Residential Off-Grid Solar + Storage Systems

A Case Study Comparison of On-Grid and Off-Grid Power for Residential Consumers

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ABSTRACT

The rapid fall in prices of solar panels and battery storage have led some to suggest that it will soon be advantageous for consumers to create their own independent power systems with locally-installed solar and storage and to disconnect from the grid entirely. While it is technically possible to produce such isolated off-grid systems with present-day technology, there is typically a tradeoff between cost and reliability in their design. This paper explores the design of such off-grid systems and various ways the cost/reliability tradeoff might be mitigated through load management and local backup generation using fossil fuels. It also explores the opportunity costs associated with the absence of the grid connection, such as the loss of the ability to sell unused power and thus avoid energy waste. An analysis finds that residential off-grid solar + storage systems are technically feasible with present-day technology, though at a cost of energy several times that of grid-supplied power. In addition, the off-grid solar + storage systems must be significantly oversized to a degree that a very large amount of the generated energy must be curtailed. The amount of curtailed energy is so large that it would be economically justifiable to reconnect to the grid to be able to export it for sale.

Keywords
Solar
Storage
Off-grid
Microgrid
Residential

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1 INTRODUCTION

For most of the last century, consumers have received electric power via transmission lines and distribution networks that deliver power generated by large central power plants located relatively far away from population centers. This arrangement evolved gradually from the natural advantages deriving from economies of scale and specialization, which allowed power to be produced and delivered in the quantities needed by industrial societies at a relatively low cost.

In recent years, distributed energy resources (DER), including solar photovoltaic generation and small fossil fuel plants with combined heat and power (CHP) as well as energy storage, have begun to challenge this centralized architecture. DER are typically located at or near the point of end use, increasing the reliability and resiliency of power transmission and distribution (by shortening the supply line) as well as its efficiency (by decreasing line losses and, in some cases, allowing for use of process heat). Through a combination of technological improvements, policy incentives, and consumer choices in technology and service, DER are rapidly becoming an important power source for commercial and residential customers.

The rapid fall in prices of solar panels and battery storage have led some to suggest that it will soon be advantageous for consumers to create their own independent power systems with locally-installed solar and storage, and to disconnect from the grid entirely. While it is technically possible to produce such isolated off-grid systems with present-day technology, there is typically a tradeoff between cost and reliability in their design. This paper explores the design of such off-grid systems and various ways in which these tradeoffs might be mitigated through load management, local backup generation using fossil fuels. It also explores the opportunity costs associated with the absence of the grid connection, such as the loss of the ability to sell unused power and thus avoid energy waste.

The second section of this report, "The Value of the Power Delivery Network," will describe the history of the evolution of centralized power generation, and will describe the relative advantages and disadvantages of a power transmission and distribution network to those of an islanded power generation system.

The third section of this report, "Design and Analysis of a Residential Off-Grid Power System," will describe how an off-grid system might be designed for a typical residence, illustrating the trade-offs between reliability and cost and estimating the overall cost to a typical consumer.

The fourth section of this report, "Summary and Conclusions," summarizes the findings of the report and makes recommendations for future research.

2

THE VALUE OF THE POWER DELIVERY NETWORK

The History of the Grid

In the early days of electricity, power was generated by relatively small "dynamos" located close to the load. In the 1870s and early 1880s, a number of entrepreneurs, including Thomas Edison, installed a number of coal-powered dynamos in the basement of commercial facilities. These installations required customization for the location, had to be sized to meet the variability of the individual customer load, and required on-site personnel to maintain and service. These factors made such operations commercially viable in relatively few locations.[1]

Already by 1880, Edison had proposed a centralized power generation approach that delivered electric light as a service, analogous to the provision of gas lighting. This vision was made a reality in 1882 with the commissioning of the Pearl Street Station in New York, which eventually served over 500 lower Manhattan customers with electric light, carrying a load of just under 1 MW. Today, we would call such a system a "microgrid," but at the time it was a revolutionary approach to centralized generation.[2]

The development of alternating current (ac) generation allowed generation to be placed at even more distant locations from loads, paving the way for still larger central generation plants which could take advantage of resources such as water power. Large fossil generation plants could also be built at a distance from populated areas.

As individual networks grew, operating companies began to see the advantages of connecting their networks to each other to provide additional security of supply and peak load capability. These connections were made across provincial and even national boundaries, eventually leading to the large interconnected power transmission and distribution networks in operation today.

Networked Power Delivery

To many consumers, the electric power delivery system seems to be merely a supply chain for electric power. In this somewhat incomplete view, illustrated in Figure 2-1, the power grid appears to be an exclusive delivery path by which a single supplier generates and delivers power to an individual consumer.

---

[1] "Storage Batteries", in *The Electrician*, Volume 10, February 17, 1883 329-331.

[2] *Investigation of the Technical and Economic Feasibility of Micro-Grid Based Power Systems*, EPRI, Palo Alto, CA: 2001. 1003973.

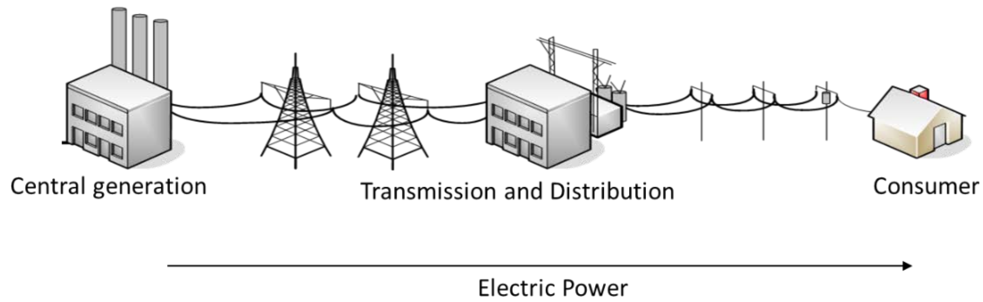

Figure 2-1
The Electric Power Grid as a Supply Chain

In actuality, the modern electric power system is a complex network, consisting of a large number of suppliers and a large number of consumers interconnected and managed in a way that ensures that electricity is delivered with a high degree of reliability. The power delivered from the grid may come from a variety of suppliers, including other consumers who may be generating their own power, as shown in Figure 2-2.

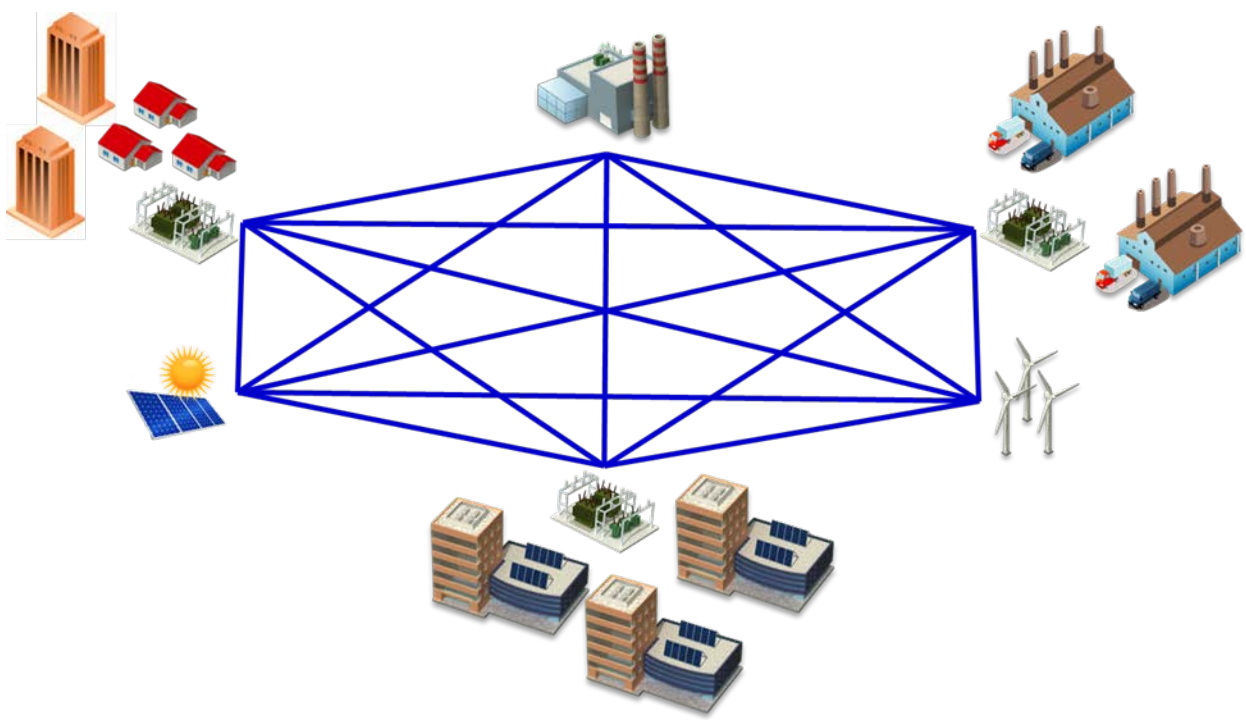

Figure 2-2
The Electric Power Grid as a Network

The networked nature of the grid provides consumers with a number of natural benefits that are not appreciated in the oversimplified supply chain model. These benefits, described in Figure

2-3, include reliability, startup power, voltage quality, and efficiency. While they have been discussed in more detail elsewhere[3], we will define them here briefly for use in our analysis.

