Nemiah Valley Photovoltaic-Diesel Mini-Grid: System Performance and Fuel Saving Based on One Year of Monitored Data

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***Abstract*—Canada's first battery-free photovoltaic (PV)-diesel mini-grid was installed in the Nemiah Valley of British Columbia, Canada in the fall of 2007. Since loads in this community are relatively small (peak load of ≈75 kW), photovoltaic penetration on the mini-grid is much higher than what has been achieved in any large-scale centralized grid: the 27.36 kW of PV represent 36% of peak load, and supply roughly 11% of the electricity used in the community on a yearly basis. The goal of this research was both to assess the performance of this PV-diesel mini-grid over a one year period, as well as to highlight some of the lessons learned and inform the design and operation of other such systems. In particular, this case study examined fuel savings that were achieved through a number of modifications to a pre-existing mini-grid, including the addition of photovoltaics, the removal of a *dump load*, the reconfiguration of the commercial load feeder and the use of a smaller genset during weeknights and weekends. The fuel savings achieved amount to about 26,000 L per year, or a reduction of ≈25% over business-as-usual. With respect to photovoltaic systems performance, the main issue encountered was the occurrence of conditions under which PV output would, if not curtailed, exceed system load. It was estimated that the PV system would deliver about 10% more energy on a yearly basis if all of its output could be absorbed (as in the case of connection to a large, centralized grid). Given that this effect will worsen as PV penetration levels are pushed beyond this system's, a number of avenues for mitigating this loss are discussed.**

***Index Terms*—photovoltaic, mini-grid, performance, genset, fuel savings, high penetration.**

I. Introduction

CANADA has over 300 remote communities, most of which rely primarily on diesel gensets for their electricity [1]. Electricity costs in these communities are considerably higher than the national average: For instance, the residential monthly energy charge in the Northwest Territories ranges from about C$0.13/kWh to C$2.45/kWh, with a median of C$0.72/kWh [2]. Meanwhile, electricity generation costs from grid-connected photovoltaics (PV) range from roughly C$0.38/kWh to C$0.75/kWh[1] [3] and have been decreasing steadily. Thus, for many communities, PV and other renewables present an economic option for lowering both electricity costs and emissions.

Given the relatively small loads involved, isolated remote grids can rapidly attain medium-to-high renewable penetration levels far beyond those likely to be achieved in large-scale grids in the near future. This gives rise to novel research needs and opportunities. For instance, the International Energy Agency Photovoltaic Systems Programme (IEA PVPS) created a special task (Task 11) dedicated to the study of *PV hybrid systems within mini-grids* where a mini-grid is defined as *a set of electricity generators and, possibly, energy storage systems interconnected to a distribution network that supplies the entire electricity demand of a localized group of customers* [4]. Issues tackled by Task 11 members include how to ensure the stability and power quality of PV mini-grids, particularly with high PV penetrations, as well as how to best design and operate such systems given trade-offs between economic, environmental and reliability considerations. The goal of the research presented here is to contribute to the knowledge base on the design and operation of PV diesel hybrid systems in remote communities by a case study of such a system currently operating in the Nemiah Valley of British Columbia, Canada.

This paper is organized as follows: Section II describes the photovoltaic diesel hybrid mini-grid under study and the rationale behind the choice of the system components and operation. Section III details the methodology used: III-A explains how the system performance was analyzed, while Section III-B describes how fuel (and therefore greenhouse gas) savings were calculated. Finally, Section IV discusses the results obtained, and Section V provides concluding comments.

II. System and Data

The Nemiah Valley is home to the Xeni Gwet'in First Nation; it is located 250 km North of Vancouver, and is separated by about 100 km of road from the nearest electricity grid. The PV-diesel mini-grid project discussed in this study built on a previous collaboration between Natural Resources Canada and the Xeni Gwet'in First Nation, in which PV hybrid systems were installed and tested for a few autonomous residences in the Nemiah Valley [5]. In August 2007, a new project was initiated in Nemiah Valley's Lohbiee Indian Reserve #3, where a mini-grid had recently been connected to houses in a new residential sub-division. Natural Resources Canada signed a contract with Xeni Gwet'in Enterprise — which manages electrical and other infrastructure for the Xeni Gwet'in First Nation — to implement, monitor and study a number of modifications to this mini-grid, notably the introduction of photovoltaics to create a PV-diesel mini-grid.

[1]Estimates from Navigant Consulting based on 2008 price data.

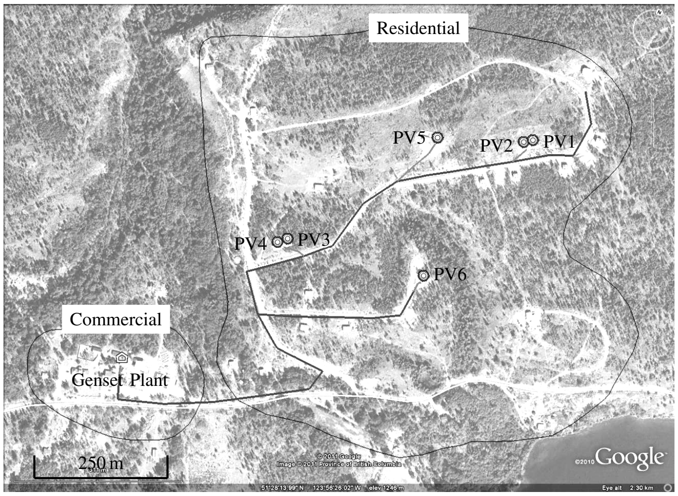

Fig. 1. Aerial view of the Nemiah Valley mini-grid showing the location of the PV systems, the genset plant and the commercial and residential zones.

