Energies **2015**, *8*, 11120-11138; doi:10.3390/en81011120

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

The Effect of Electric Load Profiles on the Performance of Off-Grid Residential Hybrid Renewable Energy Systems

Stephen Treado

Department of Architectural Engineering, the Pennsylvania State University, University Park, PA 16802, USA; E-Mail: Stready@psu.edu; Tel.: +1-814-867-3323; Fax: +1-814-863-4789.

Academic Editor: Nyuk Wong

Received: 23 August 2015 / Accepted: 29 September 2015 / Published: 7 October 2015

Abstract: This paper investigates the energy performance of off-grid residential hybrid renewable electric power systems, particularly the effect of electric load profiles on the ability to harvest available solar energy and avoid the consumption of auxiliary energy in the form of propane. The concepts are illustrated by an analysis of 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 power provided by a propane fueled motor/generator. Among other design decisions, 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. One interesting question is whether it is more advantageous from an energy perspective 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 available at any moment in time. Daily electric load profiles combined with variable solar energy input determine the state of charge of the battery bank, with the degree of synchronization between the two being a critical factor in determining performance. The annual 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 and dumping of excess electrical power, as well as to have sufficient battery storage capacity to minimize the need for operation of the motor/generator to meet electric loads which occur during periods when the renewable energy is not available.

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

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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 [1]. 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 [2].

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. Off-grid power systems differ from grid connected ones in that they cannot use the electric grid to "store" any excess electrical power to recover for later use.

In conventional applications, refrigeration is typically obtained via electric-powered vapor compression (VC) systems, but fuel-fired refrigerators are also available. The VC refrigerator generally has a greater refrigeration coefficient of performance (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 alone 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 could 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 implications of electric power load profiles on the energy usage of off-grid residential hybrid renewable electric power systems, and examines the preferability of electric and gas refrigerators for off-grid residential applications for a typical range of refrigerator characteristics and operating conditions. While there has been a move towards even more energy efficient solar based systems for providing power for refrigeration [3], this analysis focuses on conventional refrigerator capacities and technologies that are widely utilized in the United States. Particular emphasis is given to the impact of electrical load patterns and availability of renewable-derived electrical power on the onsite fuel consumption. Recommendations are given for effective design and operating strategies to encourage the efficient use of energy.

2. Energy Usage in Off-Grid Electrical Power Systems

2.1. Typical Off-Grid Residential Electric Power System

There are, of course, many different possible configurations for residential off-grid electrical power systems [4,5], however, it would not be unusual to encounter a hybrid solar PV/propane generator system, with a battery bank for electrical storage, as shown schematically in Figure 1. This figure displays the main 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. The solid lines represent the flow of electrical power, while the dashed line is propane flow. This type of a system would allow a consumer to use either an electric or propane powered refrigerator, which presents an interesting decision that is deceptively challenging, as will be shown. Dual powered refrigerators are also available that can use either energy source, but only one at a time.

The use of DC electrical power for refrigeration is not considered in this analysis as that technology is not widely utilized in spite of some noteworthy advantages primarily related to lower conversion losses. The vast majority of consumer appliances and equipment are designed to operate on AC power, making prices low and features high, which may eventually be the case with DC powered devices as the market matures.

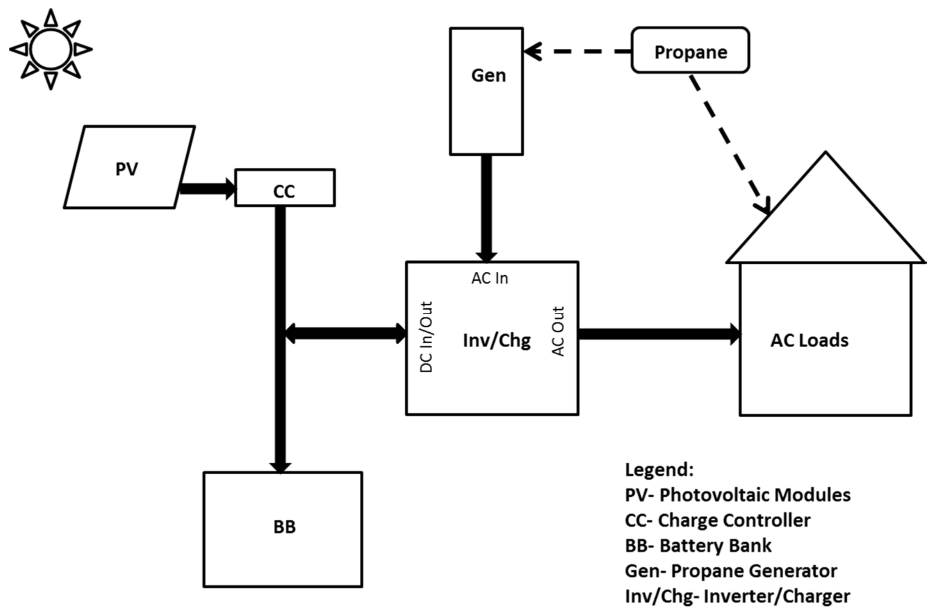


Figure 1. Typical off-grid, hybrid residential electrical power system.

