Estimating Economic and Logistic Utility of Connecting to Unreliable Power Grids

Franz D. Busse, *MIT Lincoln Laboratory*, Scott Van Broekhoven, *MIT Lincoln Laboratory*

Abstract—Remote military, scientific, refugee, and industrial facilities may operate in areas with unreliable host nation (HN) power grids. The economic and logistic utility costs and benefits of connecting the facility to the grid can be quantified. A rigorous simulation model, the Host Nation Power Analysis Tool (HPAT), was developed to analyze specific bases. A more generalized, but still useful simplified equation is also derived to help decision makers determine whether to connect to the grid or not. Several practical examples of using these models are also presented. In the cases studied, it was always found that using the Host Nation grid was better. One can think of HN power like other intermittent sources, like solar, and still design a facility energy architecture that benefits from that source when available.

Index Terms—facilities management, energy management, energy resources, power generation, power grids, power system economics, power system reliability.

I. Nomenclature

BTU	British Thermal Units
DoD	Department of Defense
HN	Host Nation
HPAT	Host Nation Power Analysis Tool
ILR	Investment to Load Ratio
kV	Kilovolt
kVA	Kilovolt-amp
kW	Kilowatt
kWh	Kilowatt-hour
LCC	Life Cycle Cost
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
MW	Megawatt
O&M	Operations and Maintenance
PV	Photovoltaic
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SHP	Simplified Host nation Power
SIR	Savings to Investment Ratio
UFC	Unified Facility
UPS	Uninterrupted Power Supply
UPW	Uniform Present Worth
US	United States
W	Watts

II. Introduction

Military bases, scientific outposts, mining or drilling operations, and humanitarian camps are just a few examples of facilities that often operate in remote regions of the world where the power grid is unreliable, and therefore use generators to provide power. For those operating these remote facilities, they must decide whether it is worth connecting to the local power grid to meet a portion of their operational energy requirements.

In countries with poor electrical system reliability where power is typically provided by diesel generators, the fuel is either purchased from the local population or transported from remote fuel depots. This incurs a significant cost for the operator, and in many cases they end up paying several multiples of the cost of electricity from the local grid [1]. This also introduces in some cases an additional security vulnerability with the transport of fuel [1].

While the host nation grid may be highly unreliable, it does not necessarily mean that the most reliable and cost effective solution is an entirely off grid solution. In these instances, the host nation power 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 photovoltaics (PV), which for most parts of the world will be less than 30% on average [2]. 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.

A modeling and simulation tool was developed to assess alternative energy management architectures for remote facilities, which is called the Host Nation Power Analysis Tool (HPAT). Furthermore, a simplified, but surprisingly accurate relationship was developed that provides an initial estimate of the value of connecting to the HN power grid. This relationship, called the Simplified Host-nation Power (SHP) Equation, can help in a wide variety of design and planning decisions.

F. D. Busse is a senior staff with MIT Lincoln Laboratory, Lexington, MA 02420 USA (e-mail: busse@ll.mit.edu).

S. Van Broekhoven is a group leader with MIT Lincoln Laboratory, Lexington, MA 02420 USA (e-mail: vanbroekhoven@ll.mit.edu).

III. Host Nation Power Analysis Tool

Fig. 1 presents a flow chart of the HN Power Analysis Tool (HPAT). It runs a time-stepped Monte Carlo simulation, and can be configured to sweep across up to three different user parameters. Inputs allow alternative scenarios to be simulated, including different load profiles, equipment, architectures, and cost parameters.
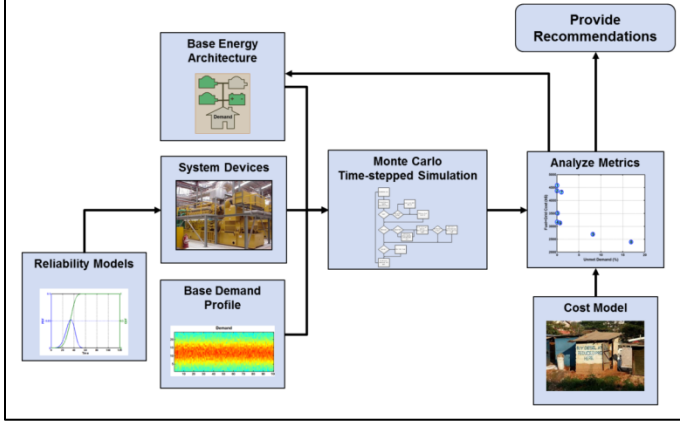