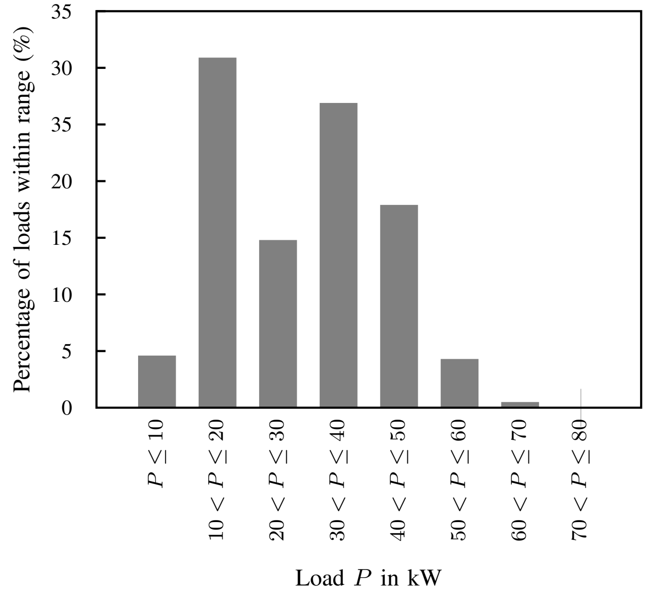

Fig. 2. Profile of the total load (PV not subtracted) for the Nemiah Valley mini-grid during the November 19, 2008 to November 18, 2009 period, indicating percentage of total loads within a given range.

A. System description

1) Mini-grid loads: A schematic of the mini-grid is shown in Figure 1. The mini-grid is divided into two zones: 1) a residential medium voltage aerial distribution grid and 2) a commercial complex supplied by underground low voltage lines. In the residential area, the mini-grid supplies electricity to 22 housing units (14 single-family houses and two 4-plexes). Note that there are a total of 38 housing units in this area; 18 units are not yet connected to the mini-grid, because they do not comply with the British Columbia electrical code or because their distance from the distribution line makes connection uneconomic. The grid-connected houses are equipped with revenue grade AMPY pay-as-you go meters that allow the wire owner to collect money up-front using a chip card that can be refilled at the community gas station.

Meanwhile, the commercial zone includes the band office, a daycare, a health centre, the Xeni Gwet'in Enterprise building, a water pumping station, a gas station, a mechanical shop and the generation plant which houses the diesel gensets. This zone operates from two distinct buses: 1) a 120/240V bus for critical loads that must remain on at all times and 2) a 120/240V bus for *daytime* or non-critical loads that only need to run when the commercial zone is in use.

The system's load profile is shown in Figure 2: peak load is 75 kW, while average load is 29 kW, making it challenging for a single genset to supply electricity efficiently over the full range of loads.

2) Mini-grid PV/diesel electricity supply: Originally, the mini-grid was supplied in electricity by three Deutz 95 kW air-cooled diesel gensets (engine model BF6L913G) operating one at a time, on rotation. As is often the case in remote communities, these gensets are oversized with respect to the loads they serve [6]. There are two main reasons for this: First, while the 95 kW genset rating is for three-phase operation, the Nemiah network is single phase and only two of the three outputs of the gensets are used. In practice, this means that only about $2/3$ of the generator power is available which makes the engine oversized for the 75 kW single phase rating of the genset. Another reason for the oversizing is the anticipation of load growth, and the eventual need for a three phase system as a backup for a future mini-hydroelectric system that would supply the whole community. The fact that the engines are larger than necessary means that they frequently operate at loads where their fuel efficiency is considerably lower than its optimum, as can be seen by comparing the load profile of Figure 2 with the 95 kW genset efficiency data of Table I. Moreover, frequent operation of the engines at low load (below 30% of their rated capacity) can lead to premature ageing and increased risk of engine failure through liners glazing [7] and wet stacking [8][2]. For this reason, non-critical loads in the commercial zone were originally left on at all times, effectively acting as a *dump load* during evenings and weekends.

While the focus of this project was on introducing photovoltaics to the mini-grid, it was clear for the reasons discussed above that the original system would benefit from a re-optimization of the genset sizing and operation. This optimization is ongoing. One measure was targeted first due to its simplicity and significant fuel saving potential: instead of leaving non-critical loads on to act as a *dump load* for the 95 kW

[2]There is however no clear understanding of what constitutes "frequent" low loading of an engine, and of when glazing and wet stacking set in.

TABLE I
FUEL CONSUMPTION FOR THE DEUTZ 95 KW GENSET. MANUFACTURER SPECIFICATIONS (IN G/KWH) AND CALCULATED CONSUMPTION IN L/KWH AND L/H BASED ON A FUEL DENSITY OF 0.85 KG/L[9]

Load	Consumption		
%	g/kWh[a]	L/kWh	L/h
100	226	0.266	25.3
75	220	0.259	18.5
50	234	0.275	13.1
25	300	0.353	8.4

[a] Information provided in this unit.