2.2. Typical System Sequence of Operation

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 of charge, 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. Furthermore, when the battery bank is fully charged, no use can be made of the PV derived electrical power beyond the instantaneous AC power being supplied to the building.

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 may 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. In off-grid residential applications, generally speaking, electrical loads are minimized through the utilization of energy efficient components and operating strategies. Typically, electrical power would not be used for heating purposes if there were a source of fuel available since the overall efficiency would be much less. The exception to this would be a heat pump or heat pump water heater which has a favorable COP, but loses its heating capacity at low temperatures, thereby requiring a backup source of heat such as electric resistance heating, which does not have a favorable overall efficiency.

2.3. Residential Electrical Power Load Profiles and Energy Performance

Residential electrical loads consist primarily of lighting, appliances and plug loads. Some may be used mainly at certain times, such as lighting at night, or the television in the evening, while others are operated when needed, such as a dishwasher or clothes washer. In contrast, a refrigerator operates continuously, generally cycling on and off to hold the contents at the desired temperature. More energy is needed at certain times to cool down food and compensate for losses through the cabinet and door openings, however, a refrigerator can approximately be considered to be a constant load. The combination of the daily operation of all of the electrically powered devices in a residence results in an electric load profile which must be satisfied by the electrical power system. The load profile can have a profound effect on the performance of a hybrid renewable energy system, because the magnitude and timing of the loads relative to the power available from the solar PV system determines how much solar power and propane are used.

There are two distinct circumstances that can lead to poor energy performance that are associated with the state of charge of the battery bank:

1. Battery bank storage depleted.
2. Battery bank fully charged.

These effects are illustrated schematically in Figure 2.

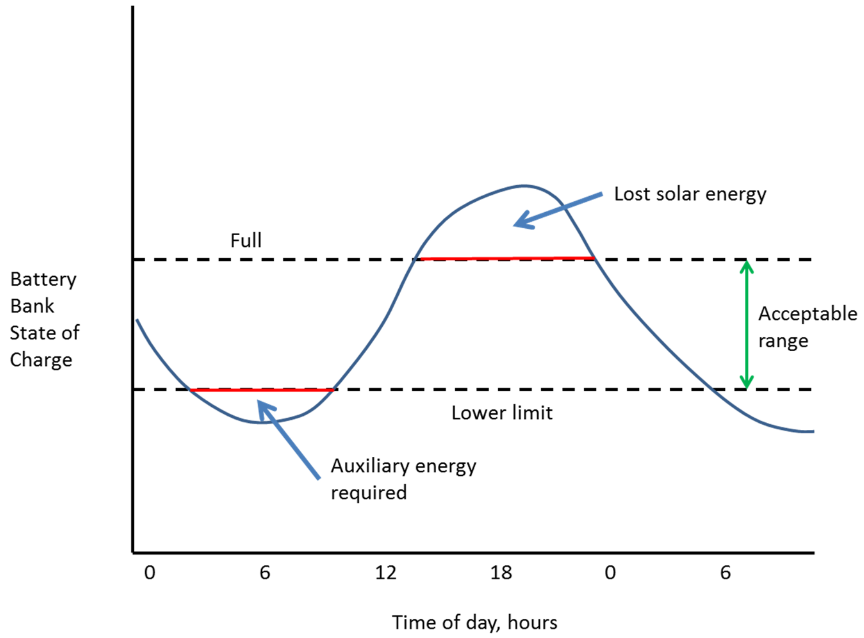


Figure 2. Typical daily variation in battery bank state of charge.

This figure shows the state of charge of a typical battery bank as energy is added and extracted to meet the electric load throughout the day. In a well-designed system, charge should vary from fully charged to partially discharged, but not be allowed to drop below the lower limit, the value of which varies by battery type, but might be in the range of 40% to 60%. A control system usually ensures this, and will activate the backup generator when the battery bank charge drops to its lower limit, and the battery bank charge will follow the lower red line. The area between the blue curve and the lower limit represents the portion of the electric load which is met by the generator. At the other extreme, once the battery bank is fully charged, any additional solar energy cannot be used, and is lost, as represented by the area between the blue curve and the full charge red line. Finally, the state of charge at the end of any daily period might be greater or less than that at the beginning of the period, and this net gain or loss carries forward into the next day.