Fig. 1: HN Power Analysis Tool (HPAT) Flowchart

A. Base Energy Architecture

In setting up the HPAT scenario, the user supplies a list of different architectures to assess. For this study, the architectures were generally limited to a facility with or without HN power, and all other backup generation or storage remaining constant. The same loads, grid outage profiles, and random number generator seed values for simulating failures, are then used in the time-stepped simulation. This approach gives a similar "apples-to-apples" comparison of performance between architecture options. The parameters specified for each architecture are: generator type, number of generators, minimum number of generators running, storage type, storage number and/or capacity, and whether connected to the grid or not.

B. Base Demand Profile

The demand at the base drives the energy system design. The demand can either be from actual hourly data or simulated, typically using a diurnal pattern with randomized variations.

C. 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.

1) HN Grid

The HN grid model is defined by these 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 residents 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—[$] this is the cost to integrate the base with the HN power grid. This includes any changes to the HN grid (including upgrades to the nearest substation, switches, and additional power lines running to the base) as well as changes of equipment on the base. The cost should include equipment as well as installation labor costs.
- Grid O&M cost—[$/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.

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).

2) Storage Devices

The storage model is defined by: capacity (kWh), "round trip" efficiency (%), MTBF (hours), MTTR (hours), cost ($), and O&M cost ($/year).

The storage model does not include decaying capacity over life. It is 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.

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.
- 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).
- 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).

Fig. 2 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 Fig. 2), different makes and models may have different efficiencies. Regardless of whether a base is connected to the grid or not, achieving maximum efficiency is always important.
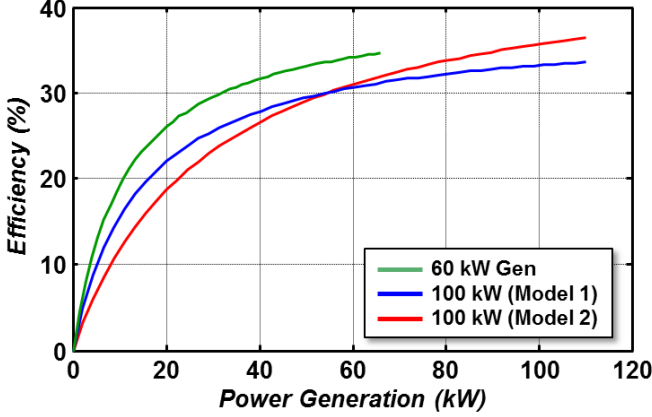

Fig. 2: Example generator efficiency curves.

D. Reliability Model

In accordance with IEEE standards and industry best practices, a Weibull distribution was used to model reliability of all components, including the grid, generators, and storage devices [3]. The Weibull distribution provides a well-proven model for both the failure (MTBF) and repair (MTTR) of devices.

E. 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.

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

F. 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.

HPAT tracks four key cost-related metrics [ref]:
- Life Cycle Cost (LCC)
- Payback Period
- Savings-Investment Ratio (SIR)
- Annual Costs

G. Model Results

1) 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. Fig. 3 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 bar 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.
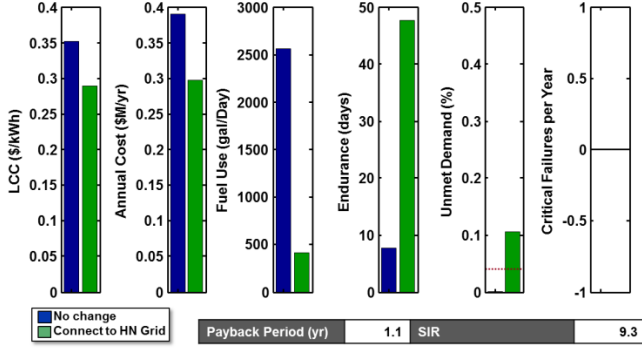
Fig. 3: HP Grid Decision Dashboard (example)

2) 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.

