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Fort Belvoir, Virginia

for

PROJECT MANAGER MOBILE ELECTRIC POWER
Fort Belvoir, Virginia

ARMY TACTICAL HYBRID POWER SYSTEM ANALYSIS AND DESIGN

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Executive Summary

The diesel generators used to support Army portable electric power requirements are expensive, noisy and produce harmful emissions. The focus of this study is to compare the advantages and disadvantages of using hybrid systems and variable displacement engines with the diesel generators in use today. Hybrid systems consist of diesel generators, photovoltaic cells, wind turbines, batteries and inverter/rectifiers. The variable displacement engine would be a smaller model of a Defense Advanced Projects Agency (DARPA) project that has higher electrical conversion efficiencies (converting diesel fuel to electrical power) at part-load ratios, than the standard diesel generator.

Electrical demand profiles were collected from units that were training at the National Training Center and assumed to be representative of deployed units. The largest and smallest averaged electrical demand profiles were modeled using an hourly computer simulation.

Due to the intermittent nature of renewable resources, a wide variety of options were investigated to take advantage of relatively large combinations of technologies that complement each other. Battery storage was investigated with all systems. Solutions were constrained to insure that hardware would fit spatially and by weight onto existing military trailers. Capital and annualized cost, fuel consumption and system weight were used to quaantify solutions. System weight inclusive and exclusive of fuel weight was considered. Due to an inability to measure reliability and ease of maintenance, these metrics were not used in the study.

Costs were annualized so that technologies that have high capital but low operating costs (such as photovoltaic cells) could be fairly compared to technologies with low capital but relatively high operating costs (such as diesel generators). We assumed that the variable displacement engine's mass production cost (excluding R&D costs) and weight would be similar to the stand-alone generator.

Results demonstrate that, with the electrical loads provided, hybrid and variable displacement engines are almost always economically attractive to stand-alone generators. At higher electrical loads the hybrid system becomes less attractive due to the weight required for a large number of batteries to store energy. Capital cost and weight (without fuel) almost always increases for the hybrid system, while the life-cycle cost and total weight (including fuel) almost always decreases.

The variable displacement engine operates at half of the annual cost and fuel consumption of the stand-alone generator with no increase in weight (excluding or including fuel weight). Hardware weight is assumed similar to the stand-alone generator. The variable displacement engine efficiency also appears to be less sensitive to the shape of the demand profile. General trends are listed in the Table provided below:

Table: Summary of General Results and Trends

General Results	Ratio, Hybrid to Stand-alone Generator	Ratio, Variable Displacement Engine to Stand-alone Generator
Capital Cost ($)	2 to 4	1
Annualized Cost ($/year)	0.3 to 1	0.5
Fuel Consumption (L)	0.3 to 1	0.5
Weight w/o fuel (lbs)	1.5 to 3.7	1.0
Weight w/ fuel (lbs)	0.4 to 1	0.5

Hybrid systems and variable displacement engines have sufficient advantages to warrant further studies. We recommend that the Army prototype, test, and field hybrid energy systems and collect data on those systems to measure reliability and ease of maintenance. We also recommend that DoD investigate developing an appropriately sized variable displacement engine to meet electrical demand over a broad range of electrical demand. Lastly, we recommend that the Army obtain electrical demand profiles from deployed units to ensure realistic data for sizing engines.

1. BACKGROUND

1.1 Preamble

The United States military is interested in developing a different approach to providing electrical power to tactical units in the field. This would lower costs, reduce noise signature and reduce harmful emissions. The diesel generators in use today have an average age of over 24 years and will soon need replacement. Project Manager Mobile Electric Power (PM-MEP) commissioned the United States Military Academy (USMA) and the Center for Army Analysis (CAA) to study possible advantages and disadvantages of using hybrid energy systems and variable displacement engines with the diesel generators in use today. Hybrid systems concentrated primarily on diesel generators, photovoltaics, wind turbines, batteries, and inverter/rectifiers. The variable displacement engine is in development via funding through the Defense Advanced Projects Agency (DARPA).

1.2 Research Objective

The objective of this project is to quantify and compare the performance of advanced energy systems to that of existing diesel generators for US Army tactical applications.

2. USER REQUIREMENTS

One of the first steps in any design is to determine customer requirements and then develop a solution to meet those requirements. Quality Function Deployment (QFD) is a method that directly ties customer desires to features in a design. Its secondary purpose is to assess competing product’s strengths and weaknesses. When used properly, QFD insures the development of a successful product. The QFD process is detailed in Eureka and Ryan (1988), Hauser and Clausing (1988) and Sullivan (1986). This section details the customer requirements for tactical mobile power systems.

2.1 Determining Customer Requirements

Using a Pairwise comparison we determined the relative importance of each of the customer requirements. The Pairwise comparison is show in Table 1 with each customer requirement compared against others. If the customer requirement on a particular row is more important than the customer requirement in the column, then that particular cell contains a value of unity. If the customer requirements are equally important, then that cell contains a 0.5. If the customer requirement in a column is more important than the customer requirement on a row, then the cell contains a zero. Each of the customer requirements has a total sum value which is divided by the total sum of all of the customer requirements to obtain the relative weights of each of the customer requirements.

Table 1: Pairwise Comparison of Customer Requirements

Hybrid power system	Simple	Efficient	Quiet	Transportable	Clean emissions	Reliable	Capital Cost	Provide power on the move	Fast set-up	Easy maintenance	Annual cost	Sum	Weight
Simple	x	1	1	0	1	0	1	0	1	0	1	6	0.11
Efficient	0	x	0	0	1	0	0.5	0	0	0	0.5	2	0.04
Quiet	0	1	x	0	1	0	0	0	1	0	0	3	0.05
Transportable	1	1	1	x	1	0.5	1	0.5	1	1	1	9	0.16
Clean emissions	0	0	0	0	x	0	0	0	0	0	0	0	0
Reliable	1	1	1	0.5	1	x	1	1	1	0.5	1	9	0.16
Capital Cost	0	0.5	1	0	1	0	x	0.5	0.5	0	0	3.5	0.06
Provide power on the move	1	1	1	0.5	1	0	0.5	x	0.5	0	0.5	6	0.11
Fast set-up	0	1	0	0	1	0	0.5	0.5	x	0	0.5	3.5	0.06
Ease of maintenance	1	1	1	0	1	0.5	1	1	1	x	1	8.5	0.15
Annual cost	0	0.5	1	0	1	0	1	0.5	0.5	0	x	4.5	0.08
													1