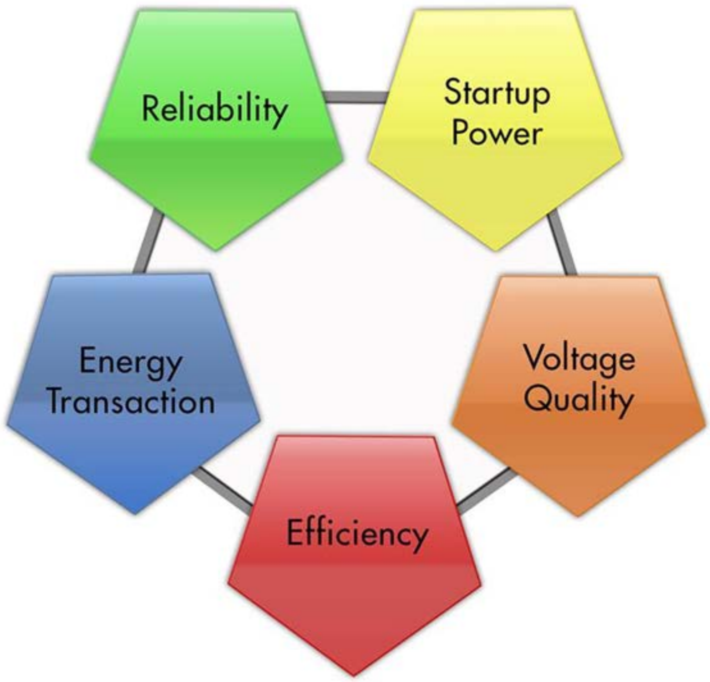

Figure 2-3
Primary Benefits of Grid Connectivity to Consumers

Reliability relates to the possibility for customers to access power at any time and with great certainty. Reliability translates into a number of hours per year during which power is indeed available. The number of suppliers on a grid network allows a diversity of supply as well as redundancy that ensures there is sufficient energy and power capacity to meet the needs of all consumers. The large number of consumers allows generation to be sized to meet the aggregate load, which is less volatile and more predictable than individual loads. This increases the overall stability and asset utilization of the network.

Startup power refers to the maximum, instantaneous input current drawn by an electrical device when first turned on. AC electric motors in particular may draw several times their normal full-load current when first energized, for a few cycles of the input waveform. Residential appliances with significant startup power requirements include compressor-based loads (e.g. HVAC, fridge, and freezer) as well as other motor-driven appliances (e.g. vacuum cleaner, washing machine, dryer). The strength of the networked grid ensures that these instantaneous loads can be met without significant strain to an individual generator.

[3] *The Integrated Grid: Realizing the Full Value of Central and Distributed Energy Resources*, EPRI, Palo Alto, CA: 2014. 3002002733.

Voltage quality can be characterized by voltage level and shape. For grid-connected customers, keeping a good voltage level is directly related to the short-circuit capability of the grid at the point of common coupling. If the grid is weak, voltages may increase or decrease when loads change. In addition to voltage levels, residential appliances need a good sine-wave shape AC voltage to operate properly.

Efficiency, in the context of grid services, relates to the ability of the grid to draw energy from generation sources in a way that minimizes energy waste. The grid network allows most generators to run close to their maximum efficiency point, because energy generated in excess at one location can be transported elsewhere on the grid. Generation and load can be balanced by a relatively small number of regulating generators. In a system in which the same number of generators are operating independently, without a grid connection, each generator would be forced to operate in balance with its load, potentially at a highly inefficient operating point.

Energy transaction describes the consumer's ability to both buy and sell energy from the grid when necessary. This is particularly important when consumers have decided to install DER, as this shifts the technical risk for reliability from the consumer to the grid operator. It also means that the grid serves as a path by which excess power can be sold back to the grid, so that other users can take advantage of it.

Consumers who have installed grid-connected DER systems benefit from all five of these natural characteristics of the network. It should be noted that the network provides these benefits without additional cost to the consumer beyond the cost of energy. Furthermore, they are provided regardless of whether the consumer purchases energy from the grid or not.

There is an overall cost that comes with the construction and maintenance of an electricity network. It has been estimated that the electricity bill paid by consumers in the United States amounts to about $110/month, on average. Of this estimate, about $40/month is estimated to arise from costs to maintain the infrastructure itself. [4] While this estimate can vary from location to location, this is believed to be a reasonable estimate on average.

Suppose a residential consumer wanted to produce a truly off-grid system. How could this design be done, and what are the costs associated with it? The next section of this update examines the trade-offs in designing such a system to provide the same levels of reliability as the grid, under different configurations of DER, such as PV, batteries, and fueled generators.

[4] "Annual Energy Outlook 2012," Energy Information Administration (EIA), Washington, DC, April 2012. DOE/EIA-0383.

3

DESIGN AND ANALYSIS OF A RESIDENTIAL OFF-GRID POWER SYSTEM

Addressing the Technical Challenges of Going Off-Grid

The off-grid system initially considered in this study is made up of three key components: solar photovoltaic modules, battery packs, and energy storage converter. The solar photovoltaic system is the only primary source of electricity generation in this initial configuration, while the battery balances power with the consumer's load in real time. Real-time balance of generation and load is critical for power system reliability; an imbalance can result in damage to power generation equipment or to loads.

Figure 3-1 is a concept drawing illustrating the various parts of a residential off-grid residential system.

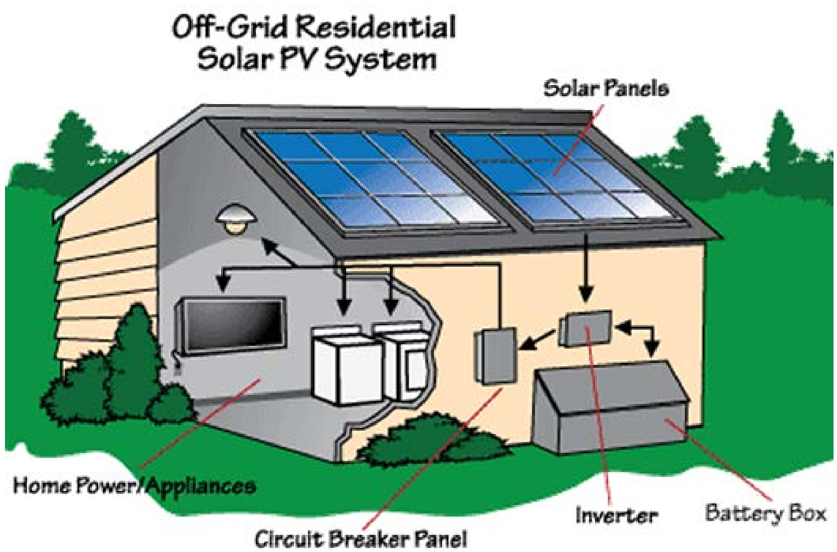

Figure 3-1
Off-Grid Residential System (Source: National Resource Conservation Services)

Note that this concept drawing shows a relatively small off-grid system. In actuality, a system may have substantially more solar panels and a significantly larger battery than shown here.

A key step in the design process of an off-grid power system is determining the size for each of its core components that provides the best trade-off between system costs, and performance. Space requirements, and more generally the various physical constraints at the residential home, set an upper bound for the largest off-grid system that could possibly be installed. For many residential homes, lack of available space may make the off-grid option simply infeasible.

A second important factor guiding the sizing process is the necessity for the off-grid system to provide the services that are essential for the residential appliances to work properly. As mentioned before, isolated power systems lack the natural network advantages vital to optimal operation. It is possible to achieve some of these characteristics – reliability, startup power, and voltage quality -- by oversizing the system appropriately, and by adding such features as load control and backup generation. On the other hand, efficiency and energy transaction benefits resulting from network connectivity are simply unavailable to off-grid systems.

Designing and operating an off-grid system capable of addressing the technical challenges discussed above comes at a cost. In addition to the substantial cost of oversizing the system, there are also the opportunity costs that relate to the lost characteristics of efficiency and energy transaction. This study focuses primarily on the costs to the individual residential consumer who is making the choice to go off-grid. The increased adoption of off-grid residential systems could also impact the electric system and those remaining on the grid, affecting all ratepayers and society as a whole. Those wider impacts, which may include both benefits and costs, while important, are not considered under the scope of the present study.

Analysis Assumptions

As the base case for a typical single-family home in the United State, we use real load data from a 3,200 ft^2 (303 m^2) residential home located in Montgomery, Alabama. One year of metered load data is available for this Montgomery home at 1-min resolution. Table 3-1 summarizes the key consumption characteristics for this household.

Table 3-1
Load Characteristics for Residential Base Case

Key metric	Value
Average monthly consumption	1.260 kWh
Power requirement	19 kVA
Maximum steady-state HVAC current (metered)	46 A

Note that the heating, ventilation and air conditioning (HVAC) is the residential load with the single largest in-rush requirement in our base case, and the power system must be sized to support it.

In addition, normalized irradiance data is obtained from a local monitoring station, also for one year at 1-min resolution. Table 3-2 provides the corresponding irradiance metrics. Days are divided into three types: Clear days (when solar power is fully available, unobscured by clouds), cloudy days (when clouds somewhat obscure the sun and solar power is only partly available), and overcast days (when little solar power is available due to heavy cloud cover). Overcast days are relatively rare, but on such days power is supplied primarily from the batteries.

Table 3-2
Irradiance Characteristics for Residential Base Case

Key irradiance metrics (one year)	Value
Average irradiance (kWh/m2/day)	4.2
Number of overcast days	47
Number of cloudy days	113
Number of clear days	205
Maximum number of consecutive overcast days	4
Maximum number of consecutive cloudy or overcast days	10

Figure 3-2 illustrates a representative sample of the load and solar data from this dataset.

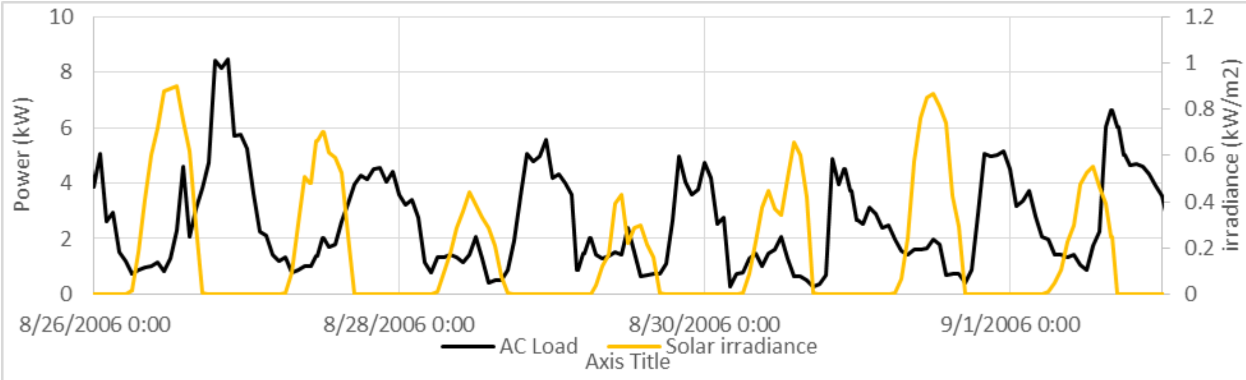

Figure 3-2
Load and Solar Data

Note that on some occasions, overcast days occur consecutively. At no point in the data set are there more than 4 consecutive overcast days. This figure drives the sizing of the energy storage component of the off-grid system.