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. Fig. 4 shows the payback period for integrating with the grid as a function of fuel and grid prices.
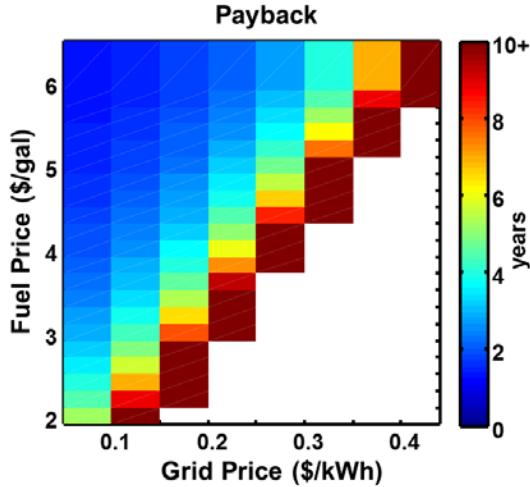

Fig. 4: Payback period as Function of Grid and Fuel Prices (example)

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.

IV. SIMPLIFIED HOST NATION POWER 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:

$$P = \frac{\Delta I}{\Delta A} \tag{1}$$

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:

$$\Delta A = (C_F - C_E) \times R \times 8760 \times L \tag{2}$$

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:

$$C_F = \frac{cf}{\eta K_{diesel}} \tag{3}$$

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:

$$ILR = \frac{\Delta I}{L} = P \times R \times 8760 \times \left(\frac{cf}{\eta K_{diesel}} - C_E \right) \tag{4}$$

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.

Fig. 5 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

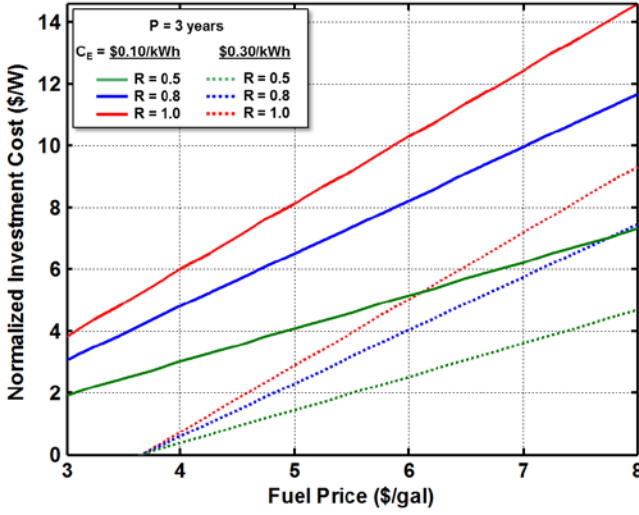base with 20 MW average demand would pay back within 3 years even if costs were up to $120M.

Fig. 5. 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

A. Estimating Accuracy of 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 Fig. 6.
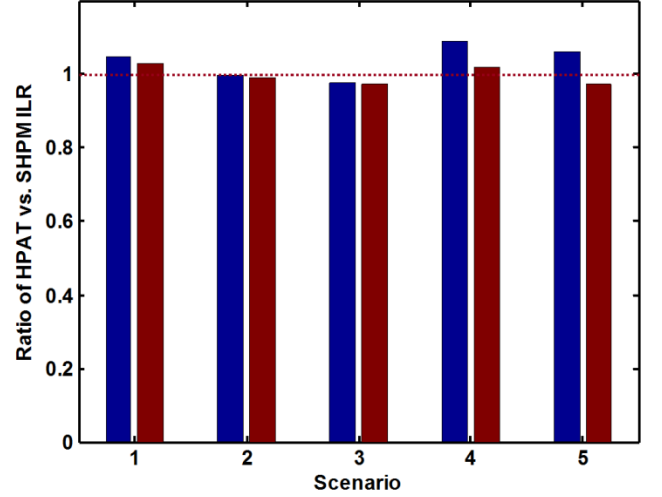

Fig. 6. Comparison of HPAT ILR and the SHP Equation ILR values

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.

V. APPLICATION EXAMPLES

Below are a few notional applications of the SHP Equation.

A. 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:

$$I = P \times R \times 8760 \times \left(\frac{cf}{\eta K_{diesel}} - C_E \right) \times L \quad (5)$$

Inserting the values, the equation would be:

$$I = 3 \times 0.7 \times 8760 \times \left(\frac{4.50}{0.35 \times 40.737} - 0.18 \right) \times 2,000 \quad (6)$$

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:

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

For this small-scale case, the interconnect budget would be $252K.