Two metrics that are useful for quantifying the energy performance of an off-grid hybrid solar power system are solar fraction (SF) and solar utilization ratio (SUR), defined as follows:

$$\text{SF} = \frac{\text{Energy provided by solar PV}}{\text{Total energy requirement}} \tag{1}$$

$$\text{SUR} = \frac{\text{Solar energy harvested}}{\text{Solar energy available}} \tag{2}$$

Two useful system parameters are battery fraction (BF) and load synchronicity factor (LSF), defined as follows:

$$\text{BF} = \frac{\text{Battery bank storage capacity}}{\text{Average daily electrical usage}} \quad (3)$$

$$\text{LSF} = \frac{\text{Electrical energy requirement during sunlit hours}}{\text{Total electrical energy requirement}} \quad (4)$$

The relative magnitudes of the daily loads and battery bank capacity coupled with the timing of the loads have a noticeable effect on both solar fraction and utilization ratios. For example, if the PV system capacity is large relative to the power usage (high SF), electric power 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 for other uses in the residence are high or out of synch with the solar power availability (low LSF), or if the battery bank is undersized (low BF) the battery bank will frequently be in a charging state, and the propane generator will need to operate more, thus increasing propane consumption.

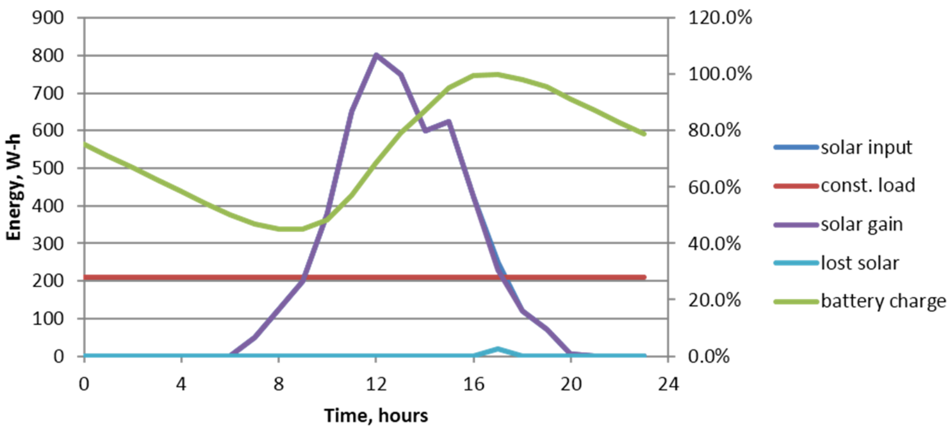
Figures 3a, b and c illustrate this point qualitatively in a using sample data for a sunny day for three different electrical load profiles covering the extremes of operation, namely constant load over 24 h (Figure 3a), constant load during nighttime hours (Figure 3b), and constant load over daylight hours (Figure 3c). The total electrical load and solar input for the day are kept constant at 5050 W·h, and each figure shows the hourly electrical energy available from the PV system, the hourly load profile and the state of battery bank charge. Electrical power is assumed to be constant over each hour, so that hourly electrical energy in W·h is equal to the power in W times one hour. Further, the storage capacity of the battery bank is assumed to be equal to the daily load of 5050 W·h, and the initial charge at time zero is assumed to be 75% for the constant hourly load case. These assumptions do not limit the applicability of the discussion, although the numerical values would be different for various load patterns and storage capacities.

The important points to be drawn from these figures are as follows:

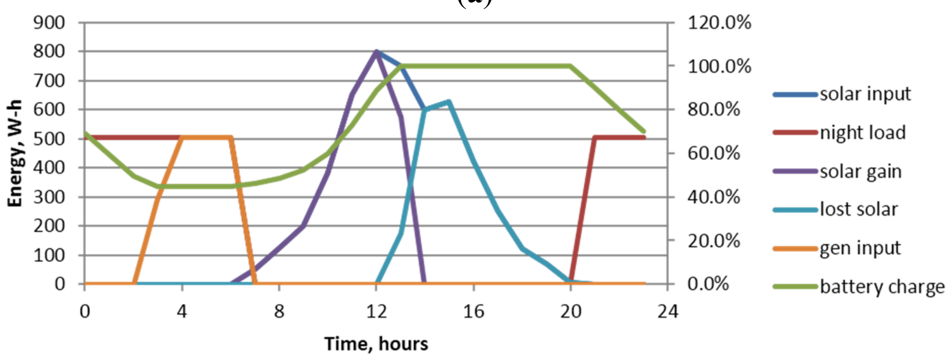
1. With the constant 24 h load (Figure 3a), the battery bank charge drops to about 45% before gradually recovering to a fully charged condition in the late afternoon (hour 17). Typically, the system controlling the charging of a battery bank will not allow the state of charge to drop below about 40% or 50% to prevent possible damage or reduced life, so this level of discharge would be acceptable, and no additional power from the propane generator would be required. Also, the energy extracted from the battery bank in the early morning hours (hours 0–6) results in a state of charge of 50% when the PV system starts to produce electrical power as the sun rises, so almost all of the available solar energy can be harvested while also meeting all of the electrical load. A small amount of lost solar is occurs at hour 17 when the battery bank becomes fully charged and thus cannot accept any more power.
2. In contrast, when the electrical loads are concentrated during the nighttime hours (Figure 3b), the battery bank charge quickly drops below 50%, and if allowed would become almost completely discharged before eventually recovering to fully charged at hour 18. As mentioned above, the charge control system generally will not allow the battery bank charge to drop to that extent, so in actuality, the propane generator would be activated during hour 3, thereby meeting

