PERFORMANCE, COSTS, AND GHG EMISSIONS OF PV-HYBRID SYSTEMS: CURRENT STATUS AND AVENUES FOR IMPROVEMENT

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ABSTRACT

The performance of a photovoltaic hybrid system (consisting of a photovoltaic array, batteries, fossil-fuel combusting engine, synchronous generator, rectifier and inverter) is affected by a number of design choices and control parameters, and is, therefore, subject to optimization. At the outset of such an optimization exercise, it is useful to benchmark the performance of an unoptimized baseline system, i.e., one built according to current standard practice. The relative merits of proposed improvements can then be established by comparison with this benchmark.

This study uses simulation to determine the performance of a baseline PV hybrid system providing power to a 300 W moderately remote off-grid industrial load; it assumes climate and costs typical for Canada. It is compared with three competing alternatives—a prime power system, a genset-battery system, and a photovoltaic-battery system—on the basis of initial and annual costs, embodied energy, and greenhouse gas emissions. This comparison is repeated assuming a less remote, residential system with less expensive fuel and components, and then the impacts of various avenues for system improvement are examined.

Prime power systems are inappropriate for loads of this size, and this is reflected in high annual costs and emissions. But even the genset battery, PV and PV hybrid systems are expensive: the cost of electricity for the remote industrial application ranges from \$2.40 to \$3.67 per kWh. The PV hybrid system provides electricity the most cheaply, the genset-battery system has the lowest initial costs (ignoring the prime power system), and PV-battery system has the lowest greenhouse gas emissions. Its emissions are one-third those of the hybrid system, which are in turn one-third those of the genset-battery system.

Various potential improvements in hybrid system design and control are explored. These would incrementally reduce the cost of electricity, and might lower GHG emissions by over 50%.

INTRODUCTION

Within the context of photovoltaic technology, the term “hybrid systems” refers to power sources combining a photovoltaic generator with one or more generators drawing on non-solar energy resources. Often these systems are used off-grid, that is, to supply electricity to sites not serviced by an electrical network, such as remote homes, monitoring equipment, and telecommunication repeater stations. In Canada, hybrid systems typically combine a photovoltaic array with a fossil-fuel driven generator (a “genset”); systems also include lead-acid batteries for energy storage over the period of a day to several days, controllers to manage charging of the battery, controllers to effect genset dispatch (starting and stopping), and circuitry to convert between AC and DC, as required.

Hybrid systems compete with prime power, genset-battery, and PV-battery systems in this off-grid market. In order to compare these options, and potential improvements to a PV hybrid system, a financial analysis of the overall life-cycle cost of providing power is necessary. For example, genset fuel consumption, a critical operational cost, can be minimized simply by using a larger array and battery, but since this will increase capital costs, this is not necessarily an improvement. In addition, any such comparison should include a comparison of the greenhouse gas emissions, and not just of the fuel consumed, but also the emissions that occurred during manufacture of the system.

This analysis can be done through simulation of system performance under various assumptions. This study, based on an earlier study ([Ross, 2005]), has focussed on remote, industrial applications requiring high reliability.

SIMULATION DETAILS

This study used PVToolbox simulations running in the Matlab/Simulink environment to characterize system performance [Sheriff et al., 2003]. For simulation of major energy flows within hybrid systems, PVToolbox has demonstrated accuracy of within 5 to 8% [Ross et al., 2005]. The benchmarks examined in this study vary by around 15%. Note, however, that if the simulation has a bias, and this is applied equally to two different systems, then comparative differences smaller than the expected level of accuracy of the tool can be identified. This study assumes that the PVToolbox will be able to accurately identify a system as being, say, 2% better than another similar system, even though its estimate of the performance of both systems is 5 to 8% in error.

In contrast, the models used by PVToolbox to estimate component aging have not been validated against monitored data, and are probably less accurate. In particular, the battery model can offer only a crude estimate of the battery aging, and will not record the impact of abusive cycling, such as occurs when the battery is consistently undercharged.

This study simulated six different PV-hybrid system configurations, 14 genset-battery configurations, two prime power configurations, and one stand-alone PV-battery system, using CWEEDS hourly monitored weather data for the five year period of 1980 through 1984 for Vancouver, Edmonton, Inuvik, Toronto, and St. John's [Meteorological Service of Canada, 2003]. In half the simulations, the systems supplied power to a constant, 300 W DC load; in the other half, a 50 W DC load and a varying AC load (only the AC/DC load was considered for the PV-only system).

These 47 simulations generated too much data to be useful. In order to facilitate comparisons, one physical location and one configuration for each of the system types (prime power, genset-battery, PV-only, and PV-hybrid) had to be selected.

The simulations revealed that performance was similar with DC and AC/DC loads; for this study, the AC/DC load was used. The diurnal pattern of variation in the AC load, which ranged from 50 W to 1450 W, is shown in Figure 1. With integration error, the average combined load was 303 W.

By selecting the hybrid PV array size so that the same solar fraction was achieved at all sites, genset operation and battery deterioration changed little from one site to the next, other factors being held constant. Thus, the Toronto site was chosen as representative of the situation across the country.

