Guidance for DoD Utilization of Host Nation Power

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Contents

1 Executive Summary

The Department of Defense (DoD) operates many bases outside the Contiguous United States (OCONUS). This study developed analytic tools that provided a quantitative model framework and qualitative considerations for determining whether OCONUS military bases should connect to the Host Nation power grid or remain isolated. Several cases involving bases of different sizes and in different regions of the world were then analyzed.

In every case, it was found that bases connected properly to Host Nation power grids and would reduce the cost of energy for those bases, reduce fuel usage (and the associated logistic challenges), and increase base endurance. This was true even in cases where the Host Nation power grid had very low reliability.

It is strongly recommended that every US military base consider using Host Nation power. For bases in the developing world, all military bases should maintain power generation capability that reliably meets their demand. Once that is in place, adding Host Nation power is similar to utilizing other sporadic sources, such as solar or wind energy. Because the cost of connecting the grid is usually relatively low, and the saved cost of fuel is high, money is saved without compromising reliability.

2 Background

2.1 Motivation

The Department of Defense (DoD) operates a significant number of bases outside of the Continental United States (CONUS) in cooperation with the local host nation. Each base relies heavily on electrical power to accomplish their mission, providing power to sensors, computing equipment, force protection systems, and convenience loads. In countries with poor electrical system reliability the power for these bases are typically provided by diesel generators with the fuel either purchased from the local population or transported from remote fuel depots. This incurs a significant cost for the DoD with many bases paying several multiples of the cost of electricity from the local grid, and introduces an additional vulnerability with the transport of fuel.

While in many situations the host nation electrical grid is highly unreliable, this does not necessarily mean the most reliable and cost effective solution is an entirely off grid solution. In these instances, the host nation grid should be considered in much the same way as an intermittent renewable resource is treated. In fact, even the most unreliable host nation grids almost always have a higher availability than solar PV, which has at best a 30% capacity factor. For installations interconnected to unreliable grids, backup diesel generation would be used to provide power during grid outages. The host nation power does not, therefore, remove the cost of having dedicated diesel generators. However, it will offset much of the fuel required and some of the maintenance cost of the on-base generation.

Reduced fuel consumption has very positive cost and cost prediction implications. This includes not only the direct cost of fuel, but for the logistics tail as well. In some parts of the world, the reduction of fuel consumption also leads directly to saving lives of US military personnel who transport or guard fuel convoys.

2.2 Scope of Study

This study is focused on assessing the quantitative and qualitative benefits and associated costs of using host nation (HN) power. HN power is just one of several energy alternatives, such as renewables like solar or wind, but those alternatives are not considered within the scope of this study.

The objective is to provide guidelines and recommendations on when the DoD should consider connecting an OCONUS base to the HN power grid. This could be in regards to an existing base making upgrades, designing a master plan for a new base, or even during negotiations with a potential host nation.

This study only considers existing technology, and so it focuses the comparison solely on architecture alternatives. Specifically, the architecture decision is whether to connect host nation power or not. This study did not assess new technologies.

This study examined four installations in detail: Soto Cano Air Base in Honduras, Puerto Castilla in Honduras, a proposed base in Agadez, Niger, and a special operations facility in Ouagadougou, Burkina Faso. These sites are of different sizes and have very different Host Nation and regional conditions.

Along with the findings and recommendations (in Sections 3 and 4, respectively), this report also includes four important supporting sections. Section 5 provides a full description of the dynamic simulation model used to generate the results presented in the paper. Section 6 presents the four detailed case studies of different OCONUS bases. Section 7 derives and shows example applications of a simple, yet powerful equation that can provide an initial assessment of whether to use HN power. Finally, Section 8 provides questionnaires that can be used to conduct more rigorous site-specific assessments of whether HN power should be utilized.

3 Key Findings

Three elements of guidance are provided in this report. First, a simplified model bounds the general problem space. Second, an analytic model helps quantify the cost-benefit tradeoffs of different energy system options. This model can also provide sensitivity analysis to see how changes in future conditions, such as fuel costs or HN electricity costs or reliability improvements or degradation, could impact future energy systems needs or requirements. Finally, it provides some general qualitative considerations which may impact the decision to use HN power or not.

3.1 Bounding the Trade Space

3.1.1 Cost Model

There are several critical parameters that will most greatly impact the decision of whether a military base should use HN power. These are related in the Simplified Host Nation Power (SHP) Equation, which was derived as part of this study:

$$C_E = \frac{cf}{\eta \times K_{diesel}} - \frac{\Delta I/_L}{P \times R \times 8760}$$

Where:

- C_E is the price of electricity from the grid (\$/kWh).
- cf is the cost of fuel delivered to the base (\$/gal). This should be the fully burdened cost, if it is known.
- η is the average annual efficiency of the on-base generators. For modern prime power generators, this is often 32%-35%.
- K is the higher heating value of the fuel. For diesel fuel, this is usually taken as 40.737 kWh/gal.
- ΔI is the cost of adding a connection to the HN power grid (including wires, transformers, etc.)
- L is the average power load of the base (kW).
- P is the desired payback period, in years. This should be the shortest of the life of the base, the life of the equipment, or investment guidance from the DoD.
- R is the reliability of the HN power grid as a percentage. For example, it can be calculated by taking the SAIDI value (usually given in minutes) and dividing it by the number of minutes in the year.
- 8,760 is the number of hours per year (conversion factor).

The resulting relationship is shown in Figure 1. This figure indicates the general threshold of when to consider using HN power: any base that falls below the line should strongly consider using HN power. Of course, this threshold depends upon the several parameters listed in the legend. One can enter site-specific parameter values into the SHP Equation, and verify their own threshold point. Even when using specific inputs, this relationship makes several simplifying approximations. It was found that the SHP Equation provides estimates within 10% of estimates calculated by higher fidelity models.

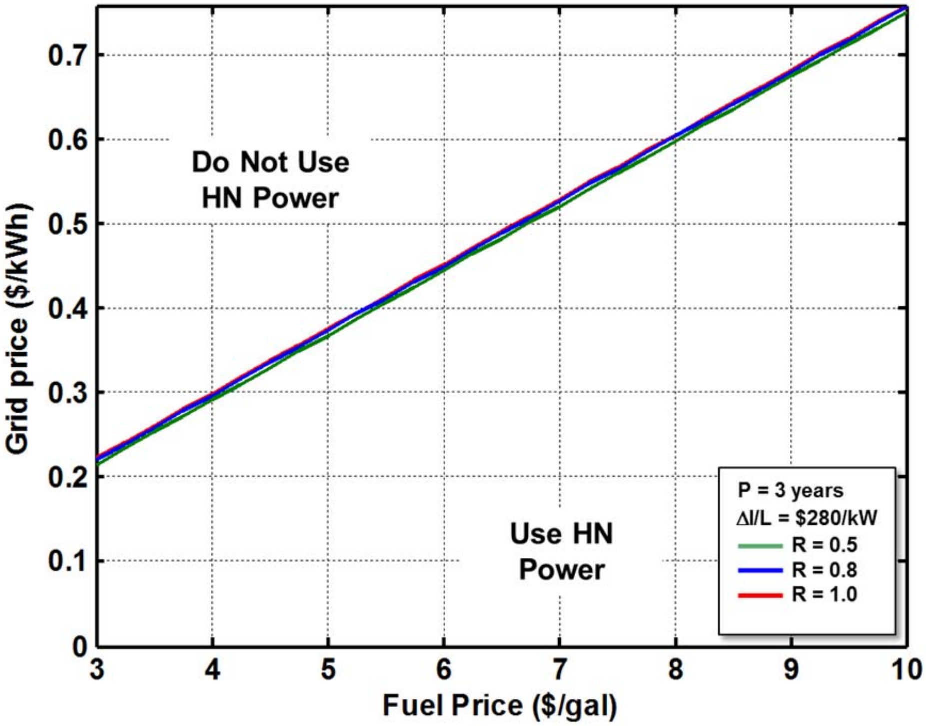


Figure 1: HN Power Threshold (SHP Equation)

For most parts of the developing world, diesel fuel costs more than $3/gal. If US military transport of the fuel is required, the cost quickly rises. Electricity in the developing world is often less than $0.25/kWh. Most locations in the world are below the threshold, and should consider using HN power.

The cost to interconnect with the grid in Figure 1 was assumed to be $280/kW; this is a conservative estimate. The parametric cost of a substation is listed at $225/kW in UFC 3-701-01 [1] but the higher cost assumption provides margin for engineering, foreign locations, and unforeseen contingencies. Even with a higher cost for an interconnection, the threshold is primarily set by the fuel cost and the engine efficiency. The second term in the SHP Equation as shown is very small compared to the fuel cost, making it weakly dependent upon payback period, reliability, or the investment-to-load ratio.

The derivation of the SHP Equation and several other example applications are shown in Section 7.

3.1.2 Fuel Savings Model

During some operational missions, cost is not a strong consideration; rather, the amount of fuel that must be transported to the base is much more important, especially in remote and/or dangerous locations with an extensive and exposed logistic tail.

The SHP Equation relationships also help estimate fuel saved by using the HN grid (see Section 7.4). The percentage of fuel saved is essentially the same as the reliability. So if a Host Nation power grid is 90% reliable, then the fuel usage is reduced by 90%. The models and analysis confirm this intuitive and perhaps obvious relationship. Note that this relationship assumes the average efficiency of the generators remains the same; the effects of breaking this assumption are seen in the Agadez Option 1 case presented later in Table 1.

Consider an example location, where the power goes out on an average of 6 hours every single day, all year round. This would be by any standard a very low reliability grid. Nevertheless, it is still 75% reliable. If a base were to connect to this grid, it would save 75% of its fuel, or in other words, it would use only 25% as much fuel. This would also mean that resupply trips could be reduced by 75% as well, which could have a significant impact on base operations and support. This also means the base endurance is 4 times longer if there were a fuel disruption.

The average grid reliability, and therefore percent fuel saved, can be estimated by either SAIDI or MTBF statistics.

$$\text{Percent fuel savings} = \frac{SAIDI\ [\text{min}]}{525{,}600} \times 100 = \frac{MTBF_{grid}}{MTTR_{grid} + MTBF_{grid}} \times 100$$

3.2 Model Results

A higher fidelity model, the Host Nation Power Analysis Tool (HPAT), was developed as part of this study. To run the tool, more detailed information about the base, the HN power, the generators, and other backup power devices is required. HPAT then uses this information in a dynamic Monte Carlo simulation and calculates several metrics. HPAT is capable of simulating a wide variety of architectures, including different generators, battery options, and operating procedures. For this study, HPAT was used primarily to examine the difference made by connecting a base to the HN power grid or keeping it isolated; all other options (such as number and type of generators) were kept constant. HPAT is described in detail in Section 5.

HPAT creates a dashboard to compare several metrics of interest, presenting the comparison in a way that is useful to different stakeholders. For a financial planner putting together a cost proposal the dashboard includes key metrics such as lifecycle cost (LCC), savings-to-investment ratio (SIR), payback period and annual cost. Whereas for an operational commander primarily focused on capabilities the dashboard includes comparisons based on endurance, unmet demand, and critical failures per year.

For this study, a fairly detailed study was performed for a 600-person, 3.6 MW base (average load was about 2 MW). Figure 2 shows the dashboard for this case.

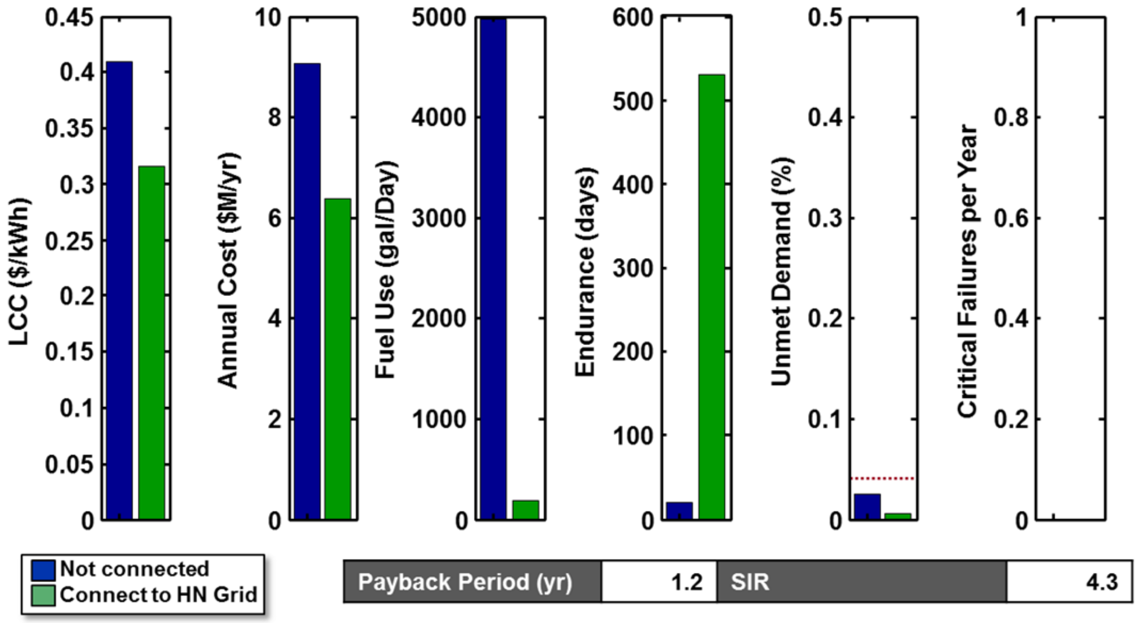


Figure 2: 600-person Base HN Power Analysis Dashboard

These results depend upon many parameters; the leading parameters are listed in Section 6.1, which provides the full analysis. However, two of the leading parameters are the cost of fuel and the price of electricity from the grid. Not only are these dominant terms, they are also in some ways the most uncertain and likely to change over the life of the base. Figure 3 shows a two-dimensional sensitivity analysis to the fuel cost (shown on the horizontal axis) and the grid price (shown on the vertical axis). Payback period is used as the defining metric, which refers to the period in which the cost of connecting to the host nation pays for itself. As can be seen, diesel fuel would have to drop below $3/gal, or electricity rise above $0.30/kWh before the grid connection would not pay for itself.

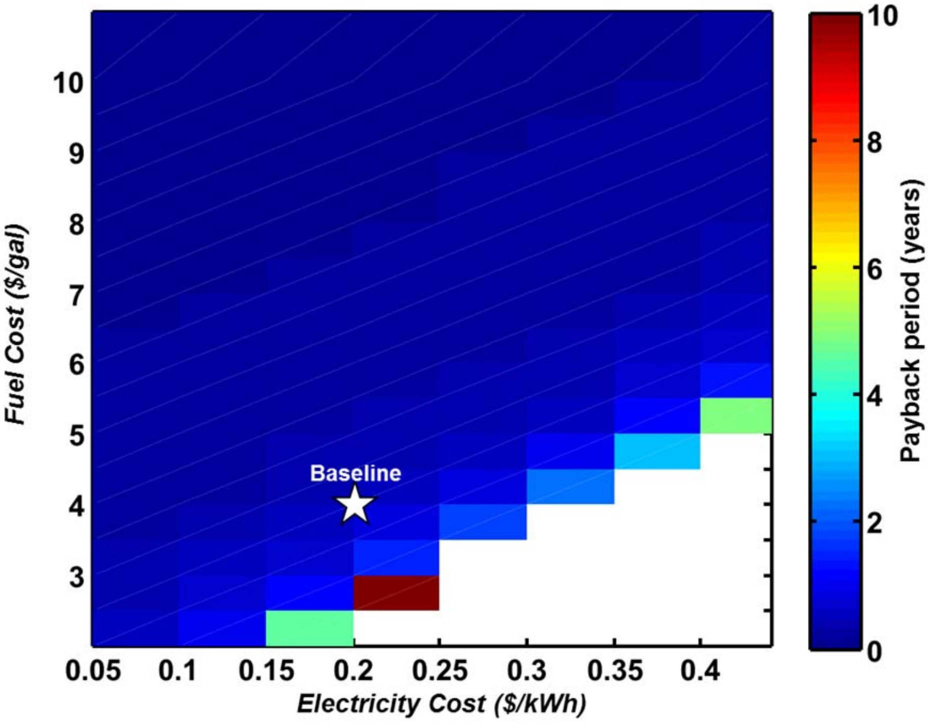


Figure 3: Sensitivity of Payback to Fuel and Grid (600-person base)

Four different scenarios were modeled and analyzed; in every case HN power provided substantial savings. The performance changes made by using HN power for each scenario are summarized in Table 1. Each of these scenarios is presented in more detail in Section 6.

Table 1: Performance Summary of Case Studies

Scenario	LCC Reduction	Annual Cost Savings	Fuel Saved	Change in Unmet Demand
Soto Cano[1]	24%	30%	96%	-75%
Puerto Castilla	5%	23%	67%	64%
Agadez (Option 1)[2]	34%	41%	75%	860%
Agadez (Option 2)[3]	26%	32%	66%	-95%
Burkina Faso	21%	29%	66%	18%

Notes:
[1] 5 MW grid connection, not including re-routing of transmission power or expanding power capacity.
[2] Starting and stopping generators with every power interruption
[3] Keeping generators on at all times, even when grid used.

For Agadez, two cases were considered. In Option 1, the generators were turned off when host nation power was available, and in Option 2, at least one generator was left idling. Because the generators in this scenario had a higher likelihood of failure during startup, there was a significant increase in generator failures when constantly turning on and off. This was alleviated by keeping the generator on, though that came at the cost of using more fuel.

In the case of Soto Cano and in Agadez Option 2, the unmet demand fell (improved) when using Host Nation power; this is because of the great reduction overall in the runtime of the generators.

The results of this analysis show that for many DoD installations connecting to the host nation grid with backup diesel generation on site provides reliable power at the lowest cost. Only at the most remote installations, or for small sites with high interconnection costs, does it not make sense to use host nation power.

3.3 Qualitative Considerations

The electric power reliability in a Host Nation is generally based on the Host Nation's governmental capacity and interest and economic ability to 1) maintain and effectively operate an electric grid to meet urban, industrial, and rural energy demands, 2) expand the existing electric grid to address changing local or regional power needs, and 3) maintain the security of the electric grid from unintentional outages or malevolent attacks. In most developed nations, where both the economic ability and government capacity exists, the electric grids generally have higher reliability. On the other hand, many developing countries often lack the economic ability or the governmental capacity to construct and maintain their electric grid, which often leads to a lower reliability of electricity. This is especially true of nations experiencing internal political and social unrest.

Even with lower reliability, the previous sections show that there is a cost advantage to include HN power in a base's energy architecture. However, there are also several other factors which are more difficult to quantify, which are discussed below.

3.3.1 Mission Assurance Energy Needs

As noted, mission critical energy demands often are only 15-25% of the average base energy demand. That means that up to about 80% of base energy demand is interruptible without having a major impact on mission performance. Since all bases include some level of on-site backup generation capability, better integration, coordination, and maintenance of these assets with the host nation power system could support higher overall power reliability to mission critical operations. If desired for cost reasons, one option would be to leave non-critical loads only on HN power. Therefore, quantifying three tiers of energy demand and reliability/availability needs, such as mission critical, priority, and non-priority can provide energy system performance goals and objectives. This then allows various options and combinations of on-site power generation operation, maintenance, and improvements with host nation power generation, maintenance, and improvements to be evaluated related to overall mission assurance, mission sustainment, and cost effectiveness.

3.3.2 Local Grid Capacity and Capability

One of the major considerations is the local transmission and distribution system capacity. Transmission and distribution systems already at or near capacity of the existing power lines often experience increased power reliability issues with even small fluctuations in local power demand fluctuations. Local distribution grids that are at greater than 80% capacity would likely need to be considered for upgrades, or new feeders constructed to the installation to improve power availability and reliability. Distribution system upgrades, less than 40 kVA systems, are significantly less expensive and often easier to get approved than transmission system upgrades.

3.3.3 Host Nation Interest in Grid and Power Improvement

Many host nations have interest in local grid and power supply improvements. In these cases, there may be an opportunity to foster a better relationship between the US military and the host nation through capability-building projects focused on improving or expanding power grid capacity. Not only does the host nation benefit from shared costs for upgrading their grid, they often also appreciate an established, consistent customer who pays their bills.

Common interest in host nation capacity building especially makes sense where there is utility support for the project, where there is a close proximity to an existing substation so energy can be easily shared locally, and where the size of the generation being considered fits within the needs of the local community so that economies of scale of upgrades reduce overall costs.

3.3.4 Power Reliability/Availability Details

While initial approximations can be made using a single reliability number (e.g., 75%) for a HN grid, the final decisions and designs require a more thorough understanding of the nature of the reliability issues. For example, reliability issues caused by power generation capacity or transmission problems are much more difficult to address than local distribution system reliability issues that might be easy and inexpensive to fix. Also, the duration and frequency of power availability should be considered. In many cases, power outages in a host nation grid each day for 2-3 hours may be easy to manage from a mission assurance perspective, if critical mission power needs can be met by on-site generation and non-priority loads can be scheduled around those outages. More difficult to manage are very long duration outages, in terms of days, or outages that are sporadic and unpredictable. While more perplexing and a larger operational nuisance, these types of outages often can also be designed around when considered in conjunction with different tiers of energy demand and availability needs and on-site generation integration and optimization.

3.3.5 Grid Security

One of the more difficult factors to evaluate when considering the utilization of host nation power is a local or national government’s ability to maintain political and social stability, such that the likelihood of intentional attacks on the power grid and the associated power outages, are minimized. While this is less of a problem in developed countries, it can be a major concern in developing countries where many military operations are conducted.

To effectively evaluate this issue, some understanding of the regional and local power generation and distribution system is needed. Historically, local power generation and distribution systems are less likely to see this type of damage than are national energy transmission systems that are often more remote and unmonitored. Power transmission systems are also more difficult to repair than local distribution systems, which impacts the duration of the outage from an intentional event. An energy system that can connect to a local distribution system powered by a nearby power generation resource historically is the easiest to recover from an intentional event.

The inability to control or influence recovery of a host nation power grid, whether in a developed or developing country, suggests that the base energy plan should always include on-site energy generation and energy storage resources integrated in a way that can support an extended power outage from either an intentional, accidental, or natural disaster type event. In some developing regions, power outages of 5-10 days may be common, so a final base energy design should consider mission assurance and mission projection requirements in developing an operational energy strategy. In most cases, including host nation power as a part of that strategy can be appropriate and cost effective if there is a reasonable recovery plan and resources managed by the local utility.

4 Recommendations

4.1 Use the Grid

Host Nation power should be strongly considered for OCONUS bases, even in areas where the power grid may be very unreliable. All indications from this analysis are that almost all OCONUS bases would benefit from connecting to the grid. These benefits include financial (saving money) as well as improved security (by reducing the amount of fuel being transported to the base, and the endurance of the base if that fuel chain is disrupted).

During several interviews over the course of this study, expert stakeholders remarked that their concern about using HN power was reliability. HN power should be thought of differently than this.

It is recommended, and should always be the case, that every OCONUS base in the developing world should have on-base generation capability that can meet their full power demand. Once that is in place, a connection to the HN grid will only improve overall energy accessibility by providing a second channel beyond just the fuel supply. In this way, HN power is like other intermittent sources such as solar or wind power. HN power should not be thought of as a replacement for traditional on-base generation, but an augmentation.

4.2 Setting a Budget

One of the key factors in determining whether to use HN power at a specific site is how much the interconnection costs. The SHP Equation can provide an initial estimate for an acceptable budget threshold. One can define a parametric relationship, the investment-to-load ratio (ILR), which sets the upper threshold for the cost of the interconnection as a function of the base size. ILR can be estimated with the SHP Equation as:

$$ILR = \frac{\Delta I}{L} = P \times R \times 8760 \times \left(\frac{cf}{\eta K_{diesel}} - C_E\right)$$

The units of ILR are dollars per kilowatt.

