# PV/GENSET/BATTERY HYBRID POWER FOR THE REMOTE HOME: COST SENSITIVITIES AND THE DEMONSTRATION AT XENI GWET'IN

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## ABSTRACT

In this paper the problem of providing off-grid electric power for the remote home is considered. A systematic analysis is conducted where gensets alone, genset / battery hybrids and photovoltaic (PV) / genset / battery hybrids are modeled and the delivered electricity costs are calculated. The hybrid scenarios are demonstrated to be superior to running the genset alone. The genset / battery hybrids and the PV / genset / battery hybrids deliver electricity for similar costs regardless of the genset technology or the amount of PV present. GHG emissions, on the other hand, are significantly reduced by adding PV to the genset / battery hybrids.

Results indicate that operating generators continuously to meet the residential load is cost prohibitive when compared to any of the hybrid-system alternatives. The results also indicate that the cost of operating either a genset / battery or PV / genset / battery hybrid is very similar; $1.4/kWh (± $0.2) regardless of the genset technology used or the amount of PV installed.

The paper concludes with a brief case study of a recently installed, highly-integrated PV / genset / battery system currently powering a residence in the Nemiah Valley of British Columbia, Canada. This installation is also the field reference for validating the modeling study and for gathering information on user preferences.

## INTRODUCTION

The functionality of PV based, off-grid yet road accessible electric power supplies has been well documented. It is understood that simple PV / battery systems offer the best cost performance for small energy systems that supply up to ~1 kWh per day – even though the delivered energy cost may be in the 10s of $/kWh. It is also understood that simple continuous run diesel gensets offer the best cost performance for supplying greater than 10s of kWh per day – often for less than $0.25/kWh.

In 2004 Xantrex Technology Inc. of Vancouver, BC in collaboration with the CANMET Energy Technology Centre in Varennes, QC commenced a demonstration project to look at improving the state-of-the-art for residential sized (~7 kWh /day) PV / genset / hybrid systems [1,2]. This work focused on reducing the system size and cost while also improving functionality in order to increase market penetration.

This paper attempts to provide economic insight for off-grid applications between ~1 kWh/day and 10s of kWh/day where PV / genset / hybrid solutions are thought to offer the lowest cost of electric energy production [3]. This range is of specific interest because it encompasses the energy demands of an efficient residential application.

In this paper three common gensets are used to compare cost performance as a function of each genset technology. Initially a simple spread-sheet model is created to run the load continuously in order to compare gensets operating on propane, gasoline, and diesel fuels. These scenarios were then compared to the genset / battery charge-cycling hybrid and the PV / genset / battery hybrid cases to further evaluate the cost performance. The results obtained using a relatively simple spread-sheet based method for comparing hybrid system cost-performance are discussed. In total 19 system scenarios are presented.

Finally, this paper presents a summary of the knowledge gained through the demonstration of a PV / genset / battery hybrid system installed with the Xeni Gwet'in First Nation in the Nemiah Valley of central British Columbia, Canada in June of 2006.

## SIMULATION / MODELING

While there are many complex and specialized hybrid system computer modeling tools available, the intent of this simulation study was to use a simple and rapid spread-sheet approach that accounts for all major system considerations. In particular our study included a baseline comparison using three popular gensets sold in Canada. These are the 5.5 kW Onan Marquis Gold fueled with propane, the 3 kW Honda EU3000i fueled with gasoline and the 6.8 kW Onan DNAC7.5 fueled with diesel. The selection and approach used in this study is influenced by the knowledge gained during the Beta PV-hybrid systems demonstration in 2005 and the Xeni Gwet'in field testing in 2006.