TABLE II
FUEL CONSUMPTION FOR THE DEUTZ 30 KW GENSET. MANUFACTURER SPECIFICATIONS (IN L/H) AND CALCULATED CONSUMPTION IN L/KWH AND G/KWH BASED ON A FUEL DENSITY OF 0.85 KG/L [9]

Load	Consumption		
%	g/kWh	L/kWh	L/h[a]
100	258	0.303	9.1
75	257	0.302	6.8
50	255	0.300	4.5
25	340	0.400	3.0

[a] Information provided in this unit.

TABLE III
ORIENTATION OF THE NEMIAH VALLEY PV SYSTEMS (DETERMINED BY ROOFTOP ORIENTATIONS)

PV System	Azimuth (°)	Tilt Angle (°)
PV1&2	30	20
PV3&4	37	20
PV5	4	42
PV6	20	25

Note: Azimuth angle is measured counter-clockwise from South.

gensets when the commercial zone is unoccupied, a smaller 30 kW Deutz genset (engine model F3L914) was introduced so that these loads could be switched off when appropriate. This genset, whose fuel consumption specifications are given in Table II, was sized specifically for meeting the remaining system loads ($critical\ commercial\ loads + residential\ loads$), which average at ≈14 kW and peak at about 29 kW. During weekday nights and on roughly every second weekend, the 30 kW genset is manually selected as the main generation unit. At the same time, the non-critical commercial load circuit is switched off, along with a 250 kVA step-down distribution transformer supplying this circuit. Unlike the 95 kW gensets, the 30 kW genset has been featured with a three phase generator that can use the full capacity of the engine while operating in single phase mode, i.e. using two legs of the three phase circuit.

Last but not least, distributed photovoltaic systems were installed on the roofs of four houses as shown in Figure 1: two 2.88 kW[3] systems were installed on individual houses (PV5 and PV6), and a set of two 5.4 kW systems were installed on each of two 4-plexes (PV1-2, and PV3-4), for a total of 27.36 kW of distributed photovoltaics. Based on a dynamic simulation of the system, it was expected that this 27.36 kW of photovoltaics would have *little or no adverse impact on power quality of the PV mini-grid* [10]. The configuration of the PV arrays is very simple: a number of PV strings are arranged in parallel, and then fed into a utility-interactive inverter which is connected to the grid. While the PV systems are installed on individual houses, they are owned by Xeni Gwet'in Enterprise, so the a.c. power is injected upstream of the client meter. In order to minimize lifetime delivered energy cost and to simplify the design, no storage was included in this system, which means that the gensets must operate continuously. All modules are 180 W Day4 48MC, while the inverters are Xantrex GT's (3.0 kW Xantrex GT 3.0-NA-DS-240 for PV5 and PV6, and 5.0 kW Xantrex GT 5.0-NA-240/208 UL-05 for PV1-PV4). The orientation (azimuth and tilt angle) of each PV system is given in Table III. Finally, the system still includes an 18 kW dump load which is activated for 1 s when diesel genset load goes below ≈1 kW in order to protect the gensets against backfeed from the PV generation. The power pulse of the dump load perturbs the grid frequency sufficiently to prompt the inverter's grid fault detection to stop power delivery. Since all inverters turn off at the same time, there is no actual control of the amount of shed power, thus a certain amount of PV output is wasted in this configuration.

[3]The PV system rating given here is the nameplate DC rating at Standard Test Conditions (STC).

B. Data collection

The monitored parameters as well as the instruments used for measuring them are specified in Table IV. The collected data indicate at each time step various characteristics of the system load and its residential and commercial components, as well as of the power generated by each PV system and by the gensets (Note: the residential feeder data gives the net residential load, i.e. the residential load minus the PV output). Meanwhile, other measurements are used to assess the performance of the PV and gensets: A fuel flow meter measures the fuel transfer from a main fuel tank outside the genset plant to a much smaller *day tank* inside the plant, giving a measure of genset fuel use. Meanwhile, PV array performance analysis is enabled by measurements of plane-of-array irradiance near the junction of arrays PV1-2 and of arrays PV3-4, as well as by measurements of back-of-module temperature (for each of arrays PV1-PV4) and ambient temperature near arrays PV1-2.

Instrumentation and remote monitoring for the system were configured to ensure remote access to key data. An internet-enabled gateway, configured by Fat Spaniel® Technologies on a Moxa UC-7110-LX computer is collecting data from an analog to digital (A/D) converter that is reading the sensors. Data is transferred from the gateway into the Fat Spaniel® server database from which it can be retrieved. Data is collected and stored each minute, and 15 minute averages are also computed and stored separately.

III. METHODOLOGY

A. System performance

The performance of the photovoltaics and diesel gensets was assessed and compared to expectations based on manufacturer specifications and relevant benchmarks. Since the silicon irradiance sensors, pyranometer and fuel flow meter were installed in mid-November 2008, this analysis focuses on a subsequent 1 year period from November 19, 2008 to November 18, 2009.