Figure 4 illustrates ILR. In this case, ILR is plotted against the cost of fuel, another major factor with great uncertainty. Observe the solid red line at the top. This represents the ILR threshold if the grid reliability was 100% (no failures), electricity was $0.10/kWh, and there was a required payback period of 3 years. In these conditions, the red line indicates the maximum that should be spent on connecting to the grid, per watt of load capacity. So if fuel cost $4/gal, then the maximum cost would be $6/W. So a connecting a small base with a 200 kW average demand load would pay back within 3 years even if costs were up to $1.2M. Likewise, a large base with 20 MW average demand would pay back within 3 years even if costs were up to $120M.

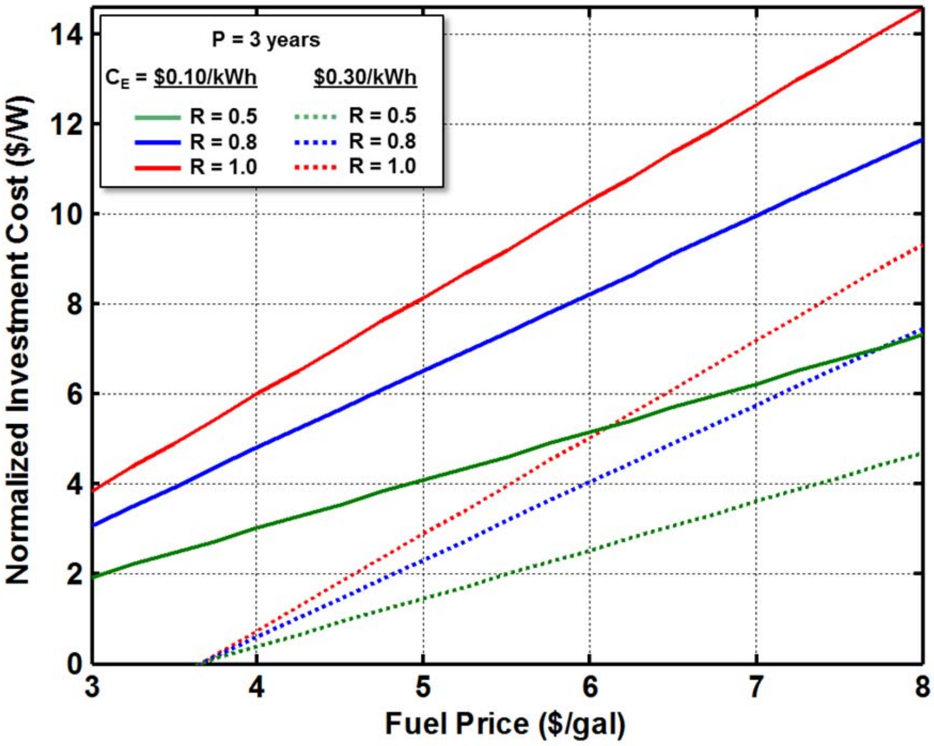


Figure 4: ILR versus Fuel Price – SHP Equation

The lines represent boundaries—any cost below the line is acceptable, any cost above the line is not.

The investment to connect to the grid will include two primary components. The first is transformers and switchgear on the base and the feeder at the HN interconnect site; these costs will typically scale with the size of the base. The second is the wires required to go from the grid to the base; while these costs scale some with the power capacity, they also scale with distance. The ILR illustrates that the first component which is variable will scale well—a larger base can afford a higher connection cost. However, distance does not scale well. Therefore, smaller bases will have a shorter distance at which they can be placed from the nearest grid connection point.

4.3 Implementation

For bases that do connect to the grid, the connection must be designed to "do no harm." Specifically, the connection should include circuit breakers that allow full isolation (or "islanding") of the base from the grid. Redundancy should be used for the transformers and breakers. All connection equipment should be sized to accommodate future base growth, and perhaps surge capacity as well. Voltage regulation may also be added where necessary. Current and volt metering should be placed on the line from the HN grid, the on-base distribution feeders, and the generators.

Switchgear should be automated for rapid response to disturbances on the HN grid line. Furthermore, all generators should have automatic startup and switch-over capability. This is fairly standard for the larger bases, but should always be implemented. In some smaller facilities, a person would be sent to manually start a generator when the grid power failed—a process which could take several minutes. For unreliable grids, this can amount to unacceptable outage times, and will drive much more expensive UPS costs for any critical components.

All standards for safety and best engineering practices should be followed in design and construction of the connection point.

4.4 Additional Observations

There are some additional miscellaneous recommendations that also arose during the course of the study:

- Even very small bases (<150 personnel) can benefit from microgrids that centrally distribute power to multiple users, instead of spot generation for every load. Regardless of whether HN power is utilized, centralized distribution with microgrids should be used, at least among the larger and more critical loads. As an additional advantage, this will also make any future connection to HN power much more feasible.
- Ideally, all power generation contracts should be based on the run time of the generators, rather than a flat annual or monthly cost. Then, if HN power or other alternative renewable power sources are added, there is less financial penalty incurred by turning off the generators, and will increase the overall savings.
- All facilities should measure load and generation information more rigorously. This will help not only in making planning and investment decisions, but also in day-to-day energy management decisions, and will quickly pay back any instrumentation costs. Measuring fuel consumption and electric load are two of the leading factors in determining whether to use HN power.

- The questionnaires listed in Sections 8.1 and 8.2 should be used when assessing specific sites for HN power suitability.
- In the past, mobile and/or transportable transformers were developed and deployed by the military. Because every HN power grid is slightly different, these mobile units met with mixed success. However, given the high potential for HN power, it may be worth revisiting those designs, perhaps with a more modular or even just a partial solution.

4.5 Way Ahead

There are several possible ways to continue this work:

1. ***Deliver the HPAT model.*** Currently, HPAT exists in MATLAB, and is used by technical engineering staff at MIT LL. If desired, the tool could be written as either a stand-alone application (either as a downloaded package or as a web client), or could be incorporated into a larger energy system analysis modeling tool. This would require rewriting the MATLAB code into an executable package and developing an intuitive graphical user interface (GUI). Once completed, planners at combatant commands, the Pentagon, or services could use the tool for their own analysis.
2. ***Validate the HPAT model.*** One could select an existing base that is not connected to the HN grid. The load, fuel consumption, generator maintenance, and associated costs would be measured and recorded for a period of 3 to 6 months. During this time, a connection to the HN grid could be designed and built. Then, in addition to the previous data, electricity from the grid, reliability, and all associated O&M costs would be measured as well for another 3 to 6 months. This data would enable validation of the HPAT model, and lessons learned would likely help further improve the model as well.
3. ***More detailed base analyses.*** One could select more bases for analysis. Detailed cost, load, and reliability data would need to be gathered for the base. Adapting the model and analyzing performance is very simple and quick (within a week) once the data is gathered.
4. ***Broad survey of bases.*** One could gather high-level data from all of US OCONUS bases (number of personnel, approximate electric load, approximate fuel used, approximate distance to grid tie-in point), and assess potential for HN grid utility for all locations. Bases could be ranked by potential savings, and prioritized for funding grid connections.
5. ***Design an improved deployable grid interconnection system.*** Operational energy for rapidly fielded contingency bases could also benefit from using HN power. In these cases, mass and volume of the interconnection may be of greater importance than cost. With a design for such a deployable system, its value could then be assessed in simulation in comparison to mass and volume of fuel and generators. It may also provide guidance on placement of those bases in country.

The following sections are supporting material.

5 Analysis Description

5.1 Framework

Figure 5 illustrates the overall framework for this study. It begins with identifying the mission and operational environment; these will set requirements. This study only considers existing technology, and so it focuses the comparison solely on architecture alternatives. Specifically, the architecture decision is whether to connect host nation power or not.

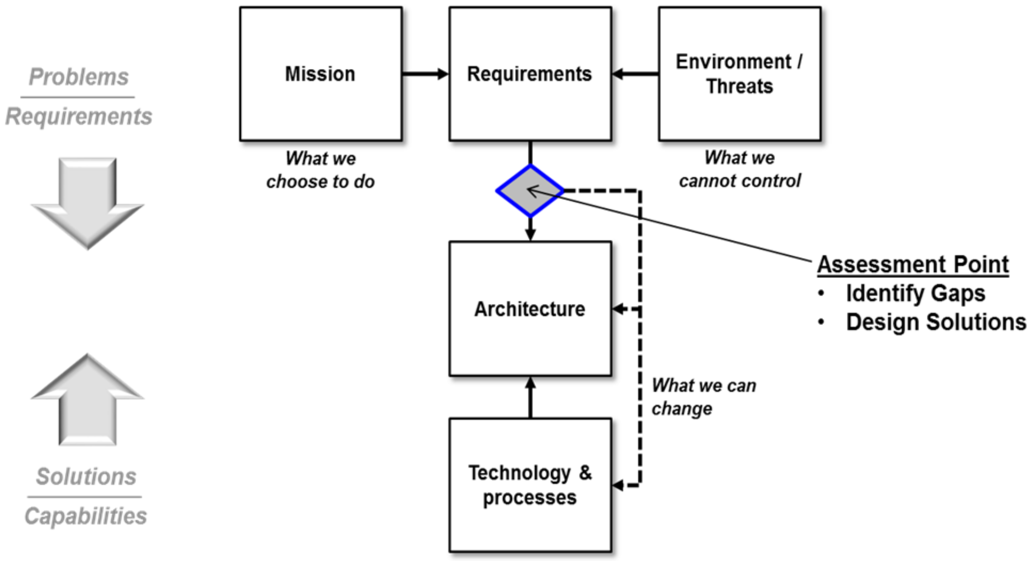


Figure 5: System Analysis Framework

To perform the assessments, an analytic model was built in MATLAB that quantifies reliability and cost of the alternative energy system architectures. It does so using Monte Carlo simulations of the demand and reliability of the generators and HN grid.

This section describes more fully the system analysis framework for this HN power study, as illustrated in Figure 5. Specifically, this section describes the mission, environment, and technologies assumed for this study.

5.1.1 Energy System Performance Objectives

The performance objectives of the energy system (i.e., the mission) are to provide reliable, sufficient, and affordable energy for all US OCONUS bases.

5.1.1.1 Attributes of Interest

The most important feature for any base energy system is sufficiency of energy and power. For this study, the first step is selecting components (generators, etc.) that can meet the required demand. It is especially important for the system to meet mission critical loads on the base. When comparing alternative architectures, it will be assumed that all power system implementations will be properly designed, installed, and maintained to meet best-practice safety.

Affordability is another critical component, which is very important in setting the long-term capacity for military operations. [2] Affordability is more than just direct fuel costs, but includes the full life-cycle cost of the energy system used by a base. Where it is known, the honest analysis should consider the fully burdened cost of fuel. Affordability in the broader perspective will also include man hours and logistics to install, maintain, and transport the energy equipment and fuel.

Another key factor is reliability. Reliability of the generators and the HN grid will be an important part of the energy system analysis. But reliability should be measured foremost with respect to critical mission function and support needs, and secondary interest with respect to non-critical or non-essential building or services reliability. This distinction is often a key consideration that can significantly impact the design of an energy system architecture and its associated costs. The threats to energy system reliability vary by region and can range from environmental, to system generation capacity, to intentional threats to both the HN and base power systems. Knowing the types, scale, and duration of these threats can impact the design of system architectures. For example, a HN grid that is out commonly 2-3 hours per day may be easier to address than a HN grid that is out less often but for extended periods. One might be more of a nuisance, while the other could have severe consequences.

While sustainability is not a focus of this report, it could be an important additional factor. In many locations in the world, power on the HN grid is supplied from alternative energy sources that have less greenhouse gas emissions than diesel; these include most commonly nuclear power, natural gas, and hydroelectric power (and wind and solar are growing). If sustainability is an important objective, that would be another reason to consider using HN power provided by these energy sources.

5.1.1.2 Metrics

Metrics should be used that provide insight for the different attributes of energy security. For this study, the primary attributes will be sufficiency, reliability, and affordability. The metrics that utilized for this study are:

- Energy generated [kWh]
- Maximum power generated [kW]
- Fuel used [gal/year]
- Amount of electricity from the grid [kWh/year]
- Percent of demand unmet [%]
- Number of failures per year when critical demand was not met [number per year]
- Life cycle cost (LCC) [$/kWh]
- Payback period [years]

- Savings-investment ratio (SIR) [dimensionless]
- Annual costs [$/year]
- Base endurance [days]

5.1.1.3 DoD Base Characteristics

The US military has a broad range of OCONUS bases, ranging from very large, long-term bases (e.g., Ramstein Air Base in Germany), to very small, contingency bases (e.g., Burkina Faso House operated in AFRICOM). Though conditions and considerations will vary greatly depending on size, mission, and location, HN power should be at least considered for any OCONUS base.

Typically, the electric demand (also referred to as the “load”) will scale proportionally with the size of the base. A base with 200 personnel may consume on the order of 200 kW average, while a large base of 5,000 personnel may consume 7.5 MW average. Care must be taken though; quite often a base will host a number of civilian or host nation buildings or activities which may also increase the demand beyond just the military personnel.

The decision whether to connect to HN power can take place under different base conditions (see Figure 6). Broadly, the decision could be made during planning of a new base or facility (a so-called “green field” project). It could take place for a small base where all loads are met with spot generation. In this case, not only would interconnect equipment need to be supplied, but also centralized distribution wiring and equipment as well. Finally, HN power could also be added to bases which already have a centralized generation and distribution system. In this case, only interconnect equipment would be required. In all cases, it would be assumed that the HN power would be connected to a base-wide distribution system.

Furthermore, it is assumed that the base would continue to maintain generators for backup as shown in Figure 6. Depending upon the HN grid reliability, the load criticality, and costs, that backup generation could be for the whole base (centralized generation) or just for mission-critical elements on the base (spot or limited microgrid). This decision may depend upon the current state of the base.

When actual data is not available, one can use a couple of “rules of thumb” regarding base loads. The maximum power draw is often about two times the average load level. The critical loads are often about one half to one third the average load.

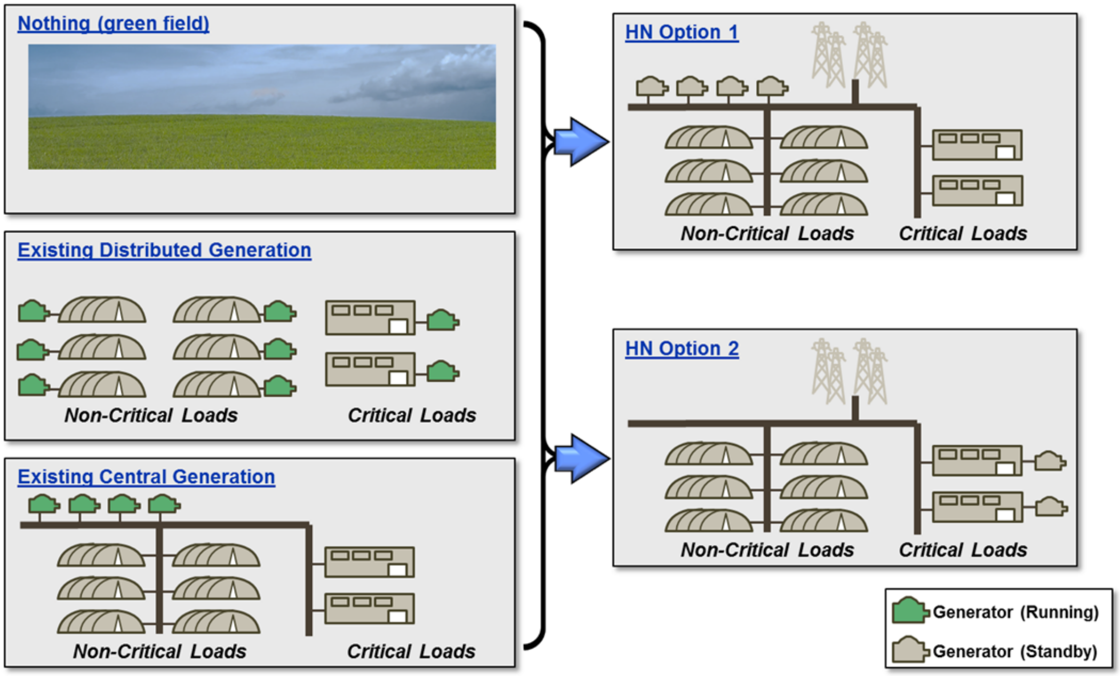


Figure 6: Different initial base conditions impact HN power connection decision

5.1.2 Host Nation Operational Environment

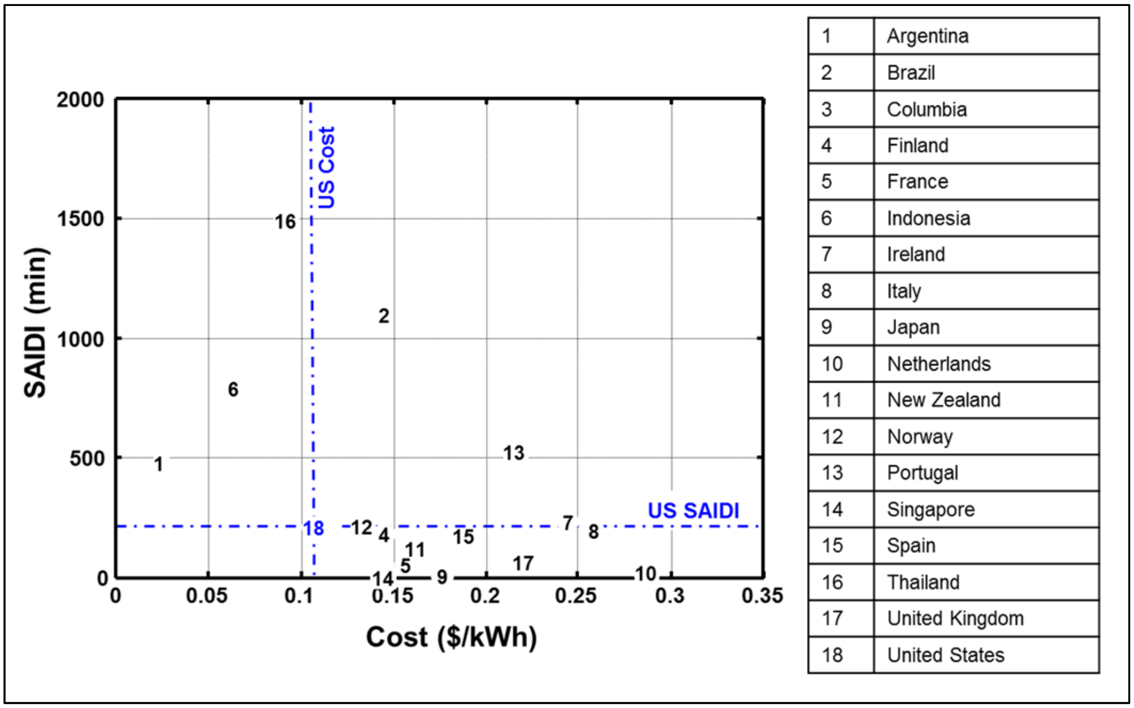
The next element of the analysis framework is the operational environment. For the purpose of this study, the key environment factor is the state of the HN power grid.

There are several metrics used to represent reliability. [3] Two important metrics are:

- **SAIFI** — System Average Interruption Frequency Index; the total number of customers interrupted, divided by the total number of customer over a given time period.
- **SAIDI** — System Average Interruption Duration Index; the total duration of interruption for the average customer, during a given time period.

These metrics are both typically presented in minutes per year.

Power reliability varies greatly around the world. Figure 7 shows SAIDI versus average electricity price for a selection of different countries around the world. Note that there is a rough correlation between price and reliability; generally one pays more for higher reliability.



1	Argentina
2	Brazil
3	Columbia
4	Finland
5	France
6	Indonesia
7	Ireland
8	Italy
9	Japan
10	Netherlands
11	New Zealand
12	Norway
13	Portugal
14	Singapore
15	Spain
16	Thailand
17	United Kingdom
18	United States

Figure 7: International SAIDI versus Cost Examples

This data only provides examples of national averages. Costs can vary across countries (the United States being a strong example, with prices varying from $0.07 to $0.30+ depending upon location). Reliability can also be highly variable across a single country. In Honduras for example, the power is very reliable around the capital Tegucigalpa with only very short outages once every couple of months, while in the more rural areas there will be 3 to 4 outages every week, often lasting more than 12 hours at a time.

5.1.3 Technology and Energy Architectures

5.1.3.1 Possible Energy Architectures

Architectures can be viewed at different levels. There is the level of planning actual electric lines, transformers, switch gear, and so forth. However, this study focuses on a higher level, a “strategic approach” level of architecture. This level asks how many generators, whether the base connects to the host nation grid, whether there are batteries, and so forth.

Figure 8 illustrates cartoons of several different possible base power architectures. These are just examples, and for several cases, architectures not illustrated in Figure 8 are the preferred approach.

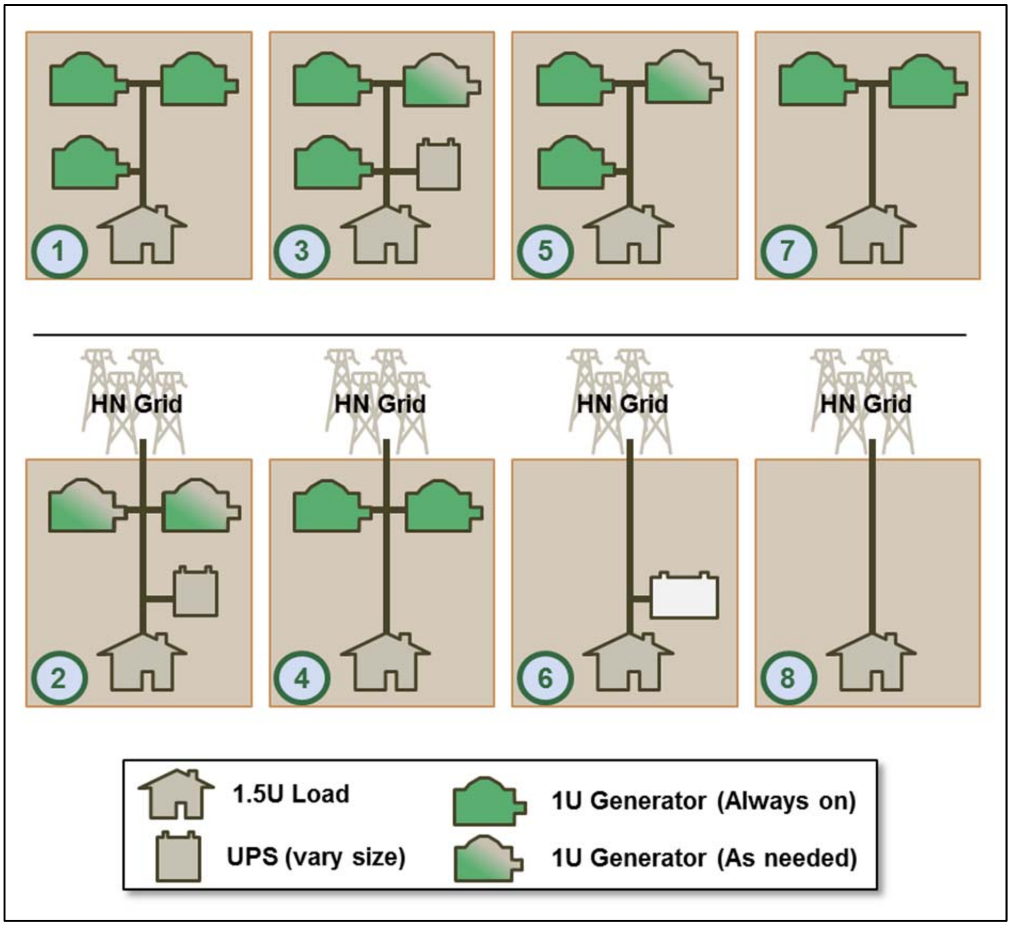


Figure 8: Examples of Candidate Power Architectures

This figure has 8 examples, roughly ordered by reliability (and also cost), with Architecture 1 being the most reliable, and Architecture 8 the least reliable. The odd numbered examples are variations with no connection to the grid; the even numbered include the HN grid. These are generic cases which could be scaled to any load value; so the "U" could be tens of kilowatts or a few megawatts.