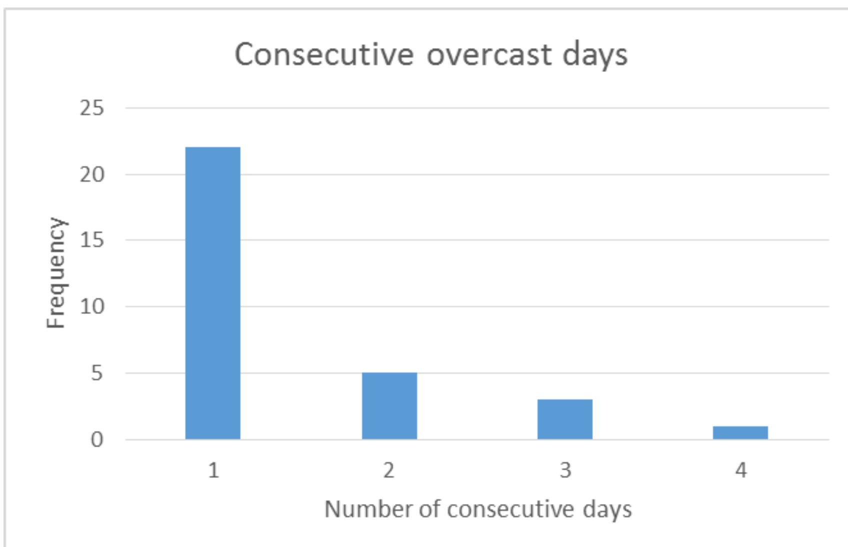

Figure 3-3
Distribution of Consecutive Overcast Days

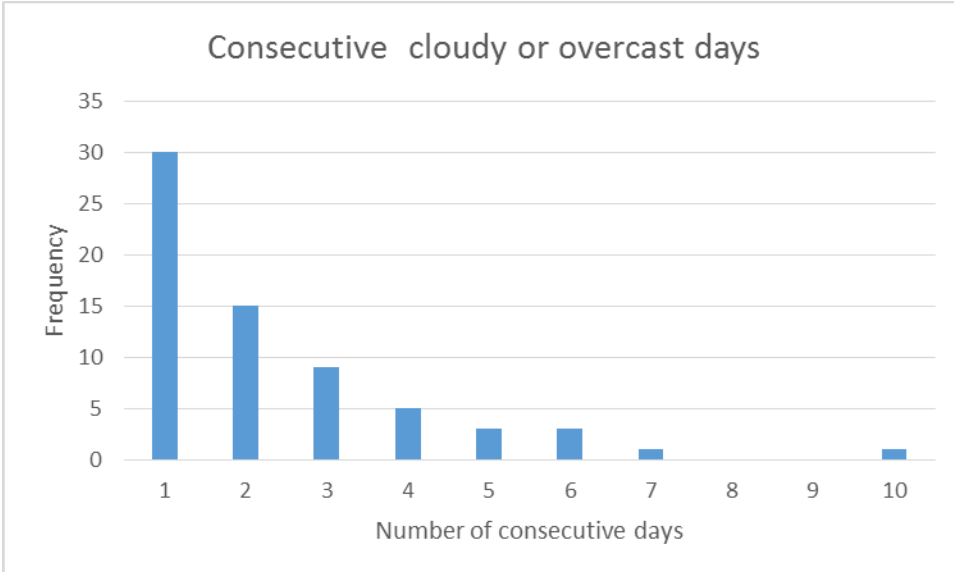

Figure 3-4
Distribution of Consecutive Cloudy or Overcast Days

There are many possible configurations for a solar photovoltaic system with storage. For the purposes of this analysis, only the DC-coupled architecture depicted in Figure X below, requiring a single converter, is considered.

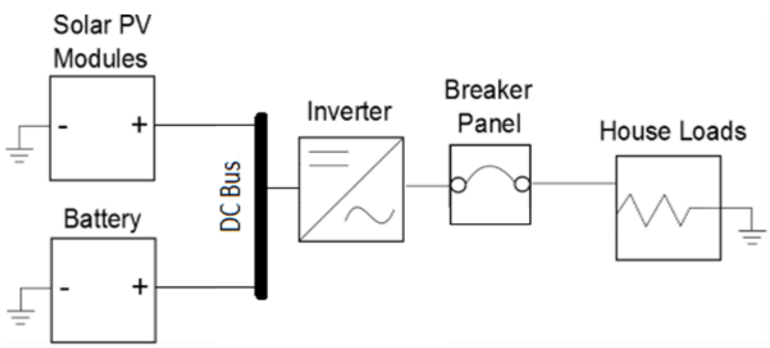

Figure 3-5
Off-grid Power System Architecture

Table 3-3 summarizes several key input assumptions used in this study for the photovoltaic panels, energy storage and power converter. More complex off-grid configurations involving load management and the addition of a backup genset are examined in subsequent sections of this report.

Table 3-3
Solar Photovoltaic, Energy Storage and Converter Assumptions

PV module	Nominal efficiency	15.3783 %
	Annual degradation	Negligible
	Asset lifetime	25 years
Energy storage	Roundtrip efficiency	90%
	Annual degradation	Negligible
	Power-to-energy ratio	1:4
	Maximum charge/discharge power	0.25kW per 1kWh of capacity
	Asset lifetime	10 years
	Minimum State of charge	20%
Energy converter	Annual degradation	Negligible
	Asset lifetime	10 years

PV panels must be installed on non-shaded roof space. In addition, appropriate spacing is required between panel installations to allow for maintenance access and avoid shading. The angle of the roof will affect the effectiveness of the solar panels. While PV panels are typically installed only on optimally angled roofs, the larger PV systems used in off-grid applications may require installation on suboptimal rooftop space, or on the grounds of the residence. Space is also required for the energy storage and power converter.

In this study, we do not consider spacing constraints in the sizing process itself, but instead size the system completely on the basis of technical requirements, and then compare the resultant system size to the space generally available at typical US residential homes. As we will see, the PV system sizes required for high-reliability systems may exceed the available roof space of many homes, necessitating the placement of some panels on the grounds or in other locations.

Software Tools

This study uses HOMER[5], a software tool for distributed generation power system design and analysis, to assist with the off-grid sizing process. HOMER allows the evaluation of the performance, and eventually cost, of various off-grid system sizes under different configurations and operating constraints.

The search algorithm implemented in HOMER identifies feasible PV and storage sizes for a given load requirement specified for one year at 1-minute resolution. An important input to the simulation is the percentage of unmet load. This input parameter relaxes peak load requirements by allowing a certain amount of load to be unmet on certain days. Based on this parameter, HOMER selects the storage size as an integer number of 1kWh Li-ion batteries with a pre-established energy/power ratio. Similarly, the PV panel is sized as a number of 1 kW solar panels whose power output is calculated using the System Advisory Model (SAM) tool developed by the National Renewable Energy Laboratory (NREL).

The sizing process simulated in HOMER is as follows. After initializing the PV and storage sizes, a dispatch simulation is obtained: the battery is charged when extra PV power is available after serving the load, and discharged when PV power is not sufficient to meet the load. Battery-

[5] www.homerenergy.com

supplied power is limited by the storage power and energy capacity. When the load requirements are greater than the maximum power available from PV and storage at a particular time, power is considered unavailable at that time.

If the allowed percentage of unmet load is surpassed, the scenario is declared infeasible. The system size (i.e. PV and/or storage capacity) is increased, and a new dispatch is obtained. If the dispatch satisfies the load for the entire year within the availability constraint, the algorithm attempts to re-run the dispatch with a smaller PV capacity and/or storage. This iterative process stops when the system size does not change significantly between iterations, or when the maximum number of iterations has been reached.

The final dispatch is obtained at the same granularity as for the load and solar input data, General information on the system operation, such as percentage of renewable generation, unused solar generation, CO_2, etc. is also available from the simulation.

Multi-Stage Sizing and Design Process

We now introduce the multi-step approach followed in this study for the design of a PV + storage off-grid system. The goal is first to ensure systematically that the PV, battery and converter constituting the off-grid system are sized to meet the desired levels of power availability, startup power requirements, and voltage quality, and then to analyze the corresponding system costs. Figure 3-6 depicts the overall approach.

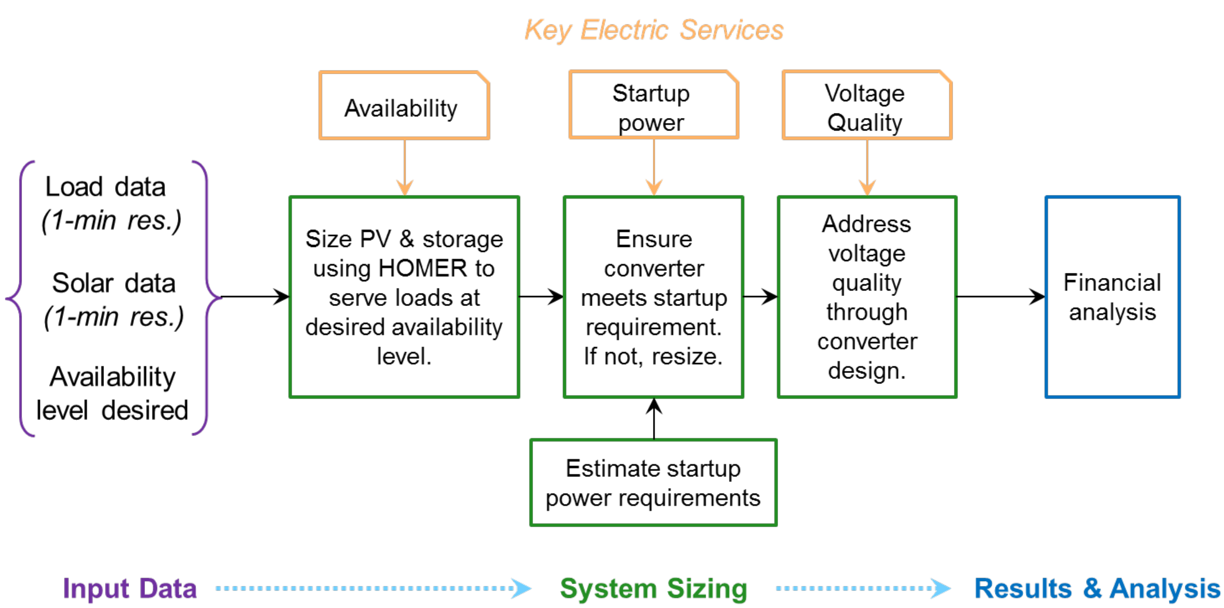

Figure 3-6
Multi-Stage Sizing and Analysis Approach

1. Input Data

The process begins with collecting the relevant load and solar data for the site of interest. In our analysis, we use the 1-min resolution data corresponding to our base case location in Montgomery, AL, for one full year.