1) Diesel genset performance: The performance of the diesel gensets was assessed by comparing their fuel consumption as measured with the fuel flow meter to the consumption that would be expected based on manufacturer specifications. A quadratic fit was performed to the fuel consumption data of each genset (see Tables I and II) and the resulting equations were used to model the fuel consumption for any load. The quadratic fit was selected since it is documented as an

TABLE IV
PARAMETERS BEING MEASURED AS WELL AS SENSOR TYPE AND LOCATION

Measured Parameter	Sensor Location	Instrumentation/Sensor
Fuel consumption	Genset plant	Kobold OMP1310L flow meter
Irradiance	Roof of the genset plant	Kipp & Zonen CMP6 with CV2 ventilated and heated base
Residential feeder energy, power, reactive power and primary voltage	Genset plant	Elkor WattsOn power meter
Commercial feeder energy, power, reactive power and primary voltage	Genset plant	Elkor WattsOn power meter
Power quality of total load at genset plant	Genset plant	ION 7650 meter
Ambient temperature	PV1-2	K-type thermocouples (Omega TT K 24 SLE thermocouple wires) with RM Young radiation shield model 41003
Back-of-module temperature	Each of PV1 to PV4	K-type thermocouples (Omega TT K 24 SLE thermocouple wires)
AC output energy, AC output power, DC input voltage, AC output voltage	Each of PV1 to PV6	Xantrex GT inverters internal measurements system
Plane-of-array irradiance	PV1-2 and PV3-4	Fronius 43,0001,1189 silicon irradiance sensors

appropriate method to draw a complete performance map for an internal combustion engine based on a limited number of measurements [11]. However, it should be noted that the fuel use analysis is quite sensitive to the type of fit used (linear vs. quadratic or other), especially for loads below 25% of rated power. This translates into relatively large uncertainties in the fuel use estimates obtained via this method.

Using the equations discussed above, the fuel consumption of the 95 kW and 30 kW gensets was modelled separately for each 15 minute period of the year. By examining the commercial loads during weekday nights, it was found that these loads tend to be fairly constant during these periods, and consistently below a cutoff of about 7 kW, while the same loads are consistently above 7 kW the rest of the time. Thus, the fuel consumption of the 95 – 30 kW genset combination was modelled by assuming that the 30 kW genset was in use when and only when commercial loads dropped below 7 kW.

As mentioned in Section II-B, the fuel flow meter does not measure instantaneous fuel consumption by the gensets, but rather fuel transfer to a *day tank* supplying the gensets, which refills roughly every 3–4 days. For this reason, the fuel flow meter data becomes meaningful and accurate only for sufficiently long periods, for which total genset fuel consumption and total fuel transfer to the genset plant tank are essentially the same. For this reason, diesel genset performance was analyzed by comparing modelled fuel consumption for the full year to the total fuel use over this period measured by the fuel flow meter. This analysis was also used to correct any estimates of fuel consumption under different scenarios by adjusting modelled fuel consumption by the ratio of measured to modelled consumption.

2) Performance of the photovoltaic systems: The performance of each distributed PV system and of the photovoltaics as a whole were assessed both on a monthly and on a yearly basis in terms of their performance ratio. This is defined as the ratio of actual system yield (kWh/kW) to a reference or nominal yield that is numerically equal to the insolation in the plane of the PV array (in kWh/m^2). The performance ratio indicates overall system losses, since the reference yield corresponds to the idealized case of no losses where the PV system performs with an efficiency equal to that of its Standard Test Conditions (STC) rating at all times.

For the PV1-PV4 arrays, insolation was obtained from the silicon cell sensors for each period under consideration by taking a sum of the corresponding 15 minute data. For PV5 and PV6, insolation in the plane of the array had to be modelled since no irradiance sensors have been installed next to these arrays. This was done using RETScreen International software, which can model monthly average daily insolation in a tilted plane from monthly average daily insolation in a horizontal plane and monthly average temperature [12]. Data from Williams Lake, 145 km Northeast of the Nemiah Valley, was used to estimate monthly average daily insolation for arrays with orientations corresponding to PV5 and PV6, and to a system representing PV1-PV4 (Note: Since the orientations of the PV1-2 and PV3-4 arrays are virtually identical, these were simulated as a single PV array with a 20° tilt and an azimuth of 33.5°). The ratio of monthly average daily insolation in the plane of arrays PV5 and PV6 to that in the plane of arrays PV1-PV4 was then calculated, and used to estimate actual monthly insolation received by arrays PV5 and PV6 based on the insolation received by PV1-PV4.

Having examined overall system losses through the performance ratio, a particular type of system loss was singled out for further analysis, namely loss occurring when PV system output would, if not curtailed, exceed system load. When this situation arises, the inverters disconnect as described in Section II-A: disconnection is triggered by the genset underpower protection whenever PV output approaches within 1 kW of the total system load (i.e. genset load $\leq$ 1 kW). Since this situation is more likely to occur in a mini-grid with medium-to-high PV penetration than in a large scale grid with low PV penetration, the associated PV system loss was singled out for further study.

The energy loss during each inverter downtime was estimated by multiplying the duration of the inverter downtime by the corresponding 15 minute average available power at the time of the disconnection event, as described below. First, the duration of the inverter downtimes was estimated by taking advantage of the fact that the ION meter logs each dump load activation, corresponding to the beginning of each inverter downtime. Meanwhile, the end of the inverter downtime (i.e. inverter restart) is not logged by the meter, so it had to be estimated. Inverters are designed by standard [13] to wait for at least 5 minutes before resuming power delivery; in practice, especially after a perturbation, this ranges from 5 to 9 minutes. Based on this, when the time interval between successive inverter disconnections was less than 10 minutes, this was counted as inverter downtime for the duration of the interval (this corresponds for instance to the case where the PV output becomes too large soon after inverter restart, causing a series of consecutive disconnections). Meanwhile intervals of more than 10 minutes between two successive inverter disconnections could indicate for instance that normal restart occurred without PV output exceeding the load, leading to a period of normal operation in between the two disconnections. In that case, the duration of the downtime was estimated as the average of measured intervals shorter than 10 minutes, i.e. 6.2 minutes.