Examples 1, 3, and 5 are all variations of "N+1" generator architectures. N refers to the number of generators required to meet the maximum load. "N+1" means that there are enough generators to meet the load plus one spare or standby generator as well. Example 7 only has N generators, so no spare, which will reduce overall reliability if there are any generator failures. Example 1 has all three generators running, so if one failed, there would be no gap in coverage whatsoever. If a generator fails in Example 5, there would be the potential of a gap in power while the standby generator starts up. In Example 3, there is a battery that would instantly provide power if one of the generators failed, and would be sized to meet the load until the next generator comes up to speed.

Modern sophisticated generators can typically come up from standby in one to three seconds, which tends to alleviate the need to ever use Example 1, and the battery in 3 becomes so small it is almost indistinguishable from 5.

Examples 2 and 4 assume that the load is usually using HN power, but has “N” generators for backup, either always running (4) or with a bridging battery backup (2). Example 6 assumes a large battery backup that would provide load during an outage in the HN power—this would typically only make sense if the outage durations were known to be short. Example 8 is what most residences in the US and Western Europe use; the grid is so reliable that there is no backup power option, and any outage is just a minor annoyance. Even in countries with highly reliable grids though, many critical loads (emergency responders, military, healthcare, etc.) will still have backup power as well.

5.1.3.2 Technology Components

This study only considered three components: HN grid, generators, and batteries. Each of these components will include any supporting equipment lumped into a single cost and reliability. The HN grid includes transformers, switchgear, wires (and poles), regulators, and metering as required to operate safely and efficiently. The generators also include transformers, wiring, and switches. The batteries include inverters, controllers, and wiring as well.

In all cases, purchase, installation, and maintenance will be assumed to meet DoD standards and best practices. Costs, performance, and reliability will be modeled based on these assumptions.

5.2 Quantitative Cost-Benefit Model

5.2.1 Overview

Figure 9 presents a flow chart of the HN Power Analysis Tool (HPAT) developed for this study. HPAT is currently coded in MATLAB. It runs a time-stepped Monte Carlo simulation, and configured to sweep across up to three different user parameters. Inputs allow alternative scenarios to be simulated, including different load profiles, different equipment, different architectures, and different cost parameters.

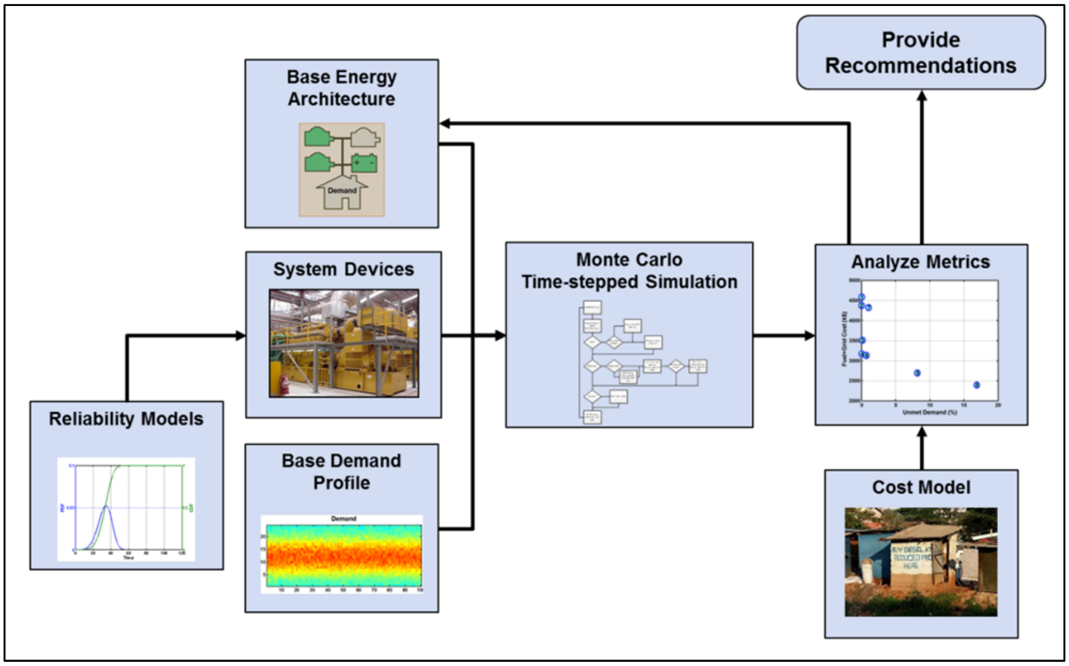


Figure 9: HN Power Analysis Tool (HPAT) Flowchart

5.2.2 Base Energy Architecture

In setting up the HPAT scenario, the user can supply a list of different architectures to assess. The same set of loads, grid outage profiles, and random number generator seed values for the generator reliability, are then used in the time-stepped simulation, but met with the different architecture, to provide a similar “apples-to-apples” comparison of performance, where conditions are held as constant as possible across the different architectures. See Section 5.1.3.1 for additional description of the architectures.

The parameters specified for each architecture are: generator type, number of generators, minimum number of generators running, battery type, battery number and/or capacity, and whether connected to the grid or not.

5.2.3 Base Demand Model

The demand at the base drives the energy system design. The demand can be modeled in several different ways. The most ideal is to get actual data from a base being analyzed. Hourly samples for one year are preferred, but any information can be extrapolated. The load can also be simulated; for purposes of study there were three simulated models: flat, alternating, and diurnal. Flat is a uniform, constant load across the entire simulation time. Alternating goes from max to zero at a specified periodicity. Diurnal is a sine curve, which can best represent the most realistic diurnal pattern. The average load and amplitude of swing can be input; the period is assumed 24 hours. Random noise can be added to all models (of user-specified magnitude). The first two simulated models are used just to define theoretical boundaries, for all actual tests, the diurnal load pattern was used.

Figure 10 shows a sample of a few days of simulated diurnal data. In this example, there is 5% random noise, with an average load of 1.5 MW and a normalized diurnal amplitude of 0.2.

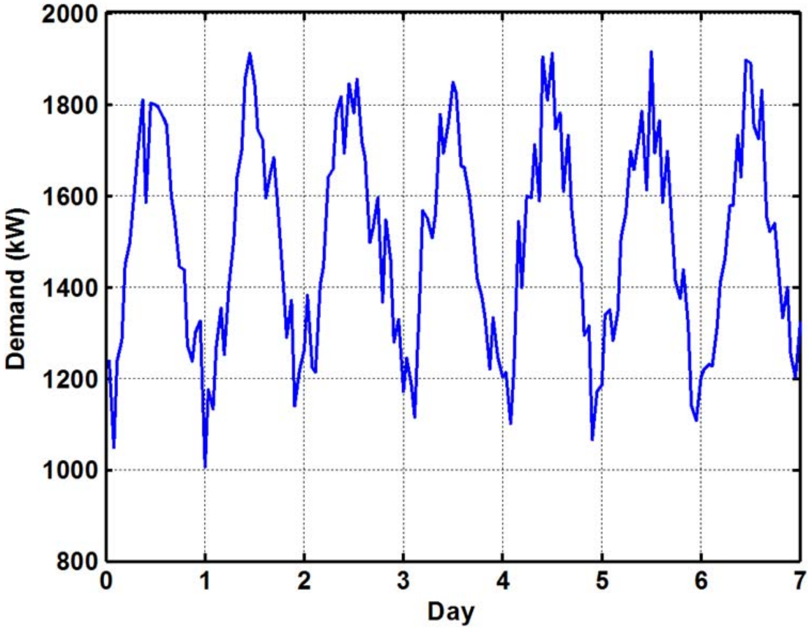


Figure 10: Base Electricity Demand (example)

Another way to view the demand is using an annual profile view. These plots show days of the year along the horizontal axis, and hours of the day on the vertical axis, with the color indicating the variable of interest—in this case the base power demand. This "annual profile" view is a useful view to observe seasonal and diurnal patterns, or just to gain a broad annual summary and will be used extensively in this report. Figure 11 shows the simulated demand for a full year.

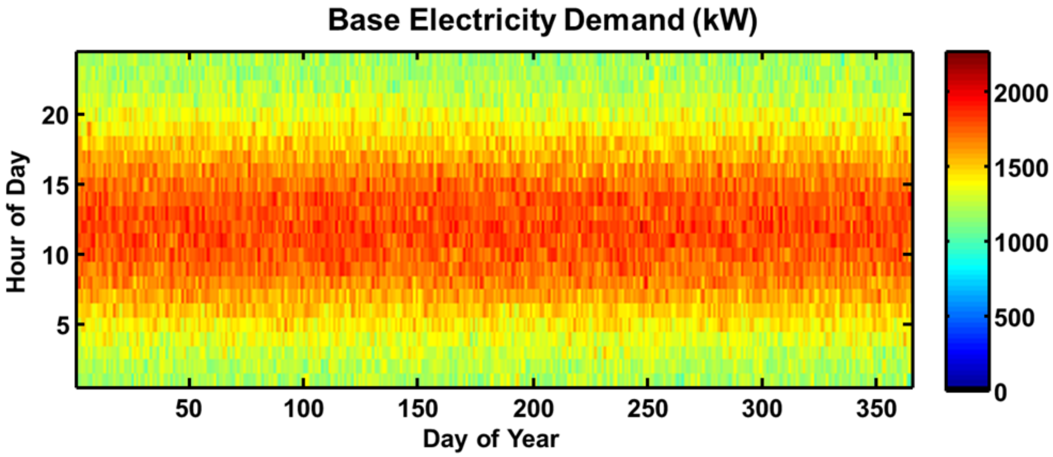


Figure 11: Annual View of Base Electricity Demand (example)

Another important metric that is tracked during simulations is how much of the "mission critical" load is met, beyond just whether the total load is met. Again, ideally, the mission critical load is provided by the base being studied. However, for cases where there is no actual data breaking out mission critical versus non-critical (sometimes called "shed" loads), there is a parameter called the "critical load factor", which sets how much of the total load is considered mission critical. This is an approximation determined by engineering expertise, and in many cases is approximately 50% of the average load.

5.2.4 Device Models

HPAT requires parameters to define the different technology components used in each architecture. These are stored in structured variables, which are then referenced throughout the simulation and analysis steps.

5.2.4.1 HN Grid

The HN grid model is defined by 6 parameters:

- **MTBF**— [hours] Mean time between failures, or the number of hours from when the grid starts running to when it fails, on average. This can be approximated from the SAIFI metric; however, in the case studies where official SAIDI values were not available, it can also be approximated from interviewing local residents. For example, if they say there is about one failure per month, that would be a MTBF of 720 hours.
- **MTTR**—[hours] Mean time to repair, or the number of hours from when the grid fails to when it is restored to service. This is very closely related to the SAIFI index; again, it can also be approximated from local observations.
- **Integration cost**—[$] this is the cost to integrate the base with the HN power grid. This includes any changes to the HN grid (including upgrades to the nearest substation, switches, and additional power lines running to the base) as well as changes of equipment on the base. This may include transformers, voltage or frequency regulators if necessary, and control and metering electronics. The cost should include equipment as well as installation labor costs.
- **Grid O&M cost**—[$/year] this is the annual cost to operate and maintain the grid connection. It may include things like servicing transformers, clearing tree limbs from wires, and so forth.
- **Base distribution cost**—[$] this is the cost to install a centralized distribution system across a base. It would include things like wires, poles, switchgear, transformers, etc.
- **Base distribution O&M cost**—[$/year] this is the annual cost to operate and maintain the base electric distribution system. It may include things like servicing transforms, clearing tree limbs, restoring power after storms, and so forth.

It is assumed that with the proper integration equipment, the power when available will meet all voltage and frequency requirements (e.g., no damaging spikes, or voltage sagging).

5.2.4.2 Batteries

The battery model is defined by 6 parameters:

- **Capacity**—[kWh] the energy capacity of the battery.
- **Efficiency**—[%] the round-trip efficiency of the battery including rectifiers and inverters.

- **MTBF**—[hours] the mean time between failures of the battery system. (Typically these values are far longer than the simulation duration, so nearly irrelevant).
- **MTTR**—[hours] the time to repair or replace the battery after failure.
- **Cost**—[$] the cost of the batteries to purchase and install.
- **O&M Cost**—[$/year] the annual cost per year to operate and maintain the batteries (not including the cost of electricity to recharge).

The battery model is fairly simple, and does not include decaying capacity over life. It is also possible to set different charge and discharge rates; the default setting was that the full battery capacity could be charged and discharged over a one hour time step.

5.2.4.3 Generators

The generators, as the primary energy provider and alternative to grid power, had a higher fidelity model. The generators were modeled with the following parameters:

- **Capacity**—[kW] The rated power capacity of the generator
- **Efficiency Curve**— this curve is generated based on model-specific data. It is a look-up table that relates the fuel consumption to the average load for that time step. The input is load in kW, the output is fuel used, in gallons (for diesel and JP8).
- **Cost**—[$] the purchase and installation cost for the generator.
- **O&M Cost**—[$/year] the annual cost to maintain the generator (does not include fuel).
- **MTBF**—[hours] the mean time between failures for the generator. This should correspond to the O&M cost. Note that this is calculated over runtime hours, so if a generator is only used sporadically, it would fail less frequently per year.
- **MTTR**—[hours] the mean time to restore service (repair or replace) after a failure.
- **Startup time**—[hours] the time to bring a generator fully online after alternative power source stops (this may be a grid outage or failure of another generator). Many modern generators have "autostart" capabilities, which reduce the startup time to well under one minute. In more austere conditions, it may take a person to detect a power outage, then go and manually start the generator, which could take many minutes.
- **Start Probability**—[%] Generators often fail during startup. Therefore, a separate probability of failure is modeled beyond just the MTBF, which checks each time the generator starts up.
- **Fuel type**—the type of fuel used; typically this will be diesel or JP-8 (for tactical generators). This is used to calculate efficiency as well as greenhouse gas emissions (if that is of interest).

Figure 12 shows example efficiency curves for three different generator models. First, it illustrates the importance of "right sizing" the generator for the expected load. To maximize efficiency, a generator should be sized as small as possible to still meet the maximum load. However, even with the same rated capacity generators (such as the "Model 1" and "Model 2" shown in Figure 12), different makes and models may have different efficiencies. Regardless of whether a base is connected to the grid or not, maximum efficiency is always important.

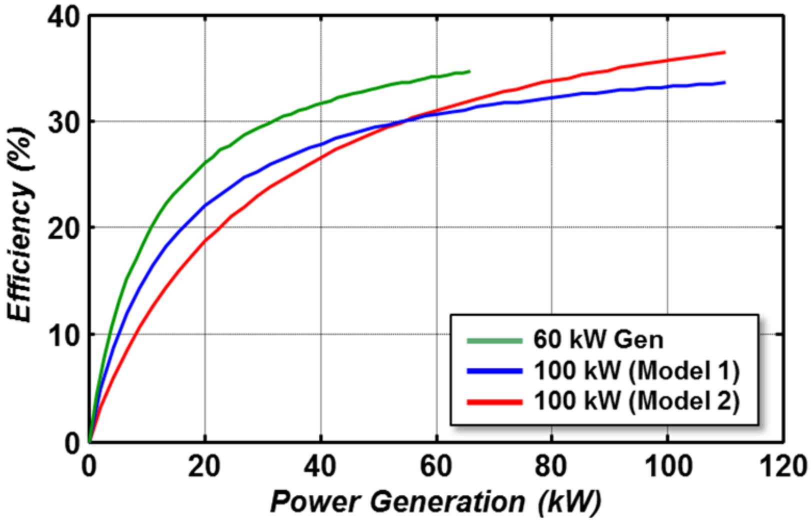


Figure 12: Example generator efficiency curves.

The non-linear nature of the efficiency curves also raises another question when running multiple generators on a common grid. Typically, there are two strategies for loading generators: even or optimal. In an "even" strategy, the load is distributed equally across the generators; this is always less efficient than the "optimal strategy" where as many generators as needed are run at full load, and only the last needed generator is run at a lower load. So for example, if 2 1-MW generators are used to provide a 1.5 MW load, it is more efficient to have one generator at 100% and the second at 50% (the "optimal case") than to run them both at 75% (the "even case"). Despite the efficiency improvement, it has been observed that more frequently generators on grids are loaded evenly, not optimally. Note also, that in almost all case though, centralized generators whether evenly or optimally loaded are still better than distributed "spot" generators.

HPAT will use these curves and a user selected loading strategy to calculate the number of generators used and the fuel used by those generators at each time step to meet the power demand. Figure 13 is an annual profile of the number of generators used in one simulation. In this example, the base experiences a fairly large diurnal swing, so during the day it has 3 generators on, and at night will sometimes reduce to a single generator. Note the two narrow blue lines where generator failures limited the available number of generators for use (see Section 5.2.5).

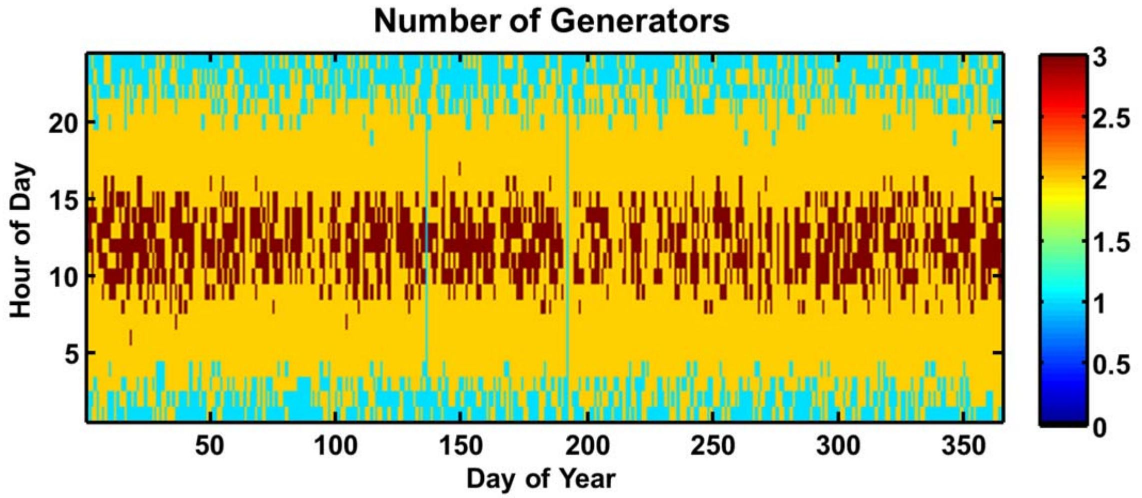


Figure 13: Number of generators used (example)

Figure 14 shows the corresponding fuel consumed by the generators at each time step. During peak hours, this example base is consuming over 160 gallons of diesel fuel per hour, dropping to around 50 gallons per hour at night.

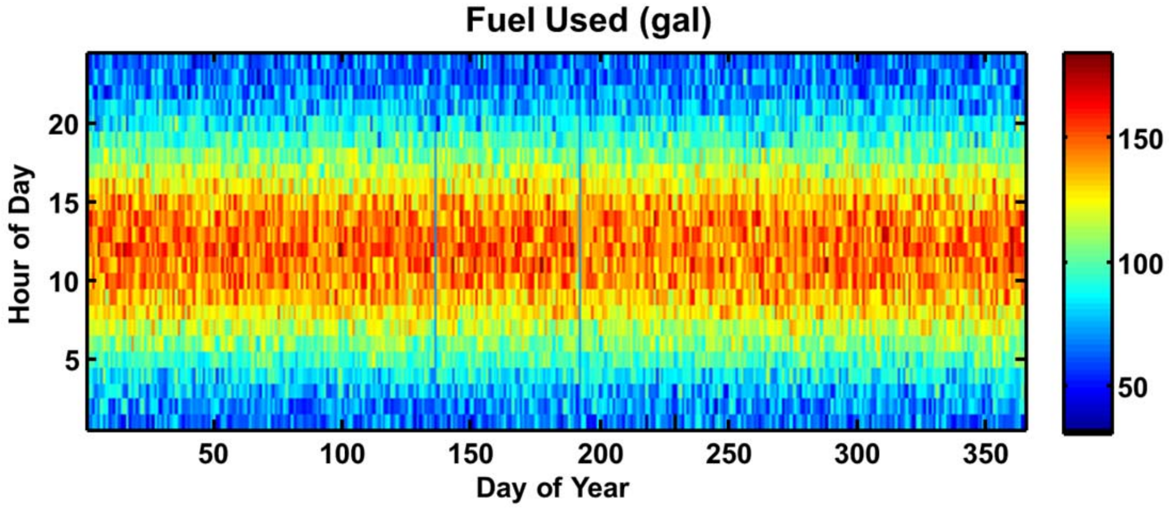


Figure 14: Gallons of Fuel Used (example)

Another parameter needed to calculate base endurance is the fuel storage capacity on the base (reported in gallons).

5.2.5 Reliability Model

Central to this study is the reliability of the HN grid, as well as the reliability of the generators. In accordance with IEEE standards and industry best practices, a Weibull distribution was used to model reliability of all components. [4]

The Weibull distribution provides a well-proven model for both the failure and repair of devices. Figure 15 shows the probability distribution function (PDF) and cumulative distribution function (CDF) of a Weibull distribution with shape of 3, and size of 24. This particular example was used from a simulation of a HN grid that failed on average once per day, i.e., its MTBF was 24 hours. The PDF curve shows that the highest likelihood of failure occurs around 24 hours; the CDF curve shows that there is about a 50% that the grid failed after 24 hours, however it has almost certainly failed by 40 hours. The shape of this curve and the sharpness of the PDF peak can all be modified by input parameters to the Weibull.

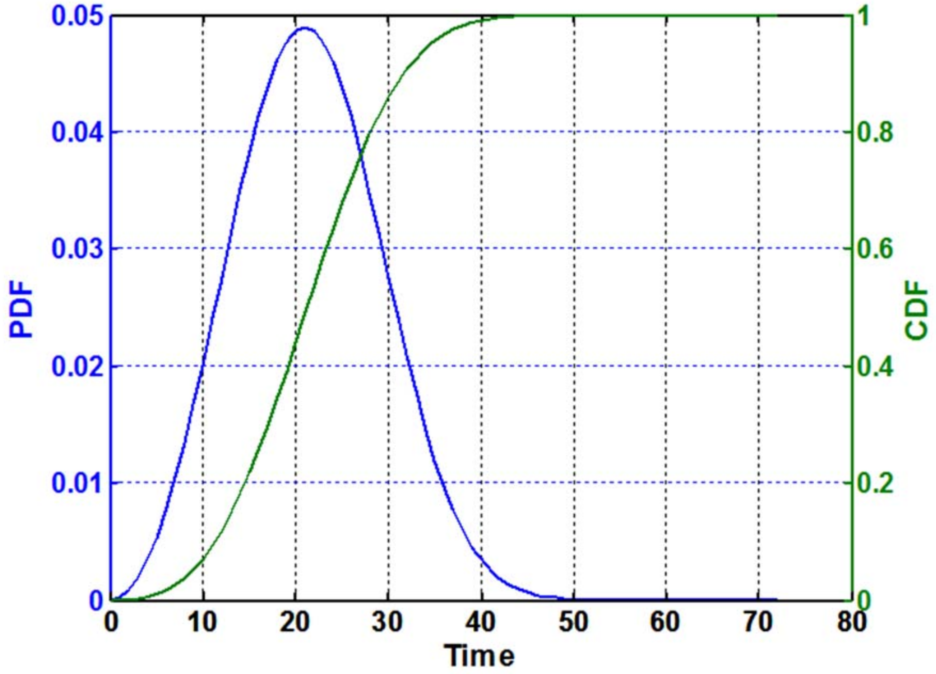


Figure 15: PDF and CDF of a Weibull Distribution (example of 24 hour MTBF)

During the simulation, the time of the next failure (or repair) is calculated by:

$$TTF = \beta\left(-\ln(1-x)^{1/\alpha}\right)$$

Where TTF is the time to the next failure, x is a uniform random number from 0 to 1, β is the sizing parameter (MTBF in this case), and α is the shaping parameter.