Another important input parameter is the desired level of availability. In this study, we use the concept of load served to operationalize the notion of availability. Load served refers to the fraction of energy demand that the off-grid system is able to fully serve over one year. This is determined against the one year, 1-min resolution demand baseline.

Several levels of load served are considered in this study: 80.0%, 90.0%, 99.0%, 99.9%, 99.99%, with 99.99% corresponding to the load served capability of today's grid. An ad-hoc analysis is conducted for each level. This includes sizing the off-grid system components, and conducting the corresponding financial analysis.

We do not include in our analysis any probability of equipment failure for the various components constituting the off-grid system. For this reason, we do not use the concept of reliability, which usually implies that device failure probabilities are accounted for. From a reliability standpoint (i.e. accounting for probability of equipment failure), it is clear that a residential off-grid system can hardly compete with a grid-tied configuration benefiting from the redundancy of the grid infrastructure.

2. System Sizing

We decompose the sizing process of the off-grid system into three consecutive steps. Each step addresses one specific service: availability, startup power, and voltage quality.

Power Availability

First, we focus on selecting a set of sizes for the PV and battery systems that meets the desired load served performance. This evidently depends on the solar irradiance values and load values provided in input.

We use HOMER to conduct a systematic search over the space of feasible PV and storage configurations. HOMER begins the search by assigning some initial sizes to PV and storage, and runs an initial dispatch simulation at 1-min resolution. If the percentage of time for which power is unavailable is higher than the maximum unavailability allowed, HOMER increases the size of the system and re-runs the dispatch algorithm. If it is lower than the maximum unavailability allowed, HOMER decreases the system size according to a binary search algorithm rule and re-runs the dispatch. The process iterates until the PV and storage sizes do not change significantly from one iteration to the next.

An important driver impacting the battery size is the maximum number of consecutive days with low solar availability. As illustrated above in Figure 3-3, for the Alabama solar data used in this study, the maximum number of consecutive overcast days observed is four. Future work could model the number of consecutive overcast days as a random variable, which might allow the possibility of even larger threads of consecutive days with poor solar resource. Such a study would yield even larger off-grid systems, since the design of battery size for high percentage of served load is driven by the worst case of consecutive unavailable solar resource.

Startup Power

The HOMER simulations run in the previous step assume a large converter size. The goal is to ensure that converter size is not a limiting factor. Once the final dispatch is obtained and the PV and storage sizes are selected, we must now ensure that the converter size previously selected is indeed able to provide for the inrush current requirement.

We assume that the HVAC system sets the maximum in-rush current capability required at the household level. The maximum steady-state HVAC current observed for our base case residential home is 46A. Recall that metered load data is available for this home at 1-min resolution, which was the best resolution available for a 1-year period. However, in-rush currents require cycle-level resolution to be fully captured. For this reason, and to ensure that startup power requirements are properly quantified, we further assume that the HVAC system may require as much as 8 times its steady-state current during the first cycles. We therefore estimate the required startup power capability to be 368A for our base case customer.

We assume a conservative size-to-surge-current ratio of 1kW:15A to verify adequacy of the surge current capability for the converter size selected in the previous step. This ratio is based on the capabilities of six inverters currently commercialized by leading manufacturers. If the surge current obtained is above or equal to 368A, no oversizing is required: the converter selected is already able to provide for the required startup power capability. If the surge current is less than 368A, the converter is oversized to 368/15 = 24.53kW. This increase in converter size translates into a higher converter cost. The cost difference can then be seen as the additional cost required to meet the startup power requirements.

Voltage quality

This last step of the sizing process focuses on power quality. Most commercial-grade inverters already provide satisfactory voltage and current waveforms. We also assume that the converter is sufficiently sized to supply startup power without affecting power quality. We are not concerned about surge withstand or dip immunity of the end-use equipment because the off-grid system has limited exposure to these disturbances by not being exposed to the larger grid. We also assume that there are no incompatibilities between the harmonic distortions created by the customer loads or by the converter. From a financial analysis standpoint, we assume that the cost of maintaining acceptable voltage quality while operating off-grid is already factored into the cost of the converter.

3. Financial Analysis

Our multi-stage approach concludes with a financial analysis component. Our focus in this study is primarily on the cost to the individual residential consumer making the decision of whether to go off-grid, or stay connected to the distribution network.

For a given off-grid configuration, we measure the profitability of the project by computing its Net Present Cost (NPC). NPC accounts for all relevant capital, replacement and O&M costs applicable to the PV, battery and converter constituting the off-grid power system. We also calculate the corresponding Levelized Cost of Load Served (LCOLS) over 20 years, which allows us to compare the off-grid and on-grid options from an energy cost standpoint. Note the distinction between LCOLS and the Levelized Cost of Electricity (LCOE). The latter assumes that electricity is always available to be drawn, while the former allows that some of the load will not be met by the power supply. The assumptions for LCOE are a reasonable approximation at high levels of power, but at lower power availability figures, LCOLS is a much more accurate term.

Our study looks only at the benefits and costs to the consumer who is seeking to go off-grid. The increased adoption of off-grid power systems at the residential level may impact the costs of electric system as a whole, impacting costs to other ratepayers as well as to society as a whole. Those impacts, which may include both benefits and costs, are also important but not considered under the scope of the present study.

The financial analysis relies on a number of assumptions which are documented below.

Financing

Several parameters affect the financing of the project and are tabulated in Table 3-4. For the purposes of this analysis, we assume the installation will be financed through a fixed interest rate loan over a period of 20 years, reflecting the current shift of financing away from lease models towards loan financing.

Table 3-4
Financing Assumptions

Solar loan time	20 years
Project lifetime	25 years
Down payment	20%
Interest rate	4%
Inflation	2%

Equipment Capital Cost and Lifetime

Capital costs are assumed to reflect real present day costs for hardware, including all installation costs. The figures are representative of the local market, and are within a reasonable range of industry costs worldwide.

Table 3-5
Assumed Initial Installed Capital Costs

Installed PV cost	$1.86 / W
Installed Battery	$1000 / kWh
Installed Inverter	$ 0.1 / W
Installed Diesel Genset	$0.5 / W

The prices of this equipment can be expected to fall sharply in the coming years, as residential solar and storage equipment becomes more widely used and can be produced economically at scale. These price declines are reflected in price escalation figures, which are negative since the prices are falling (note that these price changes are in nominal figures, meaning they are not adjusted for inflation).

Table 3-6
Assumed Price Escalation Over Project Lifetime

PV price escalation	-8.28% per year
Storage price escalation	-5% per year
Inverter price escalation	-14.28% per year
Diesel Genset price escalation	-2% per year

In this analysis, declining prices have an impact on replacement costs, since much of the equipment is not expected to last the full life of the project. The lifetime of the various components are assumed to follow the parameters in Table 3-7.

Table 3-7
Assumed Component Lifetime before Replacement

PV lifetime	25 years
Storage lifetime	10 years
Inverter lifetime	10 years
Diesel Genset lifetime	5000 hours

Operations and Maintenance (O&M) Costs

Finally, we must add some assumptions for the cost of operations and maintenance (O&M) for these assets. It is assumed that the homeowner will pay for regular maintenance of the systems, perhaps through a service contract with the solution provider. The figures shown here are representative of O&M costs in present-day installations.

Table 3-8
Assumed Operations and Maintenance (O&M) Costs

O&M PV	$20 / kW / year
O&M Battery	$5 / kWh / year
O&M Inverter	$0
O&M Genset	$0.03 / hour
Fuel Cost for Diesel Genset	$0.65 / l

Analysis Results

Overview: Load Service Capability vs. System Cost

We first analyze the trade-off between load service capability (and hence, off-grid system size), and system costs. All results presented are for the residential base case previously introduced.

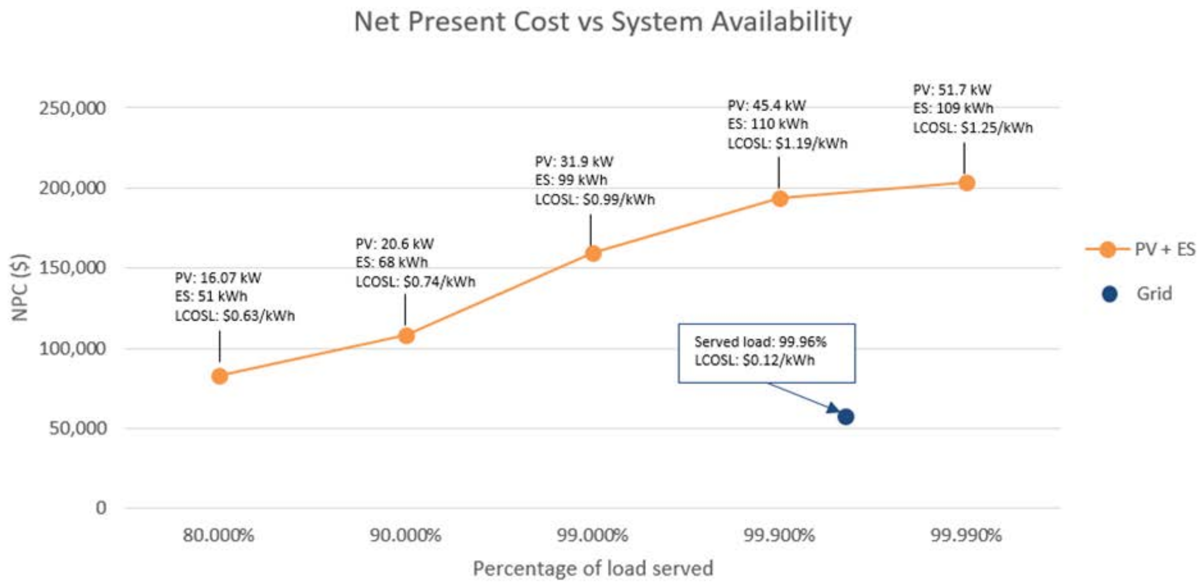

Figure 3-7
Net Present Cost of Off-Grid Systems with PV and Storage

Figure 3-7 shows the economics of going off-grid for various levels of load served: 80.0%, 90.0%, 99.0%, 99.9%, 99.99%. At each level, the system attempts to serve as much load as possible, but is allowed to leave a certain amount of the load unserved. This might happen, for example, when the battery energy is low after several cloudy days, and the homeowner may be forced to curtail some loads, such as air conditioning, television and lights, in favor of more vital loads such as refrigerators and lighting. At 80% load served, about 20% of the load that the homeowner would otherwise draw will not be served, whereas at 99.99%, only 0.01% of the load will not be served.