Having estimated the duration of the inverter downtimes, PV system losses could then be approximated. These can be defined — and therefore calculated — following two different approaches. In the first approach, the loss is defined as the PV system output that would have been generated during the downtime (this would be the case, for instance, if the PV system was connected to a large, centralized grid that could absorb all the power generated). Meanwhile, the second approach considers only the portion of the PV output that could have been absorbed by the mini-grid loads as measured during the downtime. The energy lost as defined in the second approach was the simplest to calculate: for each downtime, the downtime duration was multiplied by the average of the total system load during the 15 minute interval when the downtime occurred. Meanwhile, for the first approach, the downtime duration was multiplied by an estimate of the PV power that could have been generated during the downtime, based on the average irradiance recorded by the PV1 reference cell (vector average of all the arrays is closely matched with the PV1 reference cell plane) during the appropriate 15 minute interval. AC power was then estimated based on a proportional relation between the measured irradiance and the total production of 25 kW that would be generated at 1,000 W/m^2. In all cases, the power was saturated at a maximum of 25 kW, assuming 92% conversion efficiency and respecting inverter saturations, to ensure that only the power that could be delivered by the inverters was accounted for.

B. *Fuel savings and GHG emissions reductions*

Yearly fuel savings were estimated corresponding to each of the three main measures implemented in the Nemiah mini-grid, namely introducing distributed PV, replacing a 95 kW genset by a 30 kW genset and reducing commercial loads on weekday evenings and weekends by introducing a contactor to switch these off. This fuel savings analysis was then used to derive associated greenhouse gas (GHG) emissions reductions.

For each measure, fuel savings had to be calculated using the method described in Section III-A1, rather than based on a before-and-after analysis of fuel consumption. This is due to the fact that loads vary seasonally in Nemiah and that residential loads have been growing since the implementation of the mini-grid; moreover, a single fuel saving value cannot yield information about the relative contribution of each of the three measures.

The underlying idea is simple: the fuel savings from a given measure are the difference between what the fuel consumption would have been without the measure, and what it actually was with the measure in place. This approach becomes somewhat ambiguous when several measures are considered at the same time, since the savings attributed to each measure in effect depends on the order in which they are considered: for instance, should savings from the PV be calculated by comparing the consumption of a 95 kW genset with and without PV, or of the 95 – 30 kW genset combination with and without PV? Here, this ambiguity did not prove important, since the results were similar whichever ordering was considered.

Since the 30 kW genset could not actually supply evening and weekend loads prior to the introduction of the reduced loads, the first measure considered was commercial load reduction. Fuel savings due to this measure were calculated by examining the total system load on weekday evenings where loads were reduced (commercial load below 7 kW), and the corresponding non-reduced loads. The average system load was calculated in both cases, indicating that total system load was reduced from an average of 31.2 kW to an average of 13.1 kW over 3,299 hours (Note: average loads were calculated using the period between midnight and 5 AM to exclude any PV load reduction). Fuel savings from commercial load reduction were then estimated by calculating the fuel consumption of the 95 kW genset over 3,299 hours of reduced (13.1 kW) vs. non-reduced (31.2 kW) loads, using the quadratic fits discussed in Section III-A and by correcting for the difference between modelled and measured genset fuel consumption.

In the case of the replacement of a 95 kW genset by a 30 kW genset, fuel savings were calculated as the difference between what genset fuel consumption would have been had the 95 kW genset supplied the total system load ($residential\ feeder\ load + commercial\ feeder\ load + PV\ output$) to what it would have been had the 95 – 30 kW genset combination supplied this total load. Similarly, fuel savings due to adding photovoltaics were calculated as the difference between the amount of fuel actually consumed by the gensets, and the amount that would have been consumed if the 95 – 30 kW genset combination had supplied the total system load.

Finally, it would have been interesting to estimate fuel savings arising from the use of pay-as-you-go AMPY meters in the residential zone. However, this could not be done here, since these meters were introduced simultaneously with the mini-grid. On the other hand, residential load growth was examined by comparing two consecutive years, as will be discussed in Section IV.

Once fuel savings had been estimated, the associated greenhouse emissions reductions were calculated by using a carbon dioxide equivalent emission factor for diesel of 2.79 kg/L [14]. Multiplying this by the amount of fuel saved (in L) yielded an estimate of the GHG emissions reductions from each measure.

IV. Results and Discussion

A. System performance

1) Genset performance: Modelled genset fuel consumption was 69,273 L for the year, while actual fuel consumption was 77,872 L, or 12.4% more. In order to take into account the difference between fuel consumption modelled according to genset specification sheets and actual consumption, all other modelled fuel consumption was multiplied by a factor of 1.124 to correct for this difference.

2) Performance of the photovoltaic systems: Over the one year period considered, the distributed PV systems as a whole supplied 28,542 kWh to the mini-grid, or 11.4% of the total energy demand of 251,099 kWh. This PV system output amounts to 1,043 kWh/kW and to a yearly performance ratio of about 0.67, based on the silicon cell irradiance measurements. This can be compared to what one would expect for a typical grid-connected PV system: In an IEA PVPS Task 2 analysis of over 500 grid-connected PV systems, yearly performance ratios ranged from 0.425 to 0.925, with an average of 0.74 and with over two thirds of performance ratios falling within 15% of this average [15]. Thus, the distributed PV systems in the Nemiah Valley are performing somewhat below average ($\approx$10% below), but with system losses within a range that can be considered typical for grid-connected systems.