Figure 16 shows two examples of corresponding outages of a HN grid over a one year simulation. In Profile 1, it shows a grid with frequent, short outages—in this case the MTBF was 20 hours, and the MTTR was 4 hours. Profile 2 shows a grid with less frequent but longer outages—in this case MTBF of 30 days and a MTTR of 6 days.

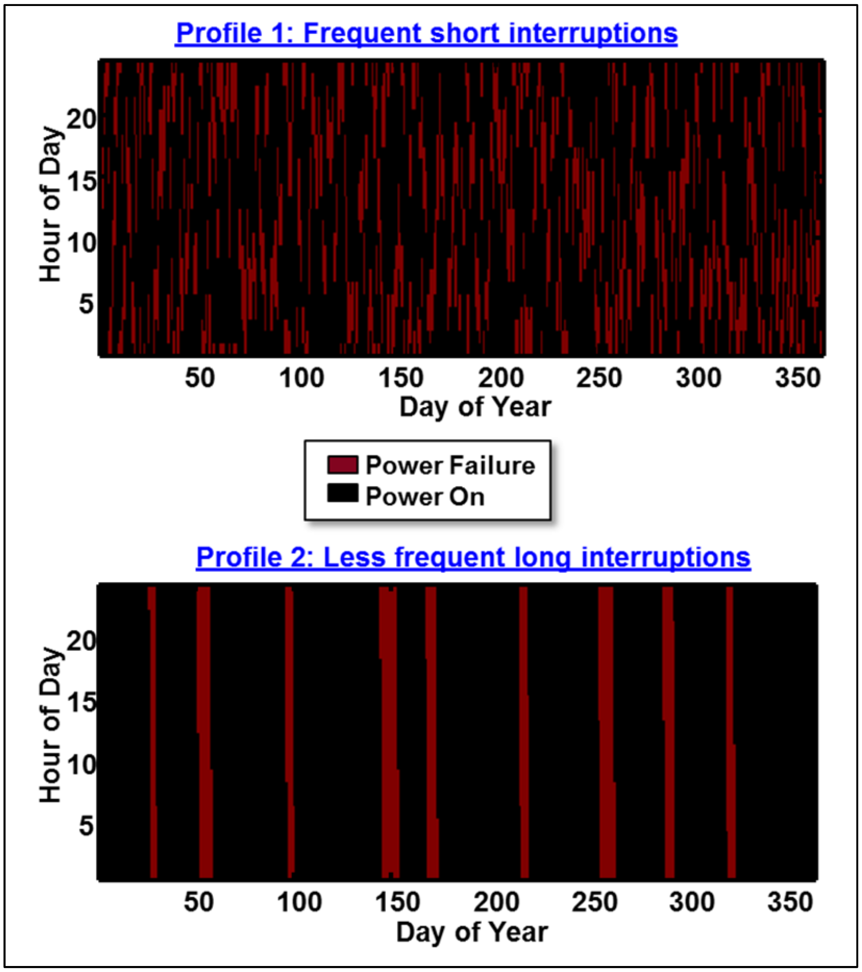


Figure 16: Example Annual Profiles of Grid Outages

The generators and batteries are also modeled similarly, using their corresponding MTBF and MTTR values.

5.2.6 Simulation Engine

Having defined the different elements, a time-stepped simulation is run that will calculate the demand met and the fuel and grid power used.

To capture the uncertainty of the demand and the component reliability, Monte Carlo simulations are run. Typically the answers converged quickly; on the order of 10 simulations were sufficient to protect against misleading outlier cases. The default settings were simulating 1 year in duration with 1 hour time steps.

Figure 17 provides a simplified flow chart of the basic logic used for each time step.

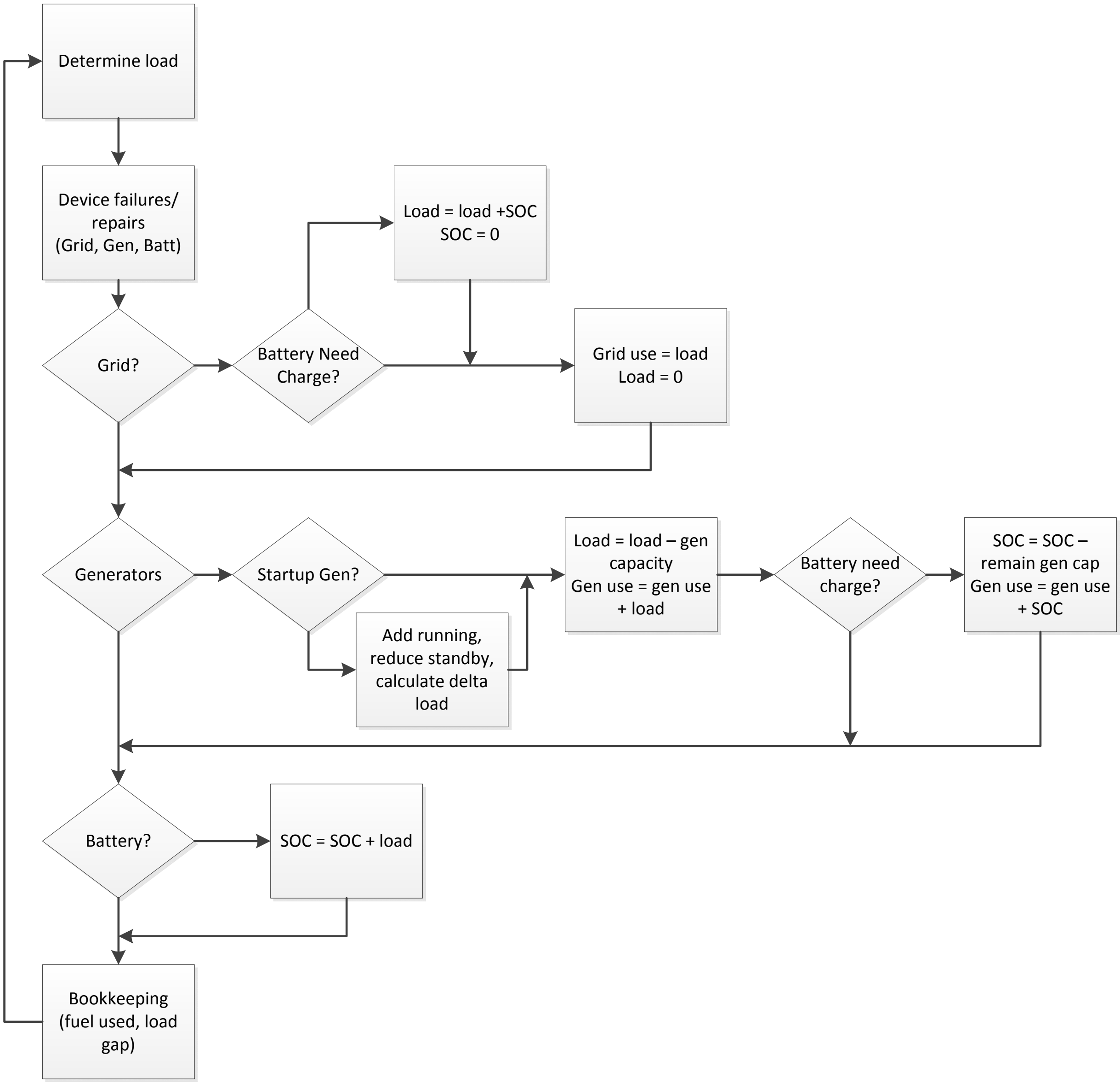


Figure 17: Simplified Logic Flowchart for HPAT Simulation

The simulation begins with taking the demand level for that time step either from the simulated data or the actual recorded data. The model then determines which components are online or offline for this time step.

Using the available components, the simulation then balances the demand with generated supply, either from the grid, generators, or batteries. The logic of that ordering is very important. The logic assumes that if the grid is available, that is always prioritized (in this regard it is very similar to renewables like solar or wind; they are always used first when available). Then, only if the grid is not available are the generators loaded. Here there is additional complexity in determining whether generators need to be turned on or off since the last time step, and accounting accordingly. Finally, there is a check whether there is any remaining load that can be met from the batteries. Finally, the amount of fuel used by the generators, the battery state of charge (SOC), the amount of grid power used, and the load met and unmet are all recorded for this time step.

This process is repeated for each time step over the course of the simulated period. So for one year, there are 8,760 hour long time steps. The values for each of the key metrics is recorded for each simulation run, and then averaged across the several Monte Carlo runs.

This is all done for each parameter and each architecture. HPAT is set up to vary multiple architectures and up to two different parameter values with the same simulation runs.

To demonstrate the consequence of the logic, one can examine the operation of the generators during the course of the simulation. Figure 18 shows the status of the grid and three generators over the course of a one-year simulation. Each device is indicated by a lane that runs from left to right, indicating time. Blue sections represent when the element is operational. Red indicates a failure. Grey indicates that the generator or grid is off. Figure 18 is from an architecture with no grid connection, and Figure 19 is the same set of generators, but with the grid attached. In this example, the grid is very unreliable (MTBF 24 hours).

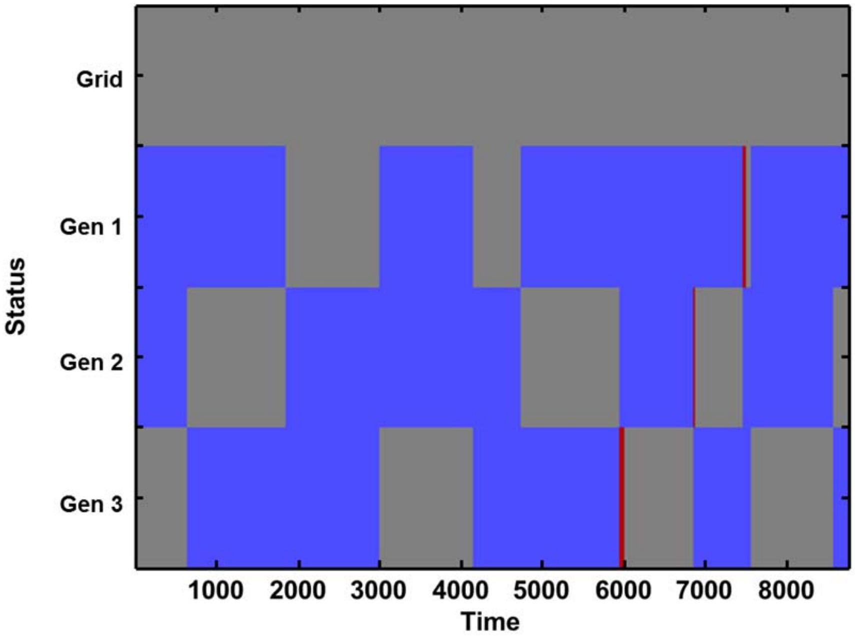


Figure 18: Generator Run Status - No Grid (example)

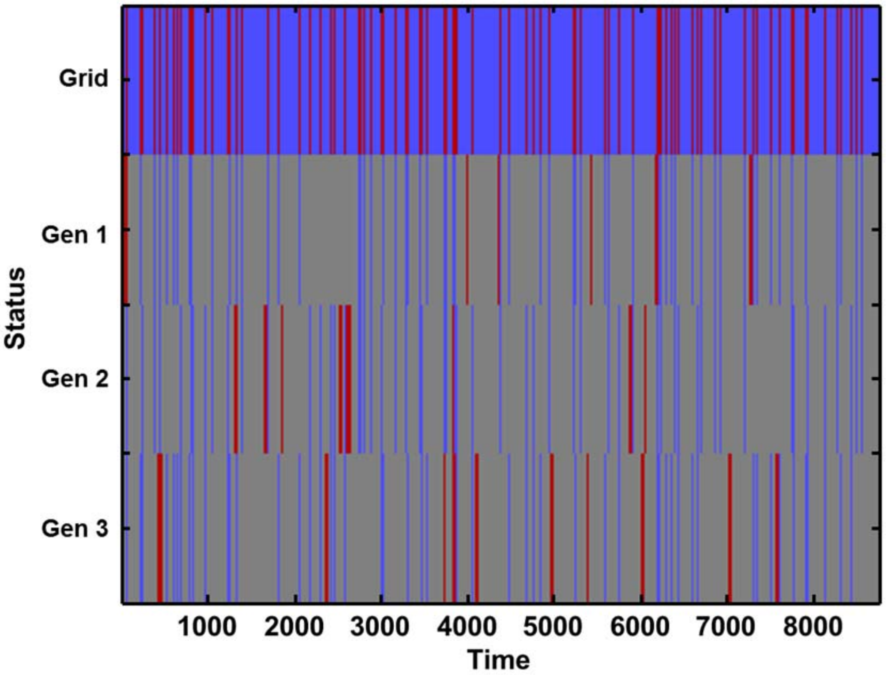


Figure 19: Generator Run Status - With Grid (example)

These two figures clearly illustrate the difference between generators as a primary power source versus using them to back up the grid. One can also observe the logic flow selecting to turn on whichever generator has the least runtime hours. As a final point, the higher failure rate on startup is also observable in Figure 19.

5.2.7 Cost Model

Once the physical model is complete, the cost model as applied to the equipment, fuel, and grid. Note that this module is independent of the physical model; frequently the costs are the more uncertain variables, and so they can be varied more quickly without redoing the full simulation.

Generally, there are four key cost-related metrics:

- Life Cycle Cost (LCC)
- Payback Period
- Savings-Investment Ratio (SIR)
- Annual Costs

The Life Cycle Cost is calculated as:

$$LCC = \frac{I + D}{E_{tot}}$$

Where LCC is the life cycle cost, I is the initial purchase and installation cost (sometimes referred to as the "overnight" cost), D is the discount cost, and E_{tot} is the total energy produced over the life of the system. For this report taxes and decommissioning costs (elements often included in LCC) were not included.

The discount cost is calculated as:

$$D = UPW(M, d) + EUPW\left(F, d, e_f\right) + EUPW(G, d, e_g)$$

Where M is the annual maintenance cost (assumed fixed), F is the annual fuel cost (escalating), and G is the annual grid cost (escalating). The discount rate (inflation) is d, and e is the rate of escalation of fuel or grid cost beyond inflation.

UPW is the Uniform Present Worth, which is calculated as:

$$W(A, d) = A\frac{(1 + d)^N - 1}{d(1 + d)^N}$$

where N is the lifetime of the system (for cost purposes).

EUPW is the Escalating Uniform Present Worth, and is calculated as:

$$EUPW(A, d, e) = A\frac{(1 + e)\left[1 - \left(\frac{1 + e}{1 + d}\right)^N\right]}{(d - e)}$$

The annual cost, O, is calculated simply as:

$$O = M + F + G$$

Which is similar to the discount cost, D, but without the present worth adjustments.

Payback period and SIR are calculated values with regards to a baseline. In these cases, the baseline is typically the system without a grid interconnection, and the new system includes grid interconnection. These values only make sense when the initial installation cost of the new system is more expensive than the baseline, and when the annual recurring costs are lower for the new system than for the baseline.

The payback period, P, is defined as:

$$P = \frac{I - I_B}{O_B - O}$$

Where the subscript B refers to the baseline values. The SIR is defined as:

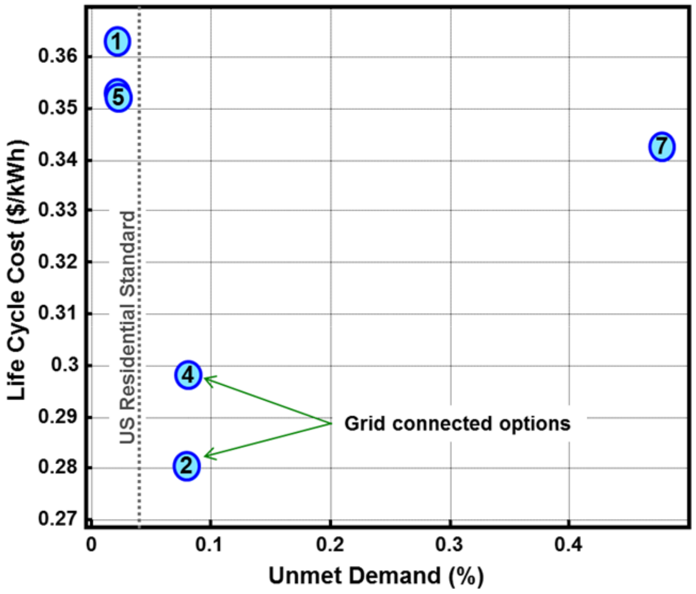
$$SIR = \frac{D_B - D}{I - I_B}$$

5.3 Model Results

5.3.1 General Finding: Cost versus Reliability

This section includes generalized results from purely notional examples intended only to illustrate the capabilities of HPAT and also gain some general insights into the HN grid question. Chapter 6 will have the more precise and accurate results for specific scenarios.

The leading tradeoff for this study is cost versus reliability. Reliability can be represented as percent of the load that is unmet; so a more reliable system will have a lower unmet demand percentage. Life cycle cost (LCC) is a very good metric for capturing the full cost of a system. Figure 20 shows 8 example architectures (the same as shown in Figure 8) all plotted in a space of LCC versus unmet demand, or in other words, cost versus reliability. One would like to be in the lower left corner of this diagram, with minimal unmet demand for minimal cost.



Element		Value
Load	Avg Load (MW)	1.5
	Type	Diurnal
Cost	Fuel ($/gal)	4.00
	Grid ($/kWh)	0.20
	Lifetime (years)	10
	Inflation	2%
Grid	MTBF (hr)	24
	MTTR (hr)	3
	Integration Cost	$1,000K
	O&M Cost	$10K
Gen	MTBF (hr)	5000
	MTTR (hr)	36
	Installed Cost	$800/kW
	O&M Cost	$50/kW
	Startup Time	20 sec
Batt.	Cost	$10/Wh
	Efficiency	85%

Figure 20: Unmet Demand vs. LCC Example Results

To the right of the plot is a table listing many of the key parameters. The results may change depending on the values of these input parameters. As with any analytic model, the results will never be better than the input data (“garbage in will give garbage out”). The plot also shows an approximation of the reliability of the US residential electric service (based on its SAIDI), which is about 0.04% unmet demand.

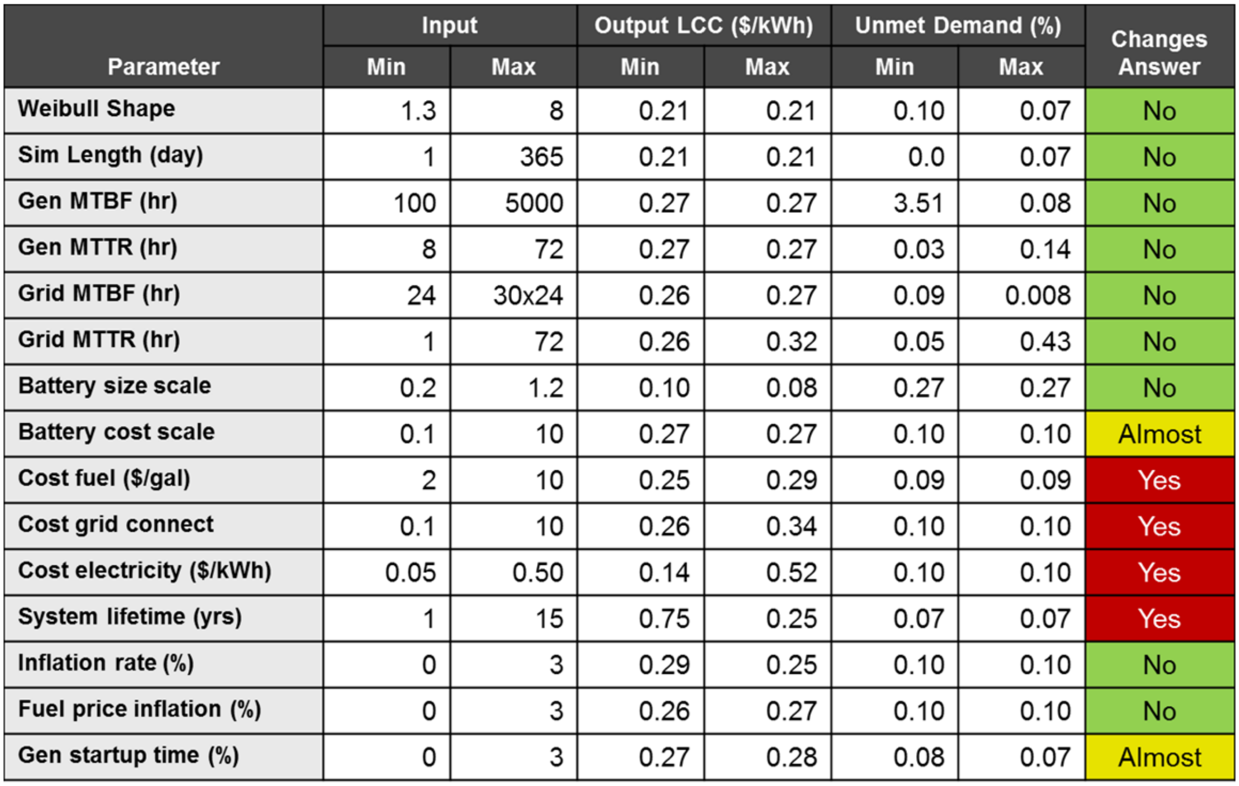
As can be seen in this example, the traditional generator-only architectures are grouped in the upper left corner—very reliable, but expensive. The grid connected options are a little less reliable, but much less expensive. To frame it another way, Architecture 2 would save about $1M every year over Architecture 1. And if the grid integration cost $1M, that would be a payback period of only 1 year. Would a base commander be willing to tolerate an extra 2-3 hours of outage per year to save $1M from the operations budget?

While this is only a notional example, the values here are realistic, and it will be seen in Section 6 that this trade is fairly typical.

5.3.2 Key Parameter Sensitivity

With such a large number of model input parameters, it is useful to determine which ones are more important. The model was run where different parameters and settings within the model were varied across a range of plausible values, holding the other input parameters constant. The output values of LCC and unmet demand were also recorded for a nominal architecture (one including a grid connection). Furthermore, they were run across several architectures, and checked whether changing the parameter changed the solution of which architecture is more effective. This would be considered a “substantial” difference (and is reported in the column “changes answer”).