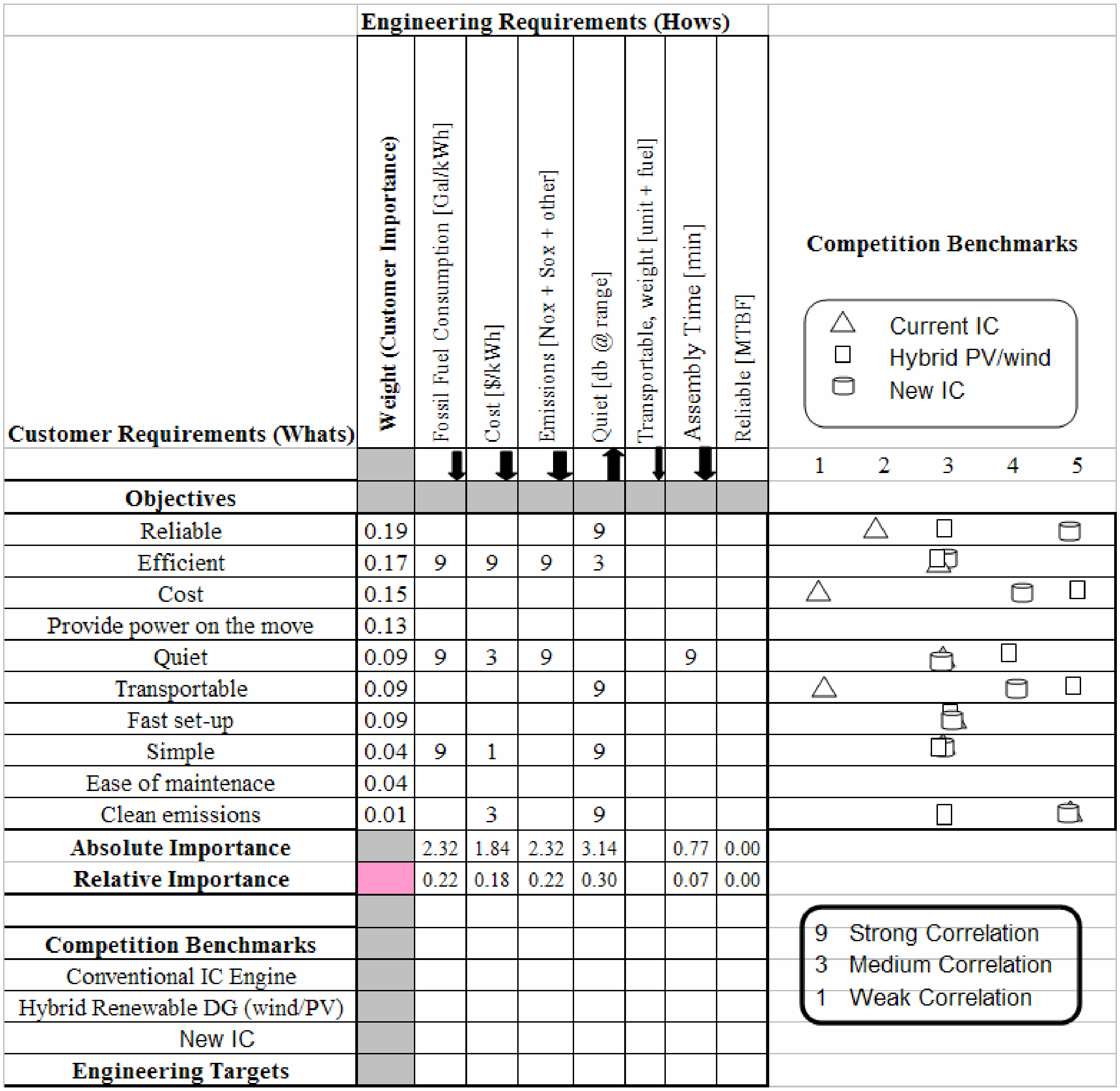
As shown in Table 2, transportability, reliability, and ease of maintenance are the traits most important for tactical power systems. A hybrid system must be easily transported due to the highly mobile nature of today's Army. These power systems must also provide power reliably as a power failure in a Tactical Operation Center could cripple the effectiveness of an Army unit. Lastly, maintenance must be fairly simple as there is little time to perform routine maintenance on power systems in the field and it often must be performed in austere conditions. Clean emissions are ranked fairly low since it is assumed that any fielded system would meet emissions standards.

Table 2: Summary of Relative weights from Pairwise Comparison

Customer Requirements	**Relative weight**
Transportable	0.16
Reliable	0.16
Ease of maintenance	0.15
Simple	0.11
Provide power on the move	0.11
Sustainment costs	0.08
Capital Cost	0.06
Fast set-up	0.06
Quiet	0.05
Efficient	0.04
Clean emissions	0.00

2.2 Relative Importance of Requirements

Using the rank ordered customer requirements in Table 2 we attempted to produce a QFD, Figure 1, to quantify the customer requirements using engineering requirements. Engineering requirements are a measure of the customer requirements and must be measurable. If units for an engineering requirement cannot be found, then the requirement is not measurable and needs to be readdressed. For example, in this case, we list “Ease of Maintenance” as a customer requirement. However, ease for which user (mechanic or operator) has not been defined and no metrics are in place to measure the requirement. This QFD has not been completed because many of the engineering requirements are not as of yet quantifiable. We recommend that this be the focus of a follow-on study.



Customer Requirements (Whats)	**Weight (Customer Importance)**	Fossil Fuel Consumption [Gal/kWh]	Cost [$/kWh]	Emissions [Nox + Sox + other]	Quiet [db @ range]	Transportable, weight [unit + fuel]	Assembly Time [min]	Reliable [MTBF]	1	2	3	4	5
		⬇	⬇	⬇	⬆	⬇	⬇						
Objectives													
Reliable	0.19				9					△	□		⌭
Efficient	0.17	9	9	9	3						□ ⌭ △		
Cost	0.15								△			⌭	□
Provide power on the move	0.13												
Quiet	0.09	9	3	9			9				⌭ △	□	
Transportable	0.09				9				△			⌭	□
Fast set-up	0.09										□ ⌭ △		
Simple	0.04	9	1		9						□ ⌭ △		
Ease of maintenace	0.04												
Clean emissions	0.01		3		9						□		⌭ △
Absolute Importance		2.32	1.84	2.32	3.14		0.77	0.00					
Relative Importance		0.22	0.18	0.22	0.30		0.07	0.00					
Competition Benchmarks													
Conventional IC Engine													
Hybrid Renewable DG (wind/PV)													
New IC													
Engineering Targets													

Engineering Requirements (Hows)

Competition Benchmarks

△ Current IC
□ Hybrid PV/wind
⌭ New IC

9 Strong Correlation
3 Medium Correlation
1 Weak Correlation

Figure 1: Quality Function Deployment of Tactical Generator Systems

3. ENERGY MODELING

Energy modeling is primarily concentrated on the demand profile, diesel generators, photovoltaics, wind turbines, batteries, and inverter/rectifiers for a possible hybrid energy system for tactical units.

Given the variable nature of electrical demand, an hourly model was chosen. Energy modeling was completed using National Renewable Energy Laboratory's Hybrid Optimization Model for Electric Renewables (HOMER). This program provides a model for distributed power and simplifies the task of evaluating designs of both off-grid and grid-connected power systems for a variety of applications. For this study, only an off-grid application was modeled. The model's sensitivity algorithm makes it possible to evaluate many system configurations and provides the ability to accurately determine the various energy system configurations such as hourly averaged electrical demand profile, capital costs, operation and maintenance costs, and natural resource information.

3.1 Model Algorithms

Photovoltaic radiation modeling is accomplished by providing the latitude and monthly clearness index. From this, the global horizontal radiation can be computed with estimated hourly variation (Graham and Hollands, 1990). The resulting hourly time series has statistically reasonable day-to-day and hour-to-hour variability. The radiation incident on a tilted PV panel is then calculated using the HDKR model (Duffie and Beckmann, 1991).

Similar to solar data, hourly wind speed data can be generated from monthly average wind speeds, their distribution pattern, a power curve scaling factor, and wind speed scaling factor to account for air density and anemometer height respectively. These parameters specify the daily pattern, hourly variability, and long-term distribution of the resulting hourly wind data. With a user specified aerogenerator power curve, realistic short, medium, and long-term patterns can be estimated.