As mentioned in Section III-A2, PV system losses due to inverter disconnection were singled out for further analysis, since these were expected to be more significant for the Nemiah Valley system than for typical PV systems connected to large-scale centralized grids. For the period of interest, inverter disconnection occurred 1,492 times for a total estimated inverter downtime of 154.4 hours, with almost all of those hours in clear sunny sky. This amounts to a total of 1.8 MWh that were lost due to the fact that power from the inverters could not be curtailed to match the load.

It is worthwhile considering how these inverter disconnection losses could be mitigated, especially since they will tend to become increasingly important as PV grid penetration increases, contributing to what [6] refers to as *the law of diminishing returns*, or the tendency of incremental fuel savings from additional renewables to decrease as renewable penetration increases.

In order to reduce inverter downtime and maximize solar resource utilization, a power curtailment method must be implemented to match the generation with the demand. Off-the-shelf PV inverters are designed to maximize the conversion of the available PV power into a.c. power without considering the capability of the grid to accept this power. A secondary control loop centralized at the genset power station could command power curtailment whenever the genset output power gets too low. Alternatively, the generation plant could implement a frequency droop characteristic as illustrated in Figure 3 that could signal to the photovoltaic inverters to reduce their generation [16].

In Figure 3a, the power delivered by the genset is relatively high; consequently the genset is operating at a frequency slightly lower than nominal, indicating that the genset is loaded. The PV curtailment is set to engage only when the frequency rises above nominal, consequently all available PV power can be returned to the grid. In Figure 3b the genset is very lightly loaded and is then operating at a significantly higher frequency than nominal. The inverters measure that frequency and curtail their power down according to their pre-programmed droop characteristic. If the genset power continues to drop, the frequency will continue to rise up to the point where the PV power will drop to zero.

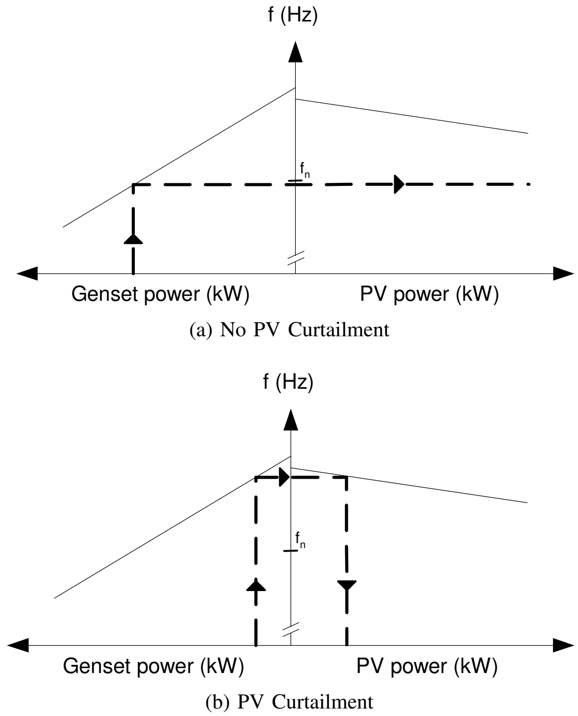

Fig. 3. Illustration of the frequency droop method as applied to PV power curtailment in a mini-grid

Finally, the six inverters could also be sequentially disconnected using dispatch signals or with increasingly stringent protection parameters. However, the average load during disconnection events was of 11.66 kW i.e. less than half of the PV system capacity; that means that a significant fraction of the available solar energy would have been lost even with perfect curtailment. Specifically, it was estimated that a total of 2.9 MWh of PV energy was available during inverter downtimes. If this 2.9 MWh could be accessed, this would represent about 10% extra energy beyond what is currently being produced; this in itself is sufficient to explain why the system is currently performing below average. Considering that 2.9 MWh of PV energy is available and that 1.8 MWh of this energy is accessible through curtailment, there remains 1.1 MWh (2.9 MWh − 1.8 MWh) which could only be harvested through methods other than curtailment, such as load dispatch or storage. For instance, low genset loading conditions could trigger the startup of heavy loads, especially those resulting in storage of commodities such as the community water pump or the garage air compressor. Alternatively, electrical storage could be implemented to store surplus of generation for later use.

Other than the production limitations mentioned above, no other significant, unusual types of loss were identified for the

