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Cost analysis of electric grid enhancement utilizing distributed generation in post-war reconstruction

Fiala, Darol D. M.

Monterey, California. Naval Postgraduate School

NAVAL POSTGRADUATE SCHOOL

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THESIS

COST ANALYSIS OF ELECTRIC GRID ENHANCEMENT UTILIZING DISTRIBUTED GENERATION IN POST-WAR RECONSTRUCTION

by

Darol D. M. Fiala

March 2009

Thesis Advisor:	Daniel Nussbaum
Second Reader:	Jomana Amara

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The current wars in Iraq and Afghanistan have presented significant civil infrastructure rebuilding challenges to these nations, as well as to the United States, coalition allies, and the United Nations. Iraqi and Afghan critical infrastructure has been destroyed, or fallen into disrepair, due to years of war, international sanctions, sabotage and neglect. Electrical infrastructure, in particular, is a critical economic and social component that is failing to meet the essential needs of these two societies. This paper is a starting point in researching the viability of integrating distributed generation (DG) resources, such as wind turbines, photovoltaic panels, and microturbines into the portfolio of power generation choices, by quantifying the fully burdened cost of electrical generation in war-torn regions. In this paper, Iraq is used as the sample case for investigating the viability of using DG technologies to enhance the existing electric grid. The fully burdened cost is expressed in the annual life-cycle cost (LCC) of each of the five systems (microturbines, diesel generators, photovoltaic panels, wind turbines and large-scale natural gas turbines) researched, "levelized" to $/kW. LCC includes capital costs, operation and maintenance, fuel costs, energy storage and security. This research concludes that microturbine systems offer the most cost effective means of making up a 3500MW deficit in Iraq when fuel prices remain at, or below, a baseline price of $2.29/gal FY09. Photovoltaic systems provide the most cost effective means of making up this deficit when fuel prices increase beyond this baseline price, as they have in Afghanistan.

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Darol D. M. Fiala
Lieutenant, United States Navy
B.S., University of Minnesota, 2000

Submitted in partial fulfillment of the
requirements for the degree of

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March 2009

Author: LT Darol D. M. Fiala

Approved by: Dr. Daniel Nussbaum
Thesis Advisor

Dr. Jomana Amara
Second Reader

Dr. Robert F. Dell
Chairman, Department of Operations Analysis

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TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

The current wars in Iraq and Afghanistan have presented significant civil infrastructure rebuilding challenges to these nations, as well as to the United States, coalition allies, and the United Nations. Iraqi and Afghan critical infrastructure has been destroyed, or fallen into disrepair, due to years of war, international sanctions, sabotage and neglect. Electrical infrastructure, in particular, is a critical economic and social component that is failing to meet the essential needs of these two societies. This paper is a starting point in researching the viability of integrating distributed generation (DG) resources, such as wind turbines, photovoltaic panels, and microturbines into the portfolio of power generation choices, by quantifying the fully burdened cost of electricity generation.

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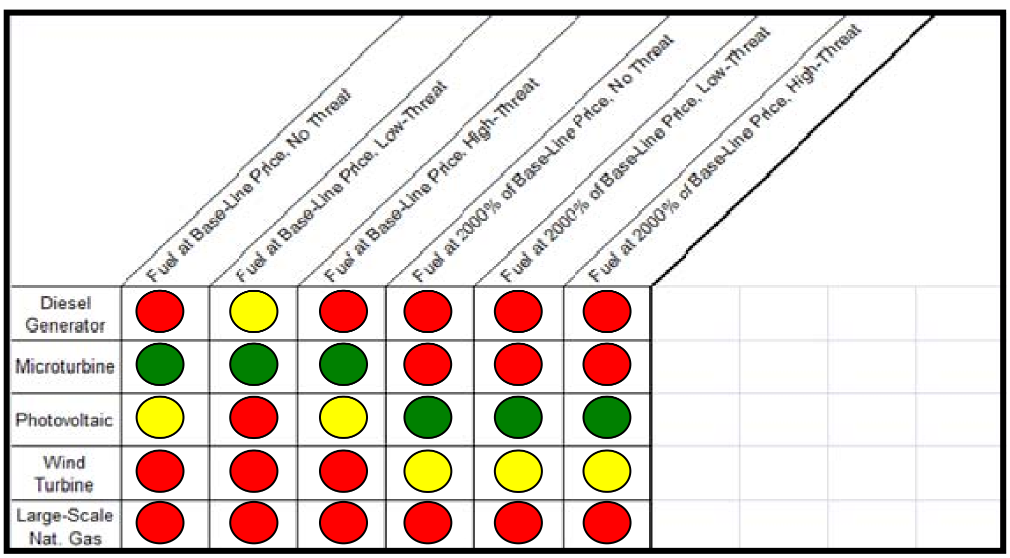

ES Figure 1: System Fuel v. Security Preference

As ES Figure 1 illustrates, microturbines offer the most cost effective means of making up the average annual 3500MW deficit in Iraq when fuel prices remain at, or below, a baseline price of $2.29/gal FY09, and there is either no security threat, or a high security threat. In both of these cases, photovoltaic systems offer a secondary choice. When fuel prices remain at baseline, and the security threat is low, microturbines remain the primary choice, but small-scale diesel generators become a secondary choice.

When fuel prices increase by 2000 % from the FY09 baseline price, an increase that corresponds with the true price currently being paid in the Afghanistan theater, photovoltaic systems provide the most cost effective means of making up the 3500MW deficit. Wind turbines become the secondary choice.

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I. BACKGROUND

A. CRIPPLED INFRASTRUCTURE

The U.S. led wars against terrorism in Iraq and Afghanistan have presented significant civil infrastructure rebuilding challenges to these respective nations, as well as to the United States, coalition allies and the United Nations. The destruction and disrepair of Iraqi and Afghan critical infrastructure are a direct result of years of civil and border conflicts, international sanctions, sabotage and neglect, and the current conflicts. Electrical infrastructure, in particular, is a backbone component that is failing to meet the essential needs of these two societies. The result is that electrical production in Iraq and Afghanistan is not keeping pace with demand.

Several recent publications, such as the U.S. Army's 2006 Counterinsurgency Manual, and the USMC/USSOC's 2006 Multi-Service Concept for Irregular Warfare, have stated that effective counterinsurgency/irregular warfare tactics must include redeveloping key civilian infrastructure. In essence, the battle for the hearts and minds of a population in turmoil is won when they are afforded the tools for successful economic development and modern conveniences.

Iraq has the world's fourth largest proven oil reserve, and as of 2006 was the world's fifteenth largest producer (Energy Information Agency 2008). Fuel oil is the primary source of electrical production in the country. Thus, oil and electrical generation are currently inseparable. Because both are infrastructure intensive industries, the entire centralized system is easily targeted and disrupted. According to the Institute for the Analysis of Global Security, from June 2003 to March 2008, there have been 469 individual attacks on Iraq's oil infrastructure alone (Institute for the Analysis of Global Security 2008).

In October 2008, the Special Inspector General for Iraq Reconstruction (SIGIR) suggested that $25-30 billion would be required to rebuild Iraq's electrical infrastructure. Iraq's 2006-2015 Electricity Master Plan estimates that $27 billion is needed to reach its goal of providing reliable (24-hour) electricity across Iraq by 2015

(GAO 2007). The United States and her coalition partners have dedicated considerable resources to rebuild electrical generation and distribution capacity. As of the end of 2008, the U.S. has expended $4.42 billion of an obligated $4.65 billion to rebuild and rehabilitate the electrical sector (Bowen 2008). Yet, it was not until June of 2008 that capacity began to increase and maintain gains above the pre-war levels of 4500 MW per month (see Figure 1).

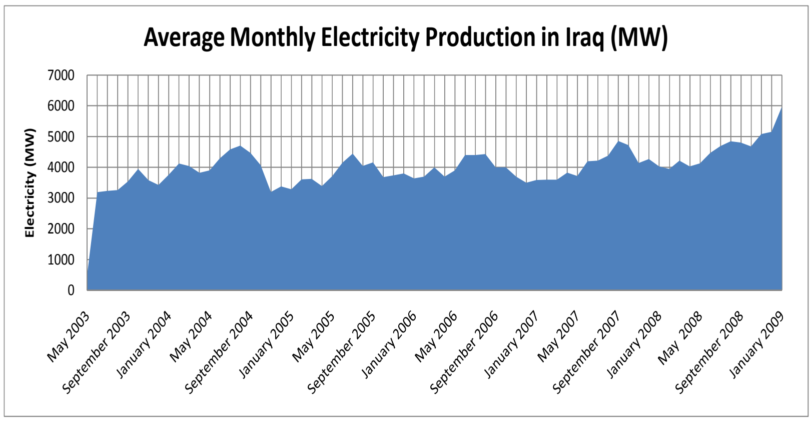

Figure 1: Average Monthly Electrical Production in Iraq (MW) (Source Data: Brookings Institute Iraq Index, Jan. 2009)

The March 2008 Department of Defense Report to Congress cites several reasons for this lag in capacity: fuel shortages, reduced water levels at hydroelectric plants, interdictions, equipment failures, damage to key transmission lines, and reliance on unreliable imported sources of power (Department of Defense 2008). Electrical demand, on the other hand, has continued to fluctuate around the 8000 MW per month mark for the past several years (see Figure 2). In 2008, average monthly production was 4500 MW, resulting in an average negative production deficit of approximately 3500 MW per day.

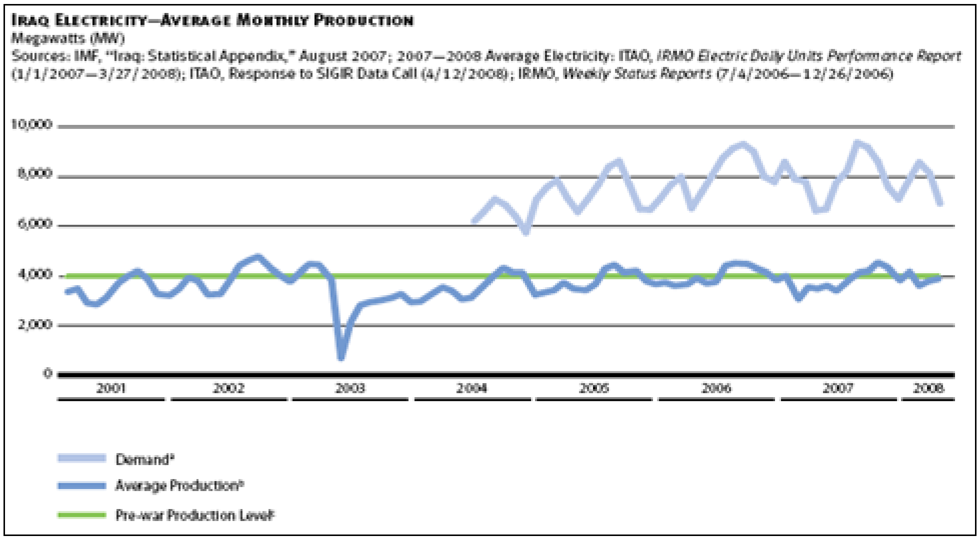

Figure 2: Average Monthly Electrical Production, 2001-2006. (From: April 2008 SIGIR Report to Congress, Figures 2-32)

Demand is met as security in the country increases and is maintained. For example, recently, due to several positive factors that have dramatically increased security throughout Iraq, such as "the Surge," Iraqis have seen electricity generation increase by 12% between September 2007 and September 2008 (Department of Defense 2008). However, until the government is able to increase levels to meet a sustained demand, Iraqis are making up the difference by utilizing private reciprocating engine generators. Almost half of Iraqis in a DoD report stated that they utilize a private generator to make up the supply gap (Cordesman 2007). The January 2008 SIGIR report estimated the actual number of generators providing this power at 30,000—50,000, generating 2000 to 4500 MW of power (Bowen 2008). This presents a problem for two reasons: small diesel generators are less efficient than larger generating units are, and they tap into the fuel market and reduce the availability of fuel for other uses. This diversion of fuel puts an additional burden on the logistical system as larger quantities of fuel are moved to dispersed points of demand. Further, it has the potential to impact security resources, as assets must be utilized to secure fuel flowing into residential areas.

A similar story has unfolded in Afghanistan. The main difference is that Afghanistan had very little infrastructure remaining, or in place, to begin with. Both countries present situations in which electrical demands need to be met in order to improve the morale of the citizenry, and to promote economic development.

B. DECENTRALIZATION

1. Iraq's Current Network Architecture

Modern national electrical grids, such as the one utilized in the United States, typically consist of large-scale generation plants fueled by hydrocarbon-based fuel such as coal, natural gas, or fuel oil. A smaller number of electric plants are fueled by non-hydrocarbon means such as: nuclear fission, hydroelectric power, and a small but growing percentage of "renewable" sources including geothermal, wind and solar. Figure 3 provides a basic overview of the pathway electricity takes from generation to final distribution.