### Obtaining a Reference Load

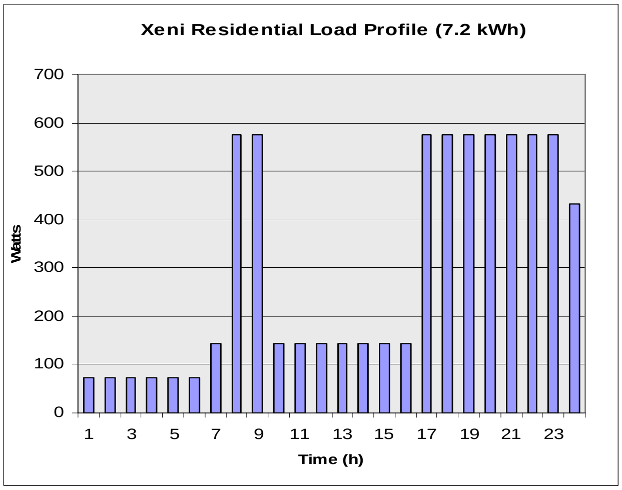


*Figure 1. Reference Load*

The performance of any hybrid system is influenced strongly by the electrical load profile. The calculations of this study are referenced to the residential-type load profile of Figure 1 which is based on real data from the example of Xeni Gwet'in. It includes the following loads: washing machine, kettle, toaster, well pump, electric fridge, lighting, computers/entertainment and a significant system tare loss. The load has a maximum demand of 2.6 kW, a sub-30 second surge demand of 4.9 kW and a daily average energy demand of 7.2 kWh/day. This reference load represents the reasonable energy consumption of an efficient family residence with basic electricity requirements. It does not include any heating loads such as a furnace or stove. These heating loads are to be powered, with more conversion efficiency, directly from the combustible fuel supply.

### Selected Gensets for Consideration

Three common gensets have been selected for consideration as fuel-based electricity sources in this analysis. The three gensets are a representative sample of genset technologies most commonly used for remote residential electrification. Gasoline, propane and diesel fuels are represented and the specific details for each genset are presented in Tables 1-3.

*Table 1. Onan Marquis Gold Genset*

| | | |
|---|---|---|
| Onan Marquis Gold 5500 | | |
| Rated Power (W) | | 5000 |
| **Fuel Data (Propane)** | | |
| power | gal/hr | L/hr |
| 0% | 0.5 | 1.9 |
| 25% | | |
| 50% | 0.8 | 3.0 |
| 75% | | |
| 100% | 1.1 | 4.2 |
| m | b | |
| 2.3 | 1.9 | |
| Oil Change Interval (hrs) | | 150 |
| Oil Change Cost ($) | | 50 |
| Rebuild Interval (h) | | 6000 |
| Rebuild Cost ($) | | 3500 |
| Fuel Cost ($/L) | | 0.7 |
| **Capital Cost** | | **4000** |

*Table 2. Honda EU300i Genset*

| | | |
|---|---|---|
| Honda EU3000i | | |
| Rated Power (W) | | 2800 |
| **Fuel Data (Gasoline)** | | |
| power | gal/hr | L/hr |
| 0% | 0.075 | 0.3 |
| 25% | 0.17 | 0.6 |
| 50% | | |
| 75% | | |
| 100% | 0.47 | 1.8 |
| m | b | |
| 1.5 | 0.3 | |
| Oil Change Interval (hrs) | | 150 |
| Oil Change Cost ($) | | 50 |
| Rebuild Interval (h) | | 5000 |
| Rebuild Cost ($) | | 2300 |
| Fuel Cost ($/L) | | 0.9 |
| **Capital Cost** | | **2300** |

For each genset, data has been presented for fuel consumption, maintenance (represented by oil change), rebuild, fuel cost and capital cost. For modeling purposes the fuel consumption is represented by a linear fuel curve based on the fuel consumption data and described by:

$$\text{Fuel/hr(L)} = (\text{Load/Full\_Power})m+b$$

*Table 3. Onan DNAC7.5 Diesel Genset*

| | | |
|---|---|---|
| DNAC7.5 | | |
| Rated Power (W) | | 6800 |
| **Fuel Data (Diesel)** | | |
| power | gal/hr | L/hr |
| 0% | 0.133 | 0.5 |
| 25% | 0.23 | 0.9 |
| 50% | 0.36 | 1.4 |
| 75% | 0.49 | 1.9 |
| 100% | 0.62 | 2.3 |
| m | b | |
| 1.8 | 0.5 | |
| Oil Change Interval (hrs) | | 200 |
| Oil Change Cost ($) | | 70 |
| Rebuild Interval (h) | | 20000 |
| Rebuild Cost ($) | | 3000 |
| Fuel Cost ($/L) | | 0.9 |
| **Capital Cost** | | **10000** |

