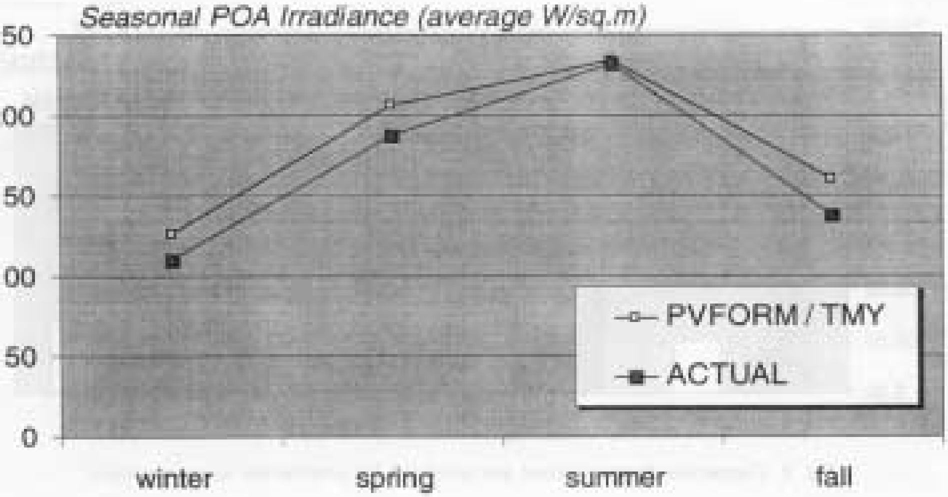

Fig. 6. Comparison between TMY and actual plane of array irradiance.

The difference is less than 1% for the summer months. Focusing on this time period, we compared experimental and simulated losses and utilization (Fig. 7). Under these similar insolation/consumption conditions, the PVFORM simulation yields smaller losses (42% PV-generator combined vs. 47%) and a higher PV load penetration (49 vs. 44%). Overall, after accounting for PV and load size, the TMY–PVFORM simulation provided a satisfactory estimation of system performance, as illustrated in Fig. 8, which compares seasonal simulated and actual PV load penetration.

4.3. Evolution of end-use loads

The residence was monitored for one year prior to the installation of the PV system. At that time, the house was powered by a diesel generator and a battery bank. The purpose of this initial monitoring was to help in designing a properly sized system. That initial data turned out to be helpful in other respects, however, because it bore witness to an unexpectedly large energy consumption increase. Fig. 9 illustrates the evolution of the residence's load from 1994 (one year before the installation of the hybrid system) to 1996. The data clearly suggests that end-use energy consumption rose substantially in the wake of the installation of the PV system.

Several causes for this increase may be advanced: (1) The reliability of the system was considerably increased, with a propane generator and a PV array requiring very little maintenance; (2) thanks to the PV array and a large battery bank, the (quieter) generator was operated less frequently than before, producing less discomfort

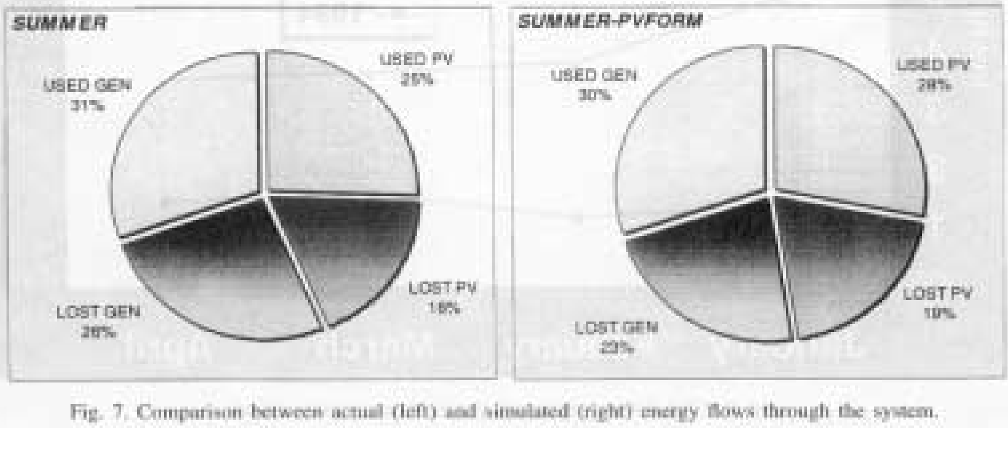

Fig. 7. Comparison between actual (left) and simulated (right) energy flows through the system.

