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An Analysis of Off-Grid Residential Refrigerator Energy Usage- Absorption vs. Electric?

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Abstract

This paper describes a detailed analysis of off-grid residential refrigeration energy usage, specifically comparing the energy performance of electric and propane-fired refrigerators. Off-grid electric power systems frequently incorporate a renewable source such as wind or solar photovoltaic (PV) with a back-up propane fueled motor/generator. Residential consumers face the choice of employing an electric refrigerator with a conventional vapor compression refrigeration system, or a fuel-fired refrigerator operating as an absorption refrigeration system. The essential question is whether it is more advantageous to use electricity to run the refrigerator, which might be provided by some combination of the PV and propane motor/generator, thereby taking advantage of the relatively higher electric refrigerator Coefficient of Performance (COP) and free solar energy but having to accept a low electrical conversion efficiency of the motor/generator, or use thermal energy from the combustion of propane to produce the refrigeration effect via an absorption system, albeit with a much lower COP. The analysis is complicated by the fact that most off-grid renewable electrical power systems utilize a battery bank to provide electrical power when it is not available from the wind turbine or PV system, so the state of charge of the battery bank will have a noticeable impact on what energy source is required. The bottom line energy usage and fuel input depend strongly on the ability to make use of the renewable sources in real time to avoid battery bank conversion losses, as well as to have sufficient battery storage capacity to minimize the need for operation of the motor/generator to meet electric loads.

Keywords: building energy, energy efficiency, hybrid electric power, off-grid energy, refrigeration, renewable energy

1. Introduction

As society becomes more mobile and communication technologies advance and proliferate, it has become possible for many individuals and families to establish domiciles in relatively remote locations with respect to the availability of traditional grid-based resources such as electric power, natural gas, telephone, internet and cable television. In many cases, it is cost-prohibitive for utilities to install the physical infrastructures required to provide, for example, electrical power for one or a few potential consumers who live a sufficient distance away from current connections[Akikur, R.K., Saidur, R., Ping, H.W., & Ullah, K.R. (2013)]. As a result, the demand for off-grid electrical power applications continues to grow, usually being satisfied by a combination of renewable sources, primarily wind and solar, along with a fuel-fired motor generator, usually fed by propane since that can be delivered conveniently in bulk quantities [Bhandari, B., Lee, K., Lee, C.S., Song, C., Maskey, R.K., &Ahn, S. (2014)]. While the first principle of off-grid energy system design is to minimize energy requirements through the use of energy efficient building designs, energy efficient lighting and appliances, and energy efficient operating procedures, inevitably, there will be some demand for electric power in a modern home. In addition to lighting and appliances, electric power is needed for plug loads, but generally would not be recommended for water or space heating purposes unless there was no fuel source on site, as it is much more advantageous to meet heating requirements via fuel combustion, which can achieve energy conversion efficiencies of over 90% versus below 30% for fuel-fired motor/generators.

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Refrigeration for food storage, if not mandatory, is at least highly desirable in residences. The time-honored ice block approach has largely been supplanted by gas or electric-fueled refrigerators. There are some dual-fuel models, which actually are thermally-activated in both modes, as opposed to the more common electric-powered vapor compression (VC) system. The VC refrigerator is the hands down winner in terms of refrigeration COP with a typical value in the neighborhood of three, while a gas refrigerator, which operates as an absorption refrigeration system, typically has a COP of less than one. On that basis alone, the electric refrigerator would appear to be preferable, however refrigeration COP does not reflect the energy conversion efficiency of the technology producing the electrical power needed by the electric refrigerator, which generally is less than one third for a small fuel-fired motor/generator. This means that the amount of propane, for example, required to operate an absorption refrigerator with a COP of one would be about the same as that required to operate an electric refrigerator with a COP of three but a propane motor/generator electrical conversion efficiency of 0.33. This paper examines the energy usage implications of the use of electric and gas refrigerators for off-grid residential applications for a typical range of refrigerator characteristics and operating conditions. Particular emphasis is given to the impact of environmental conditions, electrical load patterns and availability of renewable-derived electrical power on the onsite fuel consumption.