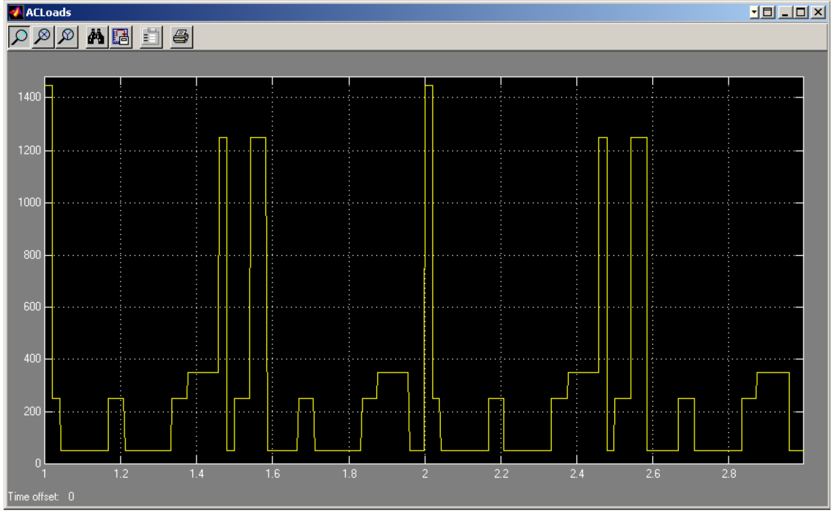

Figure 1 Diurnal Variation in AC Load (in watts) over Two Day Period

The genset-battery system was simulated with batteries of one and two days of autonomy. Fuel consumption, battery deterioration, and genset wear were similar according to simulation. Most battery manufacturers recommend charging currents no higher than the 5 hour rate; with a battery having one day of autonomy, the maximum current produced by the genset corresponded to the 2.5 hour rate. For this reason, a battery with two days of autonomy was used for both the genset-battery and PV-hybrid systems.

The prime power system consisted of a 5 kW diesel genset, running throughout the year, and a rectifier with an efficiency of 92.5% at 50 W (the DC load level). While a smaller genset would make more sense for the 300 W average load, in reality, few diesel gensets smaller than 5 kW are available.

The genset-battery system consisted of the 5 kW genset; a 5 kW rectifier; a 24V, 24 kWh battery (which, if fully charged would satisfy the load for two days before genset turn-on); and a 1.5 kW inverter. The genset was turned on when the battery was drained down to a 40% state-of-charge and turned off following two hours of constant voltage absorb charging at 28.5 V, with no equalisation. This corresponds to the default control of the commonly-used Xantrex SW series converters.

The hybrid system was identical to the genset-battery system, but with the addition of a 1.65 kW_p PV array, connected via an lossless maximum power point (MPP) converter. The photovoltaic array was sized to achieve an annual solar fraction of 65%, calculated as the total array output minus array output rejected at the charge controller, all divided by the sum of the DC load, the AC load, the losses in the inverter, and the losses in the battery. The array faced due south, and was tilted at 45º to the horizontal.

The PV-battery system was similar to the PV-hybrid system, but with a resized array and battery and no genset or rectifier. The battery and array achieved a loss-of-load probability of 1%, i.e., on average the system would supply the load for all but 3.7 days of the year. Though a relatively low level of reliability, especially for industrial loads, this required a large array and battery: for Toronto's climate, a 6.5 kWp array and 40.8 kWh battery. The battery was permitted to discharge to 20% state-of-charge before load disconnection. The array was tilted at 60º to the horizontal, favouring winter generation.

The genset was a 5 kW_{AC} diesel machine consuming 0.60 l/kWh, or 3 l/hr, at full load. At no load, it consumed 0.75 l/hr; its fuel consumption varied linearly between these two points. The nominal lifetime was assumed to be 10,000 hours of full load operation. When the genset was loaded between 50 and 100% of its nominal power, it was assumed to wear at a rate of one overhaul every 5000 h of operation. Below 50% rated power, the rate of deterioration rose linearly, such that at 0% of its nominal power, the rate of deterioration would result in one overhaul every 2500 h of operation.

The current-voltage-SOC behaviour of the battery model was based on data collected from a GNB Absolyte IIP absorbent glass mat battery. The battery was at 25 ºC at all times. Self discharge was 2% per month. The cycle life was assumed to be a linear function of the cycling depth-of-discharge (DOD), with 800 cycles achieved at 80% DOD and 1500 cycles achieved at 50% DOD. This is typical of manufacturers' claims for an industrial-quality battery built for cycling purposes, not subjected to abuse. A maximum calendar lifetime of 12 years was assumed.