the load and preventing the battery bank charge from dropping below 45% . As a result, propane will be consumed until the load drops to zero, and the solar energy will charge the battery until it reaches a fully charged condition (hour 13, at which time no more charging will occur and 40% of the available solar energy will be lost.

3. When the load is concentrated during the daylight hours (Figure 3c), the battery bank charge never drops below 65%, and all of the load will be met by solar energy, and all of the solar energy will be harvested.



(**a**)



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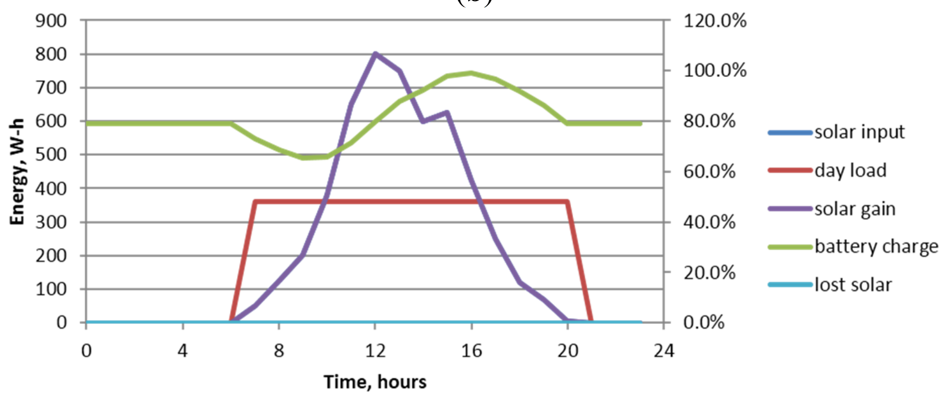
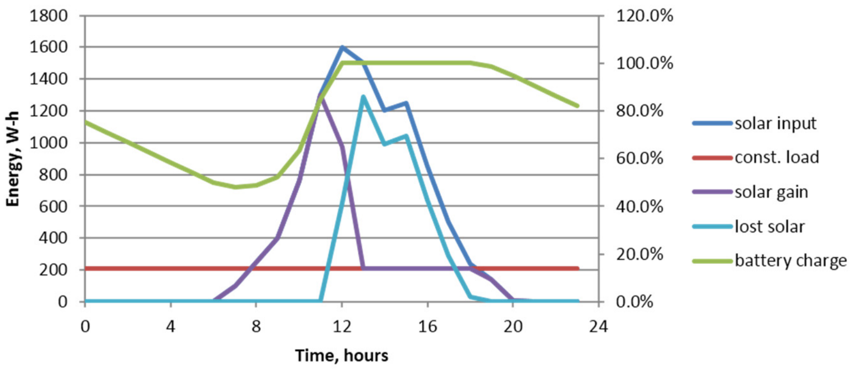


(**c**)

Figure 3. (**a**) Energy flows and state of battery bank charge for sunny day with constant electrical load over 24 hours; (**b**) Energy flows and state of battery bank charge for sunny day with constant electrical load concentrated during nighttime hours; (**c**) Energy flows and state of battery bank charge for sunny day with constant electrical load concentrated during daylight hours.

Figures 4a–c present similar plots, except that the solar input is doubled. This could represent either a location with more solar availability or a PV system with double the output due to larger collector areas and/or conversion efficiencies (high SF). Due to the increased level of PV derived electrical power, for the constant load case (Figure 4a), all of the load is met by solar, the battery bank becomes fully charged by hour 12, and 48% of the available solar gain is not harvested (lost solar). Even more solar energy is lost (73%) for the case where the loads are concentrated during nighttime hours (Figure 4b), and the propane generator has to provide 36% of the electrical power to the load. For the case where loads are concentrated during the day (Figure 4c), all of the loads are met by solar energy, but 46% of the solar is lost due to the battery bank becoming fully charged by hour 12.