2. Background

2.1 Typical Off-Grid Residential Electric Power System

There are, of course, many different possible configurations for residential off-grid electrical power systems [Ismail, M.S., Moghavvemi, M., &Mahlia, T.M.I. (2012)][Shaahid, S.M., & El-Amin, I. (2009).], but for the purposes of this analysis we have selected a hybrid solar PV/propane generator system, with a battery bank for electrical storage, as shown schematically in Figure 1. The principles applied in analysis of this particular system can be applied to other similar systems without a great deal of difficulty. This figure displays the system components and energy flows, and provides the basis for the identification of the major operating modes required to provide the electrical power for the residence in the form of AC power.

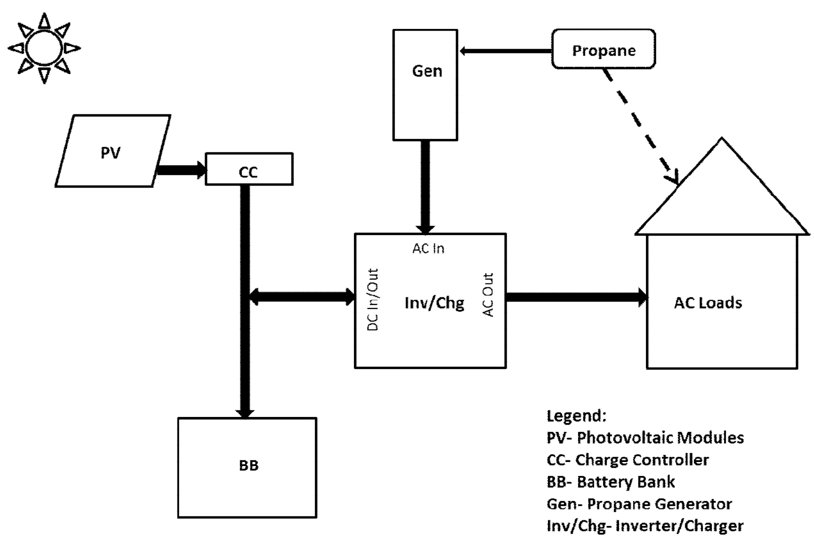

Figure 1: Typical off-Grid, Hybrid Residential Electrical Power System

The PV modules feed their DC power to a charge controller which tries to maintain the solar panels at their maximum output power point given the current level of insolation. This DC power is further made available to the battery bank for charging and to the inverter/charger for delivery as AC power to the electrical panel serving the residence. So long as the battery bank charge has not dropped below its lower limit, as indicated by its voltage, the propane generator will remain off, and all power to the residence will be provided by the PV and battery bank. If the available power from the PV exceeds the building electric load, the excess electrical power will be used to charge the battery bank until it is fully charged, at which point charging will cease. If more power is required than can be provided by the PV alone, the balance of the power will be drawn from the battery bank.

Once the battery bank charge reaches its lower limit, the propane generator will start and continue to operate until the battery bank charge reaches its upper limit, at which point the generator will shut down. While the propane generator is operating, its AC power output can be fed directly to the electrical panel providing power to the residence, and/or charge the battery bank using the charger function of the inverter/charger. At any point in time, electrical power can be flowing out of the PV and generator, in or out of the battery bank and to the AC loads of the building. The source energy to the hybrid electrical power system is solar radiation and propane, the former being free and the latter not. Even though the solar energy is free, we would like to make the best use of it we can, while at the same time minimizing our consumption of propane. If the residence AC power load consisted only of electrical power for the refrigerator, the analysis would be considerably simplified, as we could make some reasonable assumptions about system sizing and the impacts on battery bank charge. This is because if the PV system capacity is large relative to the power usage by the refrigerator, electric power to the refrigerator would mostly be provided by the PV system, either directly or via battery storage, thus requiring little if any propane consumption. On the other hand, if the AC power loads are high leaving the battery bank in a frequent charging state, the propane generator will need to operate more, thus increasing propane consumption. The same situation would apply to a location with more available solar radiation compared to a site with less. In order to analyze the interactions between the components of the hybrid off-grid power system and determine the net effects, it is necessary to model component and system performance, make some assumptions about operation, and develop the appropriate metrics and performance indicators. This is discussed in the following section.