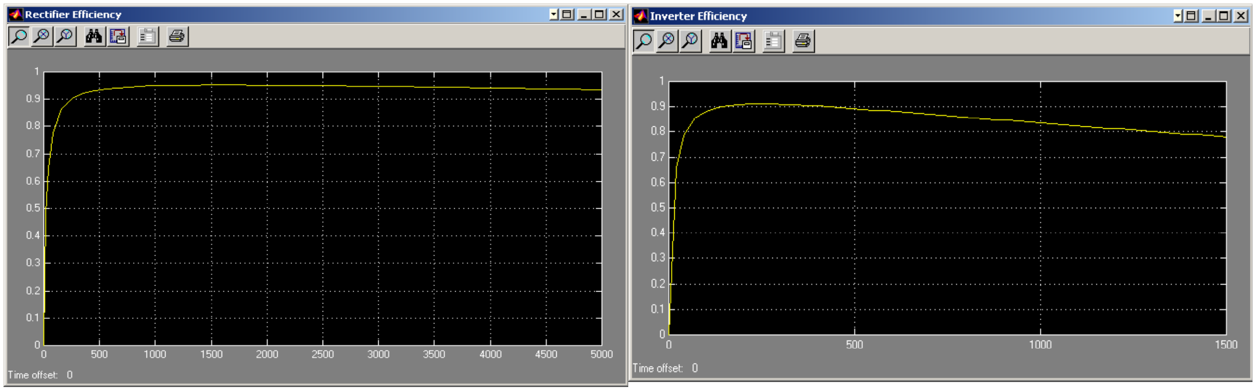

Figure 2 & 3 Rectifier and Inverter Efficiency Curves

The photovoltaic array was composed of parallel strings of two modules in series. To permit the solar fraction of 65% and the loss-of-load probability of 1% to be achieved as nearly as possible, fractions of strings were permitted. The module's open-circuit voltage was 20.6 V, the MPP voltage and current

16.5 V and 3.33 A, the short-circuit current 3.69 A, and NOCT 45°C. The open-circuit voltage declined 0.350% per °C and the short-circuit current rose by 0.041% per °C. An efficiency of 10% was assumed for the purposes of modelling solar heat gain. A lifetime of 25 years was assumed.

Since the rectifier in the genset-battery and hybrid power systems performed constant voltage absorb charging, it operated over a range of power levels; its efficiency curve is shown in Figure 2. The inverter, a 1.5 kW device, has the efficiency curve shown in Figure 3. The shape of the curve is based on the Xantrex SW series.

SYSTEM PERFORMANCE

The simulated performance of the systems is given, on an annual basis, in Table 1. The "Battery capacity deterioration" is the annual battery wear, expressed as an amount of capacity "used up". This estimate should be treated with caution; the aging model is very crude. The cycle life is limiting except for the PV-battery system, which has a lifetime of 12 years and therefore "uses up" 3400 Wh per year.

The "Fraction of rejected solar energy that could be avoided with non-seasonal storage" indicates the upper limit on improvements possible through avoiding genset operation prior to sunny periods. The rejected solar energy falls with larger batteries and can be reduced to arbitrarily low levels by permitting seasonal storage, defined to be an autonomy of one month or longer. In a month when the total array output exceeds the load and system losses, any PV output rejected in excess of the difference between the total array output and the total load and system losses is here considered avoidable with non-seasonal storage. In a month when the total array output is less than the load and system losses, all rejected PV output is considered avoidable. Summing over all months and dividing by the total annual rejected solar energy results in the fraction of rejected solar energy that could be avoided with non-seasonal storage.

	Prime Power	**Genset-Battery**	**PV-Battery**	**PV Hybrid**
Genset Fuel Consumption	7769 l	2245 l	NA	781 l
Genset Run Time	8760 h	884 h	NA	314 h
Genset Overhauls	3.29	0.19	NA	0.07
Genset Starts	1	212	NA	76
Genset Efficiency	3%	11%	NA	11%
Battery Capacity Deterioration	NA	1933 Wh	446/3400 Wh	1189 Wh
Fraction Solar	NA	NA	98.9%	64.6%
Fraction of Solar Energy Wasted	NA	NA	59.1%	3.7%
Fraction of Wasted Energy that can be Avoided with Nonseasonal Storage	NA	NA	0.8%	99.5%

Table 1 Annual Performance of Various Systems

The results confirm that prime power is not suited to small loads. Because the genset operates at a very low loading, it is inefficient and wears quickly. Fuel consumption and wear are lower in the genset-battery and PV hybrid systems. The efficiency jumps from 3 to 11%, but does not attain the 15% efficiency of the genset operating at full load, due to the two hours of absorb charging at the end of every genset run. The difficulty of decreasing the PV-battery system's loss-of-load probability below 1% is hinted at by the nearly 60% of the solar energy it is already rejecting, and the less than 1% of this waste that could be avoided with non-seasonal storage. The PV hybrid system, on the other hand, wastes less than 4% of its solar energy, and virtually all of this could be avoided with a moderately larger battery.

COST OF ELECTRICITY AT A REMOTE INDUSTRIAL SITE

The overall cost of generating electricity was calculated. A moderately remote industrial site, where transportation of equipment, fuel, and personnel to the system was expensive, and the necessity of reliable power justified higher quality components, was assumed. A 10% discount rate, no inflation, and a project life of 25 years were used. The analysis calculated the equivalent annual costs, summed these, and divided by the electrical energy required annually by the load to find the cost of electricity.

Component lifetimes are shown in Table 2.The genset was assumed to need replacement after two overhaul periods. Thus, if *x* overhauls were required per year, then every period of 2/*x* years one genset purchase and one genset overhaul were required. The genset of the PV hybrid system was estimated to last 29 years, longer than the duration of the project. Nevertheless, its equivalent annual cost was calculated based on a 29 year period, due to its salvage value at the end of the project.