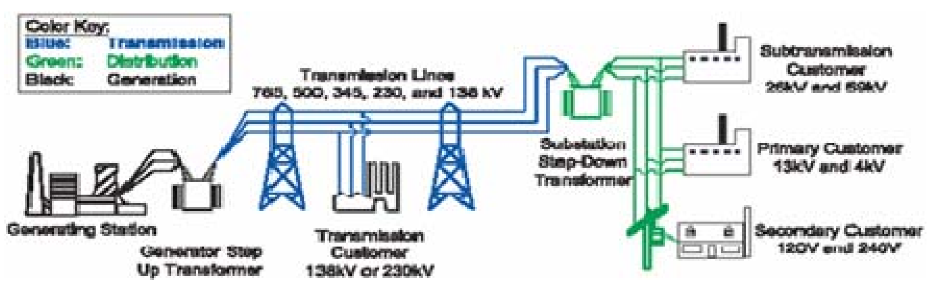

Figure 3: Typical Large-scale U.S. Generation and Distribution System (From: DOE Office of Electricity Delivery and Energy Reliability Website, http://www.oe.energy.gov/)

The four predominant generation plant types in Iraq are hydroelectric, geothermal, gas turbine and diesel (Bowen 2008). Iraq's electricity infrastructure is comprised of the same basic components as the national grid in the United States, with the exception that its transmission lines are principally 400 and 132 kilovolts (see Figure 4). Transmission lines in the U.S. range from 138 to 765 (see Figure 3).

Generation facilities produce the power, while transmission stations and lines move that electrical power from the power stations to distribution networks. The distribution network moves power to the end users, such as residential units, city and military facilities.

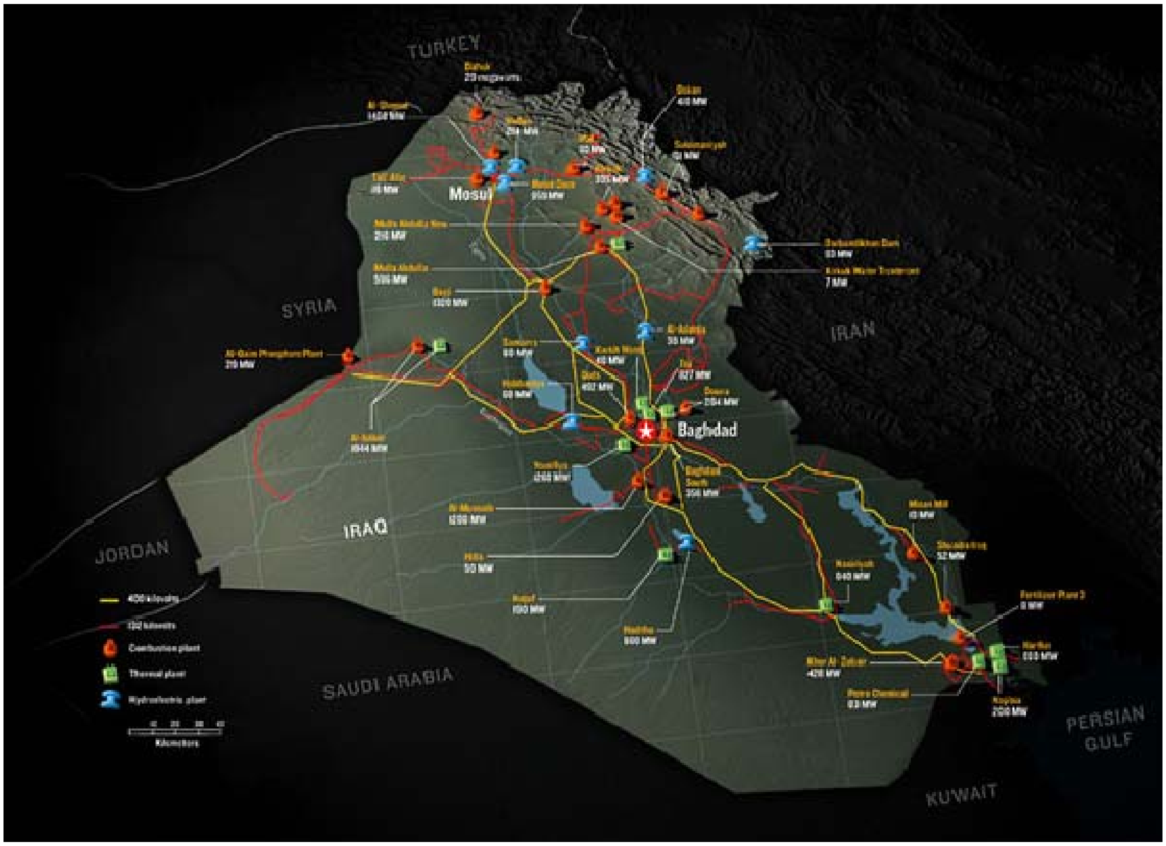

Figure 4: Iraq Electrical Grid as of 2006 (From: IEEE Spectrum Online Article, "Re-engineering Iraq," Feb. 2006.)

In the United States, a complex communications and control system is in place to ensure the efficient operation of the entire network. As of 2007, an Iraqi national communications and control system was being designed in order to monitor system performance and ensure equitable distribution of electricity (Government Accountability Office 2007). Once in place, this type of national network provides *understood* efficiencies in terms of electricity generation, distribution and costs. However, the concept relies on a large, centralized, and easily targeted network comprised of generation and transfer nodes connected by thousands of miles of electrical line (arcs, in networking parlance). Unfortunately, the scope of the deterioration of the system in Iraq, as well as government corruption, and the lack of coordination between the Ministries of Oil and Electricity, has resulted in massive economic and structural problems.

The construction costs for building the components of a national system are high. For example, an Army Corps of Engineers refurbishment project at the Mussayib Gas Generation Power Plant station, roughly 40 miles south of Baghdad, cost $26.8 million. This plant produces approximately 400 MW of electricity, which is enough to power 36,000 Iraqi homes (Langer 2008). That translates to $67,000 per MW in capital reconstruction costs. Another project, building two gas-combustion towers at a substation in the northern Iraqi province of Kirkuk, which is projected to generate 325 MW when completed, is estimated to cost $536,000 per MW in FY2005 dollars (USAID 2005). By comparison, in the United States, a traditional coal fired power plant's capital costs average approximately $2.0 to $3.2 million per MW (Puckett 2008). When compared to the $/MW price in the United States, it would appear that these two examples of plant construction/enhancements are reasonable. However, the uncertain security environment in Iraq significantly complicates the calculation of reconstruction costs.

Several U.S. government reports cite specific examples of the "hidden" costs associated with rebuilding Iraq's large-scale generation and distribution network in such a dynamic security environment. A 2005 USAID report, documents the repair of a 205 km (127.4 miles), 400 KV transmission line and towers along the Khor Al Zubayer - Nassiriyah corridor, which had been severely damaged by hostile actors. The price tag for the ten-month long project was $17.7 million (USAID 2005). A 2007 Government Accounting Office (GAO) report on the reconstruction of Iraq's oil and electricity sectors cites a U.S. government estimate that Iraq is losing approximately $4.1 billion per year in possible fuel revenues due to inefficient energy production practices (GAO 2007). Finally, in 2008, the GAO, referring to data from the Department of Defense (DoD), stated that despite significant security gains, electricity production is still far below goals due to fuel shortages, fuel and electricity interdictions, infrastructure damage, and the shear task of rebuilding both sectors after years of damage and neglect (GAO 2008). The United State's total economic burden, as of 2008, reached roughly 7.4 billion in reconstruction aid for both interdependent sectors (GAO 2008).

2. The Cost of Oil

Iraq generates approximately 94% of its electricity from oil (EIA 2004). Therefore, under its current structure, Iraq's electricity sector cannot shed the burdens of its reliance on the oil sector. Therefore, the costs of electricity are inextricably linked to the costs of oil. These are not just economic costs, but also political, social and security. For example, there are costs manifested in the political rivalry between Kurds and the majority Arab government as they struggle to develop an agreement in oil revenue sharing. The societal costs in Iraq take the form of decreased quality of life and productivity as the nation is subject to limited hours of electricity per day and rolling blackouts. Finally, U.S., Iraqi and coalition forces have incurred economic and human costs in the effort to move crude oil and processed fuels across the country in easily targeted convoys.

a. Current Military Energy Considerations

The war in Iraq has caused U.S. commanders to think of, and call for, new ways to power forward operating bases and to manage fuel logistics.

On July 25, 2006, Marine Corps Major General Richard Zilmer submitted a "Priority 1" request for a "self-sustainable energy solution" for his area of responsibility in western Iraq. He specifically requested "solar panels and wind turbines" (Clayton 2006, 01). The rationale, according to the memo, was that without alternative sources of power, United States military forces would "remain unnecessarily exposed" and would "continue to accrue preventable….serious and grave casualties" (Zilmer 2006). In the one-year period after Maj. Gen. Zilmer's memo was submitted, total attacks in the country reached a sustained level of roughly 150 per day (GAO 2008). Transporting and protecting oil, refined fuel products, and oil and electrical infrastructure consumes coalition resources. Maj. Gen. Zilmer's memo warns, "Without this solution, personnel loss rates are likely to continue at their current rate. Continued casualty accumulation exhibits potential to jeopardize mission success" (Zilmer 2006).

Further data on the impact of current energy production on military operations is found in academic research. In 2004, Amory Lovins, founder of the Rocky Mountain Institute (RMI), an energy research and policy institute, found that approximately 70% of the gross tonnage moved when the U.S. Army deploys is dedicated to fuel. According to RMI, in 2004, $0.2 billion was spent on fuel every year, and $3.2 billion was spent on maintaining the personnel to move it (Lovins, Amory B. and E. Kyle Datta 2005). In 2007, following three years of fuel price increases, the Army's fuel costs alone were over $2 billion (Defense Energy Support Center 2007). "Fuel logistics, as much as anything, prevents America's most lethally effective forces from being rapidly deployable and its most rapidly deployable forces from assuredly winning" (Lovins and Datta 2005).

Both Maj. Gen. Zilmer and Dr. Lovins were writing about how the burdens of military related energy production and logistics negatively affect the mission. These burdens are magnified when, as in Iraq, logistical fuel loads are increased significantly in order to shore up the country's oil and electrical infrastructure as it struggles to meet a portion of Iraq's consumer demand. In an interview with Mark Clayton, Lovins summed up the issue in a 2006 Christian Science Monitor article, "At the tip of the spear is where the need to avoid the cost of fuel logistics is most acute. If you don't need divisions of people hauling fuel, you can realign your force structure to be more effective as well as less vulnerable."

3. A Tactical Argument for Diversification and Decentralization

The Marine Corps' Combat Development Command and U.S. Special Operations Command Center for Knowledge and Futures joint publication, titled "Multi-Service Concept for Irregular Warfare" (MSCIW), asserts that emphasizing economic development reduces "the root causes of popular discontent and helps to prevent further conflict" (United States Marine Corps Combat Development Command and U.S. Special Operations Command Center for Knowledge and Futures 2006). Iraq has provided a fruitful test bed for all aspects of modern warfare. Taking from lessons learned, several recent publications by both military and civil agencies have written about the ways in which the new global extremist threat is to be countered. The MSCIW asserts that finding expedient ways to create meaningful, long-term employment opportunities, and to reconstruct and/or bolster basic service infrastructure work to temper extremist's movements and influence within impoverished communities.

Funding small-scale (two megawatts and smaller) electric generation works projects offers an opportunity to create local jobs, rebuild infrastructure and reestablish economic and social viability. Entrepreneurial Iraqi's have already done this with the emergence of a local energy market, populated by individuals who have purchased small diesel reciprocating engine generators and sell energy to the community (Bowen 2008). However, as previously noted, this type of small-scale production has served to create a large-scale problem by increasing demand of diesel fuel. An alternative would be to invest in other types of distributed generation (DG) systems that would bring regulated and more efficient energy on-line, decrease the demand for diesel fuel, provide employment opportunities, and help bridge the supply vs. demand deficit. DG systems could be made up of small, highly efficient microturbines; solar photovoltaic panels that would require no fuel and little maintenance; small-scale wind turbines that require no fuel inputs; or even small-scale diesel generators that can be operated more efficiently and produce more energy than small domestic generators. There is no single technology solution for this problem. However, a diverse energy portfolio would produce electricity efficiently, reliably, reduce the logistical burden and footprint, and provide opportunities for job creation in the fields of maintenance and security.

MSCIW points out that once a reconstruction effort begins, it should be followed through to the end (United States Marine Corps Combat Development Command and U.S. Special Operations Command Center for Knowledge and Futures 2006). For example, the U.S. led coalition and the host government risk losing credibility when grid enhancement/reconstruction projects become burdened with frequent delays or are abandoned once hostilities appear to cease. Investing in small-scale, distributed generation systems would allow for incremental approaches to rebuilding the grid. If pauses in rebuilding were required, it would be less noteworthy then stopping mid-stream in constructing a multi-billion dollar generation plant.