An hourly electrical load profile is obtained from historical records that account for variations for each day. Randomness is added to the daily profiles so that every day is unique, but matched to historical records. Historical records are used to establish the base case for electrical costs. Section 4.2 discusses this in more detail.

A diesel fueled internal combustion engine, capable of load following is considered. Power generation and fuel consumption is estimated from typical part load efficiency curves and thermal heat recovery is not considered.

Batteries are modeled using vendor measured product information. Battery curves consider the capacity (Ah) as a function of discharge current, round trip efficiency, minimum state of charge, maximum charge rate, depth of discharge and cycles to failure.

Converters (inverters and rectifiers) are considered anytime a conversion from AC to DC or DC to AC is required. All converters are assumed to have an efficiency of 90%.

3.2 Modeling limits and constraints

When designing a power system, one must make many decisions about the system configuration. What components make sense to include in the system design? How many and what size of each component should be used? The large number of technology options and the variation in technology costs and availability of energy resources make these decisions difficult.

As an initial step to meeting the user requirements of Table 2, one solution boundary was established by only considering operation of a diesel generator using a load following algorithm.

This is considered a limit since this configuration does not take advantage of other technologies and is generally inefficient at low part load ratios. This configuration was termed the "Stand-alone generator." A second limit was established where increased hardware (such as batteries, photovoltaic arrays, wind turbines, etc.) are not constrained. The optimal solution is deemed "best" when the annual least cost solution is found, even if it would not be feasible due to weight and spatial concerns. This configuration was termed "Unconstrained." Once these limits are established, any constrained solution can be measured relative to the extremes.

Modeling of the unconstrained system results in lower annualized costs and fuel consumption, but the system is impractical as a tactical system because of the large number of wind turbines (50) and batteries (100). The large number of batteries and wind turbines render the unconstrained system non-deployable due to weight and volume as it would weigh about 13,000 pounds and require at least three M200A1 trailers to transport.

4. MODEL INPUTS

Accurate results are dependent upon input information such as electrical demand, equipment operating characteristics, equipment capital cost, operating and maintenance cost and geographic location where the system might be used.

This study collected data from a wide variety of sources to include DoD agencies and industry. Some costs were estimated since some of the modeled components have not been militarized.

4.1 Electrical Demand profiles

PM-MEP gathered five-minute electrical demand data from various US Army units fighting mock battles at Fort Irwin, home of the National Training Center. Due to the large number of computations required to develop accurate models, only the units with the largest and smallest electrical load profiles were used. This ensures that accurate models from large and small units can be compared instead of just one type or size of unit. The large electrical demand profile was obtained from a Brigade Tactical Operation Center (TOC) and the small electrical demand profile was from a Digital Bridge unit. A Digital Bridge unit converts data between analog and digital formats.

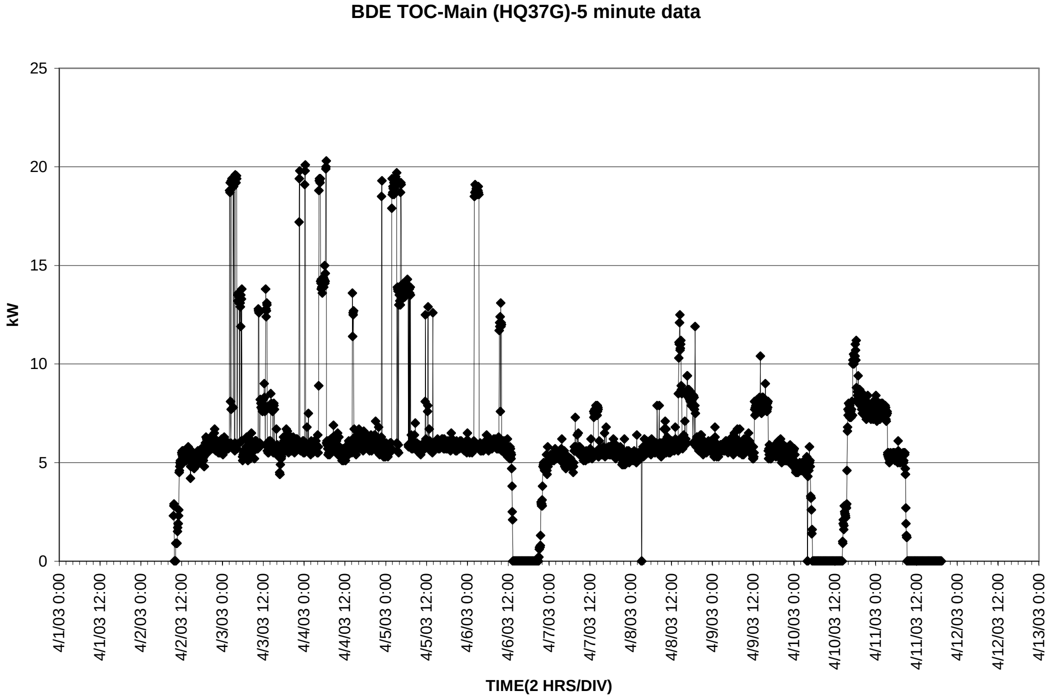


Figure 2: Brigade TOC 5 minute data

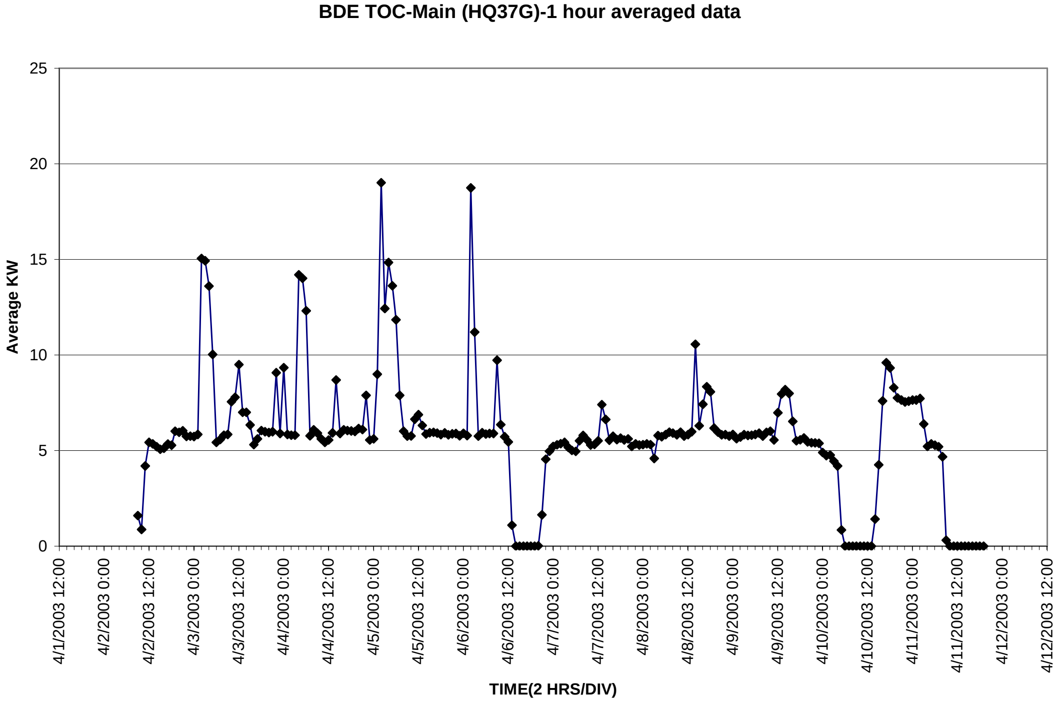


Figure 3: BDE TOC 1 hour averaged data

4.1.1 Incorporation of peak demand into averaged data

Due to the large number of calculations that would be required to model a five-minute electrical demand profile, data were averaged to obtain the value for an hour. Anytime data are collapsed from a fine resolution to a larger resolution there is a loss in accuracy. However, electrical demand varies by geographic location and unit mission, each of which introduces more uncertainty into the demand profile than does one-hour averaging. Therefore, it is believed that any error obtained from averaging the data is small in comparison.