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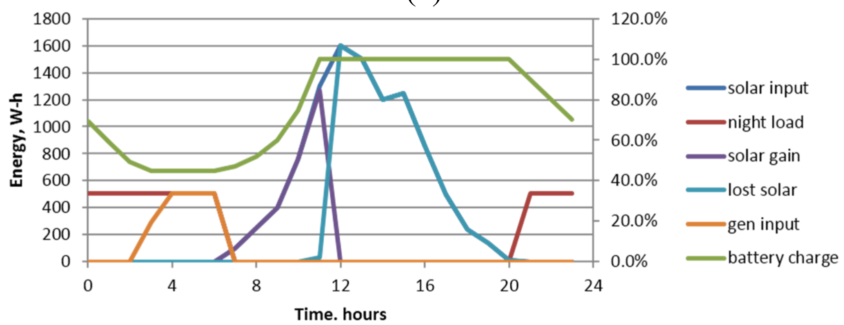

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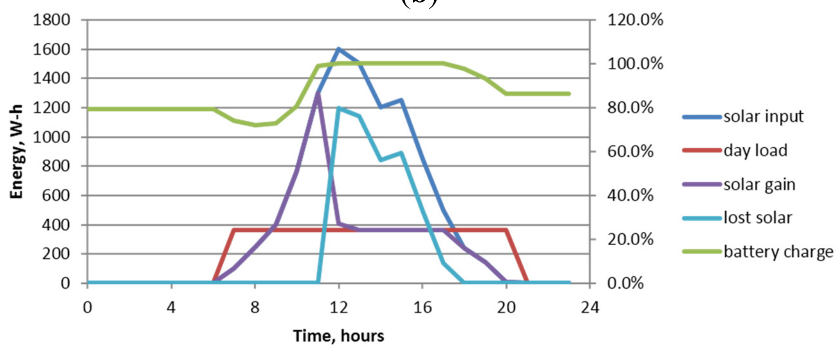

(**c**)

Figure 4. (**a**) Energy flows and state of battery bank charge for sunny day with constant electrical load over 24 hours with double the solar input; (**b**) Energy flows and state of battery bank charge for sunny day with constant electrical load concentrated during nighttime hours with double the solar input; (**c**) Energy flows and state of battery bank charge for sunny day with constant electrical load concentrated during daylight hours with double the solar input.

The fraction of available solar energy that could be harvested would be greater if the storage capacity of the battery were to be increased from its current value, which is equal to the total daily electrical load. This can be seen in Figure 5a,b, which show the results for 24 h constant load, high solar, and nighttime load, low solar scenarios respectively, with double the battery bank storage capacity. Solar utilization in this case rises from 51% to 64% for the high solar case, and from 45% to 74% for the nighttime load scenarios, respectively, due to the extra capacity, and the battery is left at a higher degree of charge so less propane would be needed for the next daily period. Doubling the electrical storage capacity decreases net propane consumption by 28% (505 W·h) for the nighttime load case.

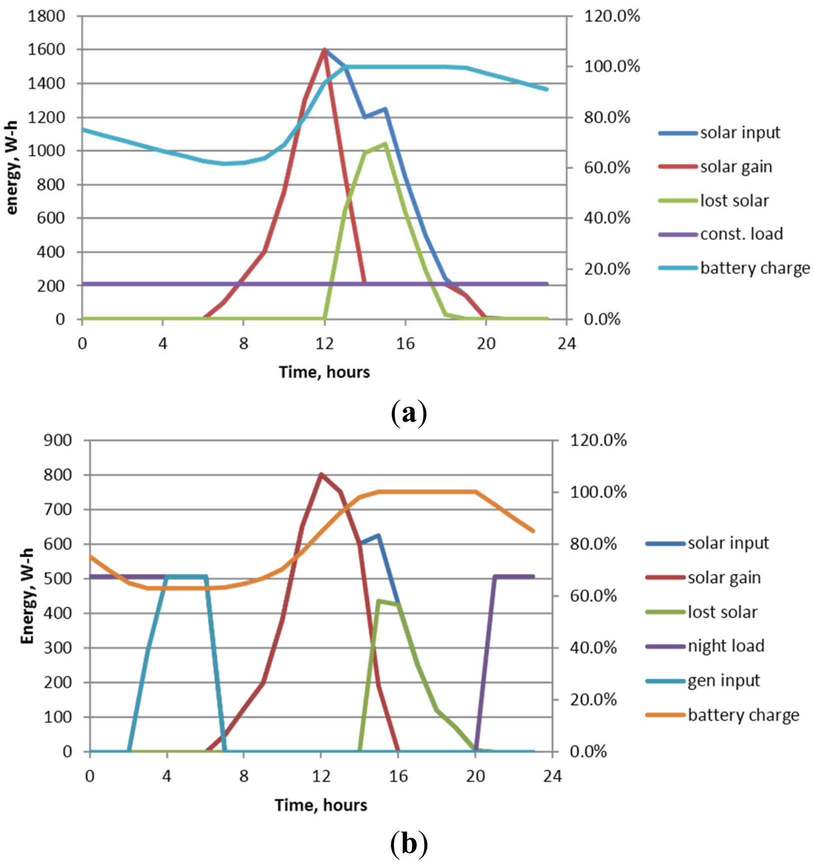

Figure 5. (**a**) Energy flows and state of battery bank charge for sunny day with constant electrical load over 24 h with double the solar input and double the battery bank storage capacity; (**b**) Energy flows and state of battery bank charge for sunny day with constant electrical load concentrated during nighttime hours with double the battery bank storage capacity.