4. Closing the Delta

Small-scale distributed generation technologies hold the possibility of providing a cost effective, logistical and tactical solution to closing the electrical generation gap in Iraq, and other places where the West has a responsibility for rebuilding or advancing civil societies. In Iraq, there continues to be a large delta between the amount of electricity that is produced, transmitted and distributed, compared to the demand. Iraqi citizens, who desire the same conveniences that any other modern society benefits from, are attempting to meet this demand by bringing in small, inefficient generators, or stealing power from existing power lines. These actions are counterproductive and produce wide-ranging negative effects on government attempts to rebuild the grid, and the military operations that attempt to bring security to the effort. Despite security gains, Iraqis quite often have to tolerate intermittent service or no electricity at all. The effect of decentralizing a portion of the electrical supply system is to increase the amount of work insurgents and other bad actors have to commit to, while decreasing the impact on electricity consumers. DG technologies that reduce fuel logistics and security burdens may be able to close the power generation delta and help the country rebuild itself into a productive, modern society.

II. DISTRIBUTED GENERATION AND MICROGRIDS

A. DISTRIBUTED GENERATION DEFINED

Distributed generation (DG) is the production of electricity from a modular, small-scale generator located close to the load, or point of demand (Akhil 2007). Another term, *distributed generation resource,* or DGR, is used when speaking of the technologies that are used to generate electricity. Both terms are used in this paper. Specifically, DGR can include reciprocating engines, small-scale hydroelectric, photovoltaic (PV) systems, wind turbines, microturbines, and fuel cells. All of these technologies can be up-and down-scaled to fit the needs of the community or individuals served.

For the purpose of this paper, "small-scale" refers to generation systems that produce two megawatts and less. Generation capacities greater than two megawatts are referred to as "large-scale." The analytical focus in this is on four specific types of small-scale DG technologies:

1. Microturbines, are small combustion engines, which utilize the same basic design of an aircraft auxiliary power unit.

2. Reciprocating engines, which is the same ubiquitous internal combustion technology that is used to power automobiles. Only engines that are powered by diesel fuel are considered in this research.

3. Photovoltaic panels (PV) which capture ambient photons from the sun, strip the electrons out, and produce electricity.

4. Small-scale wind turbines, which convert the kinetic energy of the wind blowing over their blades into electrical energy.

Fuel cells and hydroelectric power are not considered in this thesis. At this time, fuel cells have several technical hurdles to overcome, and are thus too expensive for the application in consideration. Small-scale hydroelectric is a specialized technology, and while possible in areas where water resources exist, are probably not best suited for a desert region such as Iraq.

B. DISTRIBUTED GENERATION TECHNOLOGIES

1. Microturbines

Figure 5: Capstone Microturbines (Source: Capstone Turbine Coorperation)

Microturbines (Figure 5) are small combustion turbine engines. Current models produce between 25kW and 500kW of power. Microturbine technology was originally created to serve as auxiliary power units on aircraft and large trucks (California Energy Commission 2002). The basic components of a microturbine are the compressor, combustor, turbine section, alternator, recuperator and the generator (U.S. Department of Energy, Distributed Energy Program 2006). The majority of microturbines are of single-stage, radial flow design. There are several variations in the construction; however, these details are not an important aspect of this research.

There are two primary ways of classifying microturbines: simple cycle (also called un-recuperated), and recuperated. Recuperated systems recover the heat from the exhaust gas to boost the combustion temperature and increase the overall efficiency.

Simple cycle systems are of simpler design, do not recapture this heat energy, and are thus less efficient. An offset to this lower efficiency is lower capital costs.

An attractive aspect of microturbine systems is that they have a small number of moving parts and thus require less maintenance. They also have a small special footprint relative to the amount of electricity they produce. Compared to other types of combustion DGs, microturbines produce electricity more efficiently, with reduced emissions, reduced electricity costs, and are able to utilize a wide range of fuels. While not a focus of this research, the waste heat can be captured and reused to both boost the efficiencies of the combustion, and provide energy for water and space heating (U.S. Department of Energy, Distributed Energy Program 2006).

The drawbacks of a microturbine system include high unit costs, fuel requirements, high decibel sound, requirements for security, and a loss of efficiency at higher ambient temperatures and altitudes, both of which are considerations in Iraq and Afghanistan (California Energy Commission 2002).

2. Reciprocating Engines

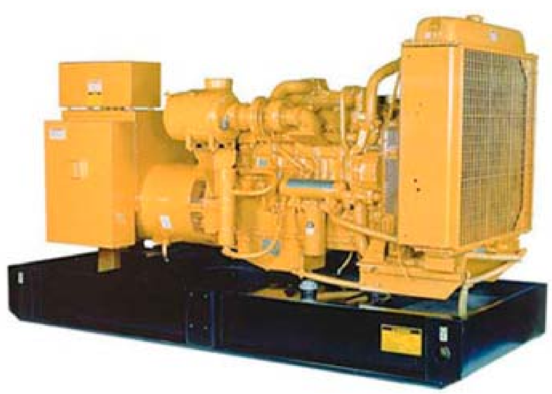

Figure 6: Caterpillar Model 3406C 300kW Reciprocating Diesel Generator (Source: Caterpillar)

DG reciprocating engines (Figure 6) are based on the same technology that can be found in an average car or small residential generator. This research only looks at reciprocating engines that consume diesel fuel due to the ease of acquiring both the technology and the fuel worldwide. Reciprocating engines are the most common and technologically mature DGR. The production size of a reciprocating engine generator ranges from less than a 1000 watts, such as a small recreational back-up generator, to utility scale units of five megawatts (California Energy Commission 2002). Reciprocating engines primarily run on petroleum products, such as gasoline, and diesel, although some engines can burn natural gas or diesel derived from organic wastes (biodiesel).

Operation is relatively simple, in that a fuel is introduced into a piston chamber where it is combusted, transforming chemical energy into mechanical energy by driving the piston and transferring that energy to a shaft system.

Attributes that make reciprocating engines attractive in Iraq include that they are common and widely available, relatively cheap, are highly reliable, have good efficiencies, and have quick start-up times.

Negative attributes of reciprocating engines are that they are noisy, produce high levels of pollutants, require frequent maintenance, and have the same security requirements as a microturbine. Their use also imposes a high logistical burden to keep pace with fuel requirements.

3. Photovoltaic Systems

Figure 7: Photovoltaic panels

Photovoltaic (PV) systems (Figure 7) directly convert the photons from sunlight into electricity. The device that is used to capture and convert this energy is called a solar cell. The most common solar cell is known as a silicon (Si) PV cell (Gibilisco 2007). Other materials used in manufacturing PV cells include gallium arsenide (GaAs), copper indium gallium deselenide (CIGS), amorphous silica (a-Si), and cadmium telluride (CdTe). New technologies and processes continue to emerge on the market every year. CIGS, a-Si and CdTe technologies represent a burgeoning industry in thin-film solar panels, foils and pliable plastics. Many are in production now, and offer several potential advantages such as lighter weights, cheaper production costs, cheaper capital and installation costs, lower profiles, moldable (can be made into roofing materials, siding, canopies, etc.), and lower maintenance. There are attributes of these systems that detract from their prospective benefits. For example, the technologies are still new to the market, and typically have half the efficiency of traditional Si panels. However, the loss in efficiency is offset by the projected cheaper price. Additionally, as investments in research have increased, so have the efficiencies of both thin film and traditional PV systems.

The structure of a basic Si PV panel is comprised of two types of silicon, called P and N types. These two types come together in the center of the panel at the P-N junction, or diode. The top of the panel is made of a clear glass that both protects the silicon, and allows light energy to enter and directly strike the diode. A metal ribbing connected by tiny wires lies on top of the two silicon wafers, and serves as the positive electrode. A metal base is placed in contact with the N-type silicon and serves as the negative electrode substrate (Gibilisco 2007).

Operation of a solar panel is relatively simple. When radiant energy from the sun hits the N-layer, an electron is knocked free, but stays in the layer. Similarly, when a photon hits the P-layer, an electron is knocked free and it crosses over to the N-layer. Electrons accumulate in the N-layer until, at a saturation point, the electrons flow onto, and down the wiring system, where they enter a DC circuit (Aldous, Yewdall, and and Ley 2007). Power can then be utilized in a DC form, which is more efficient, or it can be inverted to AC power, which is more useful due to the configuration of modern electrical systems and appliances. The power is used directly, stored in a battery system, or fed back into an electrical grid.

PV systems offer several benefits. The fuel, sunlight, is renewable and requires no logistics support, save occasional system replacement parts. The panels are solid state, rugged, require very little maintenance, and can last for decades with only slight degradation in efficiency. PV panels are useable in a stand-alone system, or easily integrated into a network. PV system electrical capacity can be as small as watts, for small applications, or mega-watts on a utility scale (Kreith and Goswami 200723-2). As noted, newer materials can be integrated into roofs, walls, windows, and almost any other application imaginable. They are ideally suited for regions with large amounts of direct sunlight, such as the American southwest, or the desert regions of Iraq. They can be laid flat on a roof to conceal their existence, and they can be connected in series to increase generating capacity. PV systems emit no emissions at the point of use.

PV has several detractors as well. For example, the reliance on sunlight means that production is limited to daylight. It is affected by degraded environment conditions, such as cloudy days, or sand storms. Hail and wind can also interfere with, or even destroy panels. If storage is desired, batteries must be used, and they add costs and potential dangers to a system. Panels are portable and worth money, and therefore may become targets for theft. While prices have been reduced in recent years, system up-front costs are still considerably higher that reciprocating engines. However, there are reduced maintenance costs and no fuel costs. This thesis analyzes how they compare in a military theater environment.

4. Wind Turbine Systems

Figure 8: Bergey Skystream Model BWC EXCEL 10 kW Wind Turbine (Source: Bergey Windpower)

Wind turbines (Figure 8) harvest kinetic energy from the wind. With that energy, they generate electricity by capitalizing on the wind flow creating lift over the turbine blades, much like a propeller driven aircraft (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2006). Wind turbines have become a primary alternative energy solution in many areas of the world, including Europe and the U.S.

The basic structure of a wind turbine is comprised of a blade system attached to a generator, or set of generators, and mounted on a tower. Gears are required in most common types of generators in order to transform the low rotor speeds to those that are required to generate electricity. There is roughly a 2% efficiency loss for every stage of gears (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2006). Generators are used singularly, or tied to an array of turbines. In other words, systems can produce as little as a few watts, up to a utility sized capacity that is limited only to the physical space available to put up towers. The large utility sized groupings of wind turbines are called *farms* (California Energy Commission 2002).

Wind energy offers several advantages. For example, generation is relatively cheap, individual units have a small footprint, and the decentralized nature of a DG wind turbine means that if a tower is knocked off-line, the impact is localized. In addition, there is no fuel requirement, which results in zero emissions and small logistical footprint. Finally, small residential units can be deployed and set up quickly (California Energy Commission 2002).

Negative aspects of wind energy include that electricity production is completely dependent on whether or not the wind is blowing. Thus, site selection is very important, and it may not correspond with local demand for power. Another aspect of this problem is that the amount of electricity produced varies, depending on wind speed. Finally, the tower and blade systems present a relatively soft target for someone looking to make an impact on power production. Finally, many people may have a problem with the esthetics of the system.

C. DISTRIBUTED GENERATION PROS AND CONS

Potential advantages of distributed generation include:

1. A reduction of required infrastructure, such as transmission lines and transfer stations. This can result in a significant decrease in construction and maintenance costs when compared to large, complicated power generation plants.

2. The decentralization of electrical generation would create more jobs throughout a wide geographic area. The types of jobs created would include maintenance and security positions located within the communities where the electricity is produced. This would produce locally created wealth, personal skill development and facilitate the notion of civil society and responsibility as individuals in a community are given a stake in the security and success of the station.

3. Reduce pollution, both in terms of emissions at the generation source, and in the transportation of liquid or gasified fuel replenishment.

4. DG provides for the decentralization of electricity production. This reduces the amount of long distance infrastructure that is part of traditional large-scale generation plants, such as those currently being invested in Iraq now. Reduced infrastructure and decentralization presents a smaller target profile and thus greater security. It also reduces efficiency losses during long distance transmission.

5. In the case of Iraq, moderating the country's reliance on oil for domestic use by shedding some of the generation load to DG technologies, especially those that do not use fossil fuels, has the potential to reduce political and social conflict over fossil fuel use. Relying almost entirely on fossil fuels to create electricity in a region with plentiful sun and wind resources is arguably a misuse of a valuable export commodity.

6. Small DG systems have the potential to be rapidly deployed to areas of high demand, and offer a reliable step up approach to bridging an electrical generation gap.