Peak demands are important in electrical demand profiles because these transients may cause a power failure for an inadequately sized power system. Thus all of the peaks on the original data set were inserted into the corresponding peaks in the hourly averaged data. The average load for the original data set was 5.78 kW, while the average load for the hourly averaged data with the new peaks was 5.86 kW, which is sufficient for modeling given the other uncertainties in this study.

4.1.2 Creation of electrical demand profiles for one year period

The hourly-averaged data were used to create demand profiles for a period of one year. A 1600 hour operating profile was developed since 1600 hours is the minimum training hours required by Army units. To develop the profile, a week's worth of data was created from the hourly averaged data. The week's worth of data was copied until it occupied 400 hours, then the remaining 1790 hours (of that particular season) remained zero. This procedure was replicated three more times, each in a different season, to capture the variability of renewable energy resources (solar and wind) at different times of the year.

To create a 3200 hours use profile the same procedure was followed except 800 hours of data was posted per season. For the 6400 hours use per year file, each season was populated with 1600 hours of data. To simulate a deployed unit which required power all year long, without long periods of down time, the demand profile was populated until it reached all 8760 hours of the year.

4.2 Costs

This section describes collected or assumed costs that were used during modeling. To fairly compare different energy systems one must annualize all costs. This is required since some options, such as renewables are characterized by high capital cost, but low annual cost, whereas diesel generators are exactly the opposite.

4.2.1 Diesel Generator

Diesel generators are characterized by low capital costs, but high operating and maintenance costs. Operating and maintenance costs for deployed Army units are particularly high due to the added costs of delivering fuel into theater. Diesel fuel costs are discussed in detail in section 4.2.1.3.

4.2.1.1 Capital Costs

The tactical quiet generator is the currently fielded generator set by the US military. The costs shown in Table 3 represent the costs of purchasing or replacing diesel generator sets. Capital costs for the tactical quiet generator sets were obtained from PM-MEP.

Table 3: Tactical Quiet Generator Capital Costs

Model	Rated Capacity (kW)	Procurement. Cost
MEP 531A	2	$4,916.35
MEP-831A	3	$8,794.81
MEP-802A	5	$11,712.01
MEP-803A	10	$13,319.68
MEP-804A	15	$13,736.68
MEP-805B	30	$25,155.19
MEP-806B	60	$28,907.28

4.2.1.2 Operation and Maintenance Costs

Diesel generator capital and operation-maintenance costs are vital to performing an adequate economic analysis. A diesel fueled internal combustion engine, capable of load following is considered. Power generation and fuel consumption is estimated from typical part load efficiency curves as shown in Figure 4. This generic figure, which is broadly applicable to internal combustion engines, shows the loss of generating efficiency as the part load to rated capacity diminishes.

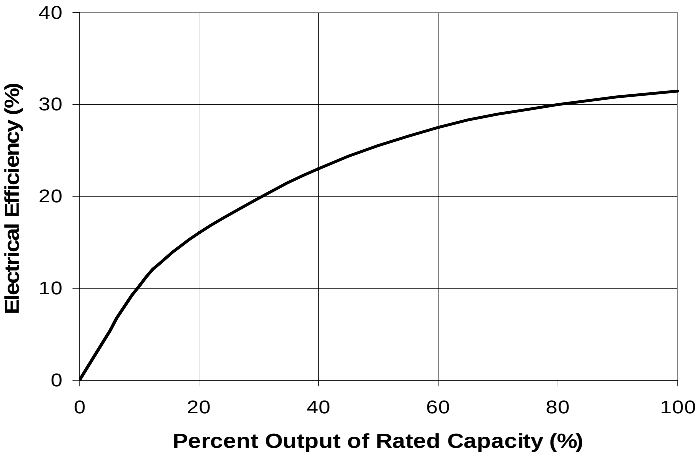


Figure 4: Internal combustion engine operating characteristics

Operating costs for gasoline generators of various sizes were determined in a study conducted by Yawitz (1988) and shown in Table 4. Although the costs are outdated and the investigated generators did not use diesel fuel, the relative cost of different sized generators remains the same with today's diesel generators. Specifically, smaller generators cost more to operate per unit of electrical energy (per kWh). Fuel consumption is a function of engine size and larger engines convert fuel more efficiently. The efficiency curve shown in Figure 4 must be modified to account for relative fuel efficiencies. At sizes of less than 20 kW, the maximum efficiency can be estimated at 20%. Thus, the fuel efficiency curve was proportionally scaled to account for this.

Table 4: Diesel generator operating costs

Size, kW	Density*	Total $/kWh	Total $/hr	Fuel $/kWh	*Fuel $/hr*
5	8142	0.364	1.82	0.127	*0.637*
10	3594	0.220	2.20	0.118	*1.18*
15	2411	0.192	2.88	0.095	*1.43*
30	3385	0.118	3.54	0.082	*2.46*
60	3071	0.164	9.85	0.087	*5.20*
100	631	0.097	9.75	0.085	*8.48*
200	54	0.760	15.28	0.060	*12.07*
500	16	0.088	44.18	0.056	*27.89*
700	5	0.074	51.58	0.059	*41.44*
750	*24*	*0.064*	*47.87*	*0.058*	*43.71*

* Number of generators studied in the respective kW rating

Operation and maintenance costs are difficult to determine for generators. This is due to large differences in costs of similar units and the lack of published costs in general. A poorly maintained generator can be more costly than one that is properly maintained. The frequency of use, length of time each machine is used and loading conditions are all major factors in operation and maintenance costs. Additionally, generators have hundreds of moving parts and the calculation of a part failure for an individual machine is difficult to predict unless all of the above factors are considered.

For this study, we estimated that if a generator was operated at less than 50% of rated capacity for the majority of operating hours, maintenance costs would be double those of a unit that was loaded above 50% of rated capacity. This estimate was made from three observations. 1) Commercial generator manufacturers will not warrantee their units if they are loaded at less than 50%, 2) In a broad agency announcement released by CECOM, the wet stacking was listed as a problem for generators loaded at less than 70%, and 3) In interviews with automotive engine mechanics, they estimated that the cost of maintaining vehicles that are used for city driving is at least double that of vehicles used for non-city use. Although these three observations do not directly justify the increased cost of minimally loaded engines, they appear to support this assumption. We should also note that O&M cost variance only changes total annual costs by around 3 percent, although reliability could be significantly enhanced.

According to the US Army Comptroller the 2002 measured the labor rate for technicians operating a diesel generator is $20.10/hr. This information was obtained from PM-MEP. From this information we calculated the total operation and maintenance cost of each of the generator sets in the US Army's inventory. In Table 5, information from the first five columns were obtained by PM-MEP. Using the annual total for costs of each associated generator set minus the fuel cost, we obtained the annual operational and maintenance cost for each generator. Using the value of 300 hours of use per year (300 hours of use was the basis of the information) we obtained the hourly operational and maintenance costs for each of the diesel generator sets.