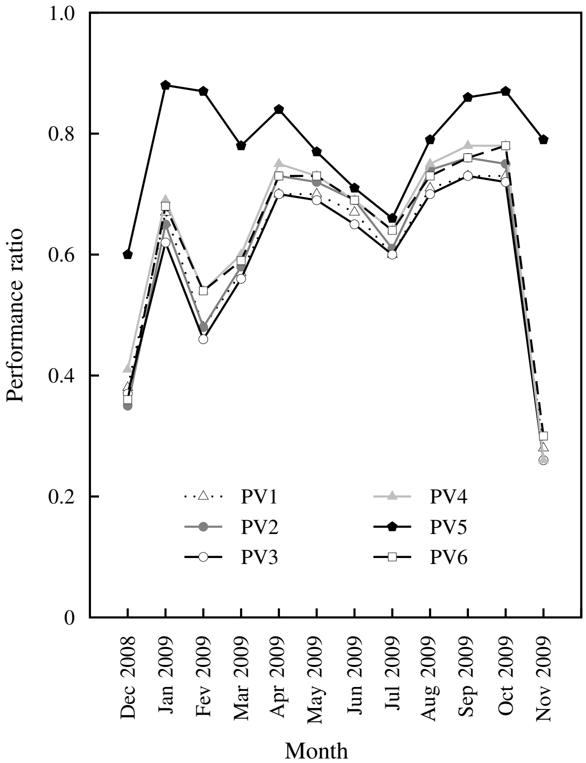

Fig. 4. Monthly performance ratio of PV1-PV6 from December 2008 to November 2009.

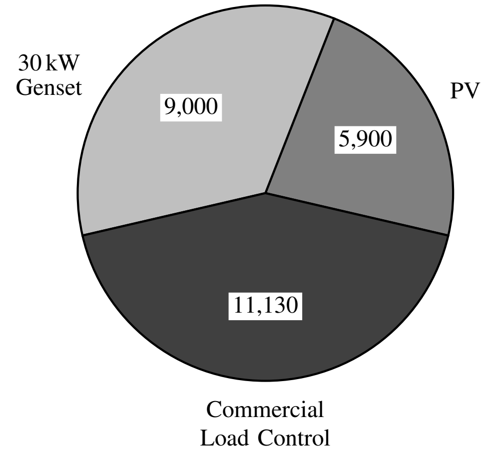

Fig. 5. Fuel Savings (in litres) from each of the three measures implemented

year under consideration. However, for the previous year, two significant losses were identified by a simplified analysis of the data (no irradiance data in the plane of the PV arrays was available for that year). One of these losses was a system loss of the order of 7% of the reference yield due to prolonged outages of the PV2 and PV6 systems (one due to inverter malfunction, and another due to a ground fault). This loss was pronounced because there were delays in system maintenance during the crucial start-up year of the project where more *debugging* is to be expected. This highlights the fact that, while PV systems are typically low maintenance, it is still important to have a plan for dealing with maintenance issues as (or before) they arise. Another loss, crudely estimated at about 6% of the reference yield, involved low performance of the PV systems in the November 2007 – January 2008 winter period, due in part to snow melting and then freezing onto the arrays as temperatures dropped.

As shown in Figure 4, which gives monthly performance ratios for PV1-PV6 for the year under consideration, winter performance was again lower, especially in December 2008 and November 2009. For November 2009, a major snowfall was primarily responsible for the drop in performance. However, the system loss due to winter underperformance was estimated at less than 1% of the reference yield for the year under consideration. As can be seen in Figure 4, the PV5 system seems to be outperforming the other systems significantly. While this could be due to individual variations between the systems, or to inaccuracies in modelling insolation in the PV5 array plane, the most likely explanation is that the PV5 system benefits from a better array orientation. Its 42° tilt angle is nearly optimal for this latitude, as compared to that of the other systems (20° or 25°), and its azimuth is also the closest to a South-facing orientation. In practice, this means not only that the PV5 array will produce more electricity on a yearly basis, but also that it will experience fewer losses due to reflection (which become problematic at high incidence angles), as well as fewer losses due to snowfall and low light conditions in winter.

B. *Fuel savings*

Figure 5 shows the estimated values of the fuel savings achieved through adding photovoltaics, reducing commercial loads, and replacing a 95 kW genset by a 30 kW genset. The fuel savings achieved are considerable, amounting to about 26,000 L per year in total, or an $\approx$25% reduction in fuel use. This corresponds to about 73 tons of greenhouse gas emissions reduction per year, the equivalent of taking 21 cars off the road [17], or about one car off the road per household connected to the mini-grid!

As noted in Section III-A1, the fuel savings estimates depend to a considerable extent on the type of fit performed to the genset fuel consumption manufacturer data. For instance, if a linear fit had been performed instead of a quadratic fit, the fuel savings estimate from the PV would yield 7,500 L, about 27% more than the estimate obtained with a quadratic fit. This highlights the shortcomings of current genset specification methods, in which data are not published for loads lower than 25%; this forces any fitting method to extrapolate the behaviour at very low loads, which is far from ideal. It also illustrates the fact that additional fuel savings can be achieved by choosing gensets with good fuel efficiency at low loads.

The fuel savings (in litres) above can simply be translated to fuel savings in $, since the cost of diesel for the year under consideration was roughly C$0.99/L. The fuel savings from the commercial load control are clearly economical: this measure saves about C$11,130 of fuel per year, while the incremental costs from the contactor and its installation were around C$9,900. This analysis suggests that the use of *dump loads* to keep gensets loaded above some minimum threshold deserves closer examination. In the case of the current system, the yearly fuel savings of about C$11,130 generated by turning off non-critical loads that were essentially acting as *dump loads* are of the same magnitude as the costs of replacing the engine (about C$20,000 for the 95 kW), making it unlikely that operating *dump loads* would be financially better than risking accelerated genset ageing or increased maintenance requirements. Moreover, the use of a dump load also restricts potential savings from photovoltaics and other load reduction measures: for instance, if the 95 kW genset had been forced to operate at 30% or more of its rated power, it was estimated that fuel savings from PV would have been about 1,800 L (31%) less.