Table 2: HPAT Parameter Sensitivity Summary



Parameter	Input		Output LCC ($/kWh)		Unmet Demand (%)		Changes Answer
	Min	Max	Min	Max	Min	Max	
Weibull Shape	1.3	8	0.21	0.21	0.10	0.07	No
Sim Length (day)	1	365	0.21	0.21	0.0	0.07	No
Gen MTBF (hr)	100	5000	0.27	0.27	3.51	0.08	No
Gen MTTR (hr)	8	72	0.27	0.27	0.03	0.14	No
Grid MTBF (hr)	24	30x24	0.26	0.27	0.09	0.008	No
Grid MTTR (hr)	1	72	0.26	0.32	0.05	0.43	No
Battery size scale	0.2	1.2	0.10	0.08	0.27	0.27	No
Battery cost scale	0.1	10	0.27	0.27	0.10	0.10	Almost
Cost fuel ($/gal)	2	10	0.25	0.29	0.09	0.09	Yes
Cost grid connect	0.1	10	0.26	0.34	0.10	0.10	Yes
Cost electricity ($/kWh)	0.05	0.50	0.14	0.52	0.10	0.10	Yes
System lifetime (yrs)	1	15	0.75	0.25	0.07	0.07	Yes
Inflation rate (%)	0	3	0.29	0.25	0.10	0.10	No
Fuel price inflation (%)	0	3	0.26	0.27	0.10	0.10	No
Gen startup time (%)	0	3	0.27	0.28	0.08	0.07	Almost

Table 2 presents a summary of the results of this parameter sensitivity study. Many of the parameters had very little impact. Some parameters, such as some of the reliability parameters, did impact the unmet demand and LCC, but did so across all architectures fairly uniformly, so it was not a "substantial" parameter.

The substantial parameters of the study were:

- Price of fuel ($/gal)
- Price of electricity from the grid ($/kWh)
- Cost to interconnect with the grid ($)
- Expected system lifetime (years)

These are some of the most important parameters to get right. They are also some of the most difficult to know beforehand, or the most variable over time. Therefore, it is important to double check the sensitivity of any result from the model before finalizing design decisions or plans.

5.3.3 Excursion: HPAT as Design Tool

With the ability to perform these parameter variations, HPAT becomes a useful design tool.

For example, consider designing a system that includes a battery to bridge the startup period of generators. One design issue is determining just how big the battery should be. Batteries are expensive, so making it too big will drive up the LCC. On the other hand, make them too small and the unmet demand will grow because the battery did not bridge the gap.

Figure 21 shows the LCC versus demand as the battery size is changed. The other key parameters are listed on the right side, as well as a cartoon of this particular architecture.

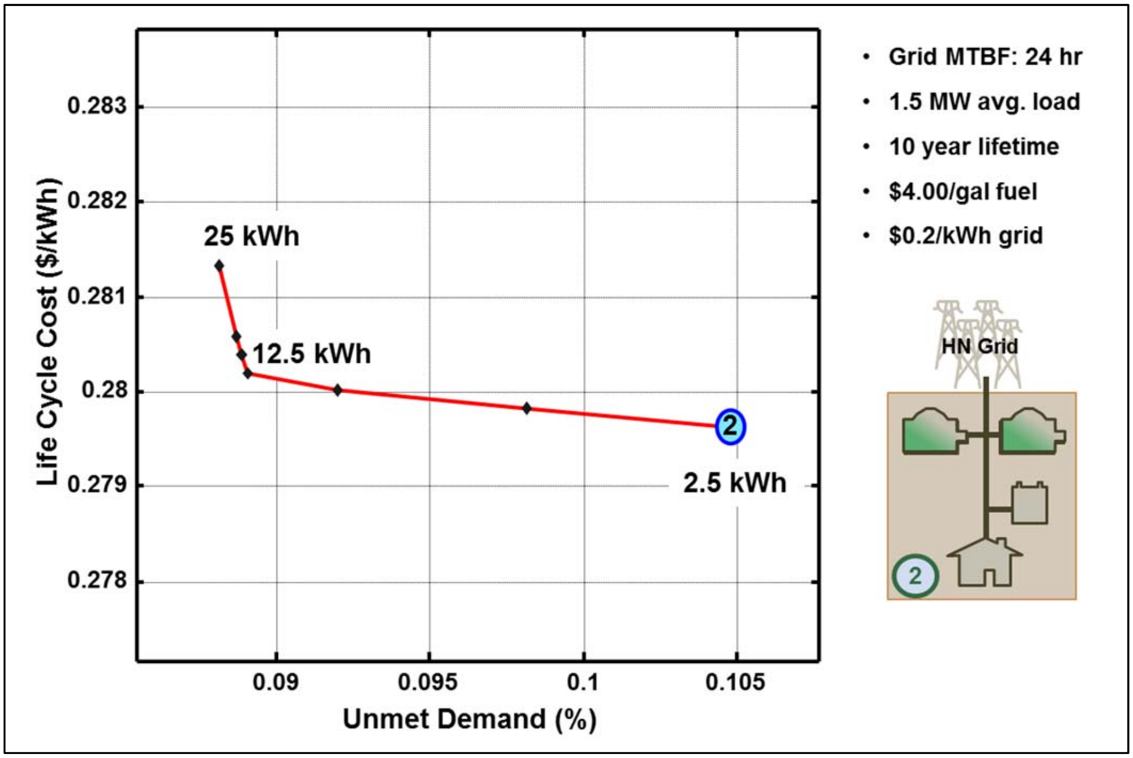


Figure 21: Using HPAT as a Design Tool (example)

The best design will be near the “knee of the curve”. In this case, it would be a backup battery around 12.5 kWh in capacity.

5.3.4 Key Parameter: Grid Integration Cost

One of the most important parameters, which in some cases may also be very uncertain, is the cost of integrating the base with the HN grid. Poles, wires, switchgear, regulators, metering equipment, control electronics, and transformers may need to be purchased and installed.

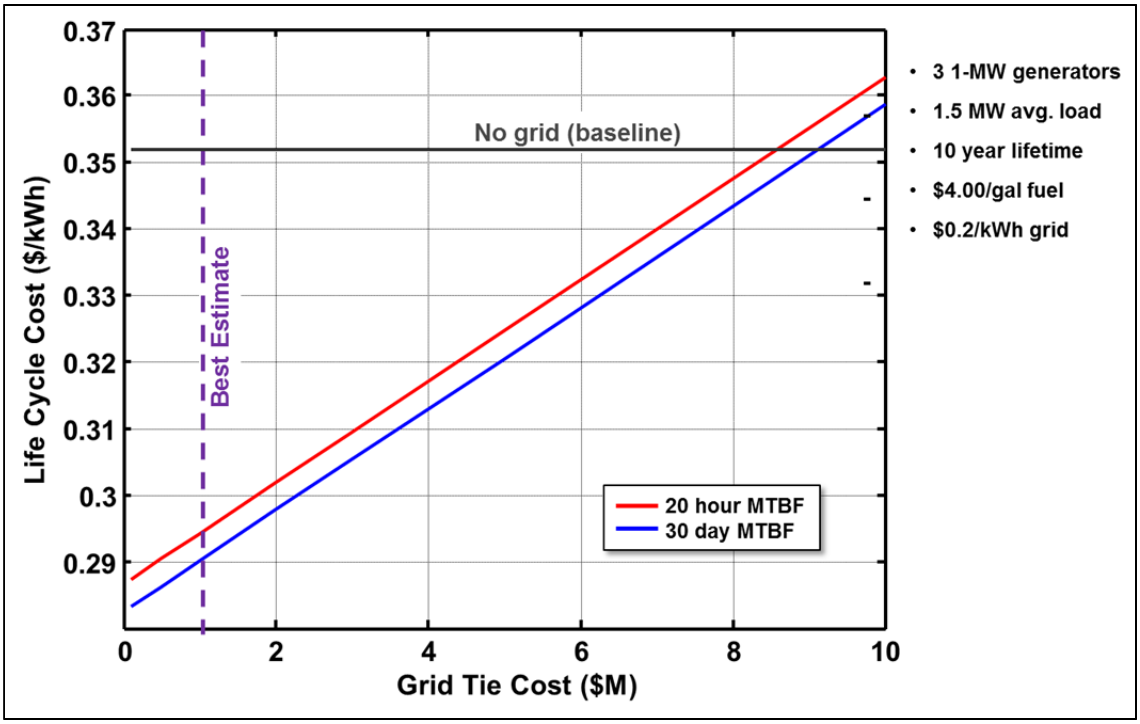


Figure 22: Grid Integration Cost Sensitivity (example)

In this example, the best estimate for the grid interconnect cost was $1M. HPAT varied between 0.1 and 10 times that value (so from $100,000 to $10,000,000). Figure 22 shows the resulting LCC versus grid interconnection cost. Two different grid reliability models were considered. The first (shown in a red line) was a grid with very frequent, but short outages (MTBF of 20 hours, MTTR of 4 hours). The second (shown in a blue line) was a grid with less frequent, but longer outages (MTBF of 30 days, MTTR of 6 days). The grey horizontal line represents the LCC of electricity without connecting to the grid, so all electricity is generated by the 3 diesel generators.

Under these conditions, the LCC of electricity is far lower using the grid. This is very robust—the cost of the interconnection would have to be around $9M before it does not pay back in the ten year lifetime. So if the best estimate of cost was to grow even two or three times because of uncertain conditions or occurrences, it would still be a prudent decision.

5.3.5 Key Parameter: Fuel and Grid Prices

Two of the most important parameters are the price of fuel and the price of electricity from the HN grid at the base location. If it is known, typically one would use the fully burdened cost of fuel for this analysis.

HPAT can be run to vary two parameters with the same Monte Carlo runs. Figure 23 illustrates the impact of varying these two parameters on the LCC. Grid price is varied across the horizontal axis, fuel price along the vertical axis, and the color indicates the LCC. Two cases are shown—the upper plot shows the price if the base is not connected to the grid, and the lower plot shows the price if the base were connected to the grid. In the "No Grid" case, as expected, the LCC is unaffected by the grid price, and only increases linearly with fuel price. In the "With Grid" case, prices increase both with fuel and with grid costs—but because it is only using fuel some of the time, it is less sensitive to the fuel price variation.

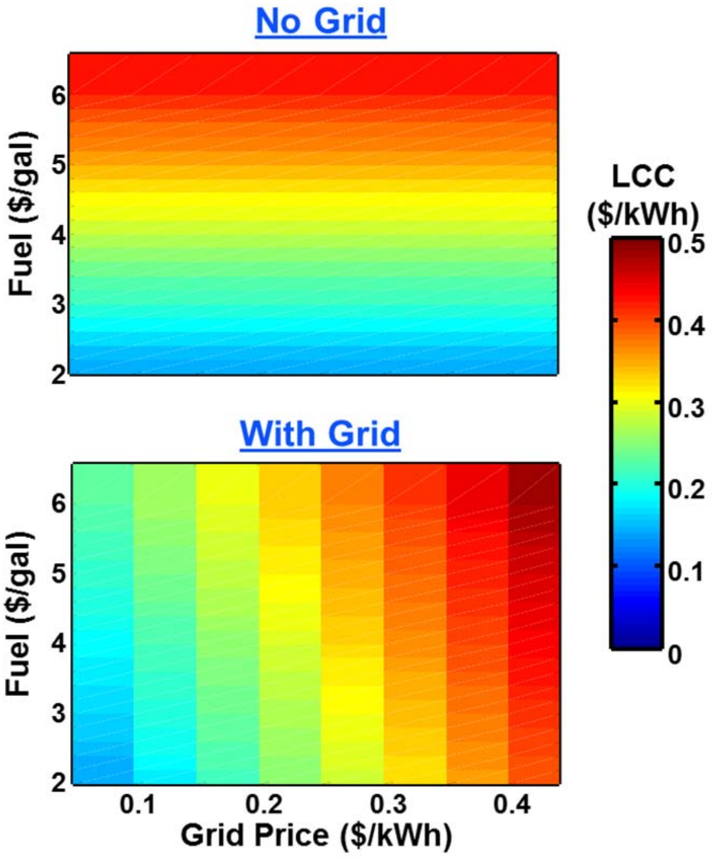


Figure 23: LCC as a Function of Grid and Fuel Prices (example)

While this is useful in predicting the expected cost of energy, it also can help determine the break-even point between using the HN grid or not. For example, suppose fuel is cheap ($2/gal) and electricity is expensive ($0.40/kWh), placing the base in the lower right corner. In this case the LCC is lower in the upper plot (the "No Grid" case) than in the lower plot (the "With Grid" case).

One way of visualizing this trade-off is by viewing the resulting payback period. Figure 24 shows the payback period for integrating with the grid as a function of fuel and grid prices.

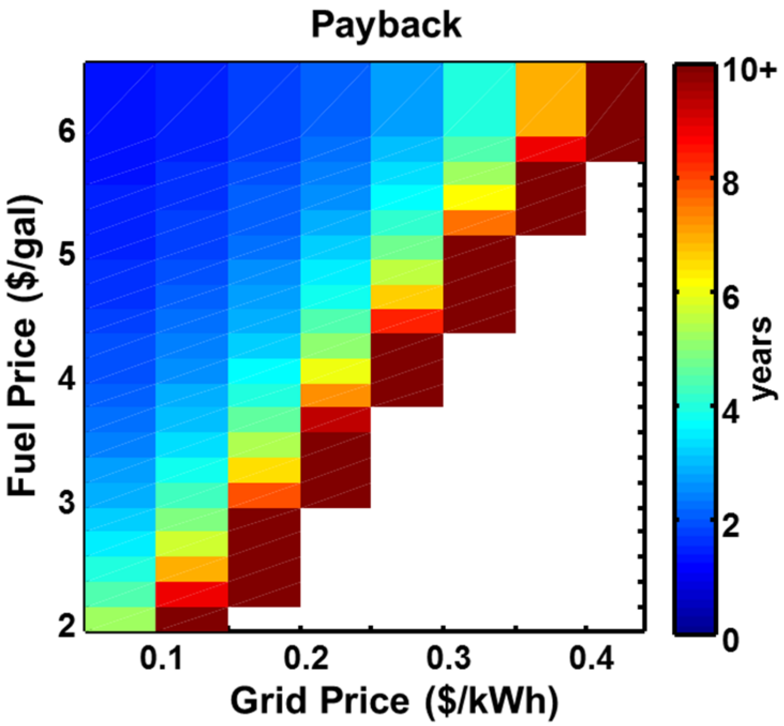


Figure 24: Payback period as Function of Grid and Fuel Prices (example)

So, for example, if fuel costs $4/gal and the grid price was $0.20/kWh, this particular system would pay back in about 4 years. The white region is where the integration cost does not ever payback—the annual energy cost is more with the grid than without. When deciding whether to pay the additional cost for the grid integration, one can check how close to the border the solution lies, and determine how robust the decision is given future uncertainty.

5.3.6 The HN Power Decision Dashboard

Different decision makers may value different metrics. Therefore, HPAT generates a "dashboard" view which summarizes several different metrics when evaluating whether to connect to the grid, or not. Figure 25 shows an example of the dashboard. The first bar graph shows LCC, which amortizes the initial system cost as well as recurring costs across each kWh generated. The second is annual costs only, which may be of more relevance to some base commanders, especially if the cost to change comes from somewhere else. The third graph shows fuel usage; this transcends just costs, but is also relevant to logistics and base security.

The fourth graph shows base endurance, i.e. if the fuel supply were disrupted, this is how long the base could continue assuming normal operating load. Note that in a real disruption, operations may be altered to reduce consumption and therefore the endurance prolonged. Also note that it assumes the grid continues to operate at the same reliability level; depending upon the nature of the fuel disruption this may not always be a good assumption (such as during a malevolent attack). Nevertheless, it still provides another very meaningful metric for assessing an additional benefit of using HN power.

The fifth and sixth graphs represent reliability. The fifth graph shows percent of unmet demand; the red dotted line shows the US residential standard as a point of reference. The sixth graph shows the average number of critical failures per year—this is when the power supply falls below the critical load level. (In the example shown, there were no critical failures). In many cases, this is far more meaningful than the broader "unmet demand" metric.

Finally the payback period and savings to investment ratio (SIR) are also reported.

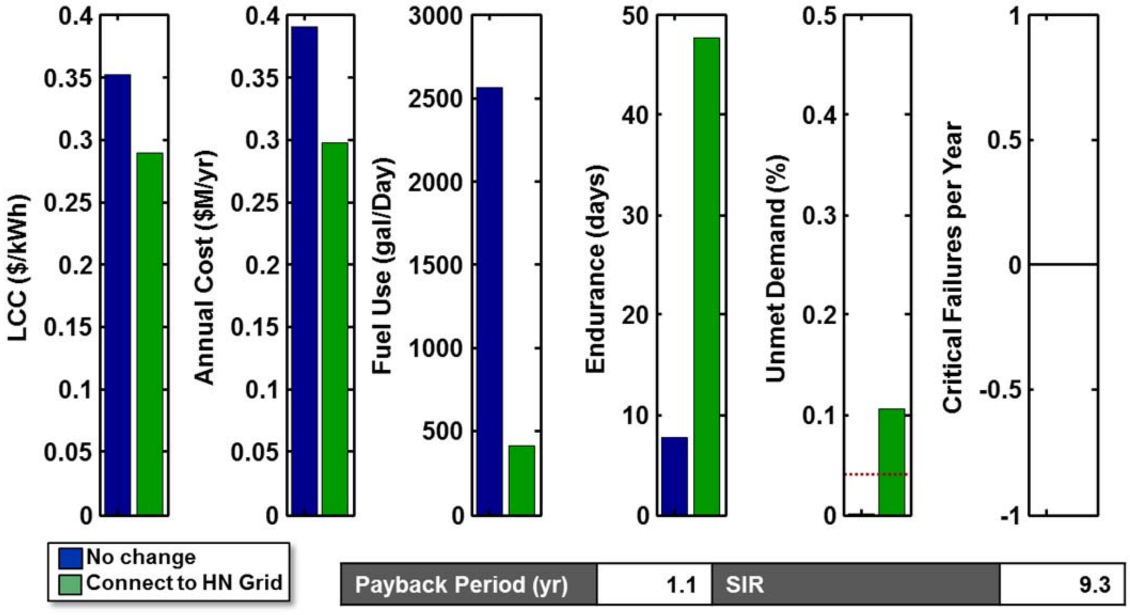


Figure 25: HP Grid Decision Dashboard (example)

6 Case Studies

Four case studies are provided to illustrate different scenarios where HN power may be considered. A range of sizes and regions were selected. As part of this study, in-person visits were made to Soto Cano Air Base and Puerto Castilla in Honduras. Information for the two other examples, a proposed base in Agadez, Niger and a special operation house in Burkina Faso, was gathered via phone conversations with subject matter experts. These four cases are included for instructional purposes only.

Any decision to actually implement HN power should only be made after obtaining all necessary data or having local site experts review assumed values where data is unavailable.

In all cases, the discount rate was assumed to be 2%, and fuel and grid prices escalated at an additional 2%. The results are relatively insensitive to these assumed values. Costs of installing and maintaining the distribution system on the base is also neglected because that is assumed to be the same with or without HN power. For this level of analysis, none of the architectures included battery (or UPS) backups. Again, those would likely be installed for critical loads whether HN power is used or not.

6.1 Soto Cano, Honduras

6.1.1 Description of Site

Soto Cano Air Base (SCAB) is a Honduran Air Base which is located approximately 50 miles northwest of the capital city Tegucigalpa, and approximately 6 miles south of the town of Comayagua, Honduras. SCAB hosts both the Honduran Military Academy of Aviation and the US-led Joint Task Force Bravo (JTF-Bravo). The primary mission of JTF-Bravo is to support and conduct joint, combined, and interagency operations in the Joint Operations Area. The efforts are to enhance regional cooperative security initiatives and support democratic development as well as support US interests by building mutually beneficial security, developing military training for the Honduran military, supporting drug interdiction efforts and performance of joint military exercises with Honduran forces.

Soto Cano Air Base currently supports all its missions, housing and support facilities (hospital, dining, etc.) by a self-contained 34.5 kV electrical distribution system supplied by five KTA50-G3 Cummings diesel generators, which are rated at about 1.2MW for prime power. At any one time, two to four of the generators are running or available for standby to supply the entire base load throughout the year. The generators are currently run in such a way, that if any one generator inadvertently fails, the remaining generators have sufficient capacity to carry the load without disruption . This “N+1+1” architecture is designed so that the maximum load could be met by three of the generators; this allows one generator to be down for long-term maintenance, and still have at least one more generator ready at any time for backup in case of failure.

The base currently has three primary diesel storage tanks with a combined capacity of 90,000 gallons of diesel fuel, and at any given time between refueling, carry from 50,000 – 90,000 gallons of fuel. Each generator also has its own 1,200 gallon storage tank. The average fuel use per day averages to approximately 4,600 gallons. Fuel shipments are typically received about twice per week, so that the base maintains a significant supply at any given time. Diesel fuel costs vary throughout the year but average ~$4.00/gallon.

Soto Cano Air Base currently employs separate contracts to supply primary generator power and maintain the electrical distribution system. The generators and associated power gear is owned and operated by IAP, who have a two-part contract with the US military. The first part is a relatively flat maintenance contract (though it does include a fixed and variable kWh component) which was worth approximately $1.7M annually in 2014 (this year is more expensive, but the exact value was not provided). The second part covers primarily fuel, and will vary directly with the demand over the year. The maintenance of the distribution system around the base and the local backup generators for different critical sites, are all covered under the much broader Base Operation and Support (BOS) contract; these costs are assumed constant whether HN power is used or not, and are not included further in this study.

The demand at SCAB typically varies from about 1.5 MW to 3.7 MW; the annual average power load for 2013 was 2.43 MW. This equals 21.3 GWh of energy per year. Figure 26 shows the demand profile over a period of about 6 weeks. The total demand is shown in black, and is made up of the four different feeders shown in the colored lines. As can be seen there is a strong, very repeatable diurnal pattern. Through most of the year, there is also a clear reduction of power consumption during the weekends.

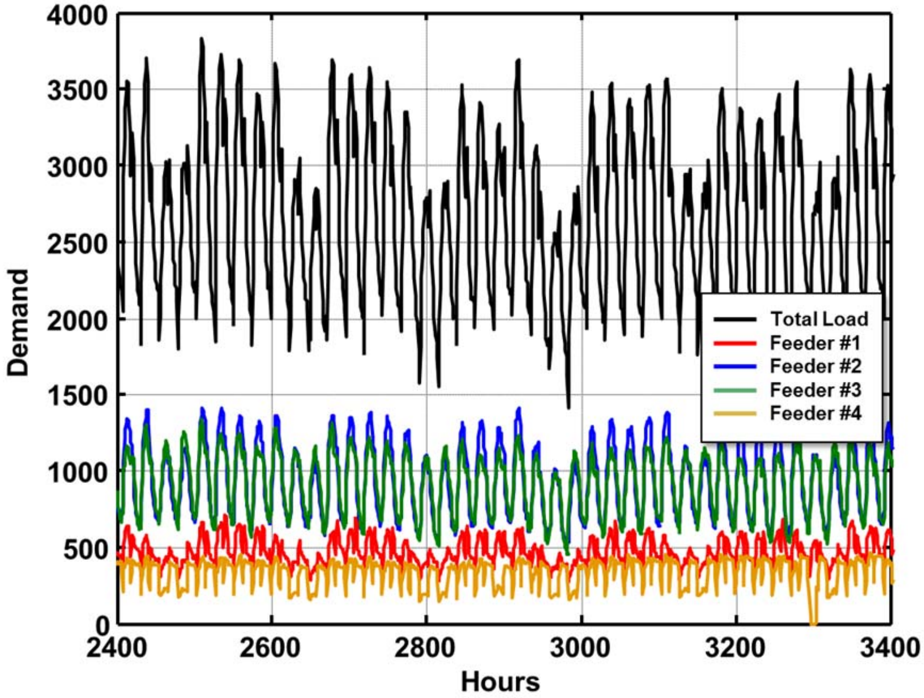


Figure 26: Demand profile at SCAB, by feeder

Figure 27 shows the power consumption over the entire year. Again, the diurnal and weekly patterns are evident. There also seems to be lower consumption through December and some other typical holiday periods.