As the desired load-served capability is increased, PV and storage sizes grow significantly from 16.07 kW PV and 51 kWh storage for 80% load served, to 51.7 kW and 109 kW for 99.99% load served. At the same time, the Net Present Cost (NPC) of system more than doubles from approximately $82,770 for 80% load served to over $203,505 for 99.99% load served.[6]

It can be seen that the levelized cost of load served (LCOLS) ranges from $0.63 / kWh for an availability of 80%, to $1.25 / kWh for an availability of 99.99%. An availability of 80% would be equivalent to having more than two months of cumulative outages every year. In comparison, the same user being connected to the traditional power grid, which offers a load-served percentage of approximately 99.96%, corresponds to a levelized cost of $0.12 / kWh.[7]

All system sizes shown in Figure 3-7 reflect only the load needs, available solar and energy storage resources, and desired load served capability, without consideration of the space required for the system. It is worth comparing the size of such systems to the space usually available at a typical US residential household. A 50 kW dc solar photovoltaic system is estimated to require

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[6] Net Present Cost is the inverse of Net Present Value (NPV).

[7] 99.96% is equivalent to a CAIDI of 120 minutes.

at least 4,000 ft^2 of non-shaded, optimally angled roof space. This number is scaled from installations today that are placed at optimal azimuths (south or west facing panels). In comparison, the size of the residential home considered as our base case in this study is 3,200 ft^2. Therefore, in practice, the PV size required to maintain a load service capability of 99.99% could not be installed exclusively on the roof, but would also require some ground space. This example illustrates that the amount of space required to install systems enabling off-grid operations, while maintaining load service levels equivalent to those provided by the grid, might be prohibitive for many residential homes.

Energy Shortage Conditions

As described above, smaller off-grid systems will not be able to meet all loads at all times. Figure 3-8 depicts the unmet load for the 80% load served scenario. While unmet load occurs throughout the year, it is most likely to occur in the summer time, when the load peaks due to HVAC intensive use.

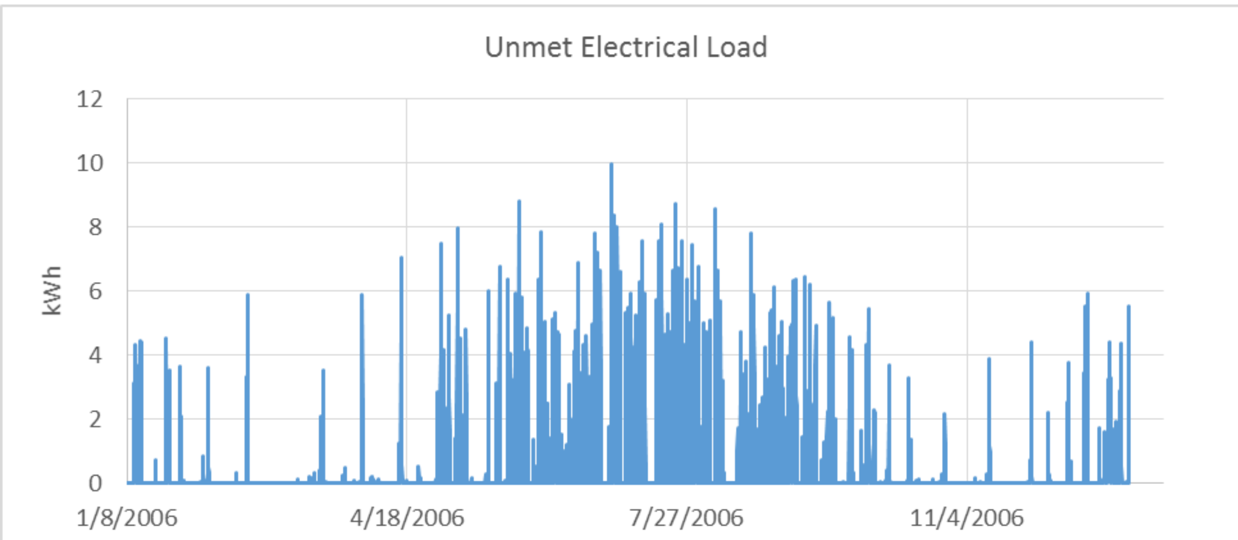

Figure 3-8
Unmet Load for 80% Load Served Scenario

Figure 3-8 shows the dispatch of PV and storage for the first week of July. Unmet load occurs every day as a result of the lack of coincidence between solar irradiance and load. On high irradiance days such as July 4th the storage unit is able to charge to full capacity during the day and discharge during the evening load peak. However, on low irradiance days such as July 1st the storage unit is depleted by the time the load peaks.

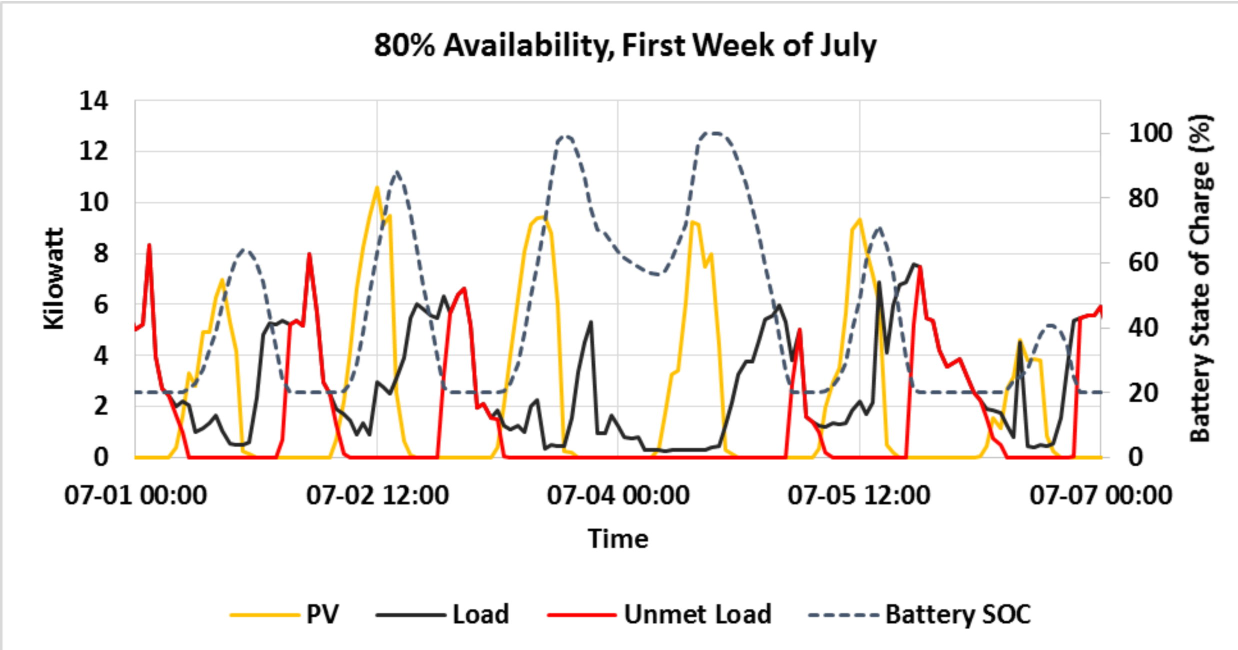

Figure 3-9
Shortage Conditions and Battery Behavior in 80% Load Served System

As the load service capability of the off-grid system is increased, the unmet load is reduced, and unmet load occurrences correspond to extended periods of low solar resource (i.e. consecutive cloudy and overcast days) . As expected, the load service factor ultimately dictates the size of the overall system. In the 99.99% availability case shown in Figure 3-10, the PV and storage are sized such that the off-grid system is able to ride through every single low irradiance event. Storage gets fully discharged only when consecutive cloudy days occur, resulting in unmet load.

The maximum number of consecutive low irradiance days observed in the Alabama base case used in this study is 4 days. This base case, and the corresponding one-year dataset, are not meant to be exhaustive and representative of all possible conditions; some years might have a greater, or lesser number of low irradiance days which therefore would require a larger, or smaller sized system to meet the same desired load service level. The predictability and consistency of annual irradiance patterns are not addressed within this study.