3. Methodology

During normal operation, electric power to meet the building AC power loads is provided by some combination of the solar PV modules and the battery bank via the inverter, and the propane generator directly, bypassing the inverter. Both the solar PV and the generator can charge the battery bank as well. At any instant in time, the energy flows depend on the building AC loads, the available solar PV power and the state of charge of the battery bank, as shown below:

- Mode 1- If solar PV AC power is greater than or equal to the building AC load, and the battery bank charge is above the minimum allowed, the generator will be off and the building AC loads will be met by the solar PV AC power from the inverter, with any excess power available for battery bank charging
- Mode 2- If solar PV AC power is less than the building AC load, and the battery bank charge is above the minimum allowed, the generator will be off and the building AC loads will be met by a combination of solar PV power and power from the battery bank from the inverter
- Mode 3- If solar PV AC power is greater than or equal to the building AC load, and the battery bank charge is below the minimum allowed, the generator will be on providing power to meet the building AC loads, and both the solar PV DC power and the generator will share charging of the battery bank
- Mode 4- If solar PV AC power is less than the building AC load, and the battery bank charge is below the minimum allowed, the generator will be on and the building AC loads will be met by a combination of solar PV power and generator power, and both the solar PV DC power and the generator will share charging of the battery bank
- Mode 5- If there is no solar power, and the battery bank charge is above the minimum allowed, the generator will be off and the building AC loads will be met by the battery bank AC power from the inverter
- Mode 6- If there is no solar power, and the battery bank charge is below the minimum allowed, the generator will be on providing power to meet the building AC loads, and charge the battery bank

3.1 Refrigerator Energy Usage

A widely used method for determining power consumption of refrigerators is based on the Coefficient of Performance (COP). Due to their nature as a heat transfer machine, it is possible for refrigerators to move more thermal energy than they consume, with the ratio being the COP. Thus, power input to an electric refrigerator (PLDRe) with a COP equal to COPe is related to the refrigerator thermal load (RTL) by:

$$PLDRe = RTL/COPe \quad \text{Eqn. 1}$$

The same is also true for the gas refrigerator, except that the input energy is in the form of heat [Southern California Gas Company. (1998)], so fuel energy input (FE) to a gas refrigerator with a COP of COPg is given by:

$$PLDRg = RTL/COPg \quad \text{Eqn. 2}$$

Strictly speaking, COP values are not constants, but are known to vary with parameters like ambient temperature. COP values will also vary for different refrigerator models. They are generally higher for vapor compression systems (electric) than for absorption systems (gas) [Srikhirin, P., Aphornratana, S., & Chungpaibulpatana, S. (2001)]. The refrigerator thermal load is due to heat gains through the insulated jacket, door openings and placement of warm objects into the refrigerator to cool down. Obviously, refrigerator thermal load can vary over a large range depending on usage patterns and temperature conditions [Boughton, B.E., Clausing, A.M., & Newell, T.A. (2012)], [Grades, E. (2011)]. Since for this analysis we are most interested in comparing the energy performance of electric and gas refrigerators, we will assume that the load is the same for both. A typical thermal load was derived from the average electrical consumption value of 525 kWh/yr reported by the U.S. Dept. of Energy for current electric refrigerator models. Assuming an average COPe of 3.0, this translates into a thermal load of 1575 kWh/yr. A typical COP for a propane refrigerator is in the range of 0.6 [U.S. Environmental Protection Agency Combined Heat and Power Partnership. (2015)]. In normal operation, an electric refrigerator will cycle on and off, with the period dependent on thermal loading [Terrell, W. (2006)]. The cycles, however, are short enough and repeated so that over a sufficiently long period of time, such as a year, an electric refrigerator can be considered a nearly constant load compared to say something like space cooling or heating which vary widely with the weather.