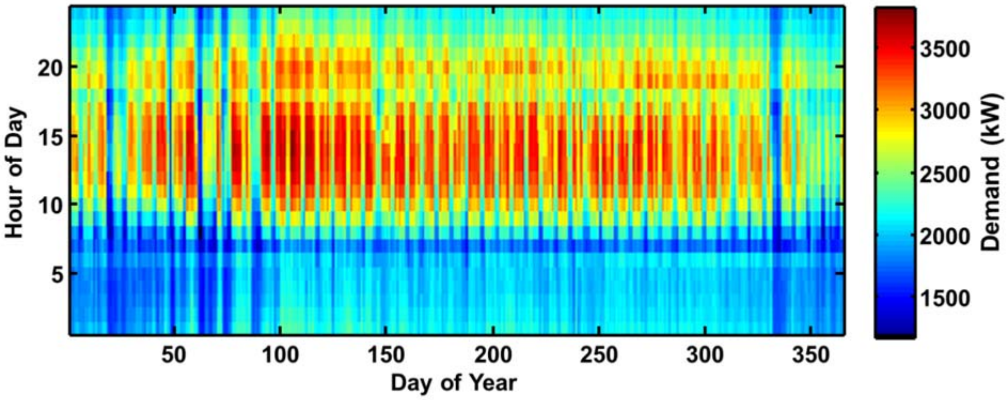


Figure 27: Annual demand profile for SCAB (2013 data)

The Honduran electric company, Empresa Nacional de Energia Electrica (ENEE) generates power and operates the national transmission and distribution grid. There is an ENEE 138 kV transmission line that crosses right through the middle of SCAB, and right past the generator farm. This line actually presents safety risks, and should be moved around the perimeter of the base, but that is beyond the scope of this study. There is also an ENEE 34.5 kV distribution line that runs right along the side of the base, and actually has a branch that runs directly to the generator farm. This distribution line runs from a substation in Comayagua 4 km from the base. Local operators say that SCAB was connected to the HN grid through this line about 14 years ago. Though there have been previous concerns about the reliability of the HN power in this region, base personnel who live in the nearby town of La Paz report that in more recent years, the power only suffers short outages perhaps once every couple of months. Based on discussions with representatives from the US Army Corps of Engineers (USACE) and representatives of the Honduran National Utility, ENE, electric power use costs were estimated to currently range from $0.15-0.20/kWh for SCAB; $0.20/kWh will be used to be conservative.

These two power lines provide two alternative connections. SCAB could connect directly to the 34.5 kV distribution line. This would alleviate the need for additional transformers. However, one expert interviewed was concerned that the demand from SCAB would be too large for the line, and result in voltage sags or frequency irregularity. The other option would be for SCAB to hook into the 135 kV transmission line. This would require transformers, but would be more reliable and should not add enough load to degrade voltage or frequency regulation. As this is the more expensive, but lower risk option, this will be the case used for this analysis, as it should represent a more conservative approach.

A third approach would be to run a new 34.5 kV distribution line from the substation in Comayagua to the base on a dedicated feeder. Assuming these lines could run along existing right-of-ways, the only cost would be the feeder switchgear and the wires themselves, which could cost below $1M. Though this option was not assessed as part of this study because there were too many unknowns, it should be reviewed by engineers with specific location expertise.

6.1.2 Model inputs

The interconnect costs will be derived from an estimate generated by the US Army Corps of Engineers (USACE). This estimate included both building a substation to connect to the 138 kV transmission line as well as the cost of increasing capacity to 7.5 MW and re-routing the transmission lines away from the center of the base. [5] The cost assumptions were also compared to those from the Unified Facility Cost (UFC) 3-701-01 Change 8 (dated July 2015). [1] In general, the USACE cost was higher than the $225/kW parametric approximation, but it did include additional security, fencing, roads, and a control room. The USACE estimate was used for this section, as it was both more rigorous and more conservative. The sustainment cost (annual O&M) will be assumed to be $100,000, based on the UFC guidance of $20/kW per year.

Table 3 shows the cost assumptions for the second interconnection option. Note that this connection is designed for a 7.5 MW load, which is much larger than needed for the current 3.6 MW maximum load. There are some plans for SCAB to host surge and or additional training units, so this may justify the higher capacity. However, if these surges or training events are short in duration, it does make the overall cost of electricity higher because all equipment capacity (transformers or generators) must be sized to the maximum load, not the average load.

Table 3: Grid Interconnect Cost for SCAB (from USACE 2015 Estimate)

Option	Item	Cost ($000)
Interconnect Only	Substation	2,049
	Enviro Assessment	125
	Design	530
	Antiterrorism Measures	200
	Contingency (5%) and Supervision, inspection, and overhead (7.5%)	357
	Total	**3,212**
Interconnect & Upgrade	Substation	2,049
	Overhead Electric Lines	4,002
	Standby Generator	1,514
	Enviro Assessment	125
	Design	530
	Antiterrorism Measures	200
	Contingency (5%) and Supervision, inspection, and overhead (7.5%)	1,084
	Total	**9,504**

Table 4 summarizes the model inputs based on the description in the previous section.

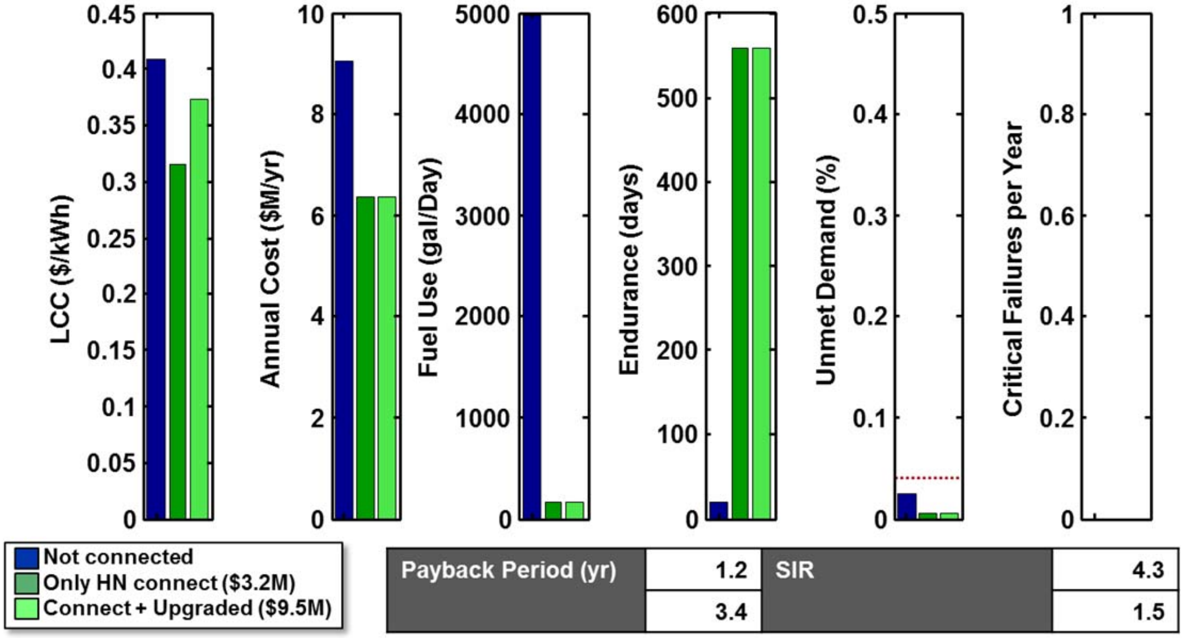
Table 4: Assumed Key Parameters for SCAB Scenario

Base	System Life (yrs)	5
Load	Average (kW)	2,500
	Peak (kW)	3,600
	Critical Load	750
	Pattern	Diurnal (see profile)
Generators	Generators	5 x 1.4 MW Cummins
	Annual O&M costs ($/yr)	$1,800,000
	Fuel Price ($/gal)	4.00
	Fuel Storage (gal)	96,000
Grid	Cost to interconnect	$3,200,000
	Annual O&M costs ($/yr)	$100,000
	MTBF/MTTR (hr)	336/12
	Price ($/kWh)	0.20

6.1.3 Results

Figure 28 shows the dashboard results for Soto Cano Air Base. For the case of only connecting to the grid (without additional electrical upgrades), LCC is reduced by almost $.10/kWh, which is nearly a 24% reduction. Annual costs are reduced by more than $2M dollars per year. Fuel use is reduced by 96%. Even when including the full upgrade cost at $9.5M, the LCC is still reduced by 9%, which results in a 3.5 year payback.

The model also shows that in both cases reliability is also improved. This result depends upon the reliability model of the generators which may be overly pessimistic, and so the result should be taken with some caution. Nevertheless, because the generators are used less frequently, and assuming IAP still maintains them to the same level they are currently, there will be less generator outages per year (since maintenance and failures are both a function of run time). Importantly, it can be claimed with confidence that reliability is not reduced by using HN power.



Payback Period (yr)		SIR	
	1.2		4.3
	3.4		1.5

Figure 28: SCAB HN Power Dashboard

These results depend upon many parameters; however, two of the leading parameters are the cost of fuel and the price of electricity from the grid. Not only are these dominant terms, they are also in some ways the most uncertain and likely to change over the life of the base. Figure 29 shows a two-dimensional sensitivity analysis to the fuel cost (shown on the horizontal axis) and the grid price (shown on the vertical axis). Payback period is used as the defining metric, which refers to the period in which the cost of connecting to the host nation pays for itself. As can be seen, diesel fuel would have to drop below $3/gal, or electricity rise above $0.30/kWh before the grid connection would not pay for itself.

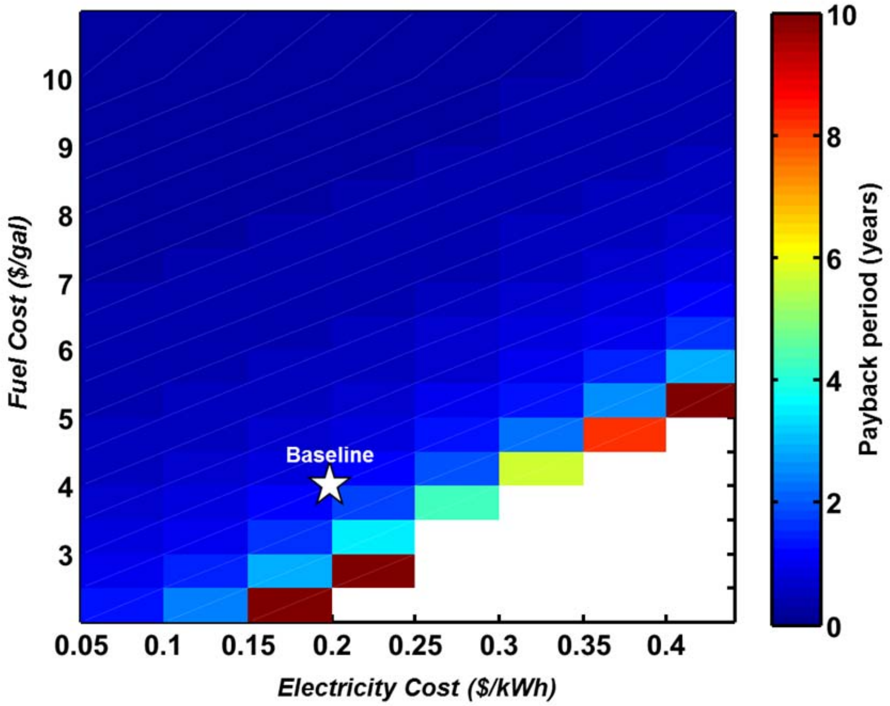


Figure 29: Sensitivity of Payback to Fuel and Grid (Soto Cano-interconnect only)

6.1.4 Recommendations

In 2012, Sandia National Laboratory and the National Renewable Energy Laboratory (NREL) performed an assessment of Soto Cano. Most of the conditions at Soto Cano have not changed since then, and so the findings and recommendations in that report are still considered valid. [6]

This analysis is focused only on the very specific question of whether Soto Cano should connect to the HN power grid. Based on the analysis presented here, the recommendation is that Soto Cano should reconnect to the HN power grid.

There are two alternative approaches. It is recommended that the power capacity on the existing ENEE 34.5 kV distribution line be measured. If there is sufficient capacity on the line to carry the maximum SCAB load of 3.6 MW, then that would be the lowest-cost option for Soto Cano. Given that the base already maintains full generator backup with the five 1.4 MW generators, the reliability of the existing ENEE line is more than sufficient.

One could also change the location of some of the recloser switches on the existing distribution line. By adding one on to the other arm and moving the existing switch until after SCAB as shown in Figure 30, then even greater reliability could be achieved. But this change would be unnecessary from a simple cost-reliability model perspective.

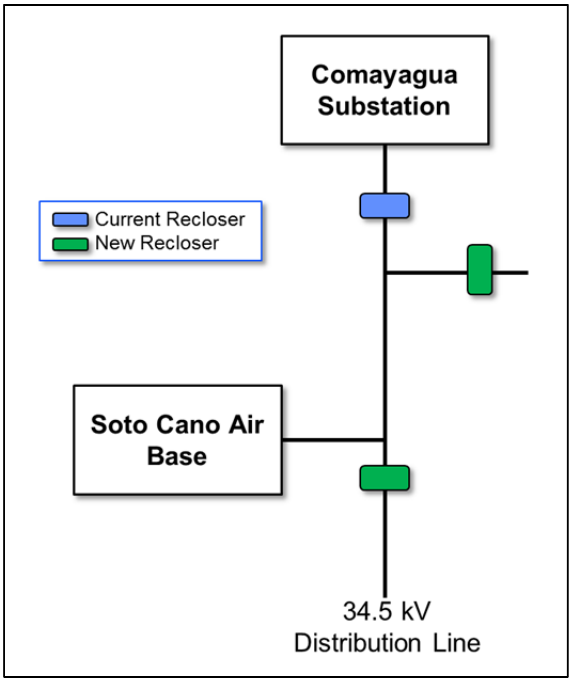


Figure 30: Possible Switch Change to Improve Grid Reliability at SCAB

If the existing line does not have sufficient capacity, then it is recommended that SCAB place a transformer station along the 138 kV ENEE transmission line.

Yet a third option would be to place a dedicated feeder at the substation in Comayagua and run a dedicated distribution line over the 4 km to SCAB. This option should be studied further before proceeding with connecting to the 138 kV transmission line.

6.2 Puerto Castilla, Honduras

6.2.1 Site Description

The Puerto Castilla Navy Base site is a Honduran Navy facility. It is located approximately 250 kilometers north-northeast of Tegucigalpa on the Caribbean coast. The base uses buildings that were formerly built by the United States during World War II. It is used to train Honduran sailors and Special Forces, as well as a base for several coastal patrol boats. Plans to expand Puerto Castilla facility are being considered.

The current facility has an existing power distribution system using overhead wires, which are supposed to run at 34.5 kV. The base is at the end of a fairly lengthy transmission line from the power station, and often experiences voltage sags. Personnel on the base estimate that the voltage which is rated at 220 V is often 195-205 V (88-93% of rated); voltage levels should always be above 95% at all times to meet standard equipment service requirements. During a tour of the facility, we observed three 75 kVA, one 50 kVA, and one 100 kVA transformers.

There are two backup generators, both of which are inoperative, and have been for at least two years. One supports the headquarters building and is rated 100 kW, the other supports the main barracks and is rated at 160 kW. Maintenance of both the distribution system and the generators is virtually non-existent (which is also true of their maintenance of other equipment such as the patrol boats). The generators both ran on diesel fuel; there is a 10,000 gallon storage tank for diesel, though that is also used for the boats.

The base currently experiences almost daily outages, often for many hours at a time. Though the military personnel were unaware, upon questioning ENEE representatives, it turns out that most of these outages are planned by ENEE as way of managing demand for their limited generation capacity. The transmission lines also experience fires which disrupt service; these occur once or twice a month on average.

ENEE is currently building a new hydroelectric power station in the town of Bonito Oriental, which is approximately 45 km away. This is expected to resolve most of both the capacity and quality concerns for the base. ENEE claimed the station would be completed by September 2015; the commander of the base thought it would still be two to three years away. Currently, power is generated at a 250 MW plant near La Ceiba, transmitted at 138 kV to Bonito Oriental, which is a distance of about 120 km, where it is stepped down to 34.5 kV for the remaining 45 km to the base.

The rates that ENEE charges Puerto Castilla were not entirely clear; examining the most recent bill, it appears that the base was charged about $0.22/kWh. Power usage was not clearly monitored. ENEE records indicate an average monthly demand of 10,733 kWh. If power is on for roughly 70% of the time, then this would suggest about 22 kW average demand load. While this seems surprisingly low, there is no other data to use. Given that electricity is so unreliable and there is not even backup generation, it seems plausible that the personnel have minimized their reliance on electric devices. There was certainly no evidence of electricity being used in the kitchens or living quarters.

However, if the base grows significantly as planned and if the US establishes a larger presence, then clearly this demand will greatly increase.

6.2.2 Model Inputs

For this study, we will assume that the HN power remains at the same reliability and cost. We will include the cost of a voltage regulator in the interconnection cost. However, we will assume that the existing generators are replaced with two properly maintained 100 kW diesel generators. We will also assume that demand grows somewhat as electricity becomes more reliable. Table 5 shows the key model inputs.

Table 5: Assumed Key Parameters for Puerto Castilla Scenario

Base	System Life (yrs)	5
Load	Average (kW)	50
	Peak (kW)	80
	Critical Load	25% of total
	Pattern	diurnal
Generators	Generators	2 x 100 kW
	Fuel Price ($/gal)	4.50
	Fuel Storage (gal)	10,000
Grid	Cost to interconnect	$150,000
	Annual O&M costs ($/yr)	$3,000
	MTBF/MTTR (hr)	16/8
	Price ($/kWh)	0.22

The cost includes an estimate of $100K for the voltage regulator, and then about $30K for the required controllers and switch gear, plus $20K margin. The area cost factor for Honduras is 0.96. Wiring is already in place.

6.2.3 Results

In this case, there is already an existing HN power connection; nevertheless, by using the cost to replace and repair the existing connection, it still remains a relevant case study. Figure 31 shows the overview dashboard. In this case, there is only a small drop in LCC; for the small load size, the expense of the voltage regulator becomes a significant portion of the lifetime cost. HN power does save nearly $50,000 per year, and the fuel usage is greatly reduced. Payback of the grid connection would take about 3.5 years for the base at its current size.

One striking feature of this scenario is the increase in critical failures. This model output is because the generators were modeled to have a 5% likelihood of failure on every startup. With a very intermittent grid, this leads to a much higher probability of an outage even with the shorter overall runtime per year. Furthermore, for this architecture, there is no additional generator redundancy—it is an “N” architecture, not “N+1”; this leads to the large number of critical failures.

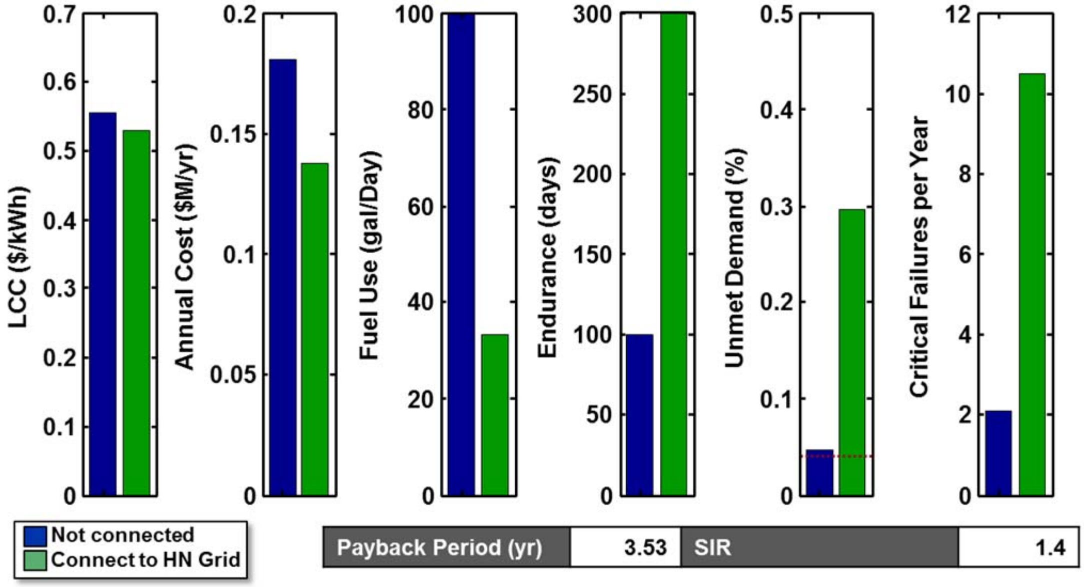


Figure 31: HN Power Dashboard for Puerto Castilla

Figure 32 shows how the outcome is impacted by electricity and fuel prices. As can be seen, this case is already in a very marginal location.

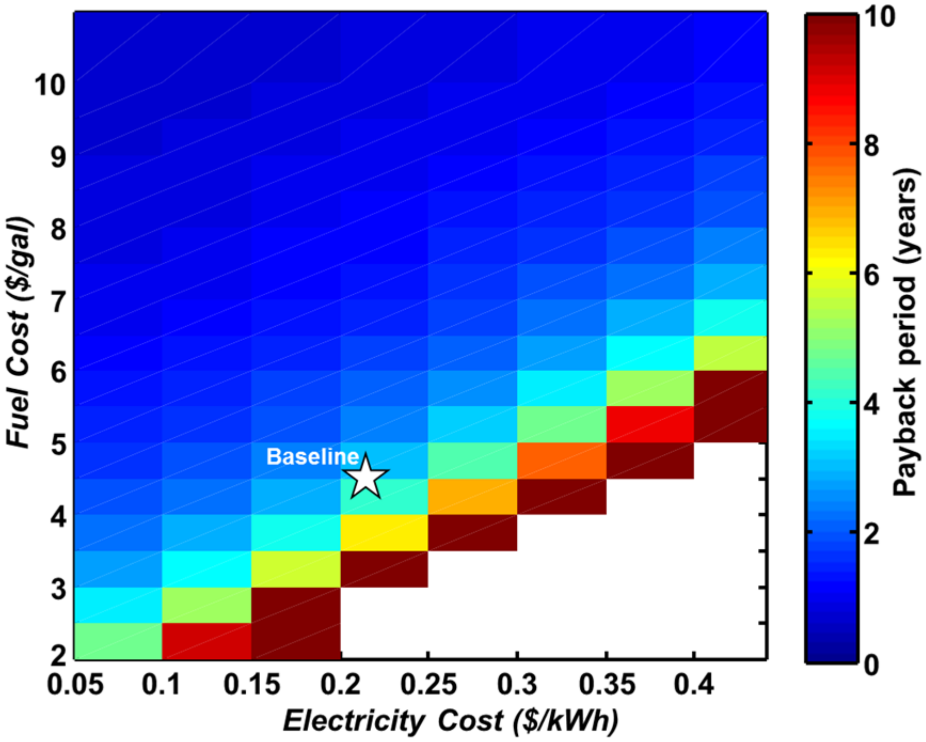


Figure 32: Sensitivity of Payback to Fuel and Grid (Puerto Castilla)

It is also of interest to look at what happens if the base were to grow four times larger. We increase the load to 200 kW, increase the number of generators to 5, and increase the interconnect cost because of the higher required capacity to $400,000. In this case, Figure 33 shows the results.