7. DG systems can be installed to complement each other. For example, PV can be installed in combination with a wind turbine to generate electricity day and night. Or, a PV system can be installed with a battery backup that would pick up a partial load at night, and be recharged during the day.

Drawbacks of distributed generation include:

1. *May* lose on economy of scale savings provided by large centralized plants. In addition, large hydrocarbon burning plants are a known and well-understood generation platform. They are also well engineered in many respects, and there is a lot of money in contracts made available by governments that benefit international, national and local businesses.

2. Decentralizing maintenance and security responsibilities to a local area, perhaps even directly to the consumer, can have unexpected downsides. It may be difficult to find and/or train people to maintain and secure equipment.

3. The logistics of deploying thousands of units may be a significant challenge. While the logistical footprint is smaller than the oil/electricity sectors, there is still an initial burden in deploying both the DG unit and the accompanying wiring, storage and mounting equipment, batteries, charge controllers, DC-AC inverters, etc.

4. The implications of doing a large-scale tie-in of DGs into the existing electrical network and infrastructure in a place like Iraq are unknown to this author.

5. While new DG technologies, such as thin film PV, have the potential to have competitive $/kW rates, the technologies are often new and relatively unproven. Traditional DG technology prices are coming down, especially as international investment increases. Therefore, the

competitiveness of DG to traditional large-scale generation in a unique and hostile environment, such as in Iraq, is unknown. Analysis of this issue is the focus of this thesis.

6. All machines require certain conditions for efficient and effective operation. The physical and atmospheric conditions in which a DGR is operated have an effect on generation efficiency. For example, solar panels lose efficiency as temperature increases. Wind turbine efficiencies are dependent on specific winds speeds, as designed by the manufacturer. Engines work less efficiently at higher altitudes due to decreased oxygen levels. All DGRs have proper and improper, site installation locations. It is important to do a complete site survey to properly design a DG system that generates electricity efficiently and reliably. This may result in increased system prices.

D. MICROGRID DEFINED

A *microgrid*, or *minigrid*, is the interconnected structure that is formed when several DGRs are linked together. A microgrid is typically comprised of co-located distributed generation technologies, energy storage equipment, and end-use loads. Microgrids have a broad application of use. General examples range from rural electrification, residential/community power networks, commercial, municipal, hospital, campus, and military base power grids (Ye 2005). China Lake Naval Air Weapons Station serves as a specific example of an operational microgrid. Following the experience of the impact of a commercial utility failure on strategic operations at China Lake, the United States Navy began the process of installing DG technologies on the base in order to ensure power to critical loads. The system currently includes several small-scale solar installations, with plans for a large-scale array of PV panels that can handle all of the base's critical load demands whenever the utility company has problems delivering supply.

The importance of the concept of a microgrid to this research is that it is the bridge that would tie any DGRs deployed in, say an Iraqi neighborhood, to the greater National grid, or *macrogrid*. In a village that was not near national grid infrastructure, a microgrid, such as that depicted in Figure 9, would form the basis for the way in which that village distributes the DG generated power throughout the village. The goal of this paper is not to analyze the relationship between DGRs, microgrids and macrogrids. It is to begin to analyze and quantify the fully burdened costs of DG in post-war reconstruction. However, without understanding microgrids, one cannot know how DG would be able to help solve the greater problem.

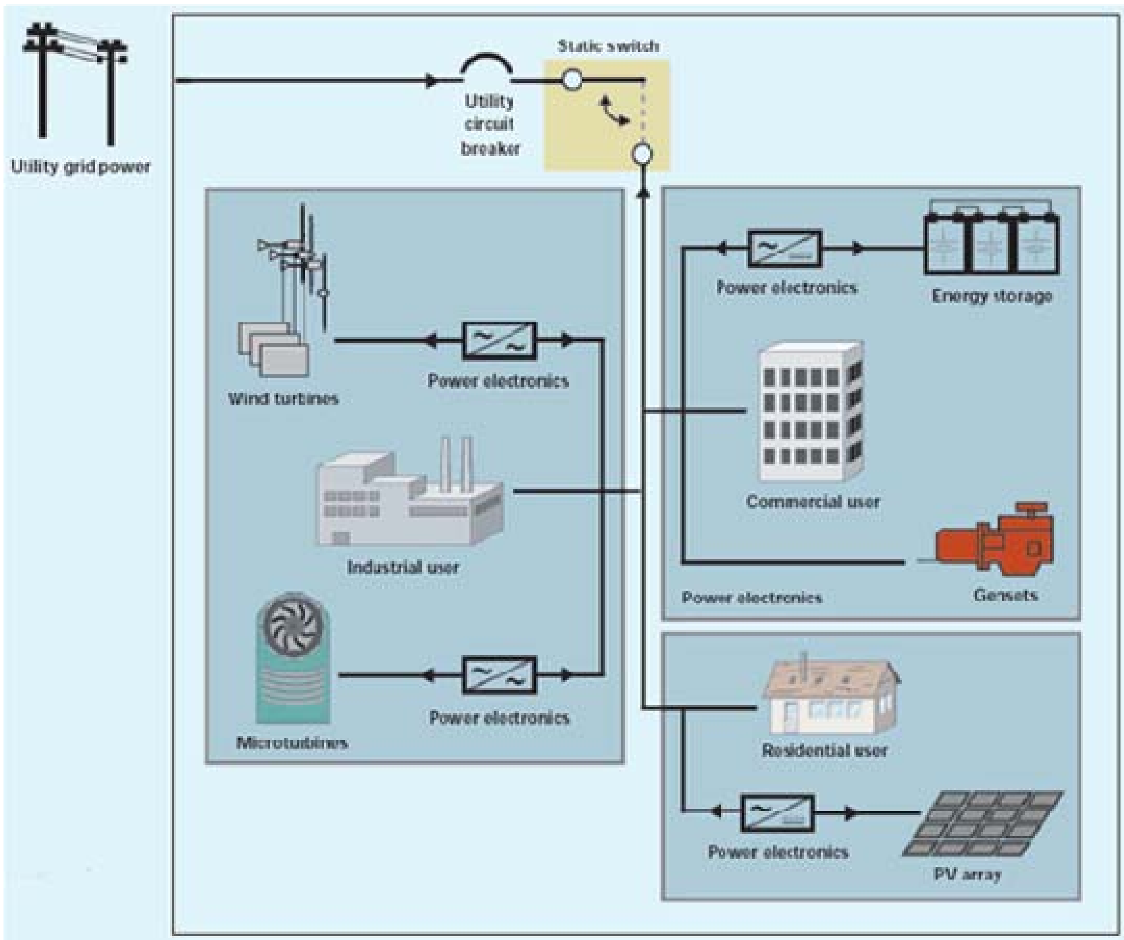

Figure 9: Microgrid Example (Source: Sandia National Labs White Paper, "Microgrid Characterization in the United States," p. 15)

Sandia National Labs defines three classifications of microgrids, Simple, Master Control, and Peer-to-Peer. The characteristics of each are summarized in Figure 10 (EPS = electric power system):

Microgrid Characteristic	Simple (Class I)	Master Control (Class II)	Peer-to-Peer Control (Class III)
Multiple generators serving loads in multiple buildings	✓	✓	✓
Served by Local EPS	✓	✓	✓
Interconnected with Area EPS	✓	✓	✓
Event detection and response control	✓	✓	✓
Generators located in central power plant	✓		
Generators distributed among buildings (separate buses)		✓	✓
Master microgrid control	✓	✓	
Peer-to-peer microgrid control			✓

Figure 10: Microgrid Characteristics (From: Sandia National Labs Report, "Characterization of Microgrids," 2005.

A microgrid system should meet the specific and unique needs of a site. If those needs are critical, i.e., power has to be available with little or no interruption, such as at a hospital, then a microgrid is tailor designed to handle those circumstances. In order to create a near seamless transition from area EPS to local EPS, either a static transfer switch in conjunction with a battery storage system, or a DG system operating in parallel with the area EPS must be installed (Friedman and Stevens 2005). In either case, non-critical loads are dropped, unless the system is designed to provide enough generation capacity to maintain them. The process of disconnecting from an area grid, or utility provider, in order to supply electricity only via DG systems is called islanding (Ye 2005). Islanding can present several technical complications in terms of how the microgrid interacts with the macrogrid; however, these complications are not a concern of this paper, and are not addressed.

Microgrids operate in three specific modes, as defined by Sandia National Labs:

- Mode 1 is called Partial Baseload, and is a condition in which DGRs provide baseload power to a portion of a sites loads, but rely on an area EPS to supply supplemental and backup power.
- Mode 2 is a Full Baseload, and is a situation in which distributed generators provide power to all the loads of a site, and the area EPS provides a backup system.
- Mode 3 is referred to as a Backup/Peaking mode. This is when an area EPS provides power to all the loads at a site. It relies on DG resources to provide backup and peak load resources (Friedman and Stevens 2005).

It is not the purpose of this research to decide what class microgrid should be used, and under what mode. Rather it is our purpose to begin to quantify the fully burdened cost of electricity production in a Phase IV military stabilization operation, as embodied by the current situation in Iraq. We believe that microgrids powered by DGR provide an option for expanding electrical production through modularity and increased security and reliability.

Some coalition forces responsible for rebuilding the grid in Iraq have already recognized this and are currently installing microgrids. They refer to the concept as "micro-generation." Projects are based on 200-400 kW sized reciprocating engine generators, formed around a neighborhood/business coop system (Coalition Force Iraq Reconstruction Unit 2007). According to 2007 briefs acquired through sources in Iraq, the actual installation of the system is relatively easy, but the authors acknowledge that reciprocating engines create a problem due to the fuel requirement (Coalition Force Iraq Reconstruction Unit 2007). This is where the question of what type of DGR makes sense in post-war reconstruction becomes relevant. The following analysis attempts to determine whether reciprocating engines, microturbines, PV and/or solar, either singularly, or in combination make economic sense when utilized for electrical grid enhancement.

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III. ANALYSIS AND DISCUSSION

A. DEFINITION OF THE OBJECTIVE

The goal of this research is to quantify the fully burdened cost of electricity generation in post-war reconstruction using various life-cycle cost estimates. Iraq was chosen as the test case for this endeavor. All cost data is normalized to annual dollar per kilowatt ($/kW). This was done to facilitate comparative analysis between four types of deployable distributed generation technologies and a sample of the large-scale generation that was invested in Iraq during the height of the war.

B. ASSUMPTIONS AND CONSTRAINTS

During the course of this research, very little data on distributed generation technology in Iraq was discovered. Therefore, all of the capital and operation and maintenance (O&M) cost data used in this research is based on installation in the United States. In order to account for differences in regional installation (e.g., Iowa vs. Baghdad), a security multiplier was developed based on previous research by Brookhaven National Laboratory in a publication titled, “Reference Guide for Hazard Analysis in PV Facilities.” This multiplier is discussed in detail later.

Emphasis was placed on developing a detailed data set on four types of DG that might feasibly be deployed to a potentially hostile region. Specific data of interest for each of these DGs includes technology type, average generation capacity in kilowatts (kW), capital costs (initial equipment plus installation costs), operation and maintenance (O&M) costs, fuel costs, storage costs, security costs, type of fuel and fuel consumption.

There are several economic unknowns when conducting academic analysis remotely from the geographic area of interest. For example, O&M costs in this research are based on studies citing the economic realities in the United States. These costs are going to be different than the costs in another region in the world due to the difference in labor, logistics, parts availability and fuel costs, just to name a few. When and if this information becomes available, the database, and the research, can be updated. Until then, this research is offered as a reasonable attempt to calculate those costs. Because of the lack of data, this research does not actively account for economic factors such as tax breaks, contract premiums, and exact logistical costs for deployment in a hostile environment.

As noted in Chapter II, meteorological conditions affect the operation and efficiency of all equipment exposed to the elements. During a sand storm, to cite an extreme example, engine intakes may become clogged, PV cells may take in less sunlight, and wind turbine gears may become fouled. In a more mundane example, some areas of the world receive more wind and/or sunlight than others, thus affecting electrical production with renewable technologies. This research does not account for exact conditions that may influence each system.

Complete network architecture, often referred to as balance of system (BOS), is not considered in this research. The only exception to this is that the $/kW figure used for battery storage is taken from a Sandia National Labs report that included BOS in its calculations (Schoenung and Hassenzahl 2007). Recommended BOS items for integration in further work are inverters, converters, specific storage requirements, and connection technologies (wiring).

In this analysis, a system's physical life was used to determine the period of time over which the benefits between the various alternatives were expected to accrue. The estimated average number of years that each generation system could be physically used before replacement was researched. These numbers were found in various publications and technical information websites, such as on the National Renewable Energy Lab's site, www.nrel.gov. When estimates varied, the lesser value was used. Physical life spanned from around five years before a major overall was required in large-scale natural gas turbines, to approximately 30 years in a PV panel before it begins to lose a consequential amount of efficiency. The system life number was used to divide the total costs for each system. This number was then added to the other cost variables which were already given in annual $/kW figures.