## Continuous Genset Run – Non-Hybrid Operation

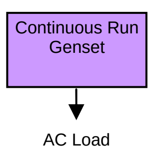


*Figure 2. Continuous Genset*

The first step of the economic performance analysis was to run the gensets continuously to meet the load (representing a 24hr uninterrupted supply). This was achieved by using a spread-sheet to calculate the fuel consumption for each hour of the load profile from the linear fuel curve. Summing the hourly fuel consumption and multiplying by the fuel cost yields the fuel cost per day. The O&M cost per day was calculated by determining the oil change and rebuild cost per hour of operation and multiplying by 24. The initial capital equipment cost was assumed to be amortized at 8% over 20 years in order to provide a daily capital equipment cost.

## Genset/Battery Hybrid – Cycle-Charge Operation

The next step of the analysis was to model a cycle charging genset / battery hybrid. A genset / battery hybrid can be created by adding batteries, a battery charger and an inverter to the genset as indicated by Figure 3. The genset can now be run at full load (most fuel efficient) for a relatively short time while supplying the load and storing surplus energy in the batteries. The inverter uses energy from the batteries to power the relatively low average-load when the genset is not running. In principle, system performance can be increased because the generator runs less hours at a higher fuel efficiency. The spread-sheet tool was used to perform the analysis. A battery energy balance method was utilized to calculate the cycle-charging performance of the system (Figure 4). Essentially a 24 hour spread-sheet of the system operation was created in increments of one hour – as with the continuous run example. However, in the genset / battery hybrid cycling case the loads are predominately run from energy in the battery via the inverter. During the day Watt-hours are removed from the battery according to the load and the system losses. In the evening the system model must run the genset for a period of time in order to achieve a neutral battery energy balance at midnight. During this charge and discharge activity all the main system inefficiencies were considered. It is up to the manipulator of the spread-sheet to manually adjust the run time as necessary to achieve the neutral energy balance. In this way the 24 hour performance of the getset / battery hybrid system can be rapidly and accurately determined with a relatively simple spread-sheet based analysis.

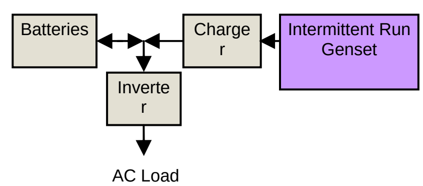


*Figure 3. Genset/Battery Hybrid*

*Table 2. Genset/Battery System Parameters*

| | |
|---|---|
| Charger Efficiency (%) | 90 |
| Inverter Efficiency (%) | 90 |
| Battery Efficiency (%) | 90 |
| Round Trip Efficiency (%) | 73 |
| Battery Wear Cost ($/kWh) | 0.25 |
| Power System Size (kW) | 6 |
| Power System Cost ($/kW) | 1000 |

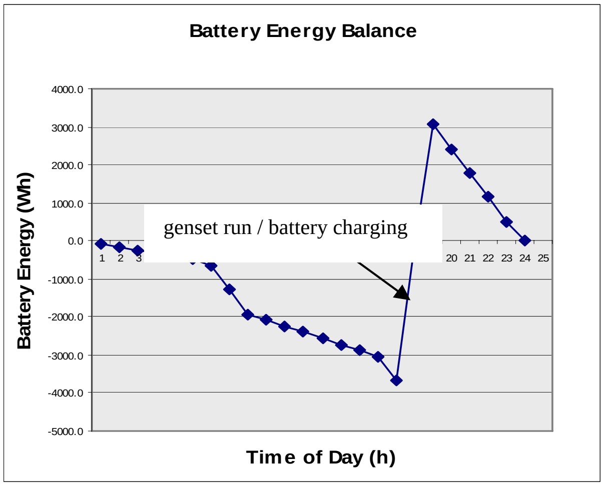


*Figure 4. Achieving Battery Energy Balance*

As with the continuous run example the capital equipment is amortized at 8% over 20 years. The batteries are considered a consumable item and are modeled as a daily wear cost. The new hybrid system parameter assumptions are noted in Table 2.