Table 5: Tactical Quiet Generator Operation and Maintenance Cost

Size (kW)	Fuel	PMCS	Sch. Maint.	Unsch. Maint.	Annual O&M Total ($)	Annual O&M Costs	Hourly O&M Costs
2	$1,584	$248.74	$82.73	$36.86	1,952.32	$368.32	$1.23
3	$1,584	$248.74	$103.48	$48.47	1,984.69	$400.69	$1.34
5	$2,736	$248.74	$108.26	$366.10	3,459.10	$723.10	$2.41
10	$4,656	$248.74	$107.50	$273.11	5,285.34	$629.34	$2.10
15	$7,200	$248.74	$82.63	$282.50	7,813.87	$613.87	$2.05
30	$12,960	$248.74	$115.25	$433.15	13,757.14	$797.14	$2.66
60	$21,648	$248.74	$120.41	$513.11	22,530.26	$882.26	$2.94

4.2.1.3 Fuel Costs

According to the Office of the Under-Secretary of Defense for Acquisition, Technology, and Logistics (2001), the US Army spends from $10 to $400 per gallon for diesel fuel in deployed areas. These costs are based on the added cost of bringing the fuel into theater, storage and handling, and transporting, it to the forward lines. The Army pays $10/gallon for modest distances near the theater depot, $40/gallon for overland transport of up to 600 km and $400/gallon if air delivery is required. The above costs were used in computer modeling to provide a sensitivity analysis of energy system configurations due to fuel cost.

Figure 5: Resupply via helicopter

4.2.2 Photovoltaic

Commercial photovoltaic costs can be estimated at around \$6.6/W_p of power under standard conditions. However, it is estimated that when modified to meet military requirements, the purchase cost will be closer to \$10/W_p. Although this cost is speculative, it is consistent with the increased cost of other military hardware.

It has been demonstrated that photovoltaic cells provide power with little degradation for over 20 years. However, for military applications, it is anticipated that cells will become damaged and need replacement. Models therefore assume a life span of 20 years. US Department of Energy's long-term goal for thin film modules estimate a tenfold cost reduction, which would require substantial progress, Zweibel (1999). Any combination of cost and performance below about \$0.5/W_p would represent a good approximation of future commercial photovoltaic cost. However, it should be noted that this estimate is contingent upon advances in material science. Furthermore, the costs to militarize photovoltaic panels are not expected to decrease at the same rate as the cost of producing them. Since costs and efficiencies are speculative, it is reasonable to believe that the real cost of replacement cells will decrease by a factor of two. Therefore, models assume a 20-year replacement cost of \$5/W_p. Photovoltaic operation and maintenance costs are insignificant and are set to zero for this study. Cost is also linearly proportional to photovoltaic array surface area.

4.2.3 Wind Turbine

Wind turbines have some deficiencies when used in tactical situations: large visual signature because of the elevation they must be placed at to generate power, high initial capital costs, moderate operation and maintenance costs (compared to photovoltaics), and an increased set up time because it must be mounted on a tower. The primary advantage of using wind turbines are that they provide more power per investment dollar than photovoltaic cells.

4.2.3.1 Capital Costs

Wind turbines come in a large variety of sizes. For modeling purposes we selected the Sunwize Whisper H40 due to its ruggedness and compact size. At rated capacity, it produces 920 W of electricity. The SW Whisper H40 sells for $1895, but for modeling purposes the price was assumed doubled (to $3790) to include the extra costs of militarization and adding a mobile tower.

4.2.3.2 Operation and Maintenance Costs

The National Renewable Energy Laboratory in Golden, Colorado estimates operation and maintenance costs of $0.015/kWh. Using this value we assumed that the wind turbines operation and maintenance costs will be similar to those of peak power. By multiplying the operation and maintenance cost of wind turbines ($0.015/kW*hr) by the peak power (0.92 kW) and then multiplying that value by the maximum hours of operation per year (8760 hours), we obtain the operation and maintenance cost for these wind turbines to be $121/year.

4.2.4 Battery

Batteries are an essential piece of equipment in any hybrid energy system because they are a reliable and mature technology for storing energy. Energy storage systems such as super-capacitors, flywheels, and hydrolysis machines (to produce hydrogen for fuel cells) are still in developmental stages so they were not used in this study. Communications and Electronics Command (CECOM) has determined that a 305 Amp-hour battery costs about $316. The Center for Army Analysis has determined that batteries of around 300 Amp-hours have an operation and maintenance cost of approximately $19.92/year. A typical battery operating characteristic curve is shown in Figure 6 and demonstrates charge and discharge characteristics at different rates.

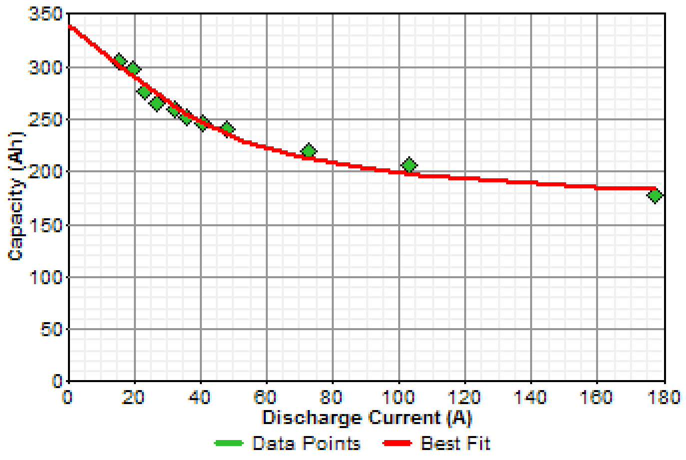


Figure 6: Operating Characteristics of Battery used during modeling

4.2.5 Inverter/Rectifier

Inverter/rectifiers are essential to convert the direct current power gathered from photovoltaics and wind turbines into alternating current power that is required for military units. This study used 2 kW and 2.5 kW units (priced at $1795 and $2245 respectively). We assumed that inverters have negligible operation and maintenance costs.

4.2.6 Economics

This study assumes that capital equipment costs will come from Congressional appropriations, thus there will be no interest charges. We also assume a lifetime of 25 years. Replacement lifetime and costs of individual items vary and are summarized in section 4.4.

4.3 Natural Resource Information (Wind and Solar resources)

Natural resources were modeled using data obtained from Colorado Springs, Colorado. This location is representative of solar and wind resources and does not over or under-estimate the amount of solar radiation that could be available to Army units. Northern Power Systems, Inc. has vast experience in installing stand-alone hybrid systems and estimates that only one site in 30 has good wind resources. Therefore, wind resources are modest with an average wind speed of only 4.5 miles per hour. The daily global solar radiation has an average of 4.7 kWh/m^2 with a clearness index of 0.6.

4.4 Summary of energy model inputs

Table 6: Summary of equipment operating characteristics

	IC Engine	Photovoltaic	Wind Turbine	Inverter/Charger
Capital cost ($/kW)	840	10,000	4200	900
Lifetime	15,000 hr	20 years	15 yr	15 yr
O&M Cost ($/kWh)	0.09	0	0.015	0
Diesel Fuel Cost ($/gal)	10/40/400	0	0	0
Diesel Fuel LHV, MJ/kg	43.2	0	0	0

4.5 Stand-Alone Generator

Stand-alone generator modeling consists of a stand-alone diesel generator. Weight and volume were assumed to be similar to that of current Tactical Quiet generator and mounted on a trailer that is similar to current models.