The number of hours a system would be used in a given day was defined by the author. The actual number of hours a DG would be used depends on several variables.

For example, whether the system is stand-alone or part of a microgrid, and, if it is part of a microgrid, whether or not the microgrid is tied into the macrogrid. This would determine if the DG is used only for power shaving at times of peak demand, or if the system was a primary source of power. Environmental factors provide another large operational variable. Where, when and for how long the wind blows and the sun shines has an obvious impact on wind and PV DG use. For the purpose of this research, it was assumed that all systems were stand-alone, and thus did not rely on power from a macrogrid. Diesel, microturbine, and wind turbine generators were assumed to operate for 20 hours a day. PV was assumed at 10 hours. The large-scale generators were specified to operate for 21.92 hours a day. This was based on an EPA report from which cost data was gathered. The costs data was based on an 8000 hour a year schedule.

All of the systems evaluated were done so with a derived annual $/kW value, thus enabling a normalized comparison of one year for systems with significantly different physical lives.

One of the reasons for researching the use of distributed generation systems in post-war reconstruction was the desire to think of a way to produce electricity on a broad scale, but decentralized in order to reduce the target appeal for insurgents, opposition militias and criminals. DG technologies, such as the four investigated in this research, offer these benefits in a package that takes up a relatively small amount of physical space. Reciprocating diesel engines, microturbines, solar PV panels and small-scale wind turbines all have a relatively small footprint and are presumably reasonably easy to deploy. This is one reason why small diesel generators have been used to make up the large-scale generation deficit by Iraqi civilians.

In addition to space, and assuming manufacturers can keep up with demand, DG technologies offer the potential for quick deployment on a broad scale as opposed to the long period of time it takes to design and construct a complex large-scale electric plant.

The price tag for rebuilding power plants presents what is arguably the largest constraint to the overall reconstruction effort. It is hoped that this research helps to cast some light on the options that decision makers and planners have at their disposal when developing and rebuilding electrical networks in post-war regions.

C. LIST OF PROBLEM ALTERNATIVES

As noted, current electrical production in Iraq is done using large-scale oil, natural gas, and hydroelectric projects. These systems currently produce, on average, half of the supply the grid system demands. Several alternatives could decrease the supply deficit.

1. Existing Methods

The first would be to build upon the status quo, large-scale technologies. In a stable political, social and military environment, this may very well be the appropriate answer. Large-scale production can offer economy- and production-of-scale benefits. They offer concentrated logistics streams for both parts and fuel. Finally, they provide well-known and understood technological and capacity benefits. In Iraq, these types of power plants are being, upgraded, retrofitted, expanded, and duplicated. However, regions engaged in postwar reconstruction often do not have the luxury of stability to rely on when making infrastructure improvements, so many of these benefits, as proven by the example in Iraq, cannot be fully realized. During the height of the war in Iraq, the country's large-scale generation systems and the grid that connected it were easy targets. As previously noted, this is one of the prime causes for the slow and inadequate pace of electric infrastructure rebuilding. A small sample of Iraqi large-scale natural gas turbine power plant data is used in order to compare to DG alternatives.

2. Alternatives

Another generation option is to invest in and deploy distributed generation technologies. As discussed, there are several types of DG systems available today. For the purpose of this research, PV, wind, microturbines, and diesel-powered reciprocating engine generators have been chosen because they offer prospective ease of deployment and a relatively small footprint. What are unknown are the costs of the broad application of these systems in a war torn region that is suffering from uncertain political, social and military environments. The goal of this research is to determine if they do, or do not, make economic sense.

3. Infeasible Alternatives

Some DG technologies are currently just not feasible for use in this application. Small-scale hydroelectric projects rely on water resources and do not have a broad application in the arid regions currently being discussed.

Another example of a technology considered currently infeasible for this application is concentrated solar power. Typical concentrated solar power (CSP) systems generate electricity by concentrating solar energy, via mirrors, on a liquid medium that is super-heated and then harnessed to power steam turbines. CSP normally comes in the form of trough or tower arrays. These systems are complicated, have a large footprint, and are currently engineered for large-scale generation. Work has been done on small-scale CSP systems, but the technology is not common, and thus was not considered for this research.

Finally, fuel cells provide the possibility for efficient, minimal emission generation with a small footprint; however, they have high installed costs (Akhil 2007). In addition, the technology is still young, complex, and untested in the type of environment considered here.

The exceptions briefly documented here should not preclude these technologies from being considered in further work. However, as of now, they appear to be poor choices given the conditions considered in this research.

D. DATA

1. Data Collection

Data for this research was collected from multiple sources. The core of the data was taken, with permission, from a data set derived by the Lawrence Berkeley National Laboratory (LBNL) Distributed Energy Resources (DER) team, led by Dr. Chris Marnay. The DER team compiled this data for use in there Distributed Energy

Resources Customer Adoption Model (DER-CAM). DER-CAM is an optimization model that uses many of the same variables that are of interest in this research. As described in one of LBNL's papers on the topic, "DER-CAM models specific sites and selects optimal DER systems to install in parallel to the macrogrid, given utility tariffs, fuel costs, and equipment performance characteristics." (Siddiqui 2004)

The DER-CAM data was evaluated for accuracy and completeness for the four types of DG systems being evaluated in this research. Discrepancies and incomplete data points were corrected by researching a multitude of reports published by Sandia National Labs, Lawrence Berkley National Labs, and the National Renewable Energy Labs (NREL). Additional data was found in the Handbook of Energy Efficiency and Renewable Energy, edited by Frank Kreith and D. Yogi Goswami (2007). Finally, in some cases open source data was utilized. Equipment costs for a small sample of diesel generators, for example, were taken from an online generator sales site.

O&M costs are an example of incomplete data that was researched via the sources named in the previous paragraph. In the case of diesel generators, these costs had to be calculated based on data from NREL Power Tech Energy Data Book (2006) that estimated average diesel generator O&M costs at .013$/kWh. This number was then multiplied times the estimated number of hours a unit would be used in a year, resulting in the annual $/kilowatt for this type of system. Microturbine O&M costs had to be calculated similarly using data from the California Distributed Energy Resources Guide (2002).

2. Data Set Design

The design of the data set was based on the desire to capture the costs of installing and running electrical systems in a post-war environment. The life-cycle costing method was used to evaluate the true costs of these systems as they are influenced by fuel logistics and security. To that end, the primary variables collected were initial costs, operation and maintenance costs, fuel costs, energy storage costs, and security costs (including a security level multiplier that is discussed in detail later).

a. Initial (Capital) Costs

Initial diesel generator costs were derived from one of three sources. First, cost estimates were obtained directly from the DER-CAM data set, most of which was taken from technical specification sheets provided by the manufacturer. Second, estimates were taken directly from open source sales data. Third, estimates were made based on the state of California's Distributed Energy website, which provides generalized costs estimates in FY$02 amounts (California Energy Commission 2002).

The sample size of microturbines was considerably smaller that diesel generators. The initial costs for three of the units were also taken from the DER-CAM data. The costs for the rest of the units were taken from a low-end FY$09 initial cost estimate presented by Resource Dynamics Corporation (Resource Dynamics Corporation 2005).

The photovoltaic panel industry currently has hundreds of manufactures. The variations in the technology are both complex and vast. Collecting cost data from an adequate sample of manufacturers would have been difficult. So, instead of accumulating an inaccurate sample of individual products, generalized numbers were used for this research. Data was used from a Lawrence Berkley National Laboratories report titled, "Letting the Sun Shine on Solar Costs" (Wiser 2006). The report provided the average installed costs for a range of system generation sizes. This range was used as the basis for the rest of the calculations on PV systems.

Wind turbine manufacturers, while fewer in number, still make a comprehensive range of turbine models. Collecting actual cost data from manufacturers proved to be too inefficient. Instead, a data set provided by the Canadian Wind Energy Association (CWEA) was used. The CWEA supplied a comprehensive matrix estimate of installed costs organized by system generation size (CWEA 2006). The CWEA matrix was used for the rest of the wind turbine calculations.

Installed/refurbish costs for the two large-scale natural gas turbine projects in Iraq were taken directly from USAID Audit Report NO. E-267-05-003 (USAID 2005). Their numbers were assumed to be in FY$03.

b. O&M Costs

Diesel generator O&M costs were derived from information provided by NREL's 2006 "Power Tech Energy Data Book." It estimated that average O&M is .013$/kWh. This value was then multiplied by the number of operating hours in a year. In this case, it was assumed that a diesel generator would run for 20 hours a day, resulting in an annual use of 7300 hours.

Microturbine O&M costs were taken from the California Distributed Energy Resource Guide, which estimated those costs at .016 $/kWh. This value was multiplied times the number of operating hours in a year, which was also assumed 7300 hours per year.

PV O&M costs were estimated at .34% of the installed cost. This estimate was taken from a January 2008 paper titled, "SAM (Solar Advisor Model) - Sample Commercial System Description." SAM is a "comprehensive solar technology systems analysis model" developed by NREL and Sandia National Labs (National Renewable Energy Lab 2008). This figure does not include balance of system (BOS) costs.

Wind Turbine estimate O&M costs were taken from the Canadian Wind Energy Association. The high-end O&M price was used for the generation capacity range, and then divided by the high-end capacity, resulting in a $/kW cost in Canadian dollars. Using an online currency exchange calculator, that number was then normalized to the January 2009 U.S. currency rate.

O&M costs for the two Iraqi facilities were calculated via regression analysis based on data from an EPA repo;rt titled, "Technology Characterization: Gas Turbines" (EPA, Prepared by: Energy Nexus Group 200218) Their numbers were based on 8000 operating hours per year. Regression was required because the EPA's analysis only included system capacities up to 40,000 kW (see Figure 10). The Doura Power Plant and Kirkuk Substation Turbines produced 320,000 kW and 324,000 kW respectively. Using this method, O&M costs for each facility were calculated at .013 and .012 $/kW, FY$02, respectively (see Figure 11).

O&M Costs[14]	System 1	System 2	System 3	System 4	System 5
Electricity Capacity, kW	1,000	5,000	10,000	25,000	40,000
Variable (service contract), $/kWh	0.0045	0.0045	0.0045	0.0040	0.0035
Variable (consumables), $/kWh	0.0001	0.0001	0.0001	0.0001	0.0001
Fixed, $/kW-yr	40	10	7.5	6	5
Fixed, $/kWh @ 8,000 hrs/yr	0.0050	0.0013	0.0009	0.0008	0.0006
Total O&M Costs, $/kWh	0.0096	0.0059	0.0055	0.0049	0.0042

Figure 11: EPA Estimated Gas Turbine Non-Fuel O&M Costs (FY$00) (From: EPA Report, p. 18)

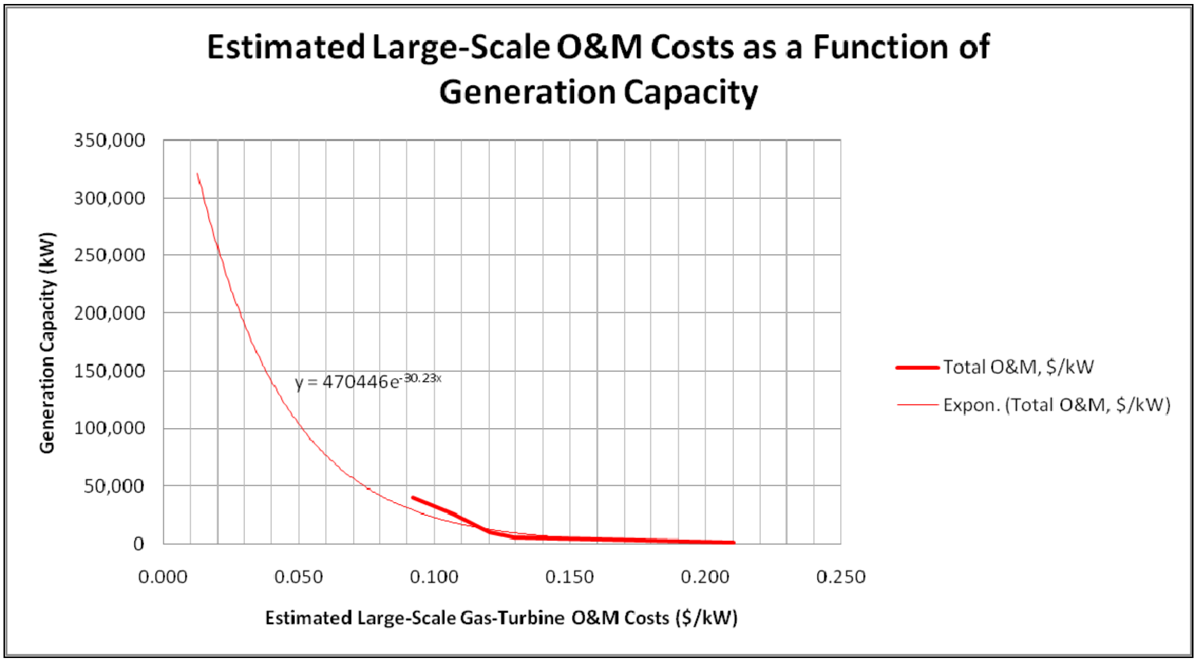

Figure 12: Est. Large-Scale O&M Costs as a Function of Generation Capacity (After: EPA Report, p. 18)

Note: No distinction is made in this research between fixed and variable O&M costs.

c. Fuel Costs

Diesel generator fuel costs were calculated by multiplying the hourly fuel costs (derived from the published/estimated fuel flow rate and the U.S. average cost of diesel fuel in January 2009, as published by the U.S. Department of Energy) times the assumed annual, hourly in-service time for each system. The result was a total annual fuel cost. This fuel cost was then divided by the kW capacity in order to produce an average annual $/kW price for each system, in gallons.