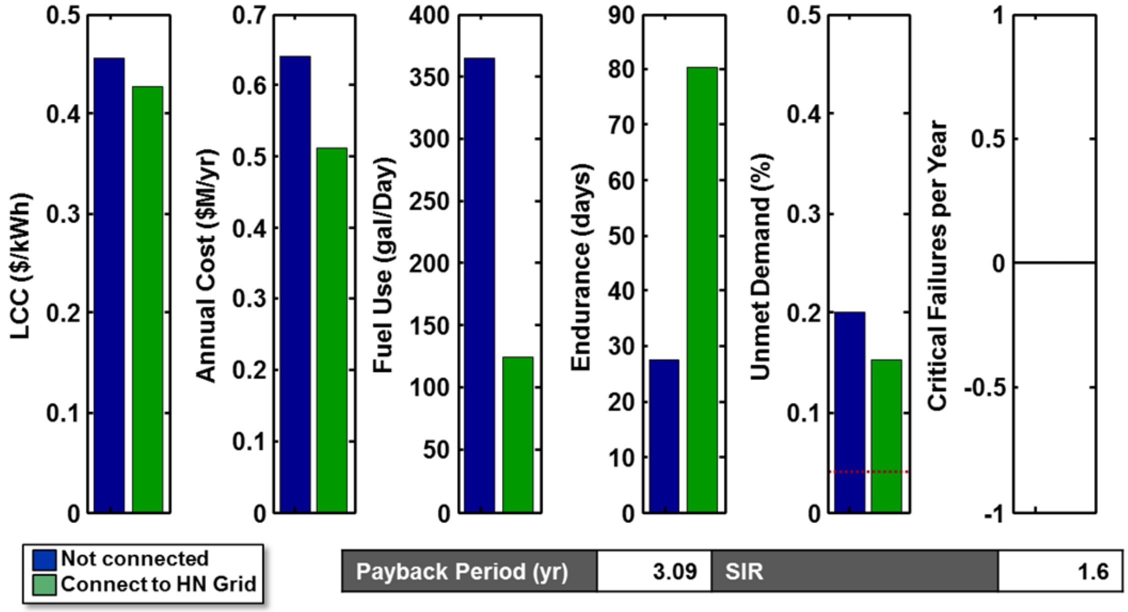


Figure 33: HN Power Dashboard for Expanded Puerto Castilla Scenario

Again, because the interconnect cost was scaled up along with demand, the overall saving percentage does not improve much. In absolute terms, there is a very large improvement: now HN power saves $130,000 per year. Also, by introducing more generators, which provide redundancy, the reliability is greatly improved, especially by avoiding any critical failures.

6.2.4 Recommendations

It is recommended that Puerto Castilla continue to utilize to the HN grid. Furthermore, as this is included as a notional case, it is also recommended that other bases in similar conditions (small load, poor grid reliability) still consider using HN power, though care must be taken—if the interconnect cost is too high, it may not be worth if from a financial perspective.

This scenario highlights an additional factor. Even though the base was connected to the grid, it is recommended that the connection be upgraded to include a voltage regulator if the grid power quality is not improved in the near future by the new power plant. In general cases, developing world power grids may suffer quality issues; therefore additional regulating equipment may need to be included in the interconnection cost.

Finally, the Puerto Castilla scenario also highlighted the need for qualified maintenance. For any US military base, arrangements must be made and budgeted to provide qualified maintenance of the grid connection, the on-base generation, and the distribution system. It should be either done by US personnel, a reliable contractor, or a clearly understood and enforceable contract or agreement with the HN provider.

6.3 Agadez, Niger

6.3.1 Site Description

Agadez, Niger is a small town in the South Sahara desert, about 730 km northeast of Niamey. AFRICOM is considering placing a 300-man base in Agadez to support anti-terrorism activities. Currently, there is no US base at this location, so it would be fresh start. The environment is remote desert.

The base is planned to house approximately 300 military personnel. At the time this was written, the type of shelters and generators on the base were still being determined. However, the leading power generator concept was to use 3 1-MW USAF generators, which will be the architecture assumed for this analysis. This would use approximately 75 gallons of diesel fuel per hour, or 650,000 gallons per year. [7]

Power is generated in Arlit, which is 200 km away from Agadez, and is carried on 138 kV transmission lines to a power station in Sonichar, which is about 40 km to the North. The town of Agadez receives power from this station.

6.3.2 Model Inputs

The key parameters used by HPAT for this study are listed in Table 6.

Table 6: Assumed Key Parameters for Agadez Scenario

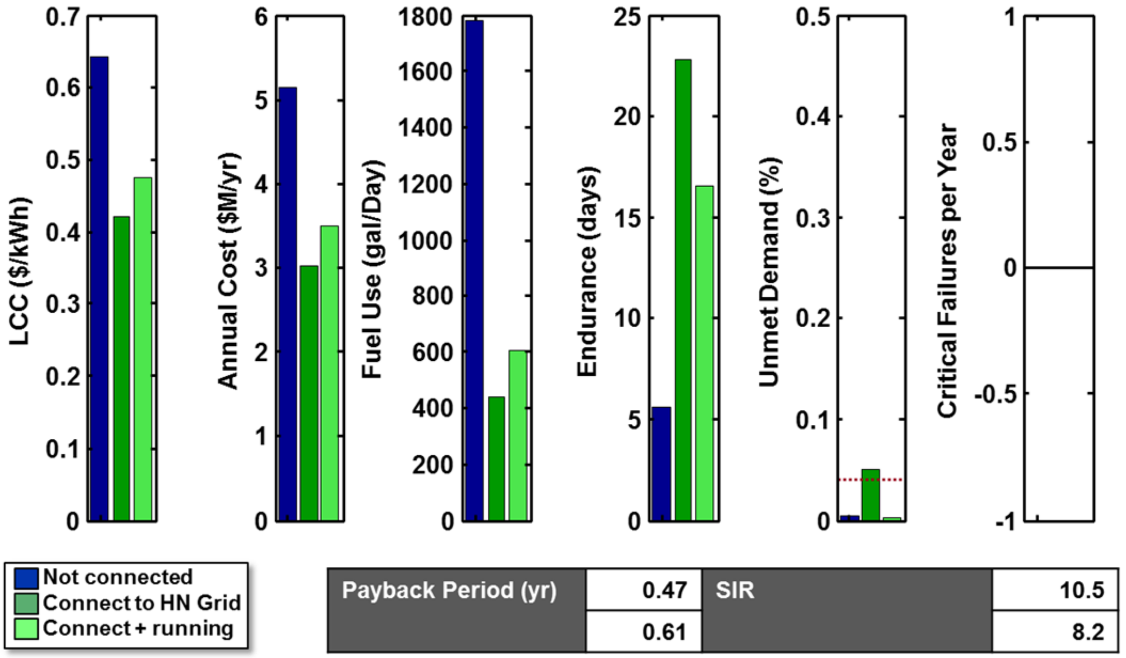
Base	System Life (yrs)	5
Load	Average (kW)	1,000
	Peak (kW)	1,200
	Critical Load	25% of total
	Pattern	diurnal
Generators	Generators	3 x 1-MW Cummins
	Fuel Price ($/gal)	7.70
	Fuel Storage (gal)	10,000
Grid	Cost to interconnect	$1,000,000
	Annual O&M costs ($/yr)	$10,000
	MTBF/MTTR (hr)	36/12
	Price ($/kWh)	0.25

An additional demand profile with less frequent but longer outages was also simulated. However, the results were very similar, and so they are not shown in the results section for the sake of clarity.

The cost of the interconnect was approximated by using the UFC substation cost of $225/kW capacity and distribution line cost of $50/LF (or $165K/km). The Area Cost UFC guide does not include Niger—most of the African nations have about 1.2 cost factor, though Djibouti is 1.8. To be conservative, this analysis will use 1.8 area cost factor for Niger. Combining these, a budget of $1M was set for the cost to connect to the grid. Sustainment costs were also taken from the UFC guide, and approximated to be $10,000/year. These cost assumptions must still be reviewed and updated by engineers with detailed knowledge of the site.

6.3.3 Results

Figure 34 shows the overview dashboard for the Agadez scenario. For this case, three architectures were modeled: one with no HN power, one with HN power and both standby generators were off (requiring 20 seconds to start), and one with HN power and one of the standby generators running idle at all times. Both HN architectures save costs and greatly increase base endurance. As expected, the architecture keeping the generators off saves the most fuel, but is slightly less reliable.



Payback Period (yr)	0.47	SIR	10.5
	0.61		8.2

Figure 34: HN Power Dashboard for Agadez Scenario

Figure 34 is based on the assumptions in Section 6.3.2. The sensitivity of this result to the cost of grid interconnection is illustrated in Figure 35. As can be seen, for the given assumptions, the interconnect can cost more than $10M, and still have a lower life cycle cost than not using HN power (the threshold shown with the dark grey line).

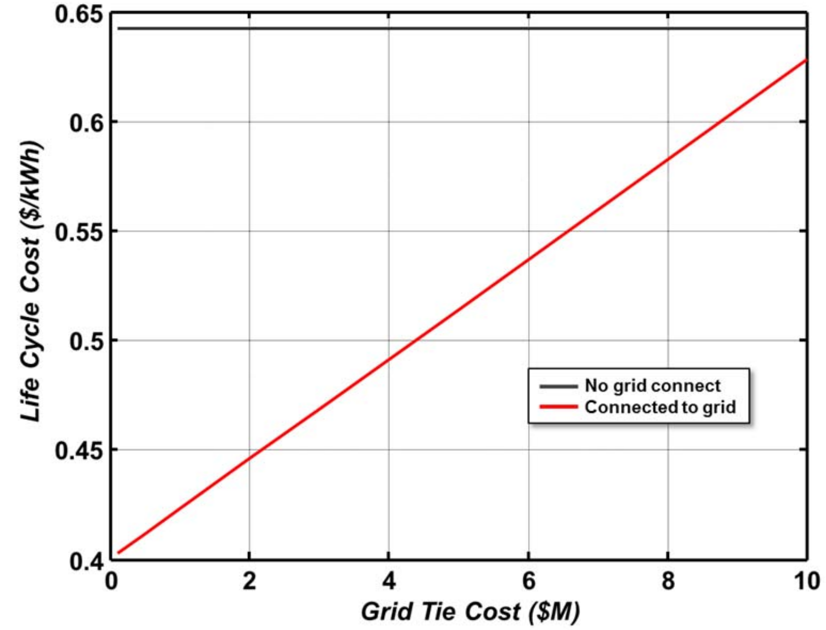


Figure 35: Sensitivity of LCC to Grid Tie Cost (Agadez Scenario)

The other key sensitivity is to fuel and electricity prices, which could fluctuate over the life of the base. Figure 36 maps that sensitivity to both of those parameters. As can be seen, there is significant margin both in electricity and fuel price; this reinforces confidence in recommending utilization of HN power at Agadez.

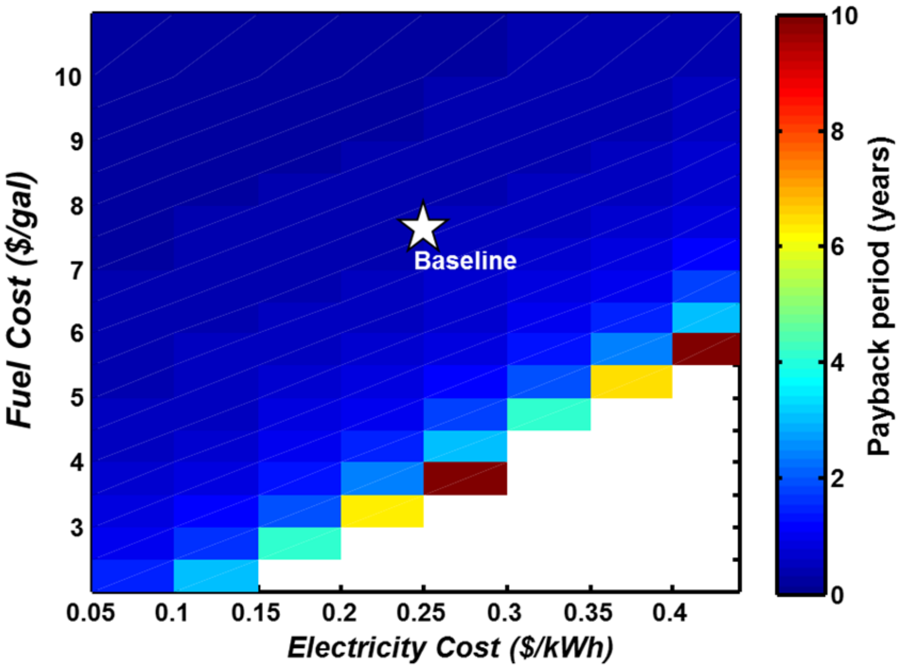


Figure 36: Sensitivity of Payback Period to Fuel and Grid (Agadez)

6.3.4 Recommendations

Based on this analysis of cost and reliability it is recommended that Agadez should strongly consider using HN power. The nearest grid tie location would need to be identified, and an estimated cost derived for installing the connection with the base. Other considerations, such as overall HN power capacity in that region, as well as security of the distribution line, should also be taken into account.

Nevertheless, Agadez would be a strong candidate for using HN power, and should be evaluated more fully.

6.4 Ouagadougou, Burkina Faso

6.4.1 Site Description

Currently, there is a US military presence in Ouagadougou, Burkina Faso. They occupy three townhouses, as well as have a facility at the airstrip near the town. The site will have 6 to 20 people stationed there typically.

These facilities are currently connected to the local power grid, though they also have backup power generators. For the houses, they have one 150 kVA, one 75 kVA, and one 60 kVA generators; at the airstrip they have two 100 kVA and one 60 kVA generators. They believe that these generators are all oversized. The power is intermittent, with failures averaging about twice a week. Because the power comes from a hydroelectric plant, during the dry summer they will often have daily rolling blackouts that will last half of the day. Sometimes the voltage is also poorly regulated, causing the circuits to trip and switch to the backup generators.

They buy diesel fuel from the local market. Sometimes the fuel quality is suspect, with a fair amount of sludge at the bottom of the 55 gallon drums. Currently, they buy about 2,000 liters for $2,600, which amounts to approximately $4.90 per gallon. They have a contractor who also comes and services the generators regularly; since hiring the contractor there have been no significant generator reliability issues.

Since this House is already connected to the HN power grid, it will be used as a hypothetical example for other similar facilities in similar conditions. The analysis will show how much is being saved already because of the decision to have connected to the grid, even with its current state of unreliability.

6.4.2 Model Inputs

This analysis will consider only the airfield facility. This scenario had very little data, so several approximating assumptions need to be made. The key inputs are listed in Table 7.

Table 7: Assumed Key Parameters for Burkina Faso Scenario

Base	System Life (yrs)	5
Load	Average (kW)	110
	Peak (kW)	150
	Critical Load	25% of total
	Pattern	diurnal
Generators	Generators	3 x 100-kVA
	Fuel Price ($/gal)	4.90
	Fuel Storage (gal)	500
Grid	Cost to interconnect	$80,000
	Annual O&M costs ($/yr)	$1,000
	MTBF/MTTR (hr)	16/8
	Price ($/kWh)	0.20

The approximated grid cost was arrived at by assuming a 100 m line length and using only a transformer and switchgear (rather than a full substation). The UFC guide does not include Burkina Faso—most of the African nations have about 1.2 cost factor, though Djibouti is 1.8. To be conservative, this analysis will use 1.8 area cost factor for Burkina Faso. A sizeable margin is also included because of the uncertainty.

6.4.3 Results

Figure 37 shows the overview dashboard for the Burkina Faso airfield scenario.

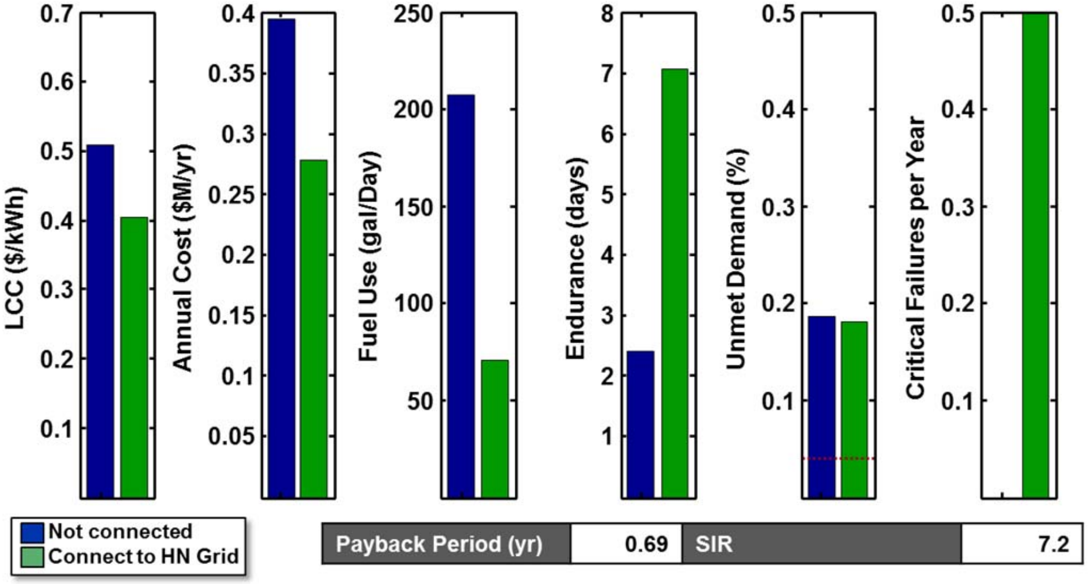


Figure 37: HN Power Dashboard for Burkina Faso Scenario

Figure 38 shows the sensitivity to fuel and electric grid prices.

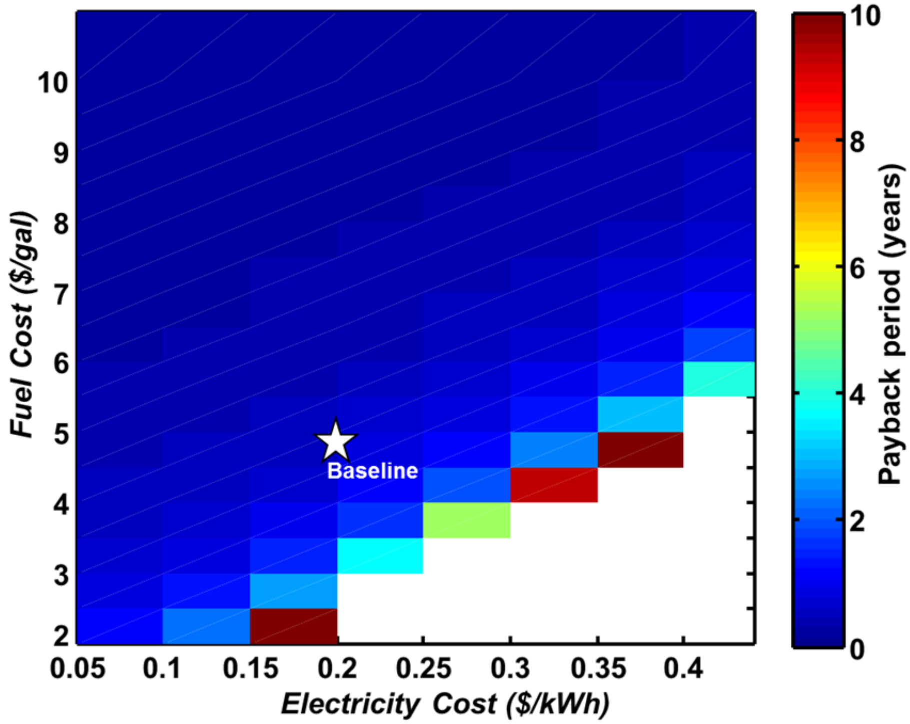


Figure 38: Sensitivity of Payback Period to Fuel and Grid (Burkina Faso)

In this case, there is significant margin in fuel price and in grid cost to make HN power a very safe option.

6.4.4 Recommendations

The Burkina Faso House is already connected to the HN grid, and this analysis shows the value of that decision. The recommendation is that other facilities in similar conditions should also strongly consider using HN power for their sites as well.

7 Simplified Host Nation Power Equation

The primary focus of this study is to compare two cases: one connected to the grid, and one not connected to the grid. In many cases, a very simple "back of the envelope" calculation is desired to check whether further investigation is warranted. There are also cases where there is such a lack of information, that there is no point in using a more sophisticated model. This simplified model will be referred to as the Simplified HN Power (SHP) Equation.

7.1 Deriving the SHP Equation

The simplified governing equation for whether to use HN power can be derived as follows.

We assume that every military base will install its own electric generation capability. Therefore, the connection to the electric grid will be an additional cost, with the expectation that the annual energy costs will be lower once connected. Therefore, the question can be framed as one of payback period for the initial connection cost. The payback period can be defined as:

$$P = \frac{\Delta I}{\Delta A}$$

Where P is the payback period, ΔI is the initial investment differential (the cost of all buying and installing all equipment to connect the base to the HN grid), and ΔA is the difference in annual energy costs between using only fuel and using the grid. The differential annual cost can be expanded as:

$$\Delta A = (C_F - C_E) \times R \times 8760 \times L$$

Where R is the reliability expressed as a percentage of time that the HN grid is on, L is the average power load, 8,760 represents the number of hours per year, C_F is the fuel cost of electricity generated from fuel ($/kWh) and C_E is the cost of electricity from the grid ($/kWh). It is worth noting that this relationship does not call out maintenance costs; this is because they are assumed to be nearly the same in the two cases (with or without grid power).

The electricity generated from fuel must account for the average efficiency of the generators over the year. Therefore, C_F is expanded to:

$$C_F = \frac{cf}{\eta K_{diesel}}$$

Where cf is the price of fuel per gallon in $/gal, η is the average generator efficiency, and K_{diesel} is the higher heating value (HHV) of diesel, typically assumed to be 139,000 BTU per gallon. The generator efficiency will depend upon what model is used and how they are operated; typical values observed in this study ranged about 30 - 35%.

Rearranging terms, one can define the investment-to-load ratio, ILR, as:

$$\boldsymbol{ILR = \frac{\Delta I}{L} = P \times R \times 8760 \times \left(\frac{cf}{\eta K_{diesel}} - C_E\right)}$$

The units of ILR are dollars per kilowatt. The ILR can be used as a budget threshold for assessing grid interconnect costs. From a cost perspective, the base should connect to the HN grid if the connection costs less than the ILR.

Figure 39 illustrates ILR. In this case, ILR is plotted against the cost of fuel, another major factor with great uncertainty. Observe the solid red line at the top. This represents the ILR threshold if the grid reliability were 100% (no failures), electricity was $0.10/kWh, and there was a required payback period of 3 years. In these conditions, the red line would indicate the maximum that should be spent on connecting to the grid, per watt of load capacity. So if fuel cost $4/gal, then the maximum cost would be $6/W. In that case a connecting a small base with a 200 kW average demand load would pay back within 3 years even if costs were up to $1.2M. Likewise, a large base with 20 MW average demand would pay back within 3 years even if costs were up to $120M.

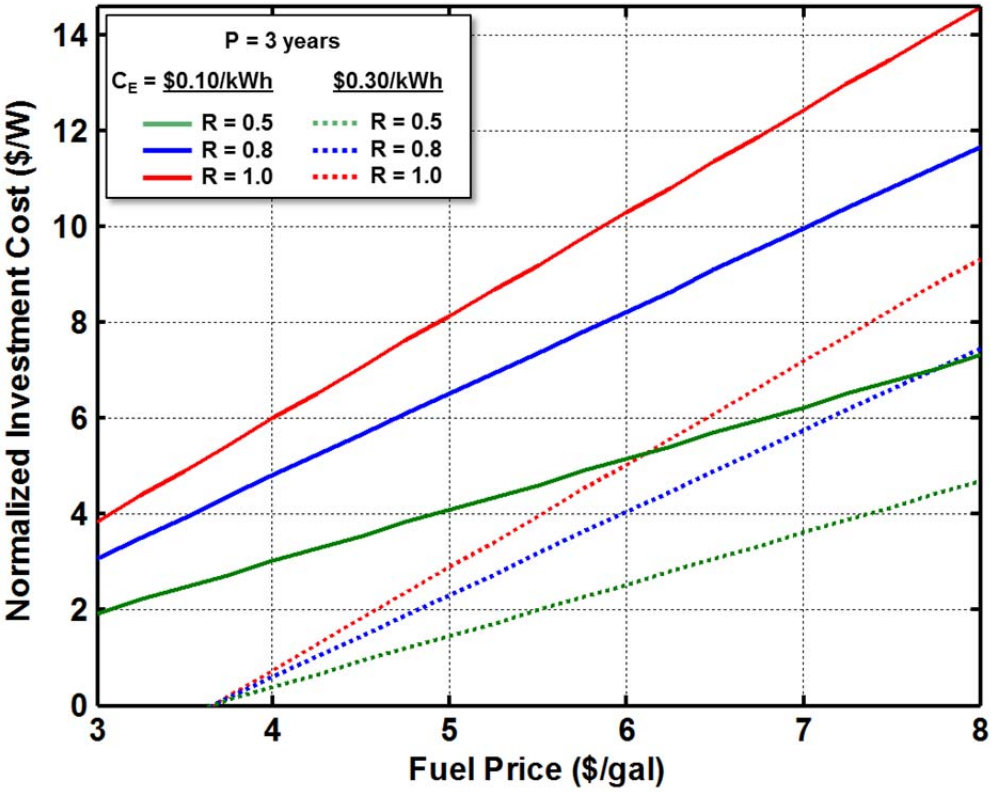


Figure 39: ILR versus Fuel Price – SHP Equation

The lines represent boundaries—any cost below the line is acceptable, any cost above the line is not.