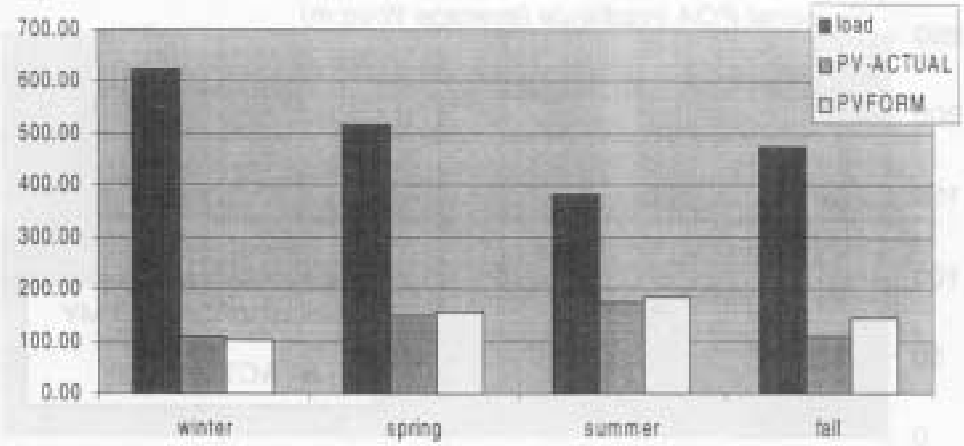

Fig. 8. Comparison between actual and simulated PV contribution to end-use load.

and (3) based on conversations with the homeowners, a perception of 'free' energy from the PV led to a more liberal use of electrical energy and an increase in the number of plug loads.

This load growth phenomenon, if corroborated by other experimental data, would be important in two respects. First, systems sized based on existing load consumption may turn out to be too small and should be designed with growth in mind. Second, this load growth could represent an untapped business opportunity for utilities and others involved in off-grid electrification.

5. CONCLUSIONS AND RECOMMENDATIONS

The detailed monitoring of a hybrid PV system in northern New York State allowed us to produce two sets of results that are of importance for utilities and others interested in the deployment of these systems as an alternative to grid extension.

1. The study produced a detailed accounting of energy flows through the system in relation to expected performance. One of the most striking observations is that almost half of the energy produced by the hybrid system is

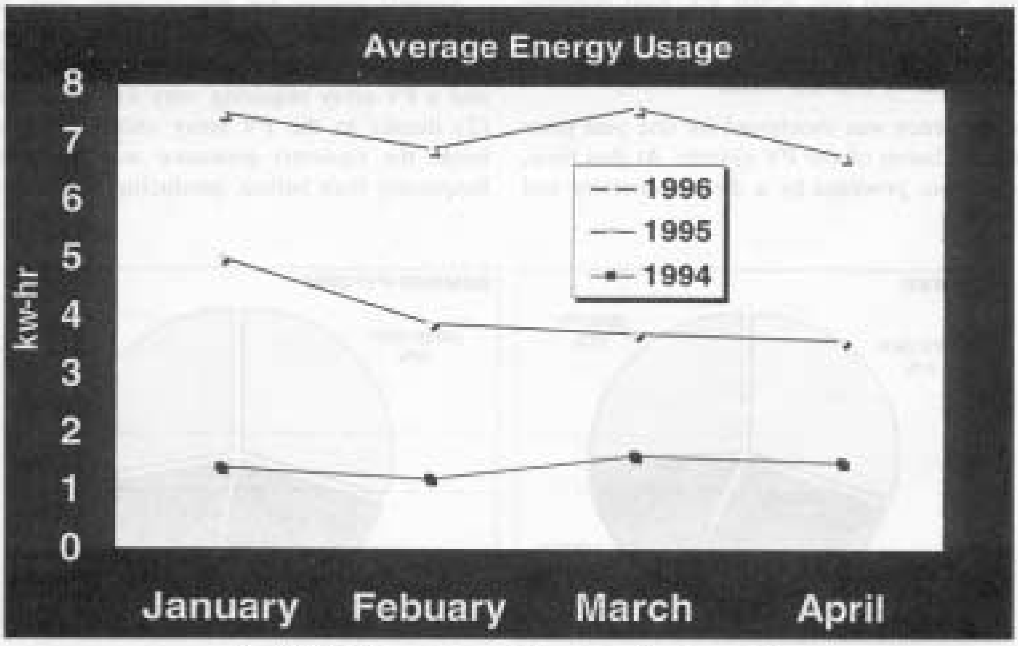

Fig. 9. 1994–1996 evolution of the residence's end-use load.

wasted. It would thus be advisable, should Niagara Mohawk decide to opt for PV hybrid systems as a solution for its off-the-grid customers, to optimize the design and operation of the system so as to minimize these losses and tap into the unused energy potential. The pie chart analysis presented in this paper could be used as a template to systematically gauge and rate the effectiveness of hybrid systems. Improvement areas to focus on include:

   - Exploring a better match between power generation and load utilization so as to minimize power transfers through the battery, which are particularly taxing energy-wise on the generator side and which have a serious long-term impact on battery life (e.g., Spiers and Rsinkoski, 1996). Dispatching strategies, such as those proposed by Barley and Winn (1996), should be explored.
   - Using a two-level inverter that could be matched to the power delivered by the array (e.g., see Keller and Affolter, 1995) and, when needed, matched to high demand situations. As it is, the 4 kW Trace inverter was not providing optimum efficiency at normal fair-weather PV output of 300–600 W.

2. The study provided strong evidence that the replacement of a diesel-battery system by a reliable hybrid PV system led to substantial load growth. We speculate that both the perception of 'free' energy from the PV and the reduction of the discomfort from a noisy and maintenance-intensive diesel engine led to this load growth. We believe that this load growth phenomenon may not be unique to this project and should be investigated further. Consequences on system sizing are not trivial. In the present case, the PV system ended up supplying a considerably smaller load fraction than planned.

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