Microturbines were calculated in the same manner as diesel generators; however, the fuel type for these systems is natural gas, so some extra unit conversions had to be done. The result was a fuel cost in $/kW, but based on MMBTU's of natural gas, at a January 2009 price, as published by the U.S. Department of Energy.

Wind turbine and photovoltaic systems do not rely on fuel directly to produce electricity.

Fuel costs of the large-scale generation facilities in Iraq were calculated based on current fuel prices as explained above. The problem initially, however, was that is was unknown what the fuel flow rate was for systems of that size. The EPA report used in the O&M calculation above again provided statistics that could be used to estimate larger facility fuel costs (see Figure 13). There appears to be a linear relationship between generation capacity and fuel consumption. The trend analysis based on the five data points provided in the EPA report provides evidence of this (see Figure 14).

Cost & Performance Characteristics[5]	System 1	System 2	System 3	System 4	System 5
Electricity Capacity (kW)	1,000	5,000	10,000	25,000	40,000
Total Installed Cost (2000 $/kW)[6]	$1,780	$1,010	$970	$860	$785
Electric Heat Rate (Btu/kWh), HHV[7]	15,580	12,590	11,765	9,945	9,220
Electrical Efficiency (%), HHV	21.9%	27.1%	29.0%	34.3%	37.0%
Fuel Input (MMBtu/hr)	15.6	62.9	117.7	248.6	368.8

Figure 13: EPA Estimated Gas Turbine Fuel Flow (Input—MMBTU/hr) (From: EPA Report, p. 8)

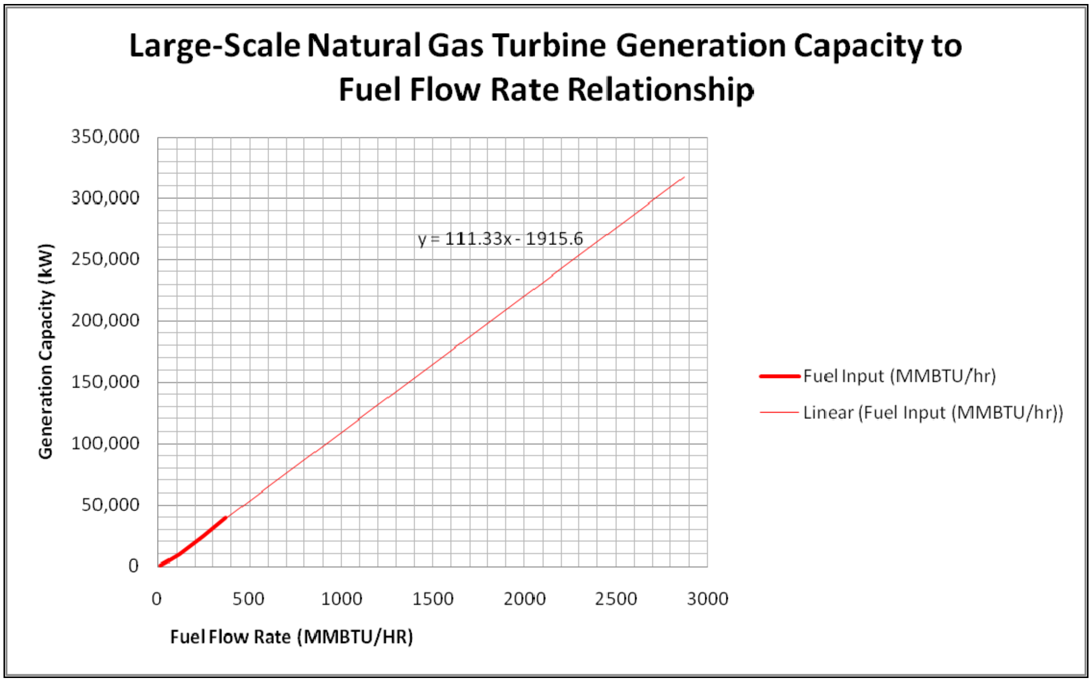

Figure 14: Large-Scale Gas Turbine Gen. Capacity to Fuel Flow Rate Trend Analysis (After: EPA Report, p. 8)

d. Energy Storage Costs

Energy storage (battery) costs were only applied to wind and PV technologies. The rational was that assuming fuel inputs are not disrupted, and barring mechanical failure, fuel consuming DGs remain operational for the assumed hours per day. It should be noted that battery storage could be used with any type of DG technology.

Wind turbines and PV rely on energy inputs from the wind and sun. These inputs can vary significantly, depending on meteorological conditions. One way to overcome this variability is to tie the DG system to a micro or macrogrid, thus making up for decreased electricity production by the wind and/or PV systems with electricity from the grid. As previously noted, for the purpose of this research, grid tying is not assumed.

A second method to assure power availability is to include battery energy storage in the cost of the PV and wind turbine systems.

The question of which storage technology should be considered for DG use in a place such as Iraq was answered in an interview with Georgianne Peek, a research scientist and energy storage expert at Sandia National Labs, Albuquerque, NM (Peek 2008). Ms. Peek recommended a gel or, absorbent glass matt (AGM), valve regulated lead acid (VRLA) battery. These types of batteries are ubiquitous, often used in automobile, boat and other similar applications. They are also maintenance free, and unlike typical lead-acid batteries, can be oriented in any manner without risk of leaking acid, which is a practical benefit in transportation, storage, installation and use.

Figure 15 shows the annual cost analysis for various types of storage systems. Taken from a 2007 report on storage costs, it shows that there are cheaper alternatives to the recommended VRLA lead acid battery. However, some of the storage systems, such as pumped hydro, have site-specific requirements. VRLA batteries are common, proven, portable, easily acquired, and easily replaced. According to the Sandia paper, VRLA lead acid batteries cost approximately $840/kW annually (Schoenung and Hassenzahl 2007). When adjusted for inflation, this type of storage system cost $873.10 FY09. This is the figure used in LCC calculations for wind and PV.

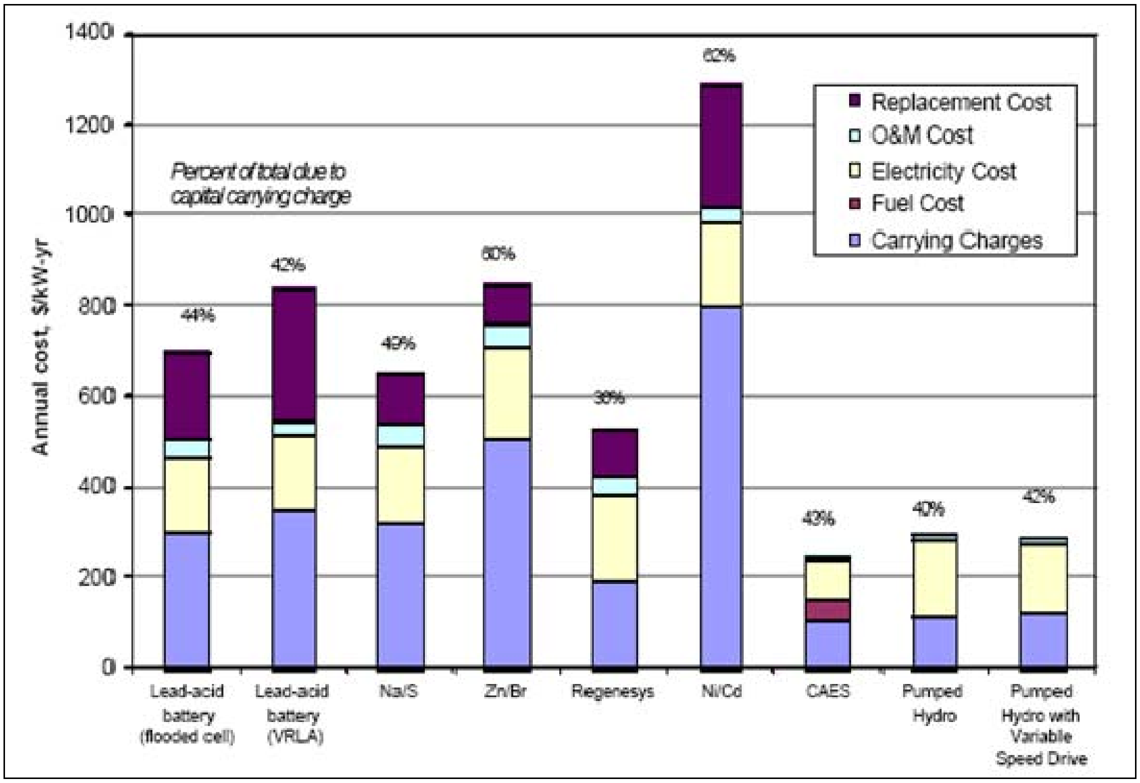

Figure 15: Annual Cost Components for 8-hr Bulk Energy Storage Technologies (From: Sandia National Labs Report SAND2007-4253)

e. Security Costs

There are two levels of security costs used in this research. First, according to the GAO, the Department of Defense estimated that its contractors incurred a 14% security premium on the "design/build" of Iraqi electrical projects in 2006 (GAO 2007). This was a significantly tighter estimate than the 10-30% estimate the GAO cited the DoD in 2004. To account for the estimate in this research, the 14% figure was applied to the entire calculated LCC, and then adjusted to FY$09.

It is unknown if the 14 % figure captures variations in project site locations, fuel logistics, long-term security, and/or actual threat after the design/build of the generation facility. We estimate the cost of these variations by using security threat analysis on each of the five types of systems being evaluated in this paper. The threat analysis is based on a paper by Fthenakis and Trammell of Brookhaven National Laboratory, titled "Reference Guide for Hazard Analysis in PV Facilities." The methodology for the analysis is generalized enough to be used to evaluate generation technologies other than PV. The methodological details are described in Section 10 of the Reference Guide (Fthenakis and Trammell 2003).

While this method of security risk analysis is site and project specific, for the purpose of this research, and without having first-hand knowledge of security constraints in the areas envisioned for the application of the systems being discussed, security threat analysis was conducted for generic high- and low-security threat possibilities. The regional model for threat analysis was Iraq, using knowledge and assumptions based on security descriptions presented in reports by U.S. government agencies, such as USAID, GAO, Special Inspector General for Iraqi Reconstruction (SIGIR), and the Iraq Study Group. The dire situation that all of these agencies recorded from the period of 2003 to mid-2008 have been documented in Chapter I of this paper.

Based on this information, low and high-risk security threat matrices were completed. Figure 16 is an example of what a completed matrix looks like, in this case, for the high-security threat environment. The first column lists the targets being evaluated: wind, PV, generator sets (diesel and microturbine), and large-scale gas turbines. Diesel and microturbines have been grouped together for the threat evaluation because they have similar security threat profiles. They both require logistical fuel support, have similar footprints in terms of size, noise and heat generation, and they can be configured to generate similar production capacities.

The second column lists the risk element for each target. The elements proposed by Fthenakis and Trammell, and adopted here, are "threat," "vulnerability," and "consequences." As interpreted for this analysis, the term "threat" refers to the potential for a given threat type against the system in question. "Vulnerability" refers to the level of damage that a threat can inflict on a system. "Consequence" refers to the impact that the potential damage by a specific threat have on a system.