**PV/Genset/Battery Hybrid**

The final step of the cost-performance analysis was to add PV (500, 1000, 1500 watt) to the genset / battery hybrid system. The idea is that PV energy can elegantly offset fuel burned by the genset. The caveat is that PV energy is initially very expensive. Including the effects of the PV also makes the spread-sheet analysis significantly more complicated. In any case, the effects of adding PV is of interest from the perspectives of fuel offset, operating cost reductions and reduction in Green-House Gas (GHG) emissions.

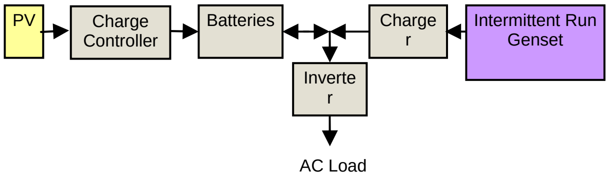


*Figure 5. PV/Genset/Battery Hybrid*

Monthly solar data for Williams Lake, BC was conveniently obtained from NRCan's RETScreen application [4]. The tilt of the panel was set to produce the most PV energy over the year on a fixed plane. This provides the best utilization for each dollar invested in PV.

*Table 3. PV/ Genset/Battery System Parameters*

| | |
|---|---|
| Location | Williams Lake, BC |
| Latitude | 52.18 |
| Optimum Tilt (Deg) | 48.00 |
| PV Array Size (W) | 0-1500W |
| Installed PV Cost ($/W) | 7.00 |
| Overall PV Perf. Factor (%) | 90 |

The daily solar energy radiated onto the plane of the PV is then converted in to Wh(dc)/day using the PV performance factor and size of the array. The Wh(dc) charging demand is known from the prior battery energy balance calculation. The genset run time can then reduced by the appropriate amount of energy supplied by the PV for that day. In this way the O&M and fuel consumption of the genset can conveniently be reduced by the input of the PV energy. The added complication is that the PV energy changes with the time of year. In order to take this into consideration the PV/genset/battery hybrid performance was calculated for each month of the year and then averaged to determine the daily effect. Figure 6 is an example how the fuel consumption and cost per delivered energy changes significantly as a function of the season.

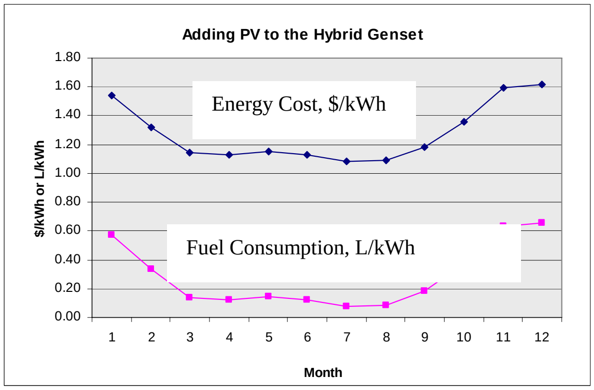


*Figure 6. PV/genset/battery hybrid with 1500W of PV and the propane genset.*

PV was added to each of three genset/battery hybrid fuel technologies in 500W increments.

## RESULTS/DISCUSSION

The results of the 19 scenarios in this study are summarized in Table 4.