3.2 Energy Conversion Efficiencies and Fuel Consumption

3.2.1Solar Photovoltaic (PV) System

For this analysis, the energy conversion efficiency of the photovoltaic modules is not in itself a critical parameter except to the extent that it correlates with providing more solar-derived electrical power in the same manner as having greater collector area. A similar comment applies to the efficiency of the charge controller; we can assume it is operating properly and delivering DC power to the battery bank and inverter. We are only concerned with the amount of solar-derived DC power relative to the AC loads, which will be abstracted as a simulation parameter.

3.2.2 Battery Bank

For this analysis, the most critical characteristics of the battery bank are its electrical storage capacity and charging and discharging characteristics. These processes are dynamic and rate dependent, but they have the net effect that can be captured in the form of an in/out energy storage efficiency. The important point is that some electrical energy is lost in the process of going in and out of the battery bank; a commonly quoted estimate for battery energy efficiency is 75%.

3.2.3 Inverter/Charger

The inverter/charger functions as the interface between the PV module charge controller, the battery bank and motor/generator converting between AC and DC power as appropriate. The efficiency of the electrical energy conversion varies somewhat with part load. A value of 85% for this parameter is not atypical, with a similar value for the charger efficiency also being appropriate. This unit can also deliver AC electrical power directly to the loads from the generator [Owner's Manual. (2012].

3.2.4 Propane Generator

A commonly used propane generator is an internal combustion engine providing mechanical power to turn the shaft of an electric generator producing AC power. The electrical conversion efficiency of this type of device is defined as the ratio of electrical power output to the fuel power input, which is known to vary with generator size and part load fraction. For smaller units such as would be deployed for residential applications, a value of about 27% is typical.

3.2.5 Delivery of Electrical Power to AC Loads

Depending on the mode of operation at any instant in time, the building AC loads will be met by some combination of electrical power from the solar PV system, the battery bank and the propane motor/generator. This precise mix of those energy sources will depend on the magnitude of the AC loads, how much solar power is available and the state of charge of the battery bank.

These in turn depend on the capacities of the solar PV system and battery bank, as well as the profiles of electric power used by AC loads other than the refrigerator. Since in this analysis the goal is to minimize the consumption of propane, conditions which allow the AC power requirements to be satisfied by the solar PV system, either directly or via the battery bank would be most favorable. These would more likely be achieved for solar PV systems with a high capacity, meaning high efficiency and large size, and a battery bank with high capacity, both of which would allow more of the AC load to be met solar PV-derived power. However, in the real world, the sizes of the PV modules, the amount of solar radiation and the battery bank capacity will vary based on site, equipment and cost factors. This variation will be captured in the analysis as part of the parameters being varied.

3.2.6 Electrical Power Supplied to the Building AC Loads

The total electric power supplied to the AC loads (PLDT) includes three possible components, power from the PV system that has passed through the inverter (PLDPV), power from the battery bank that has passed through the inverter (PLDBB), and power directly from the motor/generator (PLDGEN) such that:

$$PLDT = PLDPV + PLDGEN + PLDBB \qquad \text{Eqn. 3}$$

We define four energy conversion efficiency values including inverter efficiency (η_{inv}), charger efficiency (η_{chg}), motor/generator efficiency (η_{gen}) and battery in/out efficiency (η_{bb}). Again, while these values are not strictly constants as they can vary with part load and charging rate, we will use some typical values for comparison purposes. Using those parameters, the individual AC power supply components are given as:

$$PLDPV = \eta_{inv} * PVDC \qquad \text{Eqn. 4}$$

$$PLDGEN = \eta_{gen} * FE \qquad \text{Eqn. 5}$$

$$PLDBB = PLDBBPV + PLDBBGEN \qquad \text{Eqn. 6}$$

Where:

PVDC= DC power output from the solar PV system
PLDBBPV= power to the AC load from the battery bank that is attributed to the solar PV, or

$$PLDBBPV = RBBPV * PLDBB = \eta_{inv} * \eta_{bb} * PBBPV \qquad \text{Eqn. 7}$$

PBBPV= power input to the battery bank from solar PV
RBBPV= fraction of total AC power supplied to the load attributable to solar PV
PLDBBGEN= power to the AC load from the battery bank that is attributed to the motor/generator, or

$$PLDBBGEN = RBBGEN * PLDBB = \eta_{inv} * \eta_{bb} * \eta_{chg} * PBBGEN \qquad \text{Eqn. 8}$$

Where:

PBBGEN= power input to the battery bank from the generator
RBBGEN= fraction of total AC power supplied to the load attributable to the generator

Since the battery bank can be charged by either the PV system or the generator, it is necessary to distinguish between the two sources when trying to determine the fuel consumption. Charging of the battery bank is an ongoing process that depends on when the battery bank reaches its lower limit and needs to be charged relative to the availability of DC power from the solar PV. For example, if most of the charging were done at night the fuel usage would be much greater than if it were done during the day when solar PV was available. Finally, the total AC electrical power needs to be related to the power for the refrigerator alone, since we have only made an estimate of the latter. We can define a variable for fraction of total electric power used by the refrigerator (LFR).This value can be expected to vary considerably depending on the particular installation, but is not a critical parameter for this analysis. This takes the form:

$$PLDT = \frac{PLDR}{LFR}$$

This way, we can use the value for refrigerator electric power computed above to derive a value for total building electric power, and then proceed to solve for the required power components to meet the total load, along with the fuel input. The portion of the fuel input that is associated with the refrigerator (FER) can then be computed using LFR according to:

$$FER = LFR * FE$$

We now have all of the relations we need to determine the instantaneous electrical power components and the fuel energy input rate for the hybrid residential power system for any of the six operating modes, as will be described in the following section.

3.2.7 Energy Consumption and Fuel Usage for the Hybrid System

Another way of looking at the relative contributions of solar PV, generator and battery bank power to the building AC loads can be derived by restating Eqn. 3 as:

$$PLDT = (RPV + RGEN + RBB) * PLDT$$

Where:

RPV= fraction of total AC power supplied directly by the solar PV
RGEN= fraction of total AC power supplied directly by the generator
RBB= fraction of total AC power supplied battery bank

Subject to:

$RPV + RGEN + RBB = 1$

For the six modes of operation, the values for the three fractions take on specific values, as shown in Table 1.

Table 1: Fraction Values for the Six Operating Modes

Mode	RPV	RGEN	RBB	Notes
1	1	0	0	All AC power supplied by solar PV
2	1-BF	0	BF	AC power supply shared by solar PV and battery bank
3	0	1	0	All AC power supplied by generator, excess solar PV charges battery bank
4	SF	1-SF	0	AC power supply shared by solar PV and generator
5	0	0	1	All AC power supplied by battery bank
6	0	1	0	All AC power supplied by generator, generator charges battery bank

In Table 1, SF stands for Solar Fraction, which is the fraction of the AC power requirement that is provided by the solar PV system over some period of time, such as a month or year. Similarly, BF stands for Battery Fraction, which is defined here as the energy storage capacity of the battery bank divided by the cyclic electric energy usage (i.e. daily). Of course, electrical power from the battery bank ultimately comes from either the solar PV or generator, however, the efficiency of the power conversion and delivery is different due to losses getting the electrical power in and out of the battery bank via the charger and inverter. In the modes that involve a combination of power sources, namely modes 2 and 4, the relative magnitudes of the two components can be expected to vary considerably depending on the amount of solar PV power available, as well as the battery bank capacity and the degree of synchronization between the loads and the solar power. It is not possible to make an accurate prediction of the fractions without doing a detailed simulation which would involve making many assumptions about load profiles and solar availability, which in turn would make the results difficult to generalize and valid only for specific system characteristics.