High Security Generalized, Qualitative Threat Matrix (e.g., Iraq)											
Targets	Risk Elements	Terrorist	Criminal	Insider	Violent Activists	Intel. Collection	Vandal	Natural Disaster	Fuel Logistics	Summary IndSe	Scaled Security Level Multiplier
Wind	Threat	H	H	H	M	L	H	L	L	48	
	Vulnerability	H	M	M	M	L	M	L	L	32	10
	Consequences	Ma	Ma	Ma	Ma	N	Ma	N	N	20	
PV	Threat	H	H	H	M	L	H	L	L	48	
	Vulnerability	M	M	M	L	L	M	L	L	24	8.8
	Consequences	Ma	Ma	Ma	N	N	Ma	N	N	16	
Gen. Sets (Diesel and MicroTurbine)	Threat	H	H	H	M	L	H	L	H	57	
	Vulnerability	M	M	M	M	L	M	L	H	37	11.6
	Consequences	Ma	Ma	Ma	Ma	N	Ma	N	C	22	
Large-Scale Gas Turbine (Iraq)	Threat	H	H	H	M	L	H	L	H	57	
	Vulnerability	H	H	H	M	L	M	L	H	52	14.9
	Consequences	K	K	K	C	N	C	N	K	40	

	Cat Level		Cat Value
Threat and Vulnerability	L	=	1
	M	=	5
	H	=	10
	N	=	1
Consequences	Ma	=	3
	C	=	5
	K	=	7

Figure 16: High Security Generalized, Quantitative Security Threat Matrix

The third through tenth column list specific threat types, beginning with "terrorist" and ending in "fuel logistics." The original Fthenakis and Trammell matrix has been modified. It included columns for "psychotic," "disgruntled employee," and "militia," all of which have been removed. "Natural disaster" and "fuel logistic" categories have been added.

The body of the matrix is populated with the evaluator's categorical estimate of the threat value for each risk element. These values can be found in the key at the bottom of Figure 16. In this "high security risk" evaluation, the wind system has been deemed to have a category H threat level (circled in blue). Numerically, this means that cell has a value of 10. Each risk element/threat type cell has been graded in this manner. In another modification from the Brookings guide, a "Threat Indices" column has been added after the "threat" columns. In this column, the categorical values that have been populated in the matrix are summed across each respective row. In a final modification to the original matrix concept, a column called "Scaled Security Level Multiplier," has been added. This column contains only one value for each system type (e.g., wind, PV, etc.). The value is calculated by summing the "threat indices" for each system, and then dividing by a scaling factor of 10. The result is what is being called in this paper a Security Threat Multiplier (SLM).

The final step in the security threat analysis was to multiply the LCC by the SLM. The thought behind this is that it provides a quantitative method to measure the impact various security threats have on electrical infrastructure projects. It also provides for a method of sensitivity analysis, by varying the impact that different security threats can have on specific systems. That is how it is utilized in this paper.

Note: Security threat multipliers are derived by the author's non-expert assignment of threat ratings. While one can argue bias in the ratings, values were assigned based on study of real-world threats and their impacts on the systems. It is believed that these values represent a reasonable assessment of generic in-theater threats.

3. Data Normalization

The data collected for spanned multiple fiscal years (FY). Therefore, it was necessary to normalize from those published FY dollars to FY$09 in order to provide decision makers the most "apples to apples" information. The Naval Center for Cost Analysis (NCCA) inflation calculator was used to complete this task (http://www.ncca.navy.mil/services/inflation.cfm).

The NCCA inflation calculator is a spreadsheet-based tool that requires four inputs. In Figure 17, it can be seen that that the first input is the "Appropriation/Cost Element." The calculator offers several choices, including "Aviation" and "Fuel Procurement" elements. "Other Procurement, Navy" was used for all of the normalization done in this research.

The second input was the "Base/Input Year." This is where the fiscal year that the cost data was to be normalized from was entered. As noted, it varied considerably between data inputs. For example, most of the diesel generator data that Lawrence Berkley National Labs (LBNL) collected was from FY$2000. Whereas, the solar data obtained from LBNL was in FY$2004.

The third input requires the inflation type to be entered. FY/Constant to FY/Constant was chosen for this research. (This portion of the calculator is optional. A comprehensive table could be generated following input number two.)

The fourth and final input required is to enter the "Output/Target Year." In all cases for this research, cost data was converted to FY$09.

Following the completion of these steps, the calculator generates the inflation factor. In the example provided in Figure 16, the inflation factor between 1999 and 2009 is 1.2127. Once the inflation factor was obtained, it was multiplied by the Life-Cycle Cost (LCC) value, and the result was then added to the old FY LCC value in order to adjust for inflation.

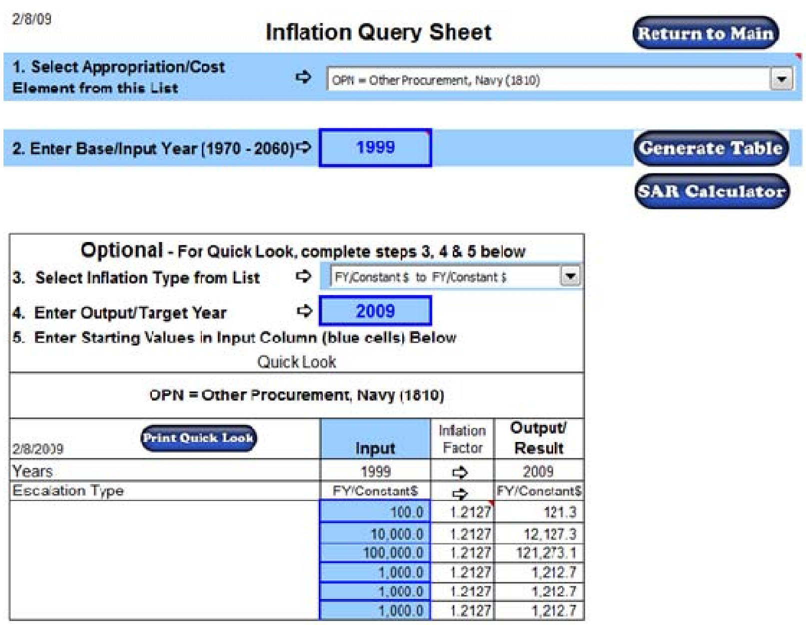

Figure 17: NCCP Inflation Calculator

Fuel costs were not adjusted for FY09 because those numbers were calculated using Department of Energy average estimates in January 2009.

4. Life-Cycle Cost

Life-cycle cost (LCC) is the base value used to analyze differences among the systems. It includes capital and O&M costs, fuel type, fuel consumption and fuel costs, storage costs, and security costs. This data was computed and presented as annual life-cycle cost in levelized units of $/kW.

(Note: The term "levelized" is commonly used in energy research and refers to the annulization of phased LCC. It is similar to annualized present worth (APW).)

Levelized (LCC) is made up of the following terms:

LCC ($/kW) = (initial capital and installation costs (**I**)

+ levelized, non-fuel O&M costs (**M**)

+ levelized annual fuel costs (**E**) (diesel gen., microturbine, and large-scale NGT plants only)

+ levelized annual storage costs, including BOS (**ST**) (wind and PV only)

+ levelized 14% annual security contract costs (**EC**))

* security level multiplier (**SLM**)

Or,

LCC ($/kW) = (I + M + E + ST + EC) * SLM

The methods for developing the terms included in this equation have been explained in detail earlier in this chapter.

E. ANALYSIS OF BENEFITS

1. Deficit Analysis

The key question that this research seeks to answer is whether the use of distributed generation technologies can have a have a positive financial impact in the rebuilding of electrical infrastructure in countries recovering from war. Iraq is the primary case study, as it still recovering from a rather large electrical generation deficit. In Iraq, in 2008, there is an average annual demand of approximately 8000MW of electricity. The electrical system is currently only able to supply 4500MW. The question is; what is the best way to make up the 3500MW annual supply deficit. To do this, the levelized annual life-cycle cost for each of the evaluated systems was multiplied times the production deficit of 3500MW.

Figure 18 compares the distributed generation systems described earlier to a sample average of the large-scale natural gas turbine systems currently being used in Iraq. Three proposed mixed strategies have been calculated. None of the Figure 18 generation methods have been calculated with the SLM.

The suggested mixed strategies are:

- One-third each of microturbines, PV and wind turbines (orange column)
- One-quarter each of diesel generators, microturbines, PV and wind (light purple column)
- One-half large-scale natural gas turbine, and one-sixth each microturbine, PV and wind (pink column).

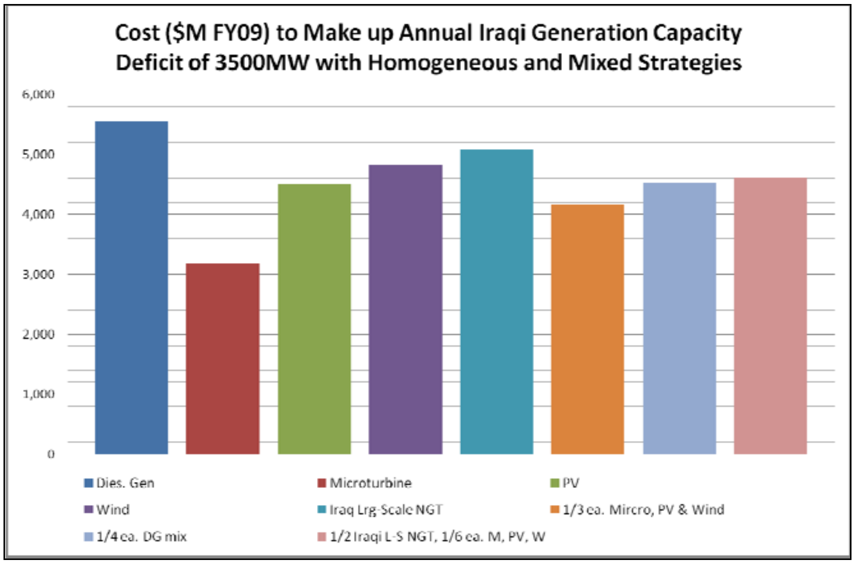

Figure 18: Cost to Make up Annual Iraqi Gen. Capacity Deficit of 3500MW using Homogeneous and Mixed Strategies

If only diesel generation were used (the first, large blue column in the Figure 18), it would cost over $5.5 billion to make up the deficit. The large-scale production systems (the last, pink column) are the second most expensive, at just under $5.1 billion. Of the five individual system types, microturbines are the least expensive at just under $3.2 billion.

The one-third mixed strategy offers a cost benefit when compared to the diesel generator, PV, wind and other two mixed strategies. However, microturbines still provides a significant cost savings benefit overall when SLM is not considered.

Using a high security threat matrix evaluation for a generic Iraqi site, SLM's were generated and applied to the LCC values. Then, as in Figure 18 above, the LCC's were multiplied times the current 3500MW deficit in Iraq. The results presented in Figure 19, are an analysis of the cost to make up the 3500MW annual supply deficit using both homogonous and mixed strategies for a high security threat environment.

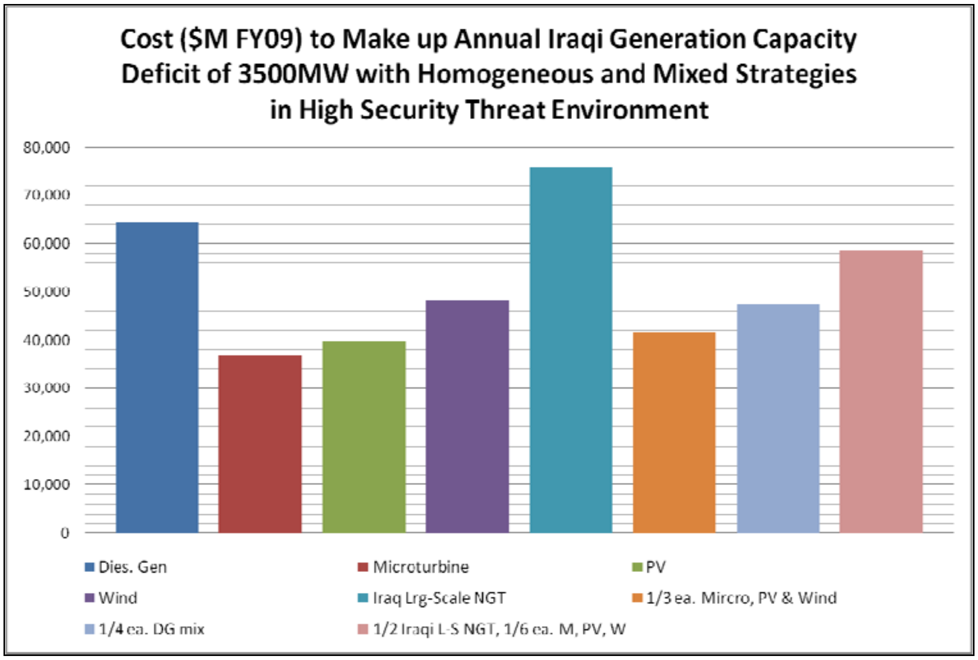

Figure 19: Cost to Make up Annual Iraqi Gen. Deficit of 3500MW with Homogeneous and Mixed Strategies in a High Security Threat Environment

Large-scale natural gas systems were rated at a higher threat level because they are assumed attractive targets. This is an assumption well documented in U.S. government reports. Because of this, the large-scale systems, when considered both homogeneously and in mixed-strategy, cost more. In the case of using large-scale systems alone to make up the 3500MW deficit, it cost just under $76 billon. Diesel generators provide a less expensive option compared to the large-scale system, because they are decentralized, and make a less appealing target. However, they are still more expensive than microturbines, PV and wind. This is primarily due to the cost of diesel fuel. Microturbines share the same fuel logistics burden that diesel generators do, but they benefit from the significantly cheaper price of fuel.