The battery lifetime of the genset-battery and PV hybrid systems was calculated by dividing the battery capacity (24 kWh) by the simulated annual battery capacity deterioration, and then dividing again by three. The arbitrary factor of one third brought the battery lifetimes into line with what is observed in the field. It was necessary because neither the battery manufacturers' estimates of cycle life nor the simulation model fully account for the difficult conditions experienced by batteries in such systems.

	Prime Power	**Genset-Battery**	**PV-Battery**	**PV Hybrid**
PV Array	NA	NA	25	25
Battery	NA	4.1	12	6.7
Genset (overhauled once)	0.61	10.6	NA	29.0
Inverter	NA	12.5	12.5	12.5
Rectifier	12.5	12.5	12.5	12.5

Table 2 Component Lifetimes, Remote Industrial Site (in years)

The delivered cost of fuel was \$2.00/l, reflecting high transportation costs. The 5 kW genset was assumed to cost \$5000 to purchase and \$2000 to overhaul. (The present value of the overhaul cost, an expense in the future, was used in the calculation of the equivalent annual cost). Genset maintenance costs other than overhaul were estimated at \$1.00 per hour of operating time.

The battery was assumed to cost \$400/kWh of capacity (or \$9600 for the hybrid and genset-battery systems and \$16,320 for the PV-battery system). This is typical of a high-quality industrial battery, possibly of the valve regulated type, that must be transported to and installed at a remote site.

The photovoltaic array was assumed to cost \$8.00 per W_p, with about one quarter of that for transportation and installation. The inverter and rectifer cost \$1.00/W and \$0.30/W, installed.

The costs of each system are as shown in Table 3. All costs are on an annual basis except for in the last two rows, which show the initial system costs and the cost of electricity.

	Prime Power	**Genset-Battery**	**PV-Battery**	**PV Hybrid**
Genset Fuel	\$15,538	\$4,490		\$1,562
Genset Purchase	\$8,882	\$787		\$534
Genset Overhaul	\$3,451	\$190		\$54
Genset Maintenance	\$8,760	\$884		\$314
Battery Purchase		\$2,968	\$2,395	\$2,034
PV Purchase			\$5,729	\$1,454
Inverter Purchase		\$215	\$215	\$215
Rectifier Purchase	\$13	\$215		\$215
Total Annual Cost	\$36,644	\$9,749	\$8,339	\$6,382
Initial System Costs	\$5,090	\$17,600	\$69,820	\$25,800
Cost of Electricity	\$13.81/kWh	\$3.67/kWh	\$3.14/kWh	\$2.40/kWh

Table 3 Costs at Remote Industrial Site (Annual, except "Initial System Costs" and "Cost of Electricity")

As noted earlier, the prime power system is unsuited to this task, and this is reflected in its extremely high cost. A 1.5 kW diesel genset would be more suitable, but is not readily available.

The genset-battery, PV-battery and PV hybrid systems are more attractive, although the cost of electricity, in the range of \$2.40 to \$3.67 per kWh, is still high in absolute terms. These cost estimates are higher than typically suggested; this probably reflects the inclusion of transport to the remote site.

The battery and array of the PV-battery system are probably smaller than would be required in reality. A loss-of-load probability of 1% is unacceptably high for many industrial applications; the larger array and battery necessary for a more reliable system would raise the cost of electricity significantly.

The equivalent annual cost of the PV hybrid system has four roughly equal components: fuel, battery, array, and everything else. The battery is the most expensive component and the genset is not particularly important. Even if the genset were free, and no maintenance required, the cost of electricity would fall by only 14%; practically realisable reductions in genset costs would be more modest.

The prime power system has the lowest initial costs, but the highest annual costs. The PV-battery system has discouragingly high initial costs. The PV hybrid system produces electricity at one-third less cost that the genset-battery system, and its initial cost is around one-third that of the PV-battery system.

COST OF ELECTRICITY AT A RESIDENTIAL SITE

The above analysis was repeated, but with assumptions appropriate to an accessible residential site (see Table 4). For the prime power system, the analysis assumed a 1.5 kW portable gasoline generator with integrated inverter and feedback to adjust the genset speed in response to the load. The genset was assumed to consume 0.6 l/kWh and last 1000 h, regardless of the loading level. For the hybrid and genset-battery systems, a 5 kW gasoline or propane genset with a 0.6 l/kWh full load fuel consumption and lifetime one-tenth that of the diesel genset was assumed. Both the 1.5 kW and the 5 kW gensets cost $1000. The fuel cost was $1.00/l, and maintenance costs were only $0.10 per hour of genset operation, reflecting the assumption that the operator would do much of the maintenance him or herself.

The analysis assumes a less expensive ($200/kWh of capacity) flooded traction battery with a cylce lifetime 60% that of the battery used in the industrial system (e.g, 2.5 years for the genset-battery system and 4 years for the hybrid system), and a calendar lifetime of 6 years for the PV-battery system.