While load reductions and associated fuel savings have been achieved in the commercial zone, the opposite is true of the residential zone. Prior to the introduction of the mini-grid, households in this community owned and operated their own gensets consuming about 637 kWh per year per household [18]. Based on the analysis in [18], it was expected that this would rise to about 1,465 kWh once electricity became available 24 hours a day. Meanwhile, electricity demand in the residential feeder was about 97 MWh i.e. roughly 4,400 kWh per household for the year under consideration. However, caution should be exercised in comparing the consumption per household before and after the introduction of the mini-grid. The load measured includes the losses associated with the step-up transformer (100 kVA) at the head of the feeder as well as the ten distribution transformers (190 kVA total) spread across the mini-grid. Unfortunately, these losses are not measured so it is impossible to provide an accurate figure for the customers' load. Generally speaking, the transformers are lightly loaded (around 4%); consequently, the no-load component will dominate the transformer losses. Depending on the models actually installed, no-load losses can vary anywhere between 0.002 and 0.010 p.u. i.e. 5 to 25 MWh total or 230 to 1,136 kWh per household. That means that even considering losses, there is a significant increase in electricity consumption per household.

Part of the explanation comes from the weather: the winter of 2008 was unseasonably cold for an extended length of time. Vehicle block heaters and some electrical space heaters definitely contributed to the rise in electrical energy consumption. Another reason for this rise no doubt lies with electricity subsidies: subdivision residents pay a low, flat rate of roughly C$0.06/kWh for electricity supplied up to 750 kWh/month, well below the true cost of this electricity. This is probably why some residents have begun operating baseboard heaters during winter months, an extremely inefficient use of the mini-grid electricity. Above 750 kWh/month, the rate escalates to C$0.40/kWh, creating a strong disincentive to individual consumption rise beyond this level. It would be worth examining whether a different rate structure with a more progressive rate increase that comes into effect at lower monthly consumption levels could favour conservation and efficiency to a greater extent.

Additional measures to reduce fuel consumption could be undertaken but from a purely economical point of view this is a significant challenge. For instance, curtailing the PV power to harvest an additional 1.8 MWh could be done relatively simply with communication links between the inverters and the power plant, but the potential savings remain marginal. In practice, the 1.8 MWh of saved energy does not translate into that much fuel saving when the generator set is operating at low load. Between no load and an average load of 11.7 kW, the calculated incremental fuel consumption is around 0.134 L/kWh; 1.8 MWh would save only about C$240 of fuel per year. The implementation would need to be very inexpensive and readily available to make it profitable. Replacing transformers or regrouping customers to allow the removal of some transformers could also lead to losses reduction. Such a plan should however be preceded by a thorough measurement of the actual losses to ensure the economic viability of such an undertaking.

V. Conclusion

Based on one year of monitored data from a PV-diesel mini-grid in the Nemiah Valley, our analysis suggests that both the diesel gensets and the photovoltaics are performing within the range that could be expected based on manufacturer specifications and on benchmarks, although with somewhat higher losses than typical systems. In the case of the diesel gensets, this could be due to frequent operation of the gensets at low loads, and to distribution losses. Meanwhile, it was estimated that the distributed PV systems would deliver about 10% more energy on a yearly basis if all of their output could be absorbed. This factor alone accounts for the $\approx$10% underperformance of the PV systems compared to typical systems connected to large, centralized grids. Methods of mitigating these losses were discussed in this paper, and are currently being investigated. Such methods will be important for determining to what extent PV penetration can be increased in systems without storage before losses due to frequent inverter disconnection make increased penetration less economically viable.

The combined measures adopted yielded annual fuel savings of about 26,000 L, or a 25% reduction over business-as-usual. Among these measures, the implementation of commercial load control to reduce weeknight/weekend loads was clearly economical. This suggests that automatic use of dump loads should be re-examined in cases such as this one where fuel savings from removing dump loads are comparable to genset costs.

Finally, genset sizing and dispatch for this system could be further optimized to yield additional fuel savings: for instance, if the larger Deutz engine was replaced by a smaller engine, and if the switch between the larger and smaller gensets was optimized, it was estimated that an additional 5100 L of fuel could be saved each year. While the 95 kW gensets were preferred in this community for reasons mentioned in Section II-A2, it would be worth exploring, in this and other cases, how sizing of the engine/generator pair can reach the best compromise between fuel economy and adaptability to future developments and load growth. For instance, if the load were to increase and present more frequent excursions above 70 kW, changing the electrical generator for a 95 kW single phase unit should also be considered to avoid having two gensets running at part load.

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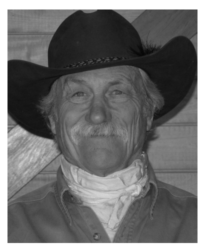

George Colgate, before retiring in the fall of 2009, was the manager of Xeni Gwet'in Enterprise, a subsidiary of the Xeni Gwet'in First Nations Government. Mr. Colgate founded the *Enterprise* in 1994 for the purpose of managing the First Nations existing infrastructure assets, constructing new assets, providing economic development opportunities and developing renewable energy resources in order to help the First Nation attain their goal of energy self sufficiency. Prior to moving to the Xeni Gwet'in community in 1976, Mr. Colgate was employed as a mechanical engineer in the cement and concrete industry. He currently resides on his ranch in Nemiah Valley and continues to provide part time technical and administrative consulting services to several isolated communities.

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