**Continuous genset Run – Non-Hybrid Operation.** The difference in performance between the different generators was substantial (Table 4). The gas and diesel gensets produced electricity for the load at ~4$ per kWh while the propane genset required ~8$ per kWh. Both the gasoline and diesel used much less fuel per kWh generated when compared to the propane genset. This is a result of two reasons. The diesel technology, in general, is superior for continuous run applications. It has better low-load fuel economy and reduced hourly O&M cost; and the Honda genset is a variable speed inverter type unit that can spin at low speed under low load and therefore the fuel consumption is reduced significantly. In contrast, the propane genset is a fixed-speed unit and has relatively poor low-average-load performance - as indicated by the results. (note: A non-inverter-based gasoline genset will be similar in light-load performance to the propane genset.)

None of these solutions are particularly interesting for off-grid applications as the cost per day for electricity ranges from 27-52$, the noise is constant and the maintenance is frequent. Often these gensets will be run intermittently, thus providing interrupted power but also a reduction in the daily cost .

### Hybrid Operation

In all three cases hybridization of the genset created an improved power supply at lower cost (Table 4). The delivered cost of energy per kWh doesn't change dramatically as a function of the genset technology or with the addition of PV. This is to say the results indicate a delivered cost of energy with the hybrid systems to be in the neighborhood of $1.4/kWh (±$0.20) regardless of the genset technology or the amount of PV. The monthly expenditure needed to support this type of power supply is in the neighborhood of $300/month.

The results don't indicate a hybrid system configuration that's clearly superior form a high-level economic perspective. However, the addition of PV, in every case, has a strong influence in reducing fuel consumption while having little influence in the overall economics. With each genset technology the addition of 1500W of PV decreases the GHG emissions by 400% as compared to the hybrid system without the PV array.

A buyer's decision regarding which type of system to purchase now appears to be a based on practical issues (e.g. fuel availability, noise tolerance, willingness to be 'green' etc.) rather than price. For example, an off-grid home or cottage owner may wish to spend as little initial capital as possible and invest in a low-cost gasoline-based PV-less hybrid system. Gasoline gensets are readily available, lighter, easier to move, and are less noisy than diesel counterparts. The home-owner will, presumably, be present to make sure all the maintenance is performed - including filling the gasoline tank. Furthermore, the installation may be a do-it-yourself application due to the small system components. On the other hand, an industrial customer (or service provider) may wish to invest more capital and install a more robust diesel based system with a large fuel tank and extended range oil sump. Since the industrial customer is less likely to be present they may place a lower requirement on noise and more of a requirement on robust maintenance-free operation. The industrial customer is also more likely to have the facilities to manage the heavier equipment. In all cases the addition of PV will further reduce the maintenance interval for these applications.

One might imagine a mass-residential market being receptive to a system that is low in cost and financial commitment. For example, if a store stocked all the systems analyzed, the $8306 Honda battery hybrid option may sell very well as compared to the $26506 PV / diesel / battery system – when essentially they do the same thing for about the same cost per kilowatt hour of electricity generated. With the former, it could be retired after a few years for virtually no financial penalty. With the latter, the PV has to be in service full-time for the life of the system or there is a financial penalty (with PV you pay for all your energy in advance – even if you don't use it).

In Canada, the current market trend for residential applications tends towards low volume and relatively large PV / battery-based systems with the genset used only as 'backup'. Smaller and lower-cost PV / genset / battery hybrid technology with advanced battery management, as discussed in this paper, is not currently available. Nor is it of significant financial interest to the small industry of niche-market off-grid dealers. For substantial future market uptake it will be important to establish a low-cost, high-performance hybrid package that can be marketed to a wide audience and sold in through volume retailers.

The relevance of adding PV as a cost-free method to significantly reduce GHG emissions can not be stressed enough. However, adding PV does not come without caveats. In order for PV to make financial sense the system has to be: 1) in full-time operation the vast majority of the time for next the two decades and 2) the capital required to purchase the PV must be available. The results of Table 4 indicate that adding PV in any amount up to 1500W (approximately the amount of PV where 5 full sun hours supplies the ~7.5 kWh load) can reduce the overall delivered cost of energy by up to 25%.