The photovoltaic array cost $7.00/Wp, due to installation costs half those of the industrial system (assuming an underlying cost of $6.00/Wp of PV modules). Inverter and rectifier costs were unchanged.

	Prime Power	**Genset-Battery**	**PV-Battery**	**PV Hybrid**
Genset Fuel	$1,593	$2,245		$781
Genset Purchase	$9,254	$1,041		$414
Genset Overhaul				
Genset Maintenance	$876	$88		$31
Battery Purchase		$2,264	$1,874	$1,514
PV Purchase			$5,013	$1,272
Inverter Purchase		$215	$215	$215
Rectifier Purchase	$13	$215		$215
Total Annual Cost	$11,736	$6,069	$7,102	$4,442
Initial System Costs	$1,090	$8,800	$55,160	$20,350
Cost of Electricity	$4.42/kWh	$2.29/kWh	$2.68/kWh	$1.67/kWh

Table 4 Costs at Residential Site (Annual, except “Initial System Costs” and “Cost of Electricity”)

The cost of electricity is lower in this scenario, mainly due to the reduced cost of fuel. Compared with the industrial site, genset purchase and overhaul costs rose slightly for the genset-battery system and fell by $174 per year for the hybrid system: the use of an inexpensive genset is not particularly advantageous in a hybrid system with a solar fraction of only 65%. Were the genset to be used for a much shorter fraction of the year, in a “backup” role only, a low cost genset might be more attractive; this would require a larger PV array.

The PV-battery system is less attractive than either the genset-battery or the PV hybrid systems. Were a higher loss-of-load probability acceptable, the cost of electricity could be reduced.

PRODUCTION ENERGY AND GREENHOUSE GAS EMISSIONS

Production of PV modules, gensets, and batteries requires energy. This “embodied” energy is associated with greenhouse gas (GHG) emissions. This energy has been estimated for the case of the remote industrial site; in the estimates below, energy used in transportation and maintenance; the energy in equipment enclosures, the inverter, and the rectifier; and other considerations are excluded.

Assumptions concerning the energy content of the major system components are indicated in Table 5 (figures from [Turcotte, 2005] and, for the genset, [Alsema, 2000]). Note that electricity consumed in the manufacture of the array, genset, and batteries has been converted to the equivalent primary energy requirement assuming an efficiency of 35%, as done by [Alsema, 1998].

Component	Materials	Fabrication	Total Primary Energy
Mono-Si PV Array	18 MJ/Wp	23 MJ/Wp	41 MJ/Wp
Diesel Genset	1480 MJ/kW	380 MJ/kW	1860 MJ/kW
Lead-Acid Batteries	880 MJ/kWh	190 MJ/kWh	1070 MJ/kWh

Table 5 Assumptions Concerning Energy Content of PV Array, Diesel Genset, and Lead-Acid Batteries

The annualized energy content is found by determining the fraction of a component lifetime used in one year, and multiplying this by the total primary energy content per unit of component capacity. For example, dividing the array size by its 25 year lifetime and multiplying by 41 MJ per Wp, the PV hybrid system's array is found to "require" 2,700 MJ of energy per year. The energy content, on an annualized basis, is shown for the three major components in the system in Table 6. The last row is for the fuel energy content. The array and the batteries account for the majority of the system's embodied energy.

	Prime Power	Genset-Battery	PV-Battery	PV Hybrid
Mono-Si PV Array	0	0	10,700 MJ	2,700 MJ
Diesel Genset	15,200 MJ	880 MJ	0	320 MJ
Lead-Acid Batteries	0	6,260 MJ	3,640 MJ	3,830 MJ
System Energy Content	15,200 MJ	7,140 MJ	14,340 MJ	6,850 MJ
Fuel Energy Content	303,000 MJ	87,600 MJ	0	30,500 MJ

Table 6 Energy Content of System and Fuel, Considered on Annual Basis

Diesel fuel contains 39 MJ/l, not including energy for extraction, refining and transportation. The fuel energy dominates the production energy, in part because these systems are inefficient.

The annualized energy content of the hybrid system array and batteries is 6,530 MJ; these supply 65% of the load, or 6,150 MJ, per year. Thus, they generate slightly less energy than is embodied in them. The embodied energy of PV-battery system is 50% greater than the energy it provides to the load.

The annual GHG emissions, in tonnes of CO_2 equivalent, are shown in Table 7. The first four rows of the table indicate emissions associated with embodied energy. Assuming that PV manufacture requires only electricity, generated at 35% efficiency and with emissions of 0.57 kg of CO_2 equivalent per kWh (i.e., roughly the level in the USA or Western Europe), array manufacture requires 0.055 kg per MJ of primary energy [Alsema, 1998]. For the battery, 0.06 kg of CO_2 equivalent per Wh of capacity is released, assuming 50% of the lead in the battery is from recycled sources [Alsema, 1998: Kertes, 1996]. In [Alsema, 2000] the embodied energy of a 6 kW genset is estimated at 1.8 GJ of electricity and 6 GJ of natural gas; assuming 0.57 kg of CO_2 equivalent emitted per kWh of electricity and 49.7 kg of CO_2 equivalent emitted per GJ of natural gas, then for a 5 kW genset emissions are 0.49 tonnes CO_2 equivalent. Emissions from diesel fuel combustion are based on a factor of 2.72 kg of CO_2 equivalent/l.