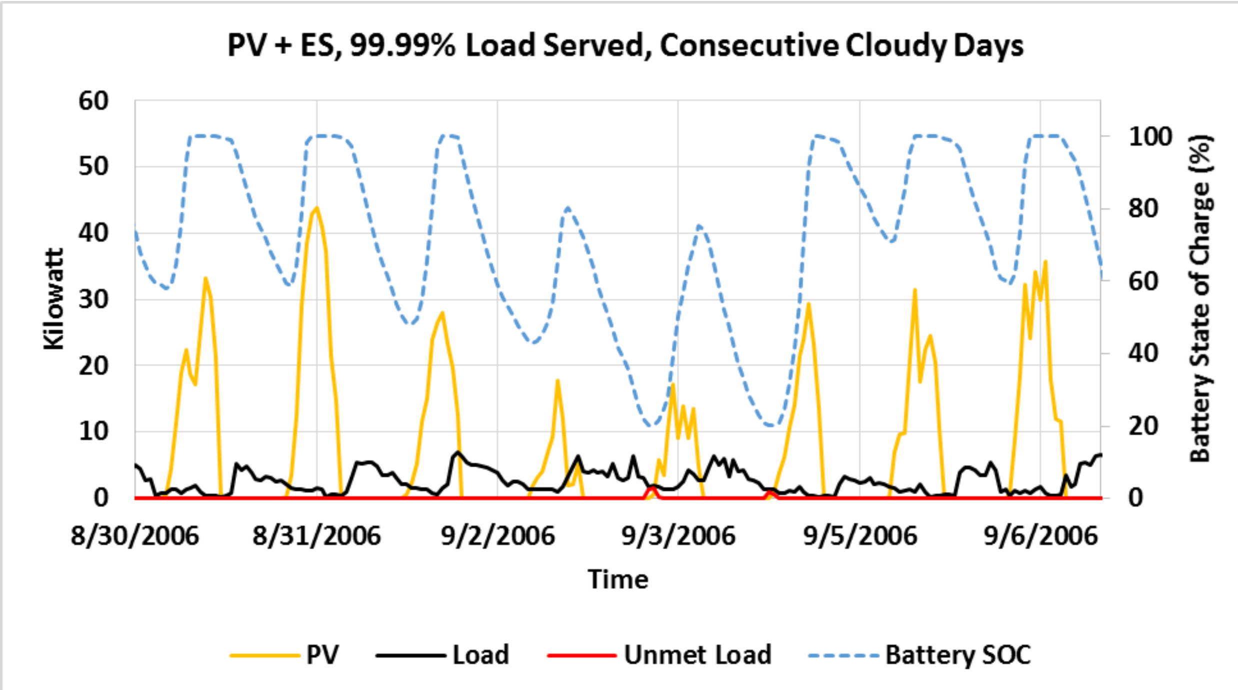

Figure 3-10
Shortage Conditions for Consecutive Cloudy Days in a 99.99% Load Served System

Energy Spillage Conditions

Energy spillage can occur when very large solar arrays are installed for off-grid generation. Significant amounts of excess power are generated during times where all load requirements are already met, and the storage system is already full. Since the excess energy has nowhere to go, it is effectively wasted.

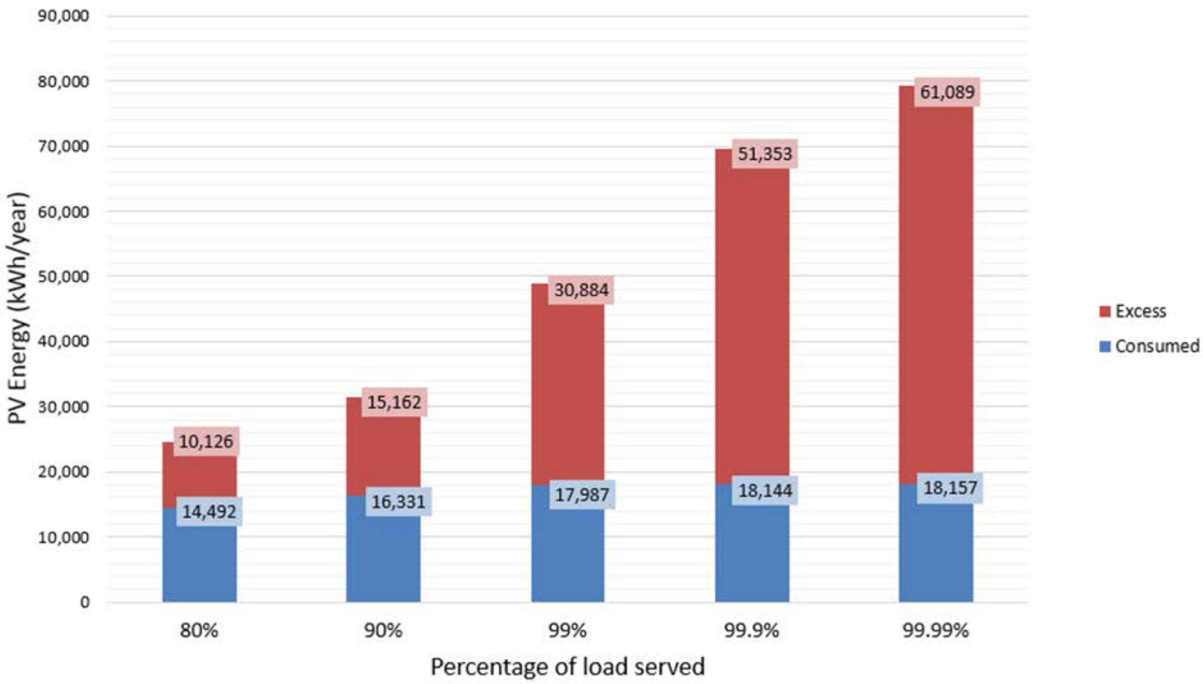

Figure 3-11
Excess Electricity and Consumed Electricity for Different Levels of Availability

Figure 3-11 displays the amount of consumed and excess electricity for each of the solar + storage configurations shown in Figure 3-7. It can be seen that for even the smallest system size, the amount of spilled energy is significant. For the largest sizes, the amount of spilled energy more than triples the consumed energy.

To the consumer with the off-grid system, the spilled energy represents significant lost revenue. With a grid connection, the homeowner would be able to sell excess energy to the grid for some level of compensation. The magnitude of lost revenue can be examined by computing the economics of a PV + storage system with 99.99% availability under two different conditions: i) completely off-grid, and ii) connected to the grid at a rate of $40/month, with different sellback rates, and no electricity purchase.

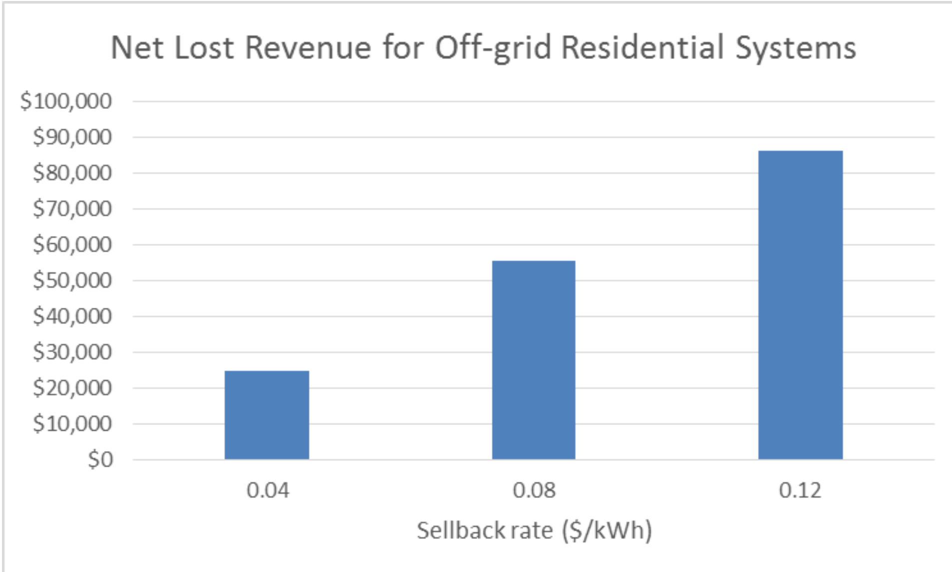

Figure 3-12
Net Lost Revenue to the Off-Grid Consumer, for Different Potential Sellback Rates

Figure 3-12 shows the net lost revenue for the off-grid user, who might (with a grid connection) sell excess electricity back to the grid at sellback rates of $0.04, $0.08, and $0.12. Note that the net lost revenue values also represent an estimate of how large the interconnection fees can be before it is better for the consumer to remain off-grid. In spite of the monthly interconnection cost of $40, the user could in principle, connect back to the grid and sell this electricity for significant revenue, even if the utility imposed a sizable upfront interconnection fee.

Addressing Energy Shortages through Load Deferral

One possible avenue to minimize the amount of unmet load, or conversely to reduce the PV and storage sizes necessary to achieve a given level of unmet load, is to employ some form of load management. In particular, there may be some loads, such as laundry or dishwashing, which are important but which can be done at any time of day. These loads can be shifted to occur on sunny days when excess power is available, and can be curtailed on cloudy and overcast days when power is short.

The portion of load that can be managed in this way is referred to as deferrable load. Our analysis indicates that while load management can be helpful in addressing the unmet load, it is relatively limited in both amount and value.

Identifying Deferrable Loads

As illustrated by the off-grid sizing results above, the battery size is driven by the largest amount of consecutive days with poor solar irradiance observed in a year. The maximum number of consecutive cloudy days in our base case is 4. This means that load deferral is an effective strategy if and only if some of the residential loads can remain unserved by more than 4 days.

For a typical residential home, only a small portion of the total load can be deferred for more than 4 days. In this study, we assume that the deferrable loads consist of the washing machine, dryer and dishwasher, and that these loads can be shifted to days where the solar resource is highly available.

The load data available for our base case site is in aggregated form, and sub-metered consumption by load type is not available. For this reason, we use additional processing to find an estimate of the deferrable load. The goal is to evaluate the effect of the load deferral strategy on PV and storage sizing.

Estimating deferrable load consumption

First, we focus on estimating the fraction of load consumption corresponding to the washing machine, dryer and dishwasher, i.e. the loads that we assume can be deferred. To that end, we use the software tool BEopt™ to model a 3,200 ft2 home in Montgomery, AL, which corresponding to the size and location of our base case home. BEopt (Building Energy Optimization) is a software tool developed by the National Renewable Energy Laboratory (NREL) to "evaluate residential building designs and identify cost-optimal efficiency packages at various levels of whole-house energy savings along the path to zero net energy."[8] Based on the local weather conditions and efficiency characterization of the household modeled, BEopt provides hourly consumption data by load type (appliances, HVAC systems, lights, etc.).

For the house simulated in BEopt, Table 3-9 shows the distribution of residential consumption by load type for one year. Load types corresponding to appliances include cooking range, refrigerator, dish washer, clothes washer, and "dryer+other". The remaining consumption is categorized as "non-appliances".

Table 3-9
Distribution of Total Residential Consumption by Load Type Obtained Using BEopt Simulated Data

Load type	Percentage of total load (%)
Non-appliances	80.79
Refrigeration	4.90
Cooking	4.54
Dish washer	1.00
Clothes washer	0.38
Dryer + others	8.36

We must further isolate the fraction of the load corresponding to the dryer since it is one of the deferrable loads in this study. Dryer and "other loads" represent 8.36% of the total electrical load; we assume that half of that load, i.e., 4.18%, corresponds to the dryer. Finally, by adding the dryer (4.18%), dish washer (1.00%) and clothes washer (0.38%), we obtain a rough estimate for the deferrable loads of 6% of the total load.