B. 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:

$$P = \frac{\Delta I}{R \times 8760 \times \left(\frac{cf}{\eta K_{diesel}} - C_E\right) \times L} \quad (8)$$

Filling in the values:

$$P = \frac{320,000 + 560,000}{0.7 \times 8760 \times \left(\frac{4.50}{0.35 \times 40.737} - 0.18\right) \times 2,000} \quad (9)$$

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

C. 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:

$$R = \frac{\Delta I}{P \times 8760 \times \left(\frac{cf}{\eta K_{diesel}} - C_E\right) \times L} \quad (10)$$

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

$$R = \frac{320,000 + 560,000}{3 \times 8760 \times \left(\frac{4.50}{0.35 \times 40.737} - 0.18\right) \times 2,000} \quad (11)$$

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.

D. Determining the 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:

$$C_E = \frac{cf}{\eta K_{diesel}} - \frac{\Delta I}{L \times R \times P \times 8760} \quad (12)$$

Filling in the values,

$$C_E = \frac{4.50}{0.35 \times 40.737} - \frac{880,000}{2,000 \times 0.7 \times 3 \times 8760} \quad (13)$$

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

E. Determining the Distance 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:

$$D = \left[P \times R \times 8760 \times \left(\frac{cf}{\eta \times K_{diesel}} - C_E\right) \times L - I_S\right] \times \frac{1}{I_L} \quad (14)$$

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,

$$D = \left[3 \times 0.7 \times 8760 \times \left(\frac{4.50}{0.35 \times 40.737} - 0.18\right) \times 2,000 - 560,000\right] \times \left(\frac{1}{164,000}\right) \quad (15)$$

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. Fig. 7 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.
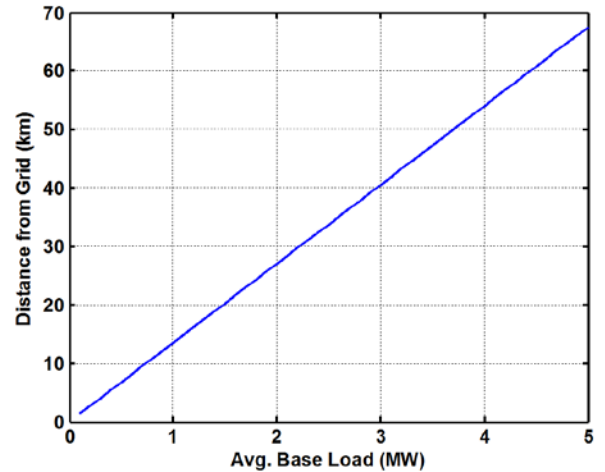

Fig. 7. Distance from Grid Related to Base Size (SHP Equation)

F. 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 [4]; 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:

$$C_E = \frac{cf}{\eta K_{diesel}} - \frac{\Delta I/L}{P \times R \times 8760} \tag{16}$$

The resulting relationship is shown in Fig. 8. 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.
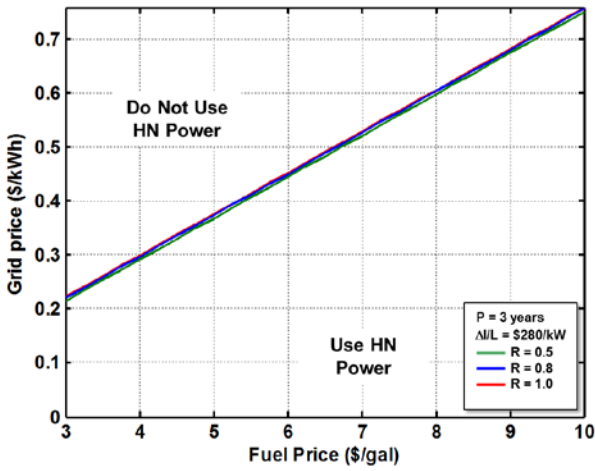

Fig. 8. HN Grid Reliability Threshold in Fuel-Grid Parameter Space

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:

$$C_E = \frac{cf}{\eta K_{diesel}} - \frac{\left(I_S/L + I_L/L \right)}{P \times R \times 8760} \tag{17}$$

The relationship is shown in Fig. 9. 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.
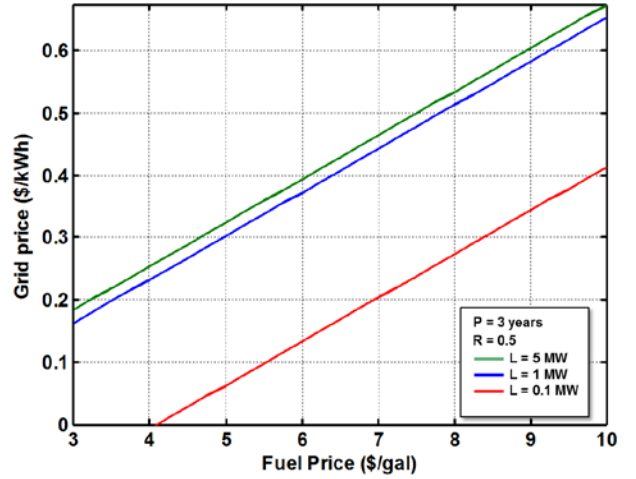