The system energy performance results are summarized in Table 1 in the form of solar fraction, solar utilization, and auxiliary input, which is energy from the propane generator. At this point, we are ignoring conversion efficiencies and focusing on energy flows. Subsequently, energy conversion and storage losses will also be incorporated.

The points to note are that of these three idealized load profiles, for both the 24 hour constant load and the daylight load, all of the load is met by solar (solar fraction equals 100%), while the nighttime load case resulted in a solar fraction of only 64%. This was the same for both the low and high solar cases because the auxiliary power input is needed at night when it otherwise can only be obtained from the battery bank. Also, a significant amount of available solar energy is not harvested for both nighttime load cases, and for the high solar cases. This suggests that if there are any discretionary electric loads, such as dishwashing or clothes washing, these should be scheduled for times in which the PV system is producing excess power. Furthermore, it would be advantageous under such conditions to make some other use of the available solar power, such as water heating which ordinarily would be avoided as an unnecessary energy drain.

Table 1. Summary of energy performance metrics for the six scenarios.

Scenario	Solar Fraction, %	Solar Utilization, %	Auxiliary Input, W·h/day
24 hour constant load, low solar	100	99.6	0
nighttime load, low solar	64.3	45.0	1805
daylight load, low solar	100	100	0
24 hour constant load, high solar	100	51.5	0
nighttime load, high solar	64.3	27.5	1805
daylight load, high solar	100	53.6	0
24 hour constant load, high solar, 2x storage	100	64.0	0
nighttime load, low solar, 2x storage	64.3	74.2	1300

Of course, many more combinations of solar availability and load profiles are possible as weather conditions and occupant factors vary, so the performance of the electrical power system will also vary. We could either:

1 Conduct an hourly annual analysis, after first specifying all of the various electrical load profiles and solar availability;

or

2 Develop a method for estimating the annual energy performance based on site and system characteristics that are known.

The following section outlines such a method for analyzing the annual performance of an off-grid hybrid electrical power system, and demonstrates the use of the methodology to compare the relative performance of an electric *versus* a propane-fired refrigerator in such an application.

3. Methodology for Analyzing Off-Grid Hybrid Electric Power Systems

In order to analyze the interactions between the components of the hybrid off-grid power system in sufficient detail 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. 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 electric refrigerators (PLDRe) is based on the Coefficient of Performance (COPe) which is related to the refrigerator thermal load (RTL) by:

$$\mathrm{PLDRe} = \frac{\mathrm{RTL}}{\mathrm{COPe}} \tag{5}$$

The same is also true for the gas refrigerator, except that the input energy is in the form of heat [6], so fuel energy input (FE) to a gas refrigerator with a COP of COPg is given by:

$$\mathrm{PLDRg} = \frac{\mathrm{RTL}}{\mathrm{COPg}} \tag{6}$$

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) [7]. Another option would be an adsorption refrigeration system [8], although these types of units generally are not intended to substitute for a conventional full-size refrigerator. Also, thermal storage in the form of ice produced when solar energy is available can be very effective for providing cooling when solar energy is not available, although that option was not considered in this analysis.

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 [9,10]. 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/year reported by the U.S. Department of Energy for typical electric refrigerator models (note: some very high efficiency refrigerator models may use up to 30% less energy to meet the same thermal load). Assuming an average COPe of 3.0, this translates into a thermal load of 1575 kWh/year. A typical COP for a propane refrigerator is in the range of 0.6 [11].

In normal operation, an electric refrigerator will cycle on and off, with the period dependent on thermal loading [12] 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. Component Performance Characteristics

For this analysis, the particular 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.

Similarly, 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%.

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 [13].

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.