4.6 Hybrid System

The hybrid energy system must be constrained by volume and weight due to Army mobility requirements. Using the M200A1 trailer for transport, we found that the energy system was primarily constrained by weight. A maximum of 2 wind turbines and 2 kW of photovoltaic cells was fixed due to the inconvenience of setting up more than 2 wind turbines and the difficulty of laying out more than 20 square meters (assuming 10 square meters of photovoltaic can generate 1 kW of electrical power) of photovoltaic panels. Even though photovoltaic cells and wind turbines alone could meet most of the demand requirements at any given moment, the diesel generator must be sized to meet peak demands due to the requirement for reliable power and the intermittent nature of renewable energy resources. The Brigade TOC power system was constrained to a maximum of 10 batteries on a M200A1 trailer because of the weight of a 30 kW diesel generator. Due to the lower weight of the 5 kW generator set the Digital Bridge unit can accommodate up to 34 batteries on the M200A1 trailer.

Energy storage in the form of batteries greatly increases the total electrical efficiency of the hybrid system because excess wind and solar power cannot be stored except in the batteries. Also, without batteries diesel generator sets must run continuously, thus necessitating long periods of low loads that result in poor fuel economy and additional operational and maintenance costs.

4.7 Future engines

Larger diesel generator sets (20kW or higher) have a maximum electrical conversion efficiency (converting diesel fuel into electrical power) of about 30%. Small diesel generator sets have a significantly lower electrical efficiency due to the higher rates of heat loss in smaller engines. Small diesel generator sets were used in both of the unit configurations, thus we assumed 20% electrical conversion efficiency. Although this efficiency is relatively low, a diesel engine is chosen based on the findings of Hess (2002). Hess ruled out fuel cells and Sterling Engines as viable solutions within the next two decades.

The Defense Advanced Research Projects Agency (DARPA) is funding a project to produce variable displacement engines with higher part-load electrical efficiencies (DARPA A160 contract number: MDA 972-03-C-0029) for engines of around 100 kW. This can be accomplished by engaging engine cylinders as demand is placed on the engine. This same technique could be applied to smaller engines and models were changed to account for this difference. Figure 7 shows a typical part load ratio (based on rated engine capacity) of today's engines. Since the engines being modeled are small, the maximum electrical efficiency will be close to 20%. Figure 8 shows the anticipated part load performance of the variable displacement engine, which has the same maximum efficiency as the conventional small engine but with a part load efficiency that rapidly increases and then levels off. This is advantageous for the Army because much of the time diesel generator sets are operated at very low part load ratios, thus wasting fuel and increasing operation and maintenance costs.

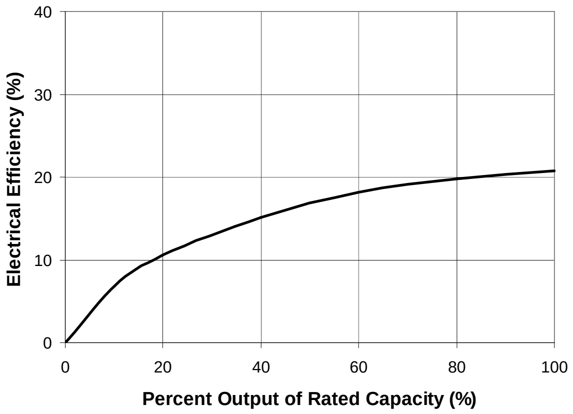


Figure 7: Conventional Small Generator Efficiency

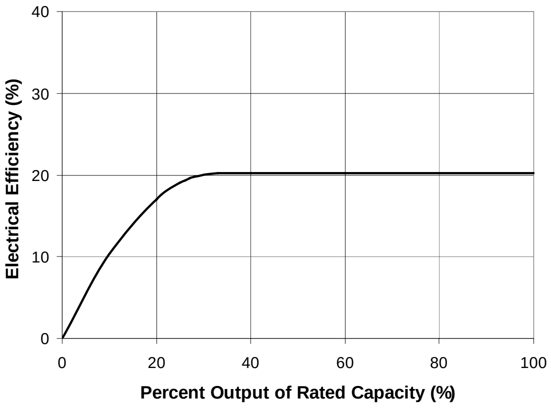


Figure 8: Variable Displacement Engine Efficiency

4.8 Control Strategy

All modeling is based using an energy balance where the energy systems supply power to meet demand (and possibly charge the batteries). The stand-alone generator and variable displacement engine models follow the demand profile directly. The hybrid system uses a control strategy that starts the generator when batteries are depleted to 40% charge or when needed to meet demand and stops the generator when the battery charge reaches 80%. At less than 40% charge, battery characteristics become unfavorable and if the charge nears zero, there is risk of reversing battery polarity. If batteries are charged above 80%, batteries accept energy at a slower rate, batteries may be damaged and there may not be sufficient storage capacity to accept additional energy from intermittent and uncontrollable renewable energy sources (wind or solar).

5. RESULTS

The models and performance data discussed above provides the ability to determine the optimal (based on life-cycle cost) energy system configuration given various inputs like hourly averaged electrical demand profiles, capital and operation-maintenance costs of various energy systems, and natural resource information. Results are provided in this section. The Appendix lists all modeling results using the inputs and scenarios provided above. Costs and fuel consumption are all annualized (dollars per year or fuel consumption per year). Capital cost refers to the one time initial cost for hardware acquisition.

5.1 Example Problem using the Digital Bridge configuration

Table 7 summarizes the results of a simulation using the Digital Bridge configuration, operating 3200 hours/year with diesel fuel priced at $10/gallon. The top row identifies the supply source (stand-alone generator, hybrid, variable displacement engine) or a ratio of supply source values. Column B lists results from modeling a stand-alone generator. Column C lists the results from modeling the hybrid energy system. Column D compares the stand-alone generator results to the hybrid results using a ratio (hybrid to stand-alone generator). Column E lists the results from modeling the variable displacement engine. Lastly, column F compares the variable displacement engine with the stand-alone generator using a ratio.

Table 7: Example of Results

	A	B	C	D	E	F
1	Digital Bridge, 3200hours/year, $10/gallon	Stand-Alone Generator	Hybrid	Ratio, Hybrid to Stand-Alone Generator	Variable Displacement Engine	Ratio, Variable Displacement engine to Stand-Alone Generator
2	Capital Cost ($)	13,320	54,531	4.1	13,320	1.0
3	Annualized Cost ($/year)	39,033	17,880	0.5	16,743	0.4
4	Fuel Consumption (L/year)	10,887	3,455	0.3	4,891	0.5
5	Weight w/o fuel (lbs)	1,182	4,406	3.7	1,182	1.0
6	Weight w/ fuel (lbs)	21,530	10,863	0.5	10,323	0.5
7	Generator size (kW)	10	5	0.5	10	1.0
8	PV (kW)		2			
9	Batteries (# of)		34			
10	Inverter (kW)		5			
	Wind Turbines (# of)		2			
11	Generator Run hours (hours/year)	3,200	1,463	0.5	3,200	1

The second row of Table 7 lists capital cost of the modeled energy systems. The hybrid's generator's capital cost is $54,531, while the stand-alone capital cost is $13,320 and has a capital cost ratio of 4.1.

Row 3 lists the annualized cost of the modeled energy systems. Unlike capital costs, the hybrid's life cycle annualized cost ($17,880) was lower than the stand-alone generator's annualized cost ($39,033). The hybrid life cycle annualized costs are lower due to reduced fuel consumption (shown in row 4) and reduced operation and maintenance costs. The stand-alone generator consumes 10,887 liters, while the hybrid consumes 3,455 liters per year. Lower reliance on fuel implies a smaller logistical tail and associated unit agility.