Where there is uncertainty, conservative estimates should be used for each parameter. In this case, the conservative estimates are:

- Fuel cost (cf): conservative is lower
- Electricity cost (C_E): conservative is higher
- Efficiency (η): conservative is higher
- Reliability (R): conservative is lower
- Payback period (P): conservative is shorter

7.2 Estimating the Accuracy of the SHP Equation

The SHP Equation can be compared to the higher fidelity HPAT. Five different scenarios—with different loads, generators, and grid reliabilities—were simulated in HPAT. The statistical input for reliability was assumed known and the average generator efficiency was estimated before running for each scenario; these values were used in the simplified ILR equation. Each scenario included two architectures: one with the grid and one without; the only substantial difference was in the resulting generator efficiency (since all other inputs remained the same between simulations). HPAT calculated the actual ILR to achieve a 3 year payback for each scenario. The ratio of the HPAT-calculated ILR versus the SHP Equation ILR for the five scenarios is shown in Figure 40.

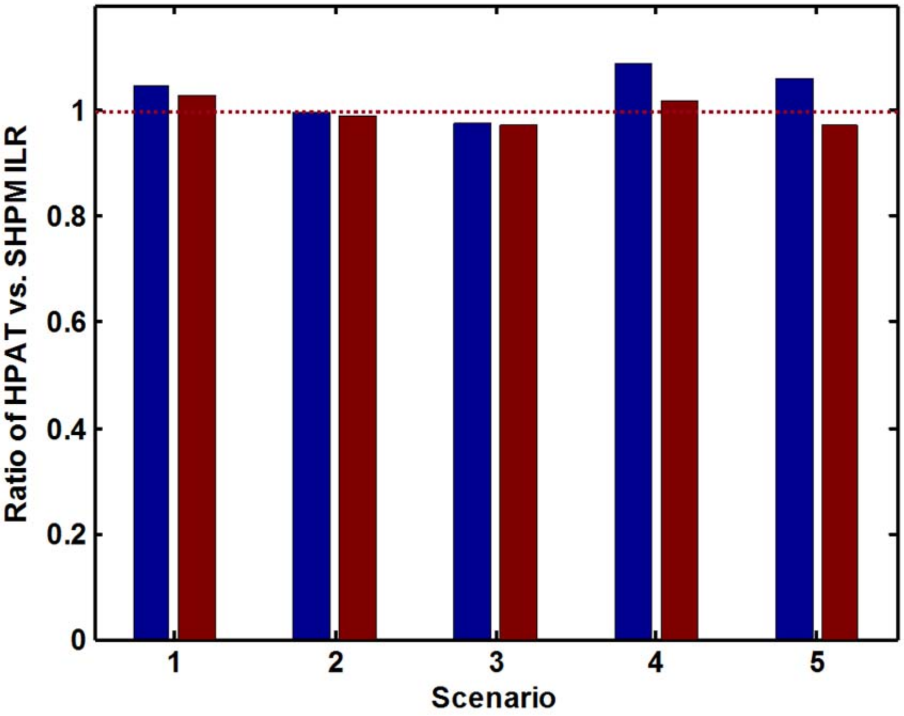


Figure 40: Comparison of HPAT ILR and the SHP Equation ILR values

This shows that the simplified equation always came within 10% (and in most cases less than 5%) of the higher-fidelity HPAT results.

To maintain budget margins, one would like to underestimate the ILR during planning. This margin can generally be maintained by slightly overestimating the average efficiency of the generators.

7.3 Examples of Applying SHP Equation

Below are a few different notional applications of using the SHP Equation.

7.3.1 Determining the budget for a grid interconnect

Suppose a base is being proposed with a 2 MW average load. The base will be in place for at least 3 years, but it is uncertain beyond that period. The region's electric grid averages about 70% reliable over the course of the year. The diesel fuel costs \$4.50/gal, including the contract to transport and fill the on-base storage tanks. The local cost of electricity is \$0.18/kWh.

In this case, we set the equation as:

$$I = P \times R \times 8760 \times \left(\frac{cf}{\eta K_{diesel}} - C_E\right) \times \boldsymbol{L}$$

Inserting the values, the equation would be:

$$I = 3 \times 0.7 \times 8760 \times \left(\frac{4.50}{0.35 \times 40.737} - 0.18\right) \times 2{,}000$$

This yields a budget of \$4.9M dollars. If the interconnect can be made for less than that amount, it should be done.

Now suppose in the same region, it was a small tactical base with a 100 kW average load. It will only be in place for 1 year, and the selected generators run JP-8 fuel, which because of remoteness will cost \$7/gal. We expect the average generators load to be around 32%. In this case, the equation would be:

$$I = 1 \times 0.7 \times 8760 \times \left(\frac{7}{0.32 \times 36.927} - 0.18\right) \times 100$$

For this tactical case, the interconnect budget would be \$252K.

7.3.2 Determining the payback period

Return to the example of the 2MW base running diesel generators. Suppose the engineers return saying that the interconnect will require a 2 km distribution line and a small substation on the base. They estimate the cost to be \$320K for the line, and the substation to cost \$280,000/MW. Therefore, the payback period will be:

$$P = \frac{\Delta I}{R \times 8760 \times \left(\frac{cf}{\eta K_{diesel}} - C_E\right) \times L}$$

Filling in the values:

$$P = \frac{320{,}000 + 560{,}000}{0.7 \times 8760 \times \left(\frac{4.50}{0.35 \times 40.737} - 0.18\right) \times 2{,}000}$$

In this case, the payback period would be 0.53 years, which is about 193 days.

7.3.3 Determining grid reliability threshold

It may be in some cases that reliability of the electric grid is not certain, but the question is what is the minimum reliability that makes the investment worthwhile?

Again, take the previous example, except in this case reliability is the unknown. The equation is modified slightly:

$$R = \frac{\Delta I}{P \times 8760 \times \left(\frac{cf}{\eta K_{diesel}} - C_E\right) \times L}$$

Using all the same cost estimates from before for the 2-MW example, the equation becomes:

$$R = \frac{320{,}000 + 560{,}000}{3 \times 8760 \times \left(\frac{4.50}{0.35 \times 40.737} - 0.18\right) \times 2{,}000}$$

In this case, the reliability threshold is 12%. This may seem a surprisingly low number, but over three years, the saved fuel from just 12% of the year will make up the estimated investment cost.

7.3.4 Determining price threshold

For yet a different use case, suppose we are in negotiations with the Host Nation regarding the price of electricity. We would like to know our Best Alternative to a Negotiated Agreement (BATNA). Once again, assuming the same notional scenario, with 70% grid reliability and our same cost estimates for the fuel and the interconnect, we can calculate the maximum price for electricity.

We rearrange the terms:

$$C_E = \frac{cf}{\eta K_{diesel}} - \frac{\Delta I}{L \times R \times P \times 8760}$$

Filling in the values,

$$C_E = \frac{4.50}{0.35 \times 40.737} - \frac{880{,}000}{2{,}000 \times 0.7 \times 3 \times 8760}$$

This gives a maximum price threshold for electricity in this scenario to be $0.29/kWh.

7.3.5 Determining the distance of a base from a grid

The SHP Equation can also be applied to other planning-related studies. For example, one may desire to place the base in a location where grid power is still economically viable.

Now we break the investment cost into two components: the set substation cost and the line cost which will vary with distance. Once again, rearranging terms, we can solve for distance, D, as:

$$D = \left[P \times R \times 8760 \times \left(\frac{cf}{\eta \times K_{diesel}} - C_E\right) \times L - I_S\right] \times \frac{1}{I_L}$$

Again, suppose the engineers provide a cost of $50 per linear foot to install the lines in this remote region; that would be $164,000 per kilometer. Using the same scenario as in the previous examples,

$$D = \left[3 \times 0.7 \times 8760 \times \left(\frac{4.50}{0.35 \times 40.737} - 0.18\right) \times 2{,}000 - 560{,}000\right] \times \left(\frac{1}{164{,}000}\right)$$

The result is that the base could be a maximum distance of 27 km from the nearest grid connection point.

This can be extended to parameterize the maximum distance as a function of base size; the larger the base, the higher the distribution line cost that can still be amortized over the load. Figure 41 shows the resulting trend. This figure is only to illustrate the general trend, it does not account for the very real effects of line losses and other pragmatic considerations over such distances.

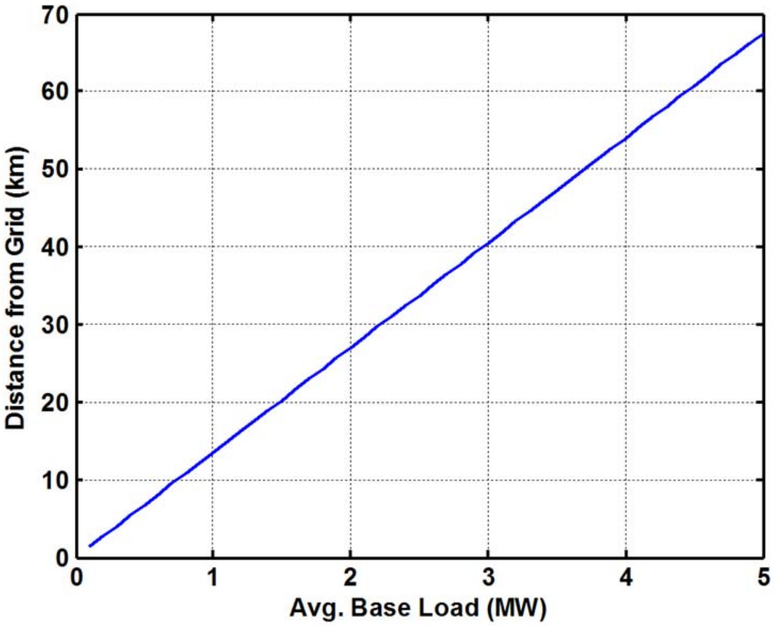


Figure 41: Distance from Grid Related to Base Size (SHP Equation)

7.3.6 Determining the fuel-grid cost zone

As simple as the SHP Equation is, there are still several variables involved, so it is hard to create a single graphic that will tell a planner whether they should consider using HN power. However, we can attempt to do so with just a couple of assumptions.

First, we will set payback period to 3 years—most bases will be in service longer than that, but it is not so long as to raise too many concerns. The second assumption will be assuming a fixed interconnect cost. For this example, we will use an inflated cost from the military UFC guide, which lists a substation as $225/kW [1]; we will assume $280/kW, which will also include the distribution line from the HN grid to the base.

The next remaining variables are reliability, fuel price, and grid price. Rearranging the governing equation to solve for CE, we get:

$$C_E = \frac{cf}{\eta K_{diesel}} - \frac{\Delta I/_L}{P \times R \times 8760}$$

The resulting relationship is shown in Figure 42. The close spacing of the lines indicates that the grid reliability is not a strong factor at this scale of trade space. To interpret the graph, if the region is anywhere below or near the line, then Host Nation power should be considered and would be recommended from a cost perspective.

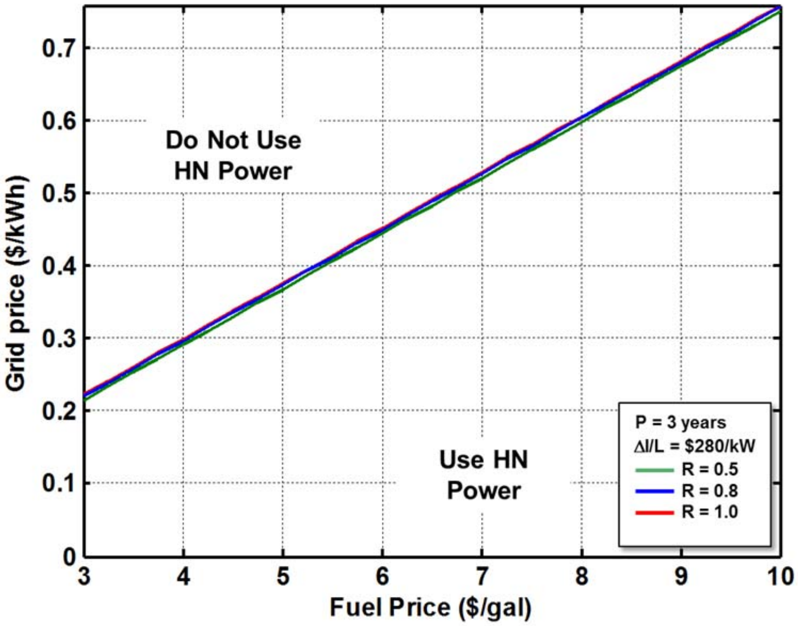


Figure 42: HN Grid Reliability Threshold in Fuel-Grid Parameter Space

Therefore, setting reliability to a very conservative 50%, the loads can now be included as a variable. This enables including a budget for the distribution line separate from the substation cost. As an example, consider a line that costs $350,000 (compare to the UFC cost of $43 per linear foot).The equation is modified again:

$$C_E = \frac{cf}{\eta K_{diesel}} - \frac{\left(I_S/_L + I_L/_L \right)}{P \times R \times 8760}$$

The relationship is shown in Figure 43. As can be seen by the blue and green lines, as the base becomes larger (above a megawatt of average load), the fixed cost of the distribution line amortizes over the total cost, and becomes less sensitive. However, for the much smaller bases, the high fixed line cost becomes more prohibitive. While this is only a notional example, it does illustrate the basic trend: when connecting to HN power, the larger the base, the more distant it can afford to be from the nearest HN grid tie in point.

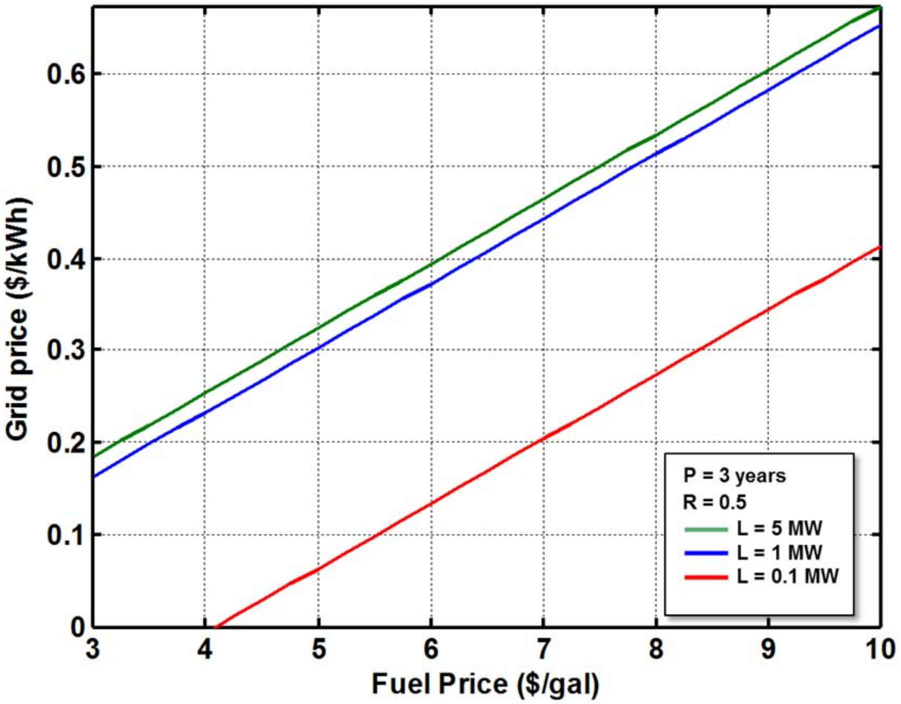


Figure 43: Base Size Threshold in Fuel-Grid Parameter Space

7.4 Operational Model Derivation

During some operational missions, cost is not a strong consideration; rather, the amount of fuel that must be transported to the base is much more important, especially in remote and/or dangerous locations with an extensive and exposed logistic tail.

The SHP Equation relationships also help estimate fuel saved by using the HN grid. The fuel used per year without the grid (the baseline case) is simply:

$$F_B = \frac{L \times 8760}{\eta \times K_{diesel}}$$

The amount used when there is a grid connection is the same relationship, except it only runs when the grid is off:

$$F_G = (1 - R)\frac{L \times 8760}{\eta \times K_{diesel}}$$

The ratio of fuel used in the two cases is:

$$\frac{F_G}{F_B} = \frac{(1 - R)\frac{L \times 8760}{\eta \times K_{diesel}}}{\frac{L \times 8760}{\eta \times K_{diesel}}} = 1 - R$$

And therefore the percent fuel saved is just the complement of fuel used,

$$\text{Percent Fuel Saved} = [1 - (1 - R)] \times 100 = R \times 100$$

The percentage of fuel saved is essentially the same as the reliability. So if a Host Nation power grid is 90% reliable, then the fuel usage is reduced by 90%. The models and analysis confirm this intuitive and perhaps obvious relationship. Note that this relationship assumes the average efficiency of the generators remains the same; the effects of breaking this assumption are seen in the Agadez Option 1 case presented previously in Section 6.3.

Consider an example location, where the power goes out on average 6 hours every single day, all year round. This would be by any standard a very low reliability grid. Nevertheless, it is still 75% reliable. If a base were to connect to this grid, it would save 75% of its fuel, or in other words, it would use only 25% as much fuel. This would also mean that resupply trips could be reduced by 75% as well, which could have a significant impact on base operations and support.

The average grid reliability, and therefore percent fuel saved, can be estimated by either SAIDI or MTBF statistics.

$$\text{Percent fuel savings} = \frac{SAIDI\ [\text{min}]}{525{,}600} \times 100 = \frac{MTBF_{grid}}{MTTR_{grid} + MTBF_{grid}} \times 100$$

8 Guidance for Base-specific Assessments

The general findings are conclusive that HN power can be very effective for saving cost, increasing robustness of the base to fuel disruptions, and without very much loss of reliability. The next step is to examine specific bases—either existed or planned—and assess them specifically for suitability for HN power. This should be done in a broader context of also considering microgrids and other alternative power sources.

8.1 Short form

When doing a preliminary analysis (for example, using the SHP Equation), the following short list of information should provide sufficient information.

- Base name & location
- Planned or estimated base lifetime (yrs)

- Average demand load (kW)
- Estimate local power reliability (SAIDI/SAIFI or MTBF/MTTR)
- Price of electricity from local grid ($/kWh)
- Number and size of generators
- Cost of fuel ($/gal)
- On-base fuel storage (gal)
- Cost to integrate base with local power grid ($)

This information should be sufficient to estimate within about 10% the cost effectiveness of connecting to the HN grid.

8.2 Long form

For a more thorough assessment of a site, to gather all the data needed for HPAT, and to understand some of the qualitative factors, this longer set of information is required:

- Base
    - Name
    - Location
    - Date of initial operation
    - Planned lifetime
- Demand
    - Load profile (a data file preferable)
    - Average annual energy used
    - Maximum load
    - Minimum load
    - Essential vs. non-essential (as a percentage or as two separate load profiles)
- HN Power Grid
    - Cost of electricity
    - Expected variability/growth in cost
    - Provider (company name, are they nationalized?)
    - Reliability: how often do power outages occur (SAIFI or MTBF)
    - Reliability: how long is it out when it goes out (SAIDI or MTTR)
    - Quality: surges, frequency drifts, or voltage sags
    - Seasonal dependence
    - Distance to nearest HN power line tie-in point
    - Distance to nearest HN power station
    - How much does sustainment or maintenance of interconnect equipment cost annually
    - Will that be performed by the HN provider or by base personnel/contractors
- Base Electrical Infrastructure
    - How much of base uses spot generation versus central power
    - Estimated length of distribution lines on base

  - Estimated number of connections (number of transformers from distribution to drop lines; and sizes of those transformers)
  - Voltage level of distribution system
  - Frequency
  - Estimated cost to install centralized distribution system
  - Estimated cost to connect to grid (line cost and equipment cost)
  - How much does sustainment or maintenance cost annually
  - Will that be performed by the HN provider or by base personnel/contractors
- Generators (fill out for each type of generator on base)
  - Generator size
  - Make and model
  - How many total of this type on the base
  - How many are typically running
  - Is the generator manual or auto-start
  - How long does it take to start from the moment of failure
  - If available, provide efficiency curves
  - Fuel type
  - Fuel price
  - Expected variability/growth in fuel price
  - Amount of on-base fuel storage
  - Is fuel bought from local economy
  - How much does sustainment or maintenance cost annually
  - How often is the generator taken out for planned maintenance
  - How long does planned maintenance take
  - How often does the generator fail
  - How long, on average, does it take to restore a failed generator to service
  - Will service be performed by the HN provider or by base personnel/contractors
  - Is the reliability different between running and standby generators
  - How is the load balanced among generators (e.g., spot, equal, optimal)
- Power storage (batteries, UPS, etc.)
  - Storage capacity per device
  - Number of devices
  - Type (make and model)
  - How many are online at one time
  - Are they kept fully charged
  - Reliability: How often do they fail
  - How long would it take to replace if it failed
  - What is the “round trip” efficiency (including the invertor and rectifier)
  - How much does replacement cost
  - How much do supporting electronics cost (cabling, invertors, rectifiers, etc.)
  - How much does sustainment or maintenance cost annually

9 Acronyms

AFRICOM	Africa Combatant Command
BATNA	Best Alternative to Negotiated Agreement
BOS	Base Operation and Support
BTU	British Thermal Units
CDF	Cumulative Distribution Function
DoD	Department of Defense
ENEE	Empresa Nacional de Energia Electrica
EUPW	Escalating Uniform Present Worth
HN	Host Nation
HPAT	Host Nation Power Analysis Tool
IAP	Ingenuity and Purpose (contractor company name)
IEEE	Institute of Electrical and Electronics Engineers
ILR	Investment to Load Ratio
JTF	Joint Task Force
kV	Kilovolt
kVA	Kilovolt-amp
kW	Kilowatt
kWh	Kilowatt-hour
LCC	Life Cycle Cost
MIT	Massachusetts Institute of Technology
MIT LL	MIT Lincoln Laboratory
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
MW	Megawatt
OCONUS	Outside Contiguous United States
O&M	Operations and Maintenance
PDF	Probability Distribution Function
PV	Photovoltaic
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCAB	Soto Cano Air Base
SCUBA	Self-Contained Underwater Breathing Apparatus
SHP	Simplified Host nation Power
SIR	Savings to Investment Ratio

SOC	State of Charge
UFC	Unified Facility
UPS	Uninterrupted Power Supply
UPW	Uniform Present Worth
US	United States
USACE	United States Army Corps of Engineers
USAF	United States Air Force
W	Watts

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