## DEMONSTRATION AT XENI GWET'IN

In June of 2006 Xantrex Technology Inc. installed a PV / genset / battery hybrid power system on one of the Xeni Gwet'in First Nation family residences in the Nemiah Valley of British Columbia, Canada. Prior to the installation of the hybrid system, the family was running a genset with manual on-off switch for a few hours each evening in order to provide electricity for lighting, appliances and entertainment loads. Installation of the fully-automatic hybrid power system has improved this family's electricity supply by:

-Providing 24 hour power.

-Allowing the retrofit to an electric refrigerator (eliminating the use of an expensive propane-refrigerator).

-Allowing for the low-cost addition of an electric freezer.

-Providing 24 hour internet access for a home computer.

-Preventing trips outside to start and stop the genset.

-Producing 70% of the delivered energy with clean PV solar energy thereby reducing noise and emissions.

-Providing real-time energy consumption data available to the user.

Perhaps most significantly, the cost of operating this system appears to be no more expensive than costs associated with purchasing and operation the existing intermittent genset only system.

### Xeni Gwet'in System Description

The installed system consists of 1.5kW of solar, a small 225Ah @ 48V battery bank comprised of ubiquitous golf-cart type batteries, advanced hybrid charge control and a propane generator. (The propane generator was chosen in this case because of pragmatic issues of noise and fuel supply). Both the genset and the inverter/charger are rated at 5.5kW. The highly-integrated system is an 'arrive and drop' style with all the components located in a single integrated enclosure. The system features an advanced hybrid control system that efficiently manages a small battery bank through aggressive yet controlled overcharge. The installed system also has a unique satellite-based real-time monitoring system that enables anyone, anywhere with an internet connection to view graphs of the system operation.

### Lessons Learned

The real-world experience with this particular system has been very positive. Some lessons learned follow:

-The online monitoring is essential for providing feedback to the user. The graphical representation allows the users inefficient habits to become obvious and changed relatively easily. The load consumption of this application went down consistently over the first three months of operation due to this direct feedback.

-The system performed as expected without the unpredictable battery behaviors of the previous beta systems.

-The rapid acid stratification and resulting capacity decrease of the small battery bank in this configuration is significant – but can be managed effectively.

-Automatic battery overcharge is essential for achieving satisfactory battery performance with a small, low-cost battery bank.

-Battery replacement of the small golf-cart-type batteries is quick and affordable.

-Simpler seems to be better when it comes to generator dispatch. Advanced generator control strategies offer only minor performance increases when compared to a simple evening top-up charge routine. There appears to be some value in the genset starting at an expected time each day.

-The user's understating of the power system appears to be quite emotional. When the user's expenses consist of genset replacement, servicing, and fuel users seem to consider only the intermittent additions of fuel as a memorable expense. Grouping all the expenses into a monthly electricity bill surprises the user as being very expensive - even if it actually cheaper than the prior system.

-The 'arrive and drop' concept was very successful.

-Propane is an easy fuel supply to deal with due to the mature service infrastructure and low cost tank rental. It is much easier to obtain and maintain a large propane supply than a large gasoline supply.

-The 350 LB generator is too heavy and compact for easy service by one person. The smaller Honda would have been much easier to deal with from a service or replacement perspective.

-Cold weather performance has not been a problem. Specifically the generator has started in below -30 conditions. However, the small 200 CCA (cold cranking amp) starting battery of the genset had to be increased to 800 CCA.


Figure 7. The Xeni Gwet'in PV/genset/battery hybrid

## CONCLUSION

This paper has shown various schemes for powering an off grid home with a hybrid power system. Initially a spread-sheet analysis was computed to show the costs associated with running three common gensets 24 hrs a day to meet the load. This proved to be expensive, maintenance intensive and not very pragmatic. Next a number of hybrid systems were analyzed with increasing PV sizes from zero to 1500W. The results show the delivered cost of energy to be relatively insensitive to the addition of PV while the reduction in fuel consumption and GHG emissions is dramatic. The results also show the cost of delivered electricity by any of the hybrid system to be in the range of 1.2 to 1.6 dollars per kWh.