3.3. 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:

$$\text{PLDT} = \text{PLDPV} + \text{PLDGEN} + \text{PLDBB} \tag{7}$$

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:

$$\text{PLDPV} = \eta_{\text{inv}} \times \text{PVDC} \tag{8}$$

$$\text{PLDGEN} = \eta_{\text{gen}} \times \text{FE} \tag{9}$$

$$\text{PLDBB} = \text{PLDBBPV} + \text{PLDBBGE} \tag{10}$$

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

$$\text{PLDBBPV} = \text{RBBPV} \times \text{PLDBB} = \eta_{\text{inv}} \times \eta_{\text{bb}} \times \text{PBBPV} \tag{11}$$

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

$$\text{PLDBBGEN} = \text{RBBGEN} \times \text{PLDBB} = \eta_{\text{inv}} \times \eta_{\text{bb}} \times \eta_{\text{chg}} \times \text{PBBGEN} \tag{12}$$

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. 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—refrigerator load fraction). 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:

$$\text{PLDT} = \frac{\text{PLDR}}{\text{LFR}} \tag{13}$$

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:

$$\text{FER} = \text{LFR} \times \text{FE} \tag{14}$$

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.

3.4 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 Equation (7) as:

$$\mathrm{PLDT} = (\mathrm{RPV} + \mathrm{RGEN} + \mathrm{RBB}) \times \mathrm{PLDT} \tag{15}$$

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:

$$\mathrm{RPV} + \mathrm{RGEN} + \mathrm{RBB} = 1 \tag{16}$$

In other words, the total energy usage is a weighted average of the three source terms, with the weights being dependent on the availability of solar energy, solar PV system size and efficiency, battery bank capacity, and electric load magnitudes, which are represented by SF, BF and LSF. For example, a higher value of RPV represents a site with good solar availability, or an application with a large collector area and/or efficiency (high SF). An undersized battery bank would be represented by a lower value of RBB (low BF), and an application with high electric loads relative to solar capacity would correspond to a higher value of RGEN (low SF). An application with high non-synchronous electrical loads would have a lower value of LSF.

Note that since the conditions are assumed constant over each hourly time interval, hourly energy in W-h is simply the hourly electrical power in W times one hour, allowing annual energy to be determined by summing the hourly energy values over a full year.

Other important parameters are the ratio of COP's for the electric and fuel-fired refrigerators, and the fraction of the electric load represented by the electric refrigerator. These and other assumed values for the component characteristics are listed in Table 2.

Table 2. Assumed values for component performance characteristics.

Characteristic	Assumed Value
Electric Refrigerator Coefficient of Performance (COPe)	2.0–3.0
Gas Refrigerator Coefficient of Performance (COPg)	0.6–1.0
Coefficient of Performance Ratio COPR = COPe/COPg	2–5
Refrigeration Thermal Load (RTL)	1575 kWh/year
Generator Efficiency (η_{gen})	0.27
Inverter Efficiency (η_{inv})	0.85
Charger Efficiency (η_{chg})	0.85
Battery Bank Efficiency (η_{bb})	0.77
Refrigerator Load Fraction	0.25

Using the values from Table 2, the steady state energy conversion efficiencies of each of the modes can be determined, as shown in Table 3, assuming solar fraction and battery fraction are each equal to 0.5 for comparison purposes.

Table 3. Steady state energy conversion efficiencies for each of the modes.

Mode	RPV	RGEN	RBB	Energy Utilization Efficiency for SF = BF = 0.5
1	1	0	0	$\eta_{inv} = 0.85$
2	1-BF	0	BF	$(RPV + RBB \times \eta_{bb}) \times \eta_{inv} = 0.75$
3	0	1	0	$\eta_{gen} = 0.27$
4	SF	1-SF	0	$(RPV + RGEN \times \eta_{gen}) \times \eta_{inv} = 0.54$
5	0	0	1	$(0.5 + \eta_{gen} \times \eta_{chg}) \times \eta_{bb} \times \eta_{inv} = 0.48$ (assumes stored energy is half solar and half generator
6	0	1	0	$\eta_{gen} = 0.27$

System efficiency varies from a high of 85% for the full solar power mode to a low of 27% for the full generator mode, with other combinations falling in between depending on the relative mix of solar and generator derived power. The worst possible case is not shown, that would be when the generator is used to charge the battery bank which later sends power to the electric load, thereby incurring losses due to power generation, battery charging and inversion ($\eta_{total} = \eta_{gen} \times \eta_{chg} \times \eta_{inv} = 0.18$).

Table 4 lists the combinations of RPV, RBB and RGEN that were used for further analysis. These were chosen to represent a typical range of solar PV systems, battery bank capacities, and load magnitudes and synchronicities. A total of twenty combinations were analyzed including COPR's ranging from 2 to 5 in five steps.

Table 4. Values of the Relative Contributions of Solar PV, Generator and Battery Bank.