System weights, excluding fuel weight, are shown in row 5. The hybrid weighs 3.7 times the stand-alone generator's weight without fuel (4,406 lbs compared to 1,182 lbs). This ratio is important when considering system transportability.

However, energy systems do not operate in a vacuum without fuel, thus system weight including fuel provides another perspective. Row 6 lists system weight including the weight of fuel. Comparing the hybrid to the stand-alone generator we observe a 50% decrease in weight, primarily due to the reduction in fuel consumption. Large overall weight reduction is a concern since fuel (measured by weight) constitutes 60% of all Army transportation requirements. This is a large problem since fuel transport is very expensive (see section 4.2.1.3) when it is delivered to theater either via ship or airplane, and transported inland by trucks or helicopters.

Row 7 lists the generator rated capacity that each scenario uses as part of its energy system. The stand-alone generator requires a 10 kW generator while the hybrid uses a 5 kW generator since the hybrid includes batteries and renewable energy systems (photovoltaic and wind turbines) that can be used during peak demand periods.

Rows 8-11 lists other energy components that are required as part of the hybrid energy system. The hybrid includes 2 kW of photovoltaics, 34 batteries, a 5 kW inverter/rectifier, and 2 wind turbines rated at 0.92 kW each.

Capital cost and weight without fuel of the stand-alone generator and the variable displacement generator are the same. We assumed that the variable displacement engine would have the same capital cost (excluding research cost) and weight without fuel as the stand-alone generator.

Annualized life-cycle cost of the variable displacement engine is $16,743 while the stand-alone generator costs $39,033. The 40% decrease in annualized cost by the variable displacement engine is largely due to the higher conversion efficiencies at part load which results in decreased fuel consumption. The variable displacement engine consumes 4,891 liters of fuel (row 4), while the stand-alone generator consumes 10,887 liters of fuel. Lastly, in row 6, we observe that the variable displacement system weighs half that of the stand-alone system (10,323 lbs compared to 21,530 lbs) when fuel weight is considered. Weight savings are attributed to the decreased fuel consumption of the variable displacement engine.

Even though Table 7 is an example using the Digital Bridge configuration, it demonstrates the general trends and results determined by all modeling. Due to a combination of a lower number of batteries and larger electrical demand, reductions in fuel consumption and annual costs for the Brigade TOC were less than the Digital Bridge. The Brigade TOC hybrid system had about 10% reduction in fuel and annual costs compared to the Digital Bridge hybrid which had reductions of about 70% in fuel and annual costs. If hybrid energy systems could be placed on platforms capable of transporting more weight than the M200A1 trailer, significant cost reductions could also be realized for Brigade TOCs that us hybrid systems.

An estimate of noise signature might be made by directly comparing generator run hours. The hybrid generator operates about 50% of the time of the stand-alone generator. There is no reduction in generator run time for the variable displacement engine and thus, one could assume no reduction in noise signature. From this perspective, the hybrid generator option is superior.

5.2 Independent Model Verification

Figures 9 and 10 demonstrate the interaction of components of the hybrid energy system. Both graphs omit the wind power harvested by the system because it is insignificant in both instances.