We recognize that by assigning 4.18% of the total load to the dryer, we may over-estimate the actual dryer consumption and its load deferral potential. In other words, the sizing results

[8] BEopt website (beopt.nrel.gov/home), accessed July 20, 2016.

obtained for the off-grid system using this estimated value of 4.18% might lead to design an off-grid system that is smaller, hence cheaper, than the sizing results that would be obtained if the metered data for the dryer was available. We are then simulating an “optimistic” off-grid scenario from a cost standpoint.

Deferral Load Strategy

Once we have established that 6% of the total load can be deferred, we now devise a methodology to estimate a best-case deferral strategy suitable for the scenario valuation. Specifically, we propose to generate a deferred load profile that varies according to availability of PV power.

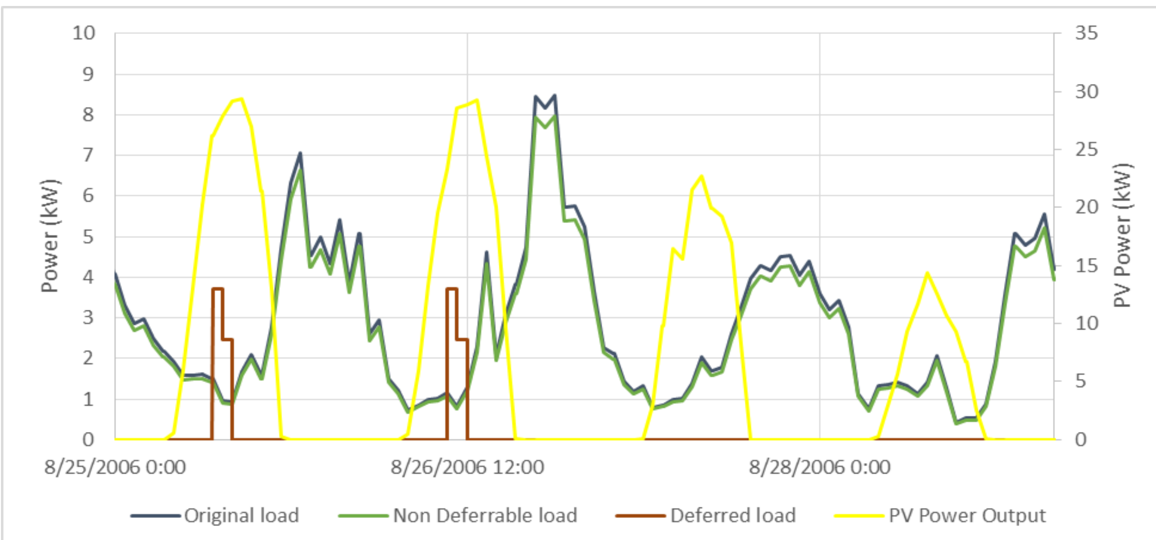

Figure 3-13
Deferrable and Non-Deferrable Loads, Compared to Original Load

For those days where the energy generated by the PV panels is less than 75% of the daily maximum, the deferrable loads are not served. It is indeed the goal of a deferrable load strategy to reduce the load consumption on these days.

For those days where the energy generated by the PV panels is higher than 75% of the daily maximum of the year, the deferrable loads are served as follows. We assume that each deferrable load must be served during either 1 or 2 continuous hours. We then assume that all the deferrable loads are turned on at 10 am, representing a load of $3x$ kW, where x is a number to be determined. After 1 hour has passed, we assume that some deferrable loads are turned off, and the ones that remain on until noon represent a deferrable load of $2x$ kW. We set $x = 1.234$ kW such that the total energy provided to the deferrable loads over one year be equal to 907.02 kWh, or our 6% estimation for the total energy consumption of the residence.

Modeling of non-deferrable loads

In this study, non-deferrable loads are modeled by scaling down the original load profile by a factor of 0.94 –removing the 6% deferrable load while conserving the original load profile shape.

Alternative approaches are possible. For example, one could scale down the original load profile only on days with low solar resource such that the resulting annual load reduction is equal to 6%

of the total load. Based on our calculations, this would result in using a scaling factor of 0.903 for those days. However, this approach is equivalent to assume that the 6% of deferrable load consumption was originally served only during days of low solar resource, which is not realistic.

A second possible approach could be to scale down by 0.94 the original load profile only for the days with low solar resource. The corresponding amount of load deferred would be re-assigned to the remaining (sunny) days by calculating the corresponding value of x as explained above. This second approach is aligned with the objective of decreasing the storage capacity required, but still serves some deferrable load at night, which might lead to a larger storage size than the one obtained should the load be served directly with the PV power.

Given the aforementioned considerations, our proposed approach is a best case scenario, since our model is such that all the energy corresponding to the deferrable load will be served during the 10 am – 12 pm segment, even the one from days with high solar resource. This ensures that the obtained system sizes are lower bounds to system sizes designed for any other deferral policy where the deferrable load is 6%.

Figure 3-13 shows in brown the behavior of the deferrable load under the load deferral strategy described above. According to the deferral load strategy previously defined, load is deferred only to days with high availability of solar resource.

Impact of Load Deferral on System Sizing

We can now use the total load, consisting of the sum of the deferred and non-deferred load, as load data input in HOMER to evaluate the impact on off-grid system sizing.

For this analysis, the investment in equipment and controls needed to enable load management is assumed to be negligible compared to the cost of the PV and battery systems.

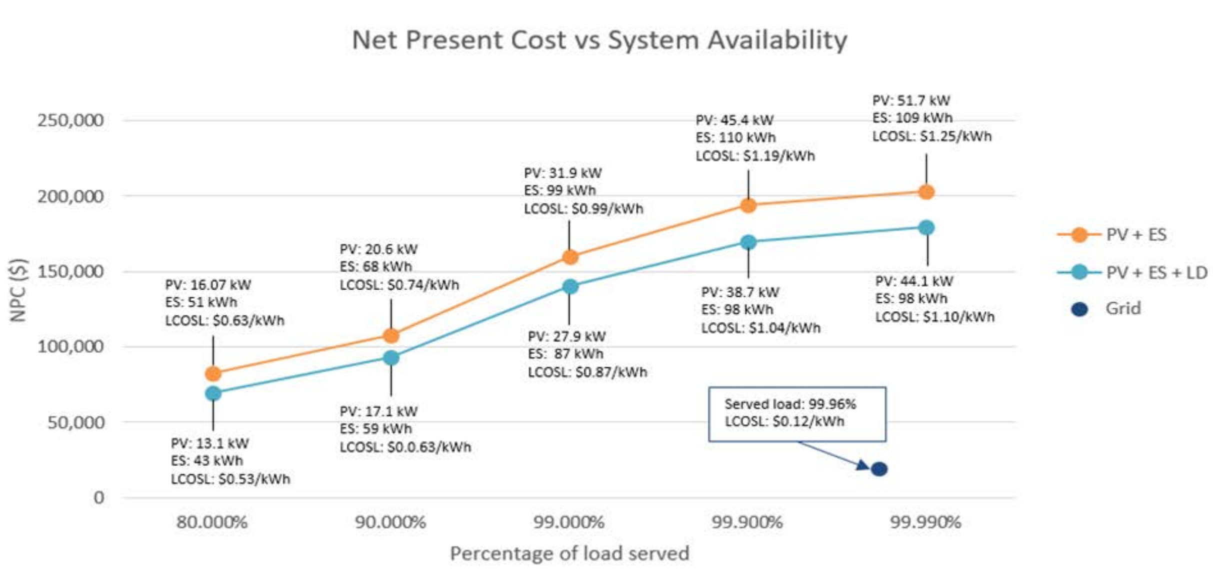

Figure 3-14
Net Present Cost of Off-Grid Systems with PV and Storage vs System Availability, with and Without a Load Deferral Strategy

Figure 3-14 shows the impact of the load deferral strategy on the cost and size of the off-grid system. At 99.99% availability, load management leads to a reduction in required storage by 11 kWh, while the required PV is reduced by 7.6 kW. This translates into a $24,312 (or 11.95%) decrease in the system Net Present Cost.

Such a significant decrease on the system size by deferring only 6% of the load suggests the energy required by deferrable loads in the original load shape, especially during critical days with low solar resource availability, implied a considerable additional investment that could potentially be avoided by taking advantage of the inherent flexibility of those loads.

Despite the positive impact of load deferral on the system design, the costs associated with going off-grid are still significantly higher, on a levelized cost of load served basis, than the purchase of electricity from the grid.

Addressing Energy Shortages by Adding a Fueled Generator

In this section, we examine the impact of adding a diesel generator to the off-grid system configuration. As we will see, this configuration results in a smaller storage system, and hence reduced costs associated to the energy storage system. However, it will also result in more energy spillage, as well as environmental impacts in the form of carbon dioxide and criteria pollutants.

Sizing a System with a Fueled Generator

We choose to analyze a case corresponding to 99.97% load served, which matches the reliability of the U.S. electricity grid. Simulating this configuration in HOMER is straightforward, and results in an optimal system consisting of a 19 kW diesel generator, with 8.33 kW PV array, and a 27 kWh battery.

Simulation results show that the diesel generator produces 39.25% of the electricity generated annually, and the PV array produces the remaining 60.75%. The smaller battery size reduces the cost of the system, but leads to further energy spillage of 2,845 kWh/year, since there is less battery capacity available to store it.