4. Simulations and Results

5. Simulations

The approach used here instead is to use the solar fraction, which represents the relative contribution of solar PV energy to the electrical loads, to assign the split between solar power and generator power for mode 4, and to use the newly defined battery fraction to assign the split between solar PV and battery bank power for mode 2. Thus, for example, if the solar fraction is 0.5, we will assume that when we are calculating the energy and fuel usage for mode 4, that the half the power is coming from the solar PV and half from the generator, which makes logical sense on average. Similarly, if the battery fraction is 0.5, then we are implying that when the system is operating in mode 2, half of the power is coming directly from the solar PV and the other half from the battery bank. This also allows us to examine the effect of varying both SF and BF on overall system energy performance. Assumed values for the component characteristics such as COP and energy conversion efficiencies are listed in Table 2.

Table 2: Assumed Values for Component Performance Characteristics

Characteristic	Assumed Value
Electric Refrigerator Coefficient of Performance-COPe	3.0 (2.5)
Gas Refrigerator Coefficient of Performance- COPg	0.6 (1.0)
Refriegration Thermal Load- RTL	1575 kWh/yr
Generator Efficiency- η_{gen}	0.27
Inverter Efficiency- η_{inv}	0.85
Charger Efficiency- η_{chg}	0.85
Battery BankEfficiency- η_{bb}	0.77
Solar Fraction- SF	0.5
Battery Fraction- BF	0.5
Refrigerator Load Fraction	0.25

5.1 Results

Using the equations referenced above, the fractions listed in Table 1 and the values from Table 2, the fuel, solar and total energy input to meet the AC electrical power load were calculated. Although electrical power is an instantaneous quantity, these are presented in units of annual energy flows for each of the modes, as shown in Table 3, assuming a full year at the stated operating mode.

Table 3: Simulation Results for the Baseline Characteristics (kWh/yr)

Mode	Fuel Input-Gas Refrigerator	Fuel Input -Electric Refrigerator	DC Energy Input from Solar PV	Total Energy Input for Electric Refrigerator
1	2625	0	618	618
2	2625	944	309	1253
3	2625	1944	0	1944
4	2625	970	309	1281
5	2625	1887	0	1887
6	2625	1944	0	1944

The gas (propane) refrigerator has only a single value for fuel input since it has only one operating mode [Adewusi, S.A., &Zubair, S.M. (2004)]. The fuel input for the electric refrigerator is, of course, fuel used by the generator to produce the electrical power required for its operation. The DC energy input from the solar PV is the additional energy required to operate the electric refrigerator. Modes 3 and 6 have the same results because in either case the generator is doing all of the work. There are two ways of interpreting these results. The first is from the perspective of propane usage, and the second from the perspective of total energy. Each way is valid in its own right, although they may lead to different conclusions. First, regarding propane consumption alone, the gas refrigerator requires more fuel input than the electric refrigerator even with zero contribution from solar PV (mode 3) being 35% higher. This is largely due to the ratio of COPe to COPg being five in spite of the energy conversion losses of the motor generator. When the solar PV power contribution is added into the mix, such as modes 1, 2 and 4, the difference becomes even greater, as we would expect, although even though the solar power is "free", if it is used for refrigeration it will not be available for other applications, so to be fair it represents consumption of a valuable resource. The calculations were repeated using COPe of 2.5 and COPg of 1.0, for a ratio of 2.5, while holding the other parameters the same. The results are shown in Table 4.