RPV	RGEN	RBB
0.5	0.25	0.25
0.25	0.5	0.25
0.25	0.25	0.5
0.33	0.33	0.33

4. Results

Using the equations referenced above, the fractions listed in Table 4 and the values from Table 2, the ratio of annual energy to operate the electric refrigerator to the energy to operate the propane refrigerator (TER) was calculated, and the results tabulated in Table 5 and plotted in Figure 6. When TER is greater than one, the propane refrigerator is more favorable, and vice versa. Based on this analysis, if COPR is greater than three, we can expect the electric refrigerator to use less energy than the propane. Switching the relative amounts of electrical power provided by the generator and the battery bank had a surprisingly small impact on total energy input. As would be expected, the least amount of propane energy input is associated with the highest values of RPV for any fixed value of COPR.

From this figure, the closer the electric and gas refrigerator COP's are to each other, the less advantage there is for the electric unit, with the breakeven point being somewhere between 2.5 and 3. 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. Therefore, if electric loads are generally high leaving the battery bank in a low state of charge, utilizing a propane refrigerator might be a better idea.

Table 5. Analysis results.

Run #	COPe	COPg	COPR	RBB	RGEN	RPV	TER
1	3	0.6	5	0.25	0.25	0.5	0.4826
2	3	0.6	5	0.25	0.5	0.25	0.6089
3	3	0.6	5	0.5	0.25	0.25	0.6035
4	3	0.6	5	0.33	0.33	0.33	0.5666
5	2.75	0.7	3.929	0.25	0.25	0.5	0.6142
6	2.75	0.7	3.929	0.25	0.5	0.25	0.775
7	2.75	0.7	3.929	0.5	0.25	0.25	0.7681
8	2.75	0.7	3.929	0.33	0.33	0.33	0.7211
9	2.5	0.8	3.125	0.25	0.25	0.5	0.7721
10	2.5	0.8	3.125	0.25	0.5	0.25	0.9743
11	2.5	0.8	3.125	0.5	0.25	0.25	0.9656
12	2.5	0.8	2.778	0.33	0.33	0.33	0.9065
13	2.25	0.9	2.5	0.25	0.25	0.5	0.9652
14	2.25	0.9	2.5	0.25	0.5	0.25	1.218
15	2.25	0.9	2.5	0.5	0.25	0.25	1.207
16	2.25	0.9	2.5	0.3	0.33	0.33	1.133
17	2	1	2	0.25	0.25	0.5	1.206
18	2	1	2	0.25	0.5	0.25	1.522
19	2	1	2	0.5	0.25	0.25	1.509
20	2	1	2	0.33	0.33	0.33	1.416

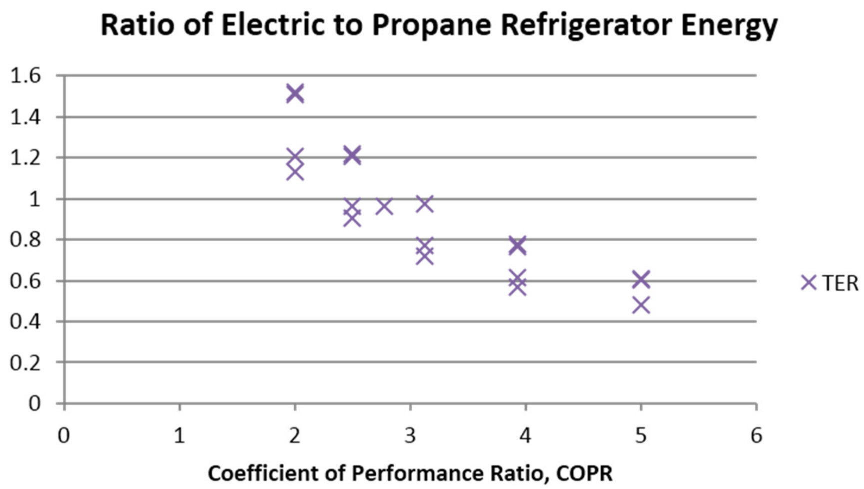

Figure 6. Ratio of electric refrigerator energy usage to propane refrigerator energy usage as a function of the Coefficient of Performance Ratio, COPR.

5. Discussion, 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 total 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 key performance parameters are the solar fraction, the battery fraction and the load synchronization factor.

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 (since solar radiation is only available during daylight hours), 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 another 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.

A few additional recommendations are:

- Schedule discretionary electric loads either during or before periods when solar power is expected to be available as excessive loads at night will incur propane consumption;
- Program the control system to avoid using the generator to charge the battery bank whenever possible when solar energy is expected to be available, or only use the generator to meet real time loads;

- Add a component to the system to enable utilization of any excess solar derived electrical power, such as an electric resistance water heater. These are modest in cost, simple to operate and can absorb quite a bit of energy in a useful fashion.

Acknowledgments

The author would like to acknowledge the support of the Pennsylvania State University Architectural Engineering Department, College of Engineering and Penn State Institutes of Energy and the Environment.

Conflicts of Interest

The authors declare no conflict of interest

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