The case study of Xeni Gwet'in has been presented where a compact integrated PV / genset / battery hybrid system has been successfully powering a monitored residence for the past year.

## ACKNOWLEDGMENT

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The author would like to further acknowledge the patient support from our group of beta hybrid-system testers.

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[3] Turcotte D, Sheriff F. PV Horizon: workshop on photovoltaic hybrid systems - summary and conclusions, Montreal, Canada, 10 September 2001.

[4] Natural Resources Canada, Photovoltaic Systems Design Manual, (Ottawa: Minister of Supply and Services, 1991).

[5] RETScreen Tool – refer to PV / genset / battery hybrid case study, www.retscreen.net.

*Table 4. Summary of the modeled economic performance*

**Summary of the example gensets running continuously to meet the load.**

| | Capital $ | O&M ($/hr) | Fuel $/day | O&M $/day | Batt $/day | Op $/day | Cap $/day | Total $/day | Total $/kWh | Fuel L/kWh |
|---|---|---|---|---|---|---|---|---|---|---|
| **Gasoline:** | 2300 | 0.8 | 9.58 | 19.04 | N/A | 28.62 | 0.6 | 29.2 | 4.1 | 1.5 |
| **Propane:** | 4000 | 0.9 | 34.04 | 22.00 | N/A | 56.04 | 1.1 | 57.1 | 7.9 | 6.8 |
| **Diesel:** | 10000 | 0.5 | 12.61 | 12.00 | N/A | 24.61 | 2.7 | 27.4 | 3.8 | 1.9 |

**Summary of the example gensets running as PV Hybrids**

| | PV (W) | Capital $ | O&M ($/hr) | Fuel $/day | O&M $/day | Batt $/day | Op $/day | Cap $/day | Total $/day | Total $/kWh | Fuel L/kWh |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gasoline:** | 0 | 8306 | 0.8 | 5.28 | 2.62 | 1.36 | 9.25 | 2.28 | 11.53 | 1.60 | 0.81 |
| | 500 | 11806 | 0.8 | 3.98 | 1.97 | 1.36 | 7.31 | 3.23 | 10.55 | 1.46 | 0.61 |
| | 1000 | 15306 | 0.8 | 2.68 | 1.33 | 1.36 | 5.37 | 4.19 | 9.56 | 1.33 | 0.41 |
| | 1500 | 18806 | 0.8 | 1.38 | 0.68 | 1.36 | 3.42 | 5.15 | 8.58 | 1.19 | 0.21 |
| **Propane:** | 0 | 10006 | 0.9 | 5.53 | 1.74 | 1.68 | 8.95 | 2.74 | 11.69 | 1.62 | 1.10 |
| | 500 | 13506 | 0.9 | 4.07 | 1.28 | 1.68 | 7.03 | 3.70 | 10.73 | 1.49 | 0.81 |
| | 1000 | 17006 | 0.9 | 2.61 | 0.82 | 1.68 | 5.12 | 4.66 | 9.78 | 1.36 | 0.52 |
| | 1500 | 20506 | 0.9 | 1.15 | 0.36 | 1.68 | 3.20 | 5.62 | 8.82 | 1.22 | 0.23 |
| **Diesel:** | 0 | 16006 | 0.5 | 2.97 | 0.70 | 1.68 | 5.36 | 4.39 | 9.74 | 1.35 | 0.46 |
| | 500 | 19506 | 0.5 | 2.19 | 0.52 | 1.68 | 4.39 | 5.34 | 9.73 | 1.35 | 0.34 |
| | 1000 | 23006 | 0.5 | 1.40 | 0.33 | 1.68 | 3.42 | 6.30 | 9.72 | 1.35 | 0.22 |
| | 1500 | 26506 | 0.5 | 0.62 | 0.15 | 1.68 | 2.45 | 7.26 | 9.71 | 1.35 | 0.10 |