	Prime Power	Genset-Battery	PV-Battery	PV Hybrid
Mono-Si PV Array	0	0	0.59	0.15
Diesel Genset	0.80	0.05	0	0.02
Lead-Acid Batteries	0	0.35	0.20	0.21
Annual Equipment GHG Emissions	0.80	0.40	0.79	0.38
Annual GHG Emissions from Fuel	21	6.1	0	2.1
Total Annual GHG Emissions	21.8	6.5	0.79	2.5
Emissions per unit of Electricity	8.2 tCO_2/MWh	2.4 tCO_2/MWh	0.3 tCO_2/MWh	0.9 tCO_2/MWh

Table 7Greenhouse Gas Emissions, Considered on Annual Basis, in tonnes of CO_2 Equivalent

Diesel fuel consumption is the dominant source of emissions, making prime power especially unattractive. But even in embodied energy, it performs poorly, due to frequent genset replacement necessitated by part load operation.

The genset-battery and PV hybrid systems have similar emissions levels in terms of embodied energy, with increased wear in the genset-battery system compensating for the emissions from the hybrid system's array. The higher fuel consumption of the genset-battery system results in emissions nearly three times those of the hybrid system. Since it consumes no fuel, the PV-battery system has the lowest overall emissions level, only one third those of the PV hybrid system. Its 1 % loss-of-load probability is probably too low for many industrial applications, however; a much larger array and battery would be required to reduce the loss-of-load probability and this would raise the greenhouse gas emissions level significantly.

The PV hybrid system generates 0.9 tonnes of CO_2 equivalent per MWh of electricity produced. This compares unfavourably with electricity available from most large grid systems: for example, in Canada as a whole, emissions are only 0.211 tonnes of CO_2 equivalent per MWh. This misses the point: PV hybrid systems are off-grid, where low emissions sources of electricity are usually unavailable or very costly. PV hybrid compares very favourably with the genset-battery and prime power options.

The PV-battery system contains more embodied energy than it generates, and yet its emissions are lower than the emissions for the grid electricity used to produce it. This arises since the embodied energy figures in Table 6 are in equivalent primary energy terms, whereas the energy produced by the PV-battery system is electricity. A factor of 0.35 is used to convert from primary energy to electricity.

AVENUES FOR HYBRID SYSTEM IMPROVEMENT

How much can changes in design, sizing, and control of the hybrid system reduce cost and the greenhouse gas emissions per unit of electricity? This is examined through further simulations.

Adequate Rectifier Sizing: Before turning to improvements, consider existing systems that utilize a rectifier that is much smaller than the rated genset power. The genset runs at part load, unless high AC loads are present when the genset is on, and performance is poor compared to the system assumed here.

The choice of small rectifier principally arises from concern that batteries are damaged by high charge rates. Battery manufacturers often recommend that charge rates not exceed the four or five hour rate. At least two Canadian PV system vendors recommend charge rates not exceeding the 10 hour rate. Such low charge rates translate into rectifiers with less capacity than the genset, since there are few small gensets available, and hybrid system batteries rarely have much more than two days of autonomy.

This conventional wisdom may or may not be well founded. Early research on lead-acid batteries found that flooded batteries could be charge with a current, in amperes, that did not exceed the capacity remaining to be recharged, in ampere·hours [Vinal, 1955]. According to this, if the genset turns off at a state-of-charge of 70%, the two hour or three hour rate should be acceptable. Moreover, certain battery manufacturers do not restrict the maximum charge current as long as the voltage is limited, and extremely rapid charging systems for lead-acid batteries also exist. Perhaps battery manufacturers and vendors make conservative recommendations, without consideration for the inefficiencies this introduces. Or perhaps vendors expect users to fully charge the battery with the genset, making a large battery charger unnecessary: the battery will accept only a limited current at higher states-of-charge.

A second reason for undersizing the rectifier may be the belief that "there are really only two sizes of genset—adequate and too small" [Perez, 1995]. This belief reflects the many pitfalls of genset sizing. For example, if the battery charger is a transformer coupled to a diode bridge, a large genset is necessary since the charger conducts current only for the part of the AC waveform near the peaks. Furthermore, when the genset powers both 120 Vac and 240 Vac loads, only half the genset's rated power is available to 120 Vac loads on one side of the split phase. The rectifier capacity cannot be larger than the genset capacity minus the maximum AC load that will be powered directly by the genset. Many gensets should not be operated at more than 75 to 80% of their rated power, or fuel efficiency and genset lifetime will suffer. And loads requiring reactive power, such as battery chargers without power factor compensation, require excess genset capacity: for example, a charger with a 0.65 power factor and an efficiency of 85% would require 1 kVA of genset capacity to produce 0.55 kW of charging power.

Advances in power electronics have addressed some of these concerns. Switchmode battery chargers, now common, make use of the entire AC waveform, not just the peaks. Some battery chargers have power factor compensation and operate near unity power factor.