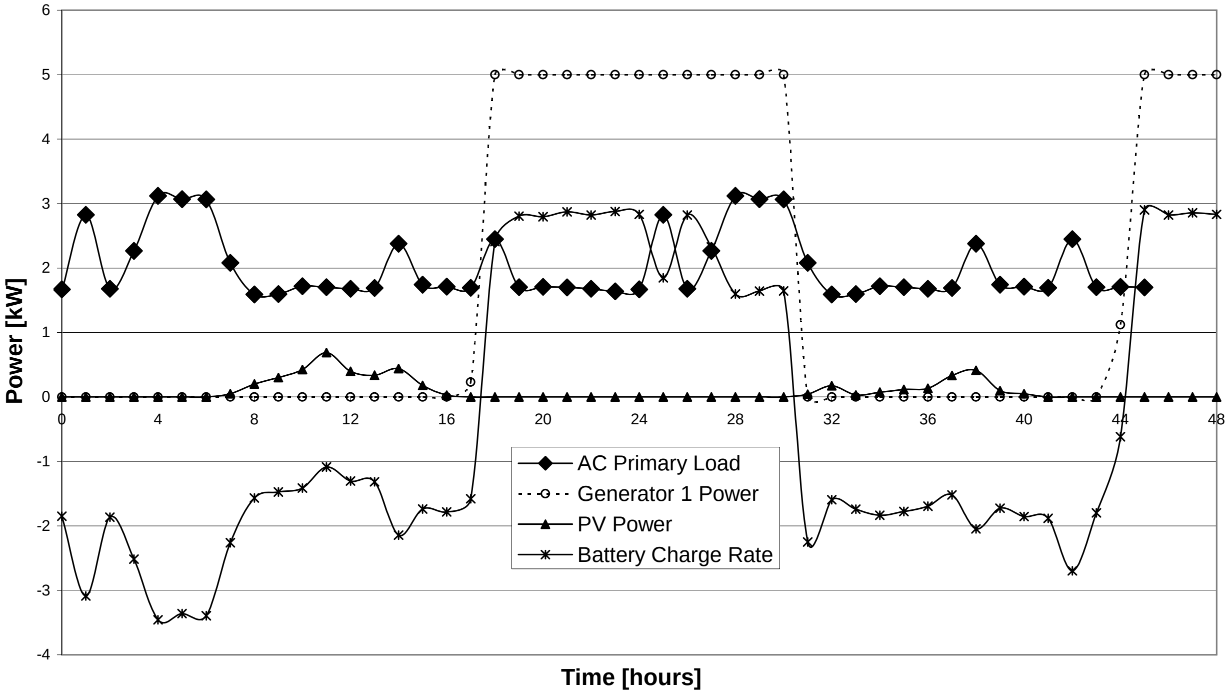


Figure 9: Sample 48 hour period

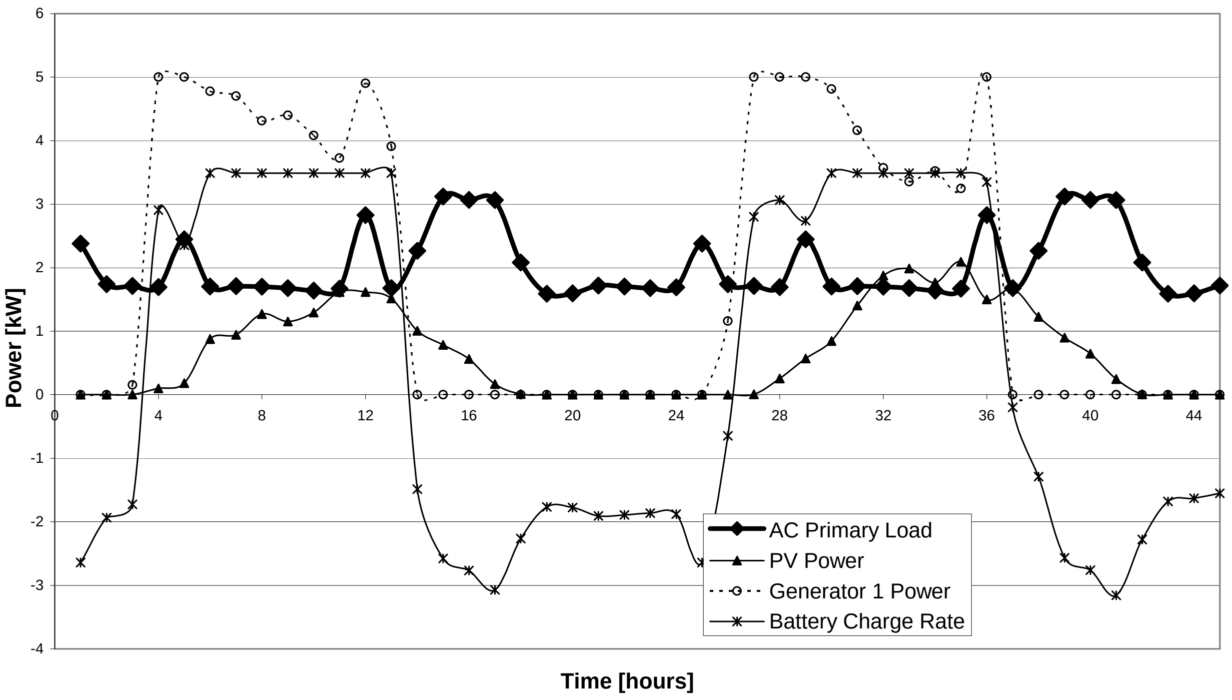


Figure 10: Sample with Significant Solar Resources

Figure 9 is representative of a cloudy day as there is little insolation (less than 1 kW from a system sized for 2 kW peak) contributing to the energy system. From Figure 9 we notice that the generators were off during the day and operated at night to meet electrical demand and charge the batteries. During the day the system relies on the batteries and a small amount of solar power to meet the electrical demand.

Figure 10 is illustrative of a sunny period with significant solar resources (nearly 2 kW peak). The availability of solar resources is variable, but significant as it displaces fuel-derived energy that would have otherwise come from the generator. During hours 6-13, the photovoltaic power displaces some of the generator power for meeting electrical demand, thus the generators can operate at a reduced load and associated fuel reduction. The generators do not operate at a higher load because the batteries accept a charge at a limited rate, thus extra generator power would be wasted. Wet stacking is not an issue for short periods of low part load operation. Additionally, the generator always produces power at greater than 50% rated capacity. We also observe that the unit can operate throughout the night without operating a noisy generator. This would enhance security.

5.3 General Results and Trends

Due to the large number of combinations of fuel prices, run hours, and tactical operation configurations (Brigade TOC or Digital Bridge) complete detailed results are included in the Appendix. Looking at Table 8 we observe that the Digital Bridge hybrid configuration weighs about four times more than the stand-alone generator while the annual costs range from 0.3 to 0.5 that of the stand-alone generator. The Digital Bridge hybrid system consumes about a third less fuel than the stand-alone generator. Lastly, the weight without fuel for the hybrid system ranges from about 2.6 to 3.7 while the weight with fuel ranges from 0.4 to 0.7.

The hybrid Brigade TOC system costs about 1.9 to 2.8 times the stand-alone generator while the annual cost ranges from 0.91 to 0.98 times the annual cost of the stand-alone generator. Fuel consumption ranges from 0.91 to 0.94 times the annual costs of the stand-alone generator. The hybrid Brigade TOC weight without fuel is about 1.6 times that of the stand-alone generator's weight without fuel. Lastly, the weight with fuel for the Brigade TOC system ranges from 0.92 to 1 times that of the stand-alone generator's weight with fuel which means there is very little difference in weight between the two systems.

For both configurations (Digital Bridge and Brigade TOC) the variable displacement engine has an annual cost of about 0.45 times that of the stand-alone generator's annual cost. Similarly, the variable displacement engine consumes fuel at a rate of 0.45 times that of the stand-alone generator. Lastly, the variable displacement engine weight, including fuel, is about half of the stand-alone generator's weight with fuel.

It should also be noted that these results are valid for electrical demand profiles similar to those modeled here. Of the four demand profiles available (only two of which were modeled), all profiles consisted of similar profiles where the peak loads were approximately four times the average. Flatter demand profiles with power supplied by an appropriately sized generator will benefit less from hybrid systems, whereas demand profiles with even greater peaks will benefit even more from hybrid systems. Performance of the variable displacement engine appears to be relatively immune from the demand shape.

Modeling demonstrated that a hybrid variable displacement engine would reduce fuel consumption by around 70% for all profiles tested. Those results are not presented in this report since the authors feel there is too much speculation about engine performance as well as how an entire system might work. When a variable displacement prototype is available, complete engine maps developed and a better QFD developed, a computer simulation of this option should be conducted again.

Table 8: Summary of General Results and Trends

	A	B	C	D	E
		Digital Bridge		Brigade TOC	
1	General Results	Ratio, Hybrid to Stand-alone Generator	Ratio, Variable Displacement Engine to Stand-alone Generator	Ratio, Hybrid to Stand-alone Generator	Ratio, Variable Displacement Engine to Stand-alone Generator
2	Capital Cost ($)	3.8 to 4.1	1	1.85 to 2.82	1
3	Annualized Cost ($/year)	0.32 to 0.55	0.42 to 0.45	0.91 to 0.98	0.45 to 0.47
4	Fuel Consumption (L)	0.31 to 0.34	0.45	0.91 to 0.94	0.45
5	Weight w/o fuel (lbs)	2.6 to 3.7	1	1.6 to 1.6	1
6	Weight w/ fuel (lbs)	0.39 to 0.67	0.46 to 0.51	0.92 to 1	0.46 to 0.5

6. CONCLUSIONS

Modeling demonstrates that hybrid energy systems would have lower life-cycle costs, lower fuel burden and higher fuel efficiency than the stand-alone generator in use today. Increased system weight not considering fuel for the hybrid is the only significant drawback compared to the stand-alone generator, but this is offset by the hybrid's reduced weight when fuel is included. Ease of maintenance and system complexity could not be quantified and was not considered. A variable displacement engine performs similarly to the Digital Bridge hybrid because it experiences similar reductions in annual costs, weight with fuel, and fuel consumption.

The Brigade TOC hybrid system did not have comparable results to the Brigade TOC variable displacement engine because of constraints on the number of batteries the trailer could carry. By increasing the weight capacity of the trailer (M200A1) or using a different trailer altogether, the Brigade TOC hybrid would probably demonstrate reduced cost and overall weight. The reduced cost and fuel consumption of the variable displacement engine is similar for all unit configurations tested. A possibility is to use the variable displacement engine in a hybrid system which would probably result in better results than either configuration by itself.

7. RECOMMENDATIONS

1. The development, prototyping, and fielding testing of hybrid generator systems for providing tactical power. These hybrid systems would attenuate the Army's problem of inefficiently operating generators since hybrids operate more efficiently at part load ratios.

2. That DARPA investigate funding a scaled-down version of a variable displacement engine. The current engine in development is rated at around 100 kW, which is too large for most tactical power applications.

3. The electrical demand data used in this study came from units fighting mock battles at the National Training Center. A logical progression is to obtain electrical demand data from field units in actual operations (Afghanistan, Iraq, Kosovo). This information would give designers a better understanding of electrical demand during actual operations, thus providing better profiles for future power source development.

4. That PM-MEP study and quantify "ease of maintenance" and "simple" for QFD analysis and to aid in the design of future engine systems.

5. A simulation be conducted to estimate fuel savings using the part load characteristics of a fuel cell, Sterling engine and hybrid variable displacement engine. While these engines are not currently available, development of these technologies has potential to reduce the noise signature and fuel consumption while meeting demand profiles that vary significantly.

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