Fig. 9. Base Size Threshold in Fuel-Grid Parameter Space

VI. Operational Model Derivation

During some situations, cost is not a strong consideration; rather, the amount of fuel that must be transported to the facility 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:

$$F_B = \frac{L \times 8760}{\eta \times K_{diesel}} \tag{18}$$

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

$$F_G = (1 - R) \frac{L \times 8760}{\eta \times K_{diesel}} \tag{19}$$

The ratio of fuel used in the two cases is:

$$\frac{F_G}{F_B} = \frac{(1 - R) \frac{L \times 8760}{\eta \times K_{diesel}}}{\frac{L \times 8760}{\eta \times K_{diesel}}} = 1 - R \tag{20}$$

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

$$F_S = [1 - (1 - R)] \times 100 = R \times 100 \tag{21}$$

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.

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.

$$F_S = \frac{SAIDI \text{ [min]}}{525,600} \times 100$$
$$= \frac{MTBF_{grid}}{MTTR_{grid} + MTBF_{grid}} \times 100 \qquad (22)$$

VII. CONCLUSIONS

For this work, a simulation tool, HPAT, was developed that enabled exploring a variety of design options and scenario conditions to study the cost-benefit trades in connecting facilities to local power grids.

A simplified, but very useful relationship was also developed to help planners and decision makers understand whether host nation power should be considered for installations, as well as appreciate the driving factors influencing that decision.

It was found that in all cases studied, that it was economically beneficial to connect the remote facility to the host nation power grid, even when it is unreliable. This was assuming that the facilities maintained a full backup generation capability, and kept those systems well maintained and fueled. Under those conditions, overall system reliability actually increased when including the host nation power grid.

VIII. ACKNOWLEDGMENT

IX. BIBLIOGRAPHY

[1] Defense Science Board, "More Fight - Less Fuel," OUSD Acquisition, Technology, and Logistics, Washington, D.C., 2008.

[2] Energy Information Agency, "Capacity Factors for Utility Scale Generators Not Primarily Using Fossil Fuels," Energy Information Agency, 26 April 2016. [Online]. Available: https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_6_07_b. [Accessed 23 May 2016].

[3] IEEE Power Systems Reliability Subcommittee, "Std. 493 (gold book) Design of Reliable Industrial and Commercial Power Systems," Institute of Electrical and Electronics Engineers, New York, NY, 2007.

[4] HQ US Army Corps of Engineers, *DoD Facilities Pricing Guice Change 8,* Washington, D.C.: Unified Facilities Criteria system, Department of Defense, 2015.

X. BIOGRAPHIES

Franz Busse is a Senior Staff in the HADR Systems Group at MIT Lincoln Laboratory. His area of research is architecting and modeling complex systems for analysis and/or design. While at Lincoln, he has been involved in system engineering, analysis, and program leadership for disaster response architectures, alternative energy architectures and technology, satellite systems and technology, missile defense technology, border patrol technology and CONOPS, and radar interference mitigations. He joined MIT Lincoln Laboratory in 2002; before that, Dr. Busse received his MS and PhD from Stanford University, and his BS from MIT, all in aerospace engineering.
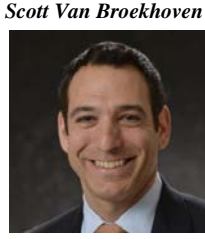
Scott Van Broekhoven is the Group Leader of the Energy Systems Group at MIT Lincoln Laboratory. In this role he oversees staff developing technology solutions that enhance the efficiency and resiliency of both tactical and domestic energy systems. This includes creating advanced architectures and system designs to improve the resiliency of power grids, prototyping new control techniques for microgrids and distributed energy resources, and the development of test assets to provide consistent evaluation of DER control strategies. Mr. Van Broekhoven earned a Bachelor's of Science degree in Mechanical Engineering from Northwestern University and a Master's in Science degree in Engineering Systems from MIT.