Table 4: Simulation Results for the Alternate COP Scenario (kWh/yr)

Mode	Fuel Input-Gas Refrigerator	Fuel Input -Electric Refrigerator	DC Energy Input from Solar PV	Total Energy Input for Electric Refrigerator
1	1575	0	741	741
2	1575	1132	371	1503
3	1575	2333	0	2333
4	1575	1167	371	1537
5	1575	2265	0	2265
6	1575	2333	0	2333

With the ratio of the refrigerator COP's being cut in half from 5 to 2.5, the results are quite different. The fuel input for the gas refrigerator drops significantly, while the fuel input for the electric refrigerator, as well as the total energy input, increases noticeably. Depending on the operating mode, the fuel input for the electric refrigerator is as much as 48% higher than for the gas refrigerator. Again, the total energy requirement is lowest when the PV contribution is large, as would be expected. What does this mean? Obviously, the closer the electric and gas refrigerator COP's are to each other, the less advantage there is for the electric unit. Since actual refrigerator models have different COP's, this should be taken into account when deciding which to use. The other critical point is that the fuel input and total energy input depend strongly on the mode of operation, which can be expected to vary throughout the year as solar availability and AC load profiles change. When the electric refrigerator is running on 100% solar PV power, the input power requirement is only 32% of the required fuel power input to the generator to provide the same electrical power output, which is a substantial difference. For that condition, the total power input to the electric refrigerator is only 47% of that for the gas refrigerator. However, the opposite is true when the electrical power is coming from the generator, particularly via the battery bank. It is hard to say how often each situation would occur in practice, as it is site, equipment and occupant dependent. If we were to observe electrical power usage over a year with the system switching modes to provide the required AC power, in the end, power will be supplied by the three sources, solar PV, generator and battery bank, in some combination, and the resulting energy and fuel usage will fall somewhere in between each of the modes. For example, if over the full year, power were to be supplied equally by the three sources, the gas refrigerator would use 13% less total energy than the electric refrigerator, when the ratio of their COP's is 2.5, while it would use 77% more when the COP ratio is 5.

6. Recommendations and Conclusions

The initial question of whether it is better to use a propane or electric refrigerator in an off-grid hybrid power system turns out to depend a lot on the availability of solar electric power relative to house power demand, and the degree of synchronicity between the two, as solar derived electrical power avoids the need for external power input in the form of propane, and has minimum total energy input. On the other hand, power that is produced by the motor generator and used to charge the battery bank through the charger only later to be supplied to the load through the inverter incurs a series of losses that seriously impact efficiency. So, the two key performance parameters are the Solar Fraction and the Battery Fraction, the first of which represents the ability of the solar PV system to meet the house electrical power demands, and the second representing the battery bank capacity relative to cyclic power demands. The first case with the high SF can be considered a design decision that can be achieved by utilizing larger collector areas with more efficient materials along with good solar availability producing a large percentage of the electrical power needed by the building, including an electric refrigerator with an efficient design (COP>3). In this case, the refrigerator will be running directly from solar power almost half of the time, and the rest of the time will be running on battery bank power provided from stored solar power. These are the two most favorable modes of operation. It should be noted that although these two modes do not require any energy input in the form of propane, they do in themselves represent the utilization of a scarce resource, namely electricity, which has usefulness and value, even though it comes from a resource considered free.

On the other hand, if the solar fraction is low, most of the house power will come from the generator, incurring both the consumption of propane and the energy conversion loss of the motor/generator. Even worse, power supplied to the building load from the battery bank that originally came from the generator would incur both the battery bank efficiency and invertor conversion efficiency losses. In that case, a propane refrigerator might be the better choice. The impact of BF is also important. If the battery bank storage capacity is large enough to meet the loads imposed during times when solar radiation is not available, this will avoid the need for the propane motor/generator to operate, and its consequence fuel usage and energy conversion losses. In contrast, with a low battery fraction, the propane generator would have to meet the house loads in the absence of solar power. This leads to one final point, that being the importance of the fraction of building electrical power demand that is due to the electric refrigerator. If the electrical power system exists primarily as a means to operate an electric refrigerator, meaning a large refrigerator load fraction, system components and capacities can be sized to ensure efficient operation.

If, on the other hand, there are other large consumers of electrical power in the building, we can never be sure of the state of charge of the battery bank or what mix of power sources are currently available. This can mean significant periods of inefficient operation and excess propane consumption.

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