To investigate this, the hybrid system was simulated with a 2.5 kW (rather than 5 kW) rectifier. Annual fuel purchases rose by $242, genset purchase and overhaul by $110, and genset maintenance by $164; battery costs fell by $42 and rectifier purchase by $108. Overall, this increased the cost of electricity by 6%, the cost of fuel and maintenance by 23%, and emissions by 11%.

Longer Battery Lifetime: The simulations predicted a 20 year life for the hybrid system battery; recognizing that this is unrealistically long, all cycle lifetime estimates were divided by three. But the resulting battery lifetime estimates were shorter than is achievable by an industrial battery under controlled conditions. The partial state-of-charge cycling in hybrid systems appears to accelerate aging.

PV hybrid system testing has shown that even with an absorbent glass mat battery, little affected by stratification, partial state-of-charge cycling produces remarkable changes cycle-to-cycle voltage-current-SOC characteristics [Ross et al., 2005]. If voltage thresholds are used to determine when to start and stop the genset, this results in shorter and shorter cycles between genset runs. This may be responsible for accelerated aging. The reduced portion of the plates that is cycled will wear more quickly than the rest of the plate; when this portion of the plate fails, so too, the battery as a whole.

Regular full charging of a battery is believed to be beneficial. It “resets” the battery, such that immediately following recharge, the charge withdrawn from the battery between genset runs is as new. Of course, if the genset must operate at part load to achieve the full charge, the benefit to the battery is paid for by deterioration of the genset and increased fuel costs; for this reason most hybrid systems do not but occasionally fully charge the battery, unless this should occur under the influence of the PV array alone.

If improved genset dispatch strategy can achieve regular full charging of the battery, and longer lifetimes result, what effect might this have on costs and emissions? To examine this, the baseline results were recalculated assuming that the simulated cycle lifetime should be divided by a factor of two, instead of three; this corresponded to a cycle life of 10.1 years instead of 6.7 years. The annual battery cost decreased by $501 and the cost of electricity fell to $2.22/kWh, an 8% decline. The emissions associated with the energy content of the battery fell by 70 kg, causing a 3% decline in the total annual emissions.

Larger Arrays: A larger array would lower fuel, overhaul, maintenance, and battery costs, and reduce emissions associated with fuel combustion. The baseline simulation was rerun with 2.1 kW_p and 2.4 kW_p arrays. The results are shown in Table 8. Genset use declined, but wasted solar energy rose. Furthermore, this wasted solar energy was increasingly due to a surplus of solar energy during the summertime, which cannot be reduced except with extremely large batteries.

	Array: 1.65 kWp	**Array: 2.1 kWp**	**Array: 2.4 kWp**
Genset Fuel Consumption	781 l	547 l	468 l
Genset Run Time	314 h	219 h	188 h
Genset Overhauls	0.07	0.05	0.04
Genset Starts	76	53	45
Battery Capacity Deterioration	1189 Wh	1043 Wh	965 Wh
Fraction Solar	64.6%	75.3%	79.0%
Fraction of Solar Energy Wasted	3.7%	11.1%	18.3%
Fraction of Wasted Energy Avoidable with Nonseasonal Storage	99.5%	69.5%	46.4%

Table 8 Performance of Hybrid System with Larger Array, Remote Industrial Site

Annual operating costs (i.e., fuel, maintenance and overhaul) fell, compared to the baseline’s 1.65 kW_p array, by 31% with the 2.1 kW_p array and 41% with the 2.4 kW_p array. The initial cost of the array increased by $6000 going from 1.65 kW_p to 2.4 kW_p. This moderated the decline in the cost of electricity: with 2.1and 2.4 kW_p arrays it was $2.25 and $2.24/kWh, a 6.5% reduction. The optimum was somewhere between 2.1 and 2.4 kW_p, but the sizing was not critical over a wide range of sizes somewhat larger than 1.65 kW_p. At 2.6 kW_p, the cost of electricity was about $2.27/kWh.

The emissions stemming from embodied energy rose only slightly with a larger array, since the genset and battery aged more slowly. Due to significant reductions in fuel consumption, overall emissions per unit of electricity fell, compared with the baseline and its 1.65 kWp array, by 25% with the 2.1 kW_p array and 33% with the 2.4 kW_p array (to 0.6 tCO_2/MWh, or twice as high as the PV-battery system).

Reduced Part Load Operation: The genset in the hybrid system operates for two hours of absorb charging every time it is run. While this achieves fuller charging of the battery whenever the genset is run, it results in part load operation of the genset, increasing fuel consumption and genset wear.

To put an upper bound on improvements achievable by reducing part load operation, the baseline simulation was rerun without this absorb charging. In reality, this would cause batteries to fail prematurely due to prolonged cycling between partial states-of-charge, but this has been ignored here.

With absorb eliminated, genset run time fell by 31%, genset overhauls by 37%, and fuel consumption by 14%. The solar fraction rose by 2 percentage points. On the other hand, the number of genset starts rose by 34%, and the battery cycled more, causing the rate of deterioration to rise by 12%. A slightly higher solar fraction was achieved, largely since less solar energy was wasted and the battery was more efficient when not being charged at a high state-of-charge (as is done during absorb charging).