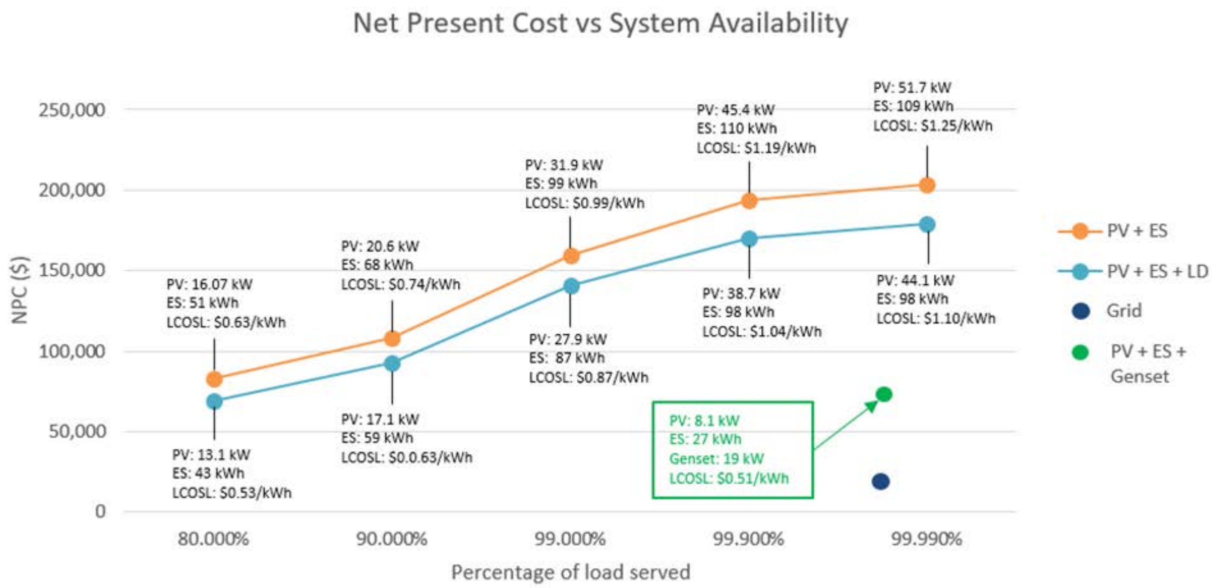

Figure 3-15
Net Present Cost of Off-grid Systems with PV, Storage, and Diesel Genset

Figure 3-15 compares the PV + storage + genset configuration with the other system configurations previously analyzed, with respect to net present cost and load service capability. The design including the genset is relatively inexpensive compared to the previously considered off-grid PV + storage systems at similar load service capability, even in the case where loads are deferred. Its cost is similar to PV + storage + load deferral at 80% load served capability, but with reliability close to the 99.99% load served capability. This leads to a LCOLS of $0.51/kWh, significantly lower than the off-grid cases considered so far, though still substantially more expensive than purchase of electricity from the grid.

The system can also be expected to have a significantly smaller physical footprint than a comparable off-grid system with only PV and storage.

The sizes of the various components for the PV + storage + genset configuration are directly driven by the fact that the genset turns on whenever PV + storage cannot supply the load. This leads to a design in which the battery fully discharges when solar power is not available. As soon as the battery is not able to fully supply the load, the diesel generator starts and supplies the load. This allows the battery to serve most of the load at peak hours, while the diesel generator serves the load when the battery charge is low.

Figure 3-16 displays one week of energy dispatch for the off-grid system designed to meet 99.97%. During the second day, despite the fact that the PV power output is typical of a clear day, the battery size is such that storage can only supply power to the load during less than a half of the night time. The rest of the night is covered by the fuel generator.

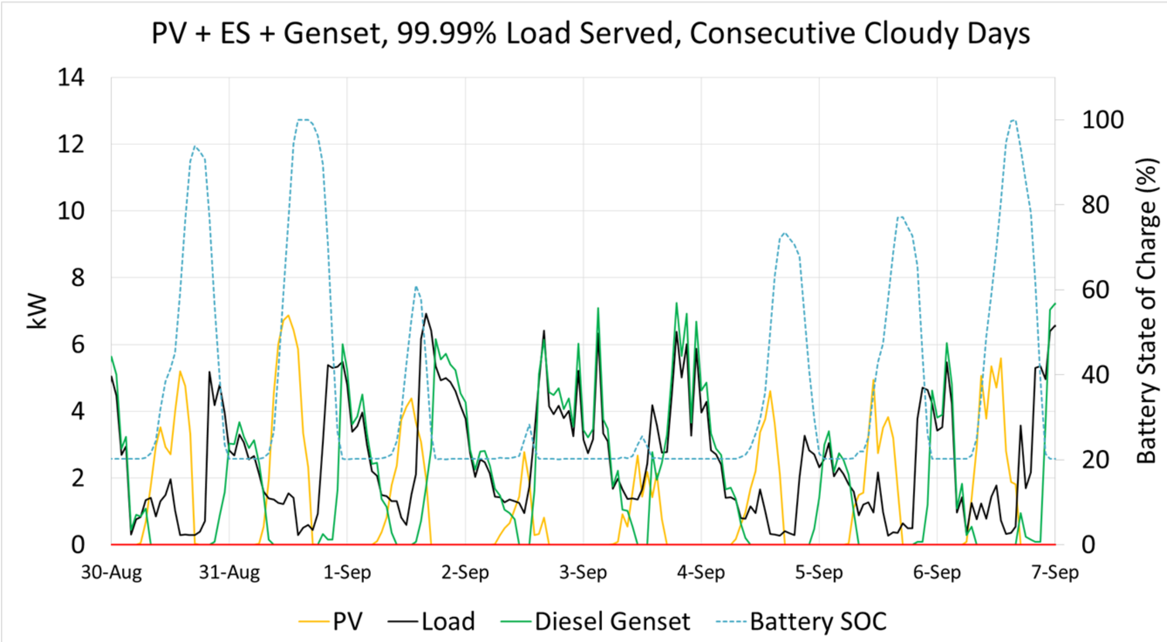

Figure 3-16
Dispatch of the Off-Grid System with PV, Storage, and Genset during a Representative Week

Environmental impact

Although adding a diesel generator to the off-grid system reduces cost to the consumer, it also affects the environmental footprint. Table 3-10 compares the emissions of the off-grid system (including a diesel generator) to the average emissions from the generation mix in Alabama as of 2014. The grid in Alabama in 2014 is reasonably representative of generation across the U.S., with most energy produced from highly centralized generation based on thermal generation from fossil fuels. While only 38% of the energy produced by the off-grid system uses fossil fuel, it produces more emissions per kWh than the grid, nullifying the environmental benefit of installing renewables.

Table 3-10
Comparison of Emissions between Off-Grid Systems with PV, Storage, and Genset and the Electricity Grid

	PV + Storage + Genset	Electricity Grid (Alabama)[9]
Carbon Dioxide [kg/kWh]	0.51	0.45
Sulfur Dioxide [kg/kWh]	0.001	0.0009
Nitrogen Oxides [kg/kWh]	0.011	0.0004

It should also be noted that the genset discharges criteria pollutants (including sulfur dioxide, nitrogen oxides, and particulates) directly into the residential environment, while the emissions from centralized power plants typically occur far from residential areas.

[9] U.S. Energy Information Administration, www.eia.gov, retrieved 25 July, 2016. Data displayed is for 2014.

Furthermore, the emissions footprint of centralized generation has fallen consistently over the past decade, reflecting a shift away from coal generation towards natural gas and renewables. Assuming this shift continues, the emissions comparison between local fueled generators and centralized generation is likely to continue to favor the latter.

4
SUMMARY AND CONCLUSIONS

Residential consumers in the U.S. have access to relatively low-cost, reliable energy from the grid, making off-grid alternatives relatively unattractive. For a typical US single-family household, our analysis shows that installing PV and storage to go off-grid while maintaining 99.99% of load served would cost the individual customer about 10 times as much per kWh consumed than drawing power from the grid. For those customers ready to make significant lifestyle changes and willing to accept only 80% of their loads served, power from an off-grid system would still cost about 5 times more per kWh than drawing power from the network.

The installation of an off-grid system also represents a relatively inefficient approach to power generation. Because of the variable nature of solar energy, a solar + storage system designed to operate off-grid must be significantly oversized to meet the energy requirements of the household. Off-grid systems must also be significantly oversized to provide for services that are presently provided by the grid, including reliability, startup power and voltage quality. The off-grid costs presented in this study account for sizing systems so they can properly deliver these services critical to powering consumer loads.

The oversizing of the off-grid system results in the spillage of significant amounts of energy during peak generation times, even as load goes unmet at other times. The spillage is particularly large if the consumer requires a level of power availability similar to that provided by the grid. The analysis found that, for a system sized to serve 99.99% of the load, more than 2/3 of the solar energy generation potential is wasted to spillage. The analysis further found that, for the sellback rates examined ($0.04 to $0.12/kWh), the consumer would actually economically benefit from reconnecting to the grid and selling the excess electricity, even after paying for a substantial one-time interconnection fee and a fixed grid maintenance cost of $40/month. This suggests that those consumers who are willing to invest in such large solar + storage systems would also choose to remain grid connected to take advantage of the opportunity to sell excess power to other consumers.

Several strategies can be considered to decrease the cost of going off-grid, including load deferral, and installing a diesel generator. We find that adding the ability to defer loads makes little to no impact on the size of PV, but does have an impact on storage sizing. The residential appliances considered for load deferral in this study include dishwasher, washing machine and dryer. Our results show that load deferral can lead to a decrease in system cost up to 12%, mostly due to a smaller storage size required.

Adding a diesel generator results in a path to significantly improve power availability to the off-grid consumer while holding down the cost of the overall system. The cost of PV + storage + genset with 99.97% load served is similar to the cost of PV + storage with 80% load served. On a $/kWh basis, this is still several times as expensive as purchasing power from the grid. Furthermore, operating a genset generates a significant amount of carbon and criteria pollutants emissions, effectively nullifying the environmental benefit of installing renewables.

Future research could extend the analysis presented in this report in several directions:

- The present analysis was performed for a single location (Montgomery, Alabama) with electric rates and solar insolation levels reasonably representative of locations in the developed world. The analysis can be repeated for a broader range of locations to examine the impact of different solar resources, load shapes, and rate structures.
- The present analysis was performed assuming that there are no more than 4 consecutive days without sun during a given year. The impact of consecutive overcast days on the off-grid system could be more systematically studied. In particular, locations with fewer than 4 consecutive days without sun may be able to work with significantly less storage, allowing for a smaller and more inexpensive off-grid system.
- The use of more complex load deferral strategies may also enable somewhat smaller off-grid systems, although this approach can be expected to have diminishing returns. This approach requires the availability of finer datasets measuring consumption patterns of schedulable loads.
- The analysis looks only at the availability of solar resource, ignoring the possibility of equipment failure. Future analyses could take into account the reliability of the solar and storage equipment itself, which in reality would be expected to be less than 100%.
- This analysis accounts for declining costs of solar and storage equipment in calculating replacement costs, but still assumes that the equipment is installed in the present day (2016). Future analyses could investigate the impact of lower equipment costs in the future, which would reduce the initial cost of the system but would also strengthen the case for export of excess electricity to the grid.
- The analysis ignores the environmental impact of the oversized systems required to go off-grid. While the environmental impacts of renewables, whether distributed or centralized, are generally significantly lower than the impacts of conventional generation sources, the inefficiencies resulting from the significant oversizing of off-grid systems will reduce the environmental savings on a $/kWh delivered basis.

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