Genset fuel, overhaul, and maintenance costs fell substantially, but genset purchase did not: the genset was used relatively infrequently, thus its replacement costs were amortized over a long period, and the discount rate of 10% meant payments made well in the future were worth little in the present. The battery purchase cost increased by 9%, due to the battery having to supply the loads during those periods when the genset was formerly performing absorb charging. This estimate did not reflect increased wear due to abusive partial state-of-charge cycling. Overall, the cost of electricity fell by 3%, and the annual operating costs declined by 18%. Decreased fuel consumption and emissions offset an increase of 5% in emissions from embodied energy; the net result was an 11% decline in total emissions.

Improved Utilisation of Solar Energy: In the baseline, the genset dispatch strategy started the genset when the state-of-charge (SOC) fell to 40% and shut it down when two hours of absorb charging had elapsed. Such a dispatch strategy may waste solar energy if the battery is fully charged prior to sunny periods. Waste tends to rise when solar fractions exceed roughly 65%. Eliminating the two hour absorb charge at the end of each genset run reduces this waste somewhat. Further reductions may be possible.

To establish an upper bound on the improvements achievable by a genset dispatch strategy that avoids charging the battery prior to sunny weather, the simulations with arrays of 1.65 kWp, 2.1 kWp, and 2.4 kWp were rerun using a dispatch strategy that started the genset when the battery reached 40% SOC and stopped it when SOC had risen to 45%. Such a strategy causes many genset starts, does not ensure full battery charging, and would be undesirable in reality.

For all three array sizes, terminating the genset run at 45% SOC resulted in significant reductions in fuel consumption (22 to 31%), run time (37 to 44%), overhaul frequency (43% to 78%), and fraction of solar energy wasted (3.0 to 3.7 percentage points). Effects were more pronounced with larger arrays: the reduction in fuel consumption was 22% with a 1.65 kWp array but 31% with a 2.4 kWp array.

Battery deterioration increased significantly (by 35 to 57%) due to prolonged operation at low SOC; the estimate ignores the rapid aging that would occur due to the battery rarely being fully charged. But increased battery wear is not an essential feature of efforts to increase solar utilisation. Smarter strategies would, for example, more fully charge the battery during winter, knowing that the likelihood of excess sunshine would be low. For this calculation, therefore, the battery wear for the system with 45% SOC termination was assumed to be the same as that for the system terminating genset charging at the beginning of absorb. Otherwise, the cost of electricity would be higher than with two hours of absorb.

The 45% SOC genset termination strategy achieved reductions of 25% to 34% in the annual operating costs (fuel plus maintenance) compared with the two hour absorb strategy, and 9 to 17% compared with terminating the genset run at the beginning of absorb, with larger arrays having bigger reductions. For all three array sizes, the cost of electricity fell by 5% compared to the two hour absorb strategy and 2.5% compared to the strategy of terminating the genset run at the beginning of absorb.

GHG emissions fell by 18 to 23% compared to the two hour absorb strategy. The larger reduction was for the 2.4 kW_p array, which achieved emissions of less than 0.5 tCO_2/MWh, a level lower than average emissions for electricity production in Western Europe and the United States.

CONCLUSIONS

Providing small quantities of reliable electric power (e.g., around 300 W) at off-grid sites is extremely expensive. Prime power is unsuitable, because the genset operates at low loading levels, causing wear and inefficient operation. Genset-battery, PV-battery, and PV hybrid systems produce electricity at around $1.50 to $4.00 per kWh when all costs are considered. The genset-battery system has the lowest initial costs, but the highest GHG emissions; the PV-battery system has the lowest emissions but a very high initial cost; the PV hybrid system captures many of the benefits of each. For loads of this size, it produces electricity the most cheaply, has moderate initial and operating costs, and generates only one third the emissions of the cycle-charge system.

Upper bounds on the improvements associated with various changes to the PV hybrid system are indicated in Table 9. Using a larger PV array may be the simplest way to reduce costs and emissions. Smarter control may reduce the cost of electricity by 3% to 8%. If it prolongs battery lifetime, the cost of electricity may fall another 8%. Many PV hybrid system use rectifiers that are small in comparison with the genset, causing it to operate at part load. This increases the cost of electricity by around 6%. Reducing the cost of the genset has a modest effect: even if it were free, and required no maintenance, the cost of electricity would decline by only 14%.

In comparison with existing typical PV system, the improvements studied could reduce GHG emissions by well over 50%. Even so, the PV hybrid system would have emissions higher than the mix of generators on the Canadian electric grid, per unit of electric energy. Emissions would be significantly lower that with competing prime power or genset-battery systems, however.

	Fuel + Maintenance Costs	**Cost of electricity**	**GHG emissions**
Baseline	$0.72/kWh	$2.40/kWh	0.9 t CO2
2.5 kW rectifier	+23%	+6%	+11%
No cost, maintenance-free genset	-21%	-14%	
50% longer battery lifetime		-8%	-3%
45% larger array	-41%	-7%	-33%
Eliminating absorb charging (part load)	-18%	-3%	-11%
Minimizing wasted solar energy	-25%	-5%	-18%

Table 9 Summary of Impacts of Various Changes to PV Hybrid System at Remote Industrial Site

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