Wind turbines, while more cost effective than diesel or large-scale systems, are less attractive due to their target profile. In other words, their very design makes them an easy target as opposed to PV cells that can be concealed on a rooftop, or a generator that can be housed in a protective building or enclosure. PV becomes a significantly more attractive option because of the lack of fuel and logistics burdens. Finally, the one-third mixed option is only slightly more expensive than using PV alone.

Figure 20 is similar to the data in Figure 19, except that it has been evaluated for a low security threat. At $16 billion, homogeneous use of microturbines is the most cost effective method of reducing the generation deficit. Large-scale gas turbines are the least cost effective in both homogeneous and mixed use at $46.5 and $37 billion, respectively. One-third and one-quarter DG mixed strategies present next best options over microturbines, with the one-quarter slightly edging out the one-third. Finally, homogeneous use of diesel generators is more cost effective than PV and wind.

Decentralized DGs benefit significantly over the centrally located, and presumably more easily targeted, large-scale systems. When fuel logistics becomes less of a threat burden, diesel generators become a more attractive option over non-fuel consuming systems. Mixed DG strategies benefit from both decentralization and low fuel costs.

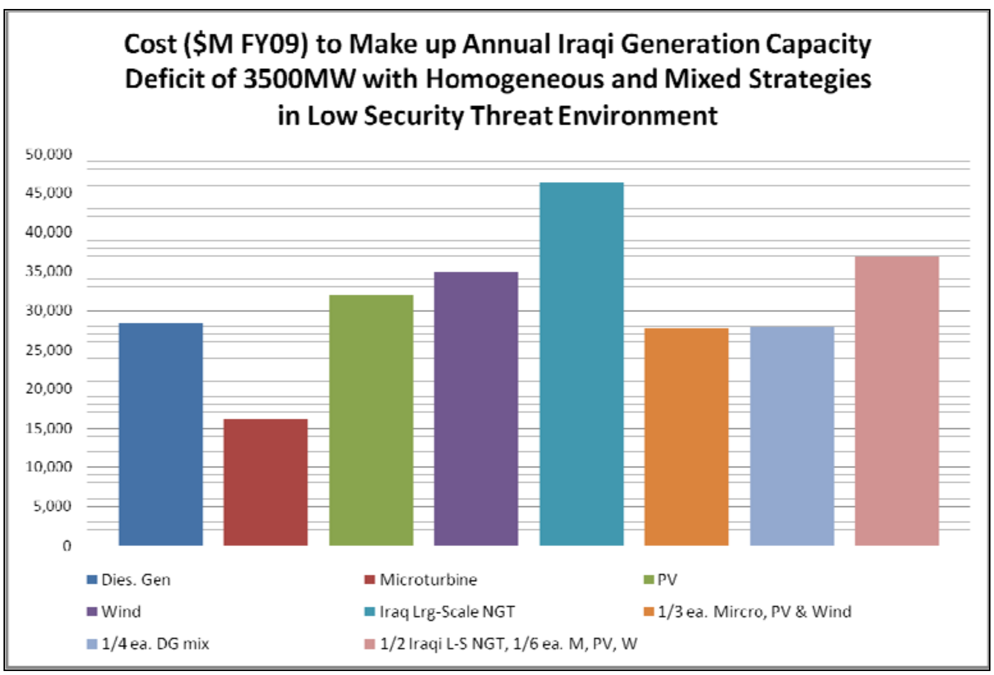

Figure 20: Cost to Make Up Annual Iraqi Gen. Deficit of 3500MW with Homogeneous and Mixed Strategies in Low Security Threat Environment

2. LCC vs. Fuel Price Analysis

As realized in the deficit analysis above, fuel prices have a significant impact on the LCC of systems that consume fuel. Base fuel prices in this analysis are constructed from the U.S. averages for diesel and natural gas in January 2009, as reported by the Energy Information Agency. It is reasonable to assume that these fuel prices do not reflect what is currently being paid in the war-zones of Iraq and Afghanistan. Indeed, in a brief at the Naval Postgraduate School on January 13, 2009, the Secretary of the Navy's Deputy Director for Renewable Energy, Mr. Chris Tindal, stated that the U.S. government was paying approximately $44 per gallon for "fuel" in Afghanistan.

To understand the impact the increase in fuel prices has on system costs, a cost comparison was conducted, evaluating the variations in annual levelized LCC ($K/kW) versus an incremental increase in fuel prices. Figure 21 is a $/gal comparison to account for diesel generator operating costs, and Figure 22 is a $/MMBTU to account for microturbine and large-scale natural gas turbine generator operating costs. Neither includes SLM in the analysis.

$/fuel type was calculated by taking the January 2009 costs for both diesel and natural gas and incrementally adjusting the price by 10%, 100%, 1000% and 2000%. By increasing diesel fuel prices from the January 2009 base price of $2.29/gal to 2000% of that base price results in a fuel price of $48.11. This is only a few dollars over the current fuel price Deputy Director Tindal referenced.

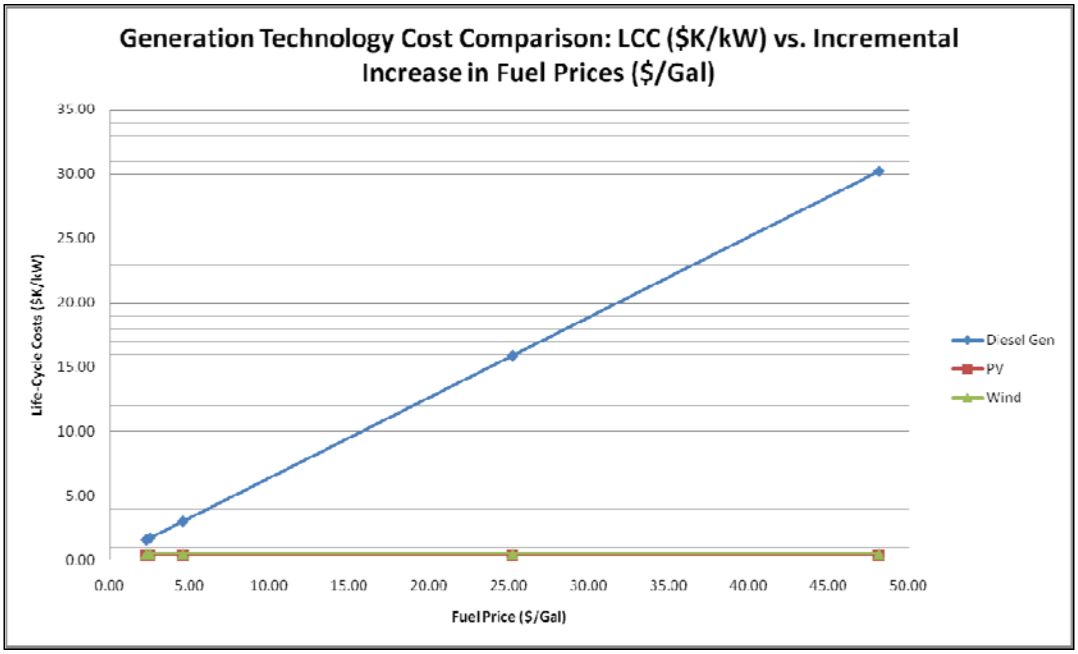

Figure 21: Production Cost Comparison: Annual LCC ($1K/kW) vs. Incremental Increase in Fuel Prices ($/gal)

Figure 21 shows that as fuel prices increase, base life-cycle costs increase linearly. While the linear relationship is clear, Figure 21 illustrates that, without consideration for SLM variations, fuel-consuming systems become less cost effective as fuel prices rise, and non-fuel consuming technologies are not impacted.

Figure 22: Production Cost Comparison: Annual $1K/kW vs. Incremental Increase in Fuel Prices ($/MMBTU) shows, similarly, linear relationships for the natural gas burning systems. The interesting observation here is that large-scale production begins to be favored over microturbine use at approximately $50/MMBTU. Non-SLM life-cycle costs are 37% higher for large-scale production over microturbines. However, at the point that fuel prices increase by 1000% from the base price, a downward pressure is exerted on the overall LCC of large-scale systems. Without consideration for security as expressed by the security level multiplier (SLM), it seems that large-scale production at higher fuel prices is a better economic choice.

When comparing the y-axis of Figure 21 and Figure 22: Production Cost Comparison: Annual $1K/kW vs. Incremental Increase in Fuel Prices ($/MMBTU), it is the case that both natural gas burning systems have significantly lower costs than the diesel system, when not SLM adjusted. For example, considering a 2000% increase in the price of both fuel types, at $48/gal of diesel fuel, diesel levelized annual LCC is approximately $30 thousand. Contrast this to the microturbine system LCC of $10.4 thousand when fuel prices are $115/MMBTU.

Regardless of the fuel used, there is a strong argument for wind and PV even before fuel prices begin to increase when SLM is not considered.

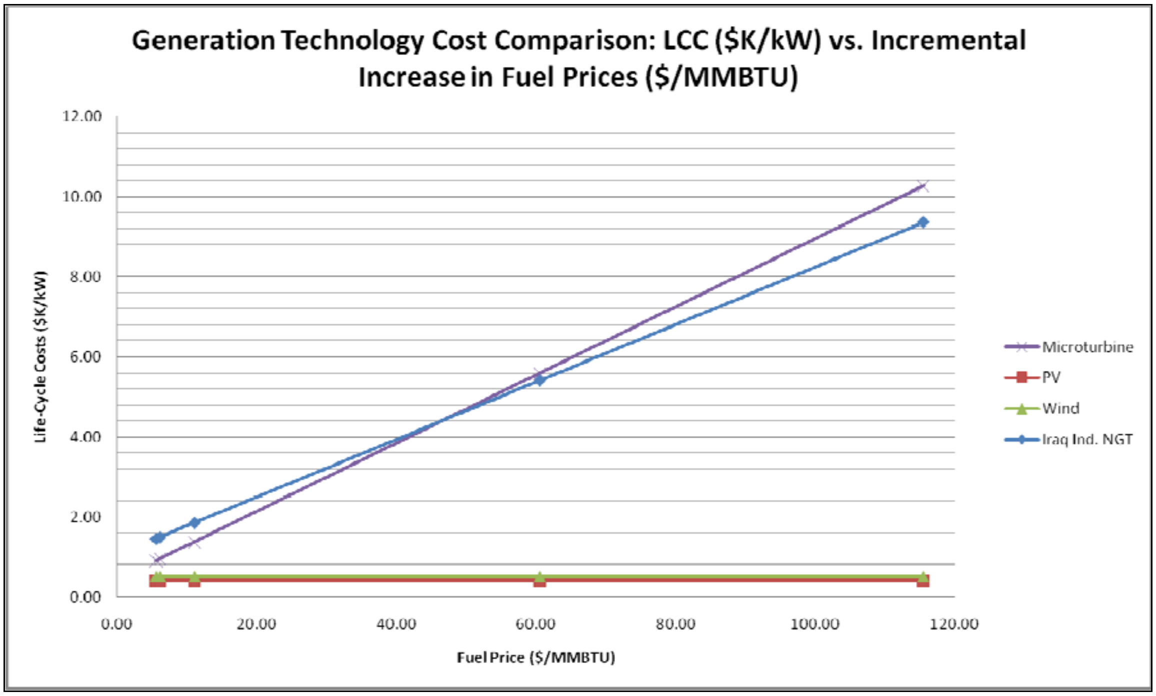

Figure 22: Production Cost Comparison: Annual $1K/kW vs. Incremental Increase in Fuel Prices ($/MMBTU)

F. ANALYSIS OF COSTS

Figure 23 is a basic cost comparison of the four distributed generation technologies alongside the large-scale Iraqi natural gas turbine projects reported on by USAID. This figure does not include SLM data. It is a comparison of each system in terms of capital, O&M, fuel/storage costs, and 14% design/installation security premium, in $FY09.

As in the analysis above, microturbines are the most cost effective technology. This is likely the result of currently low natural gas prices. The large-scale projects benefit from the low fuel prices as well. However, project costs are inflated due to the high capitalization costs, and the short period (5.7 years) before a major overhaul is required (EPA 2002).

Wind and solar appear to be attractive options. A primary reason for this is the lack of a fuel requirement. Of note is that battery storage costs have only been assigned to wind and PV. If battery storage costs were to be applied to all DG systems, or taken away from the solar and PV (an assumption that the systems were connected to the grid and the grid took care of peak shaving/non-DG production periods), these charts would look very different in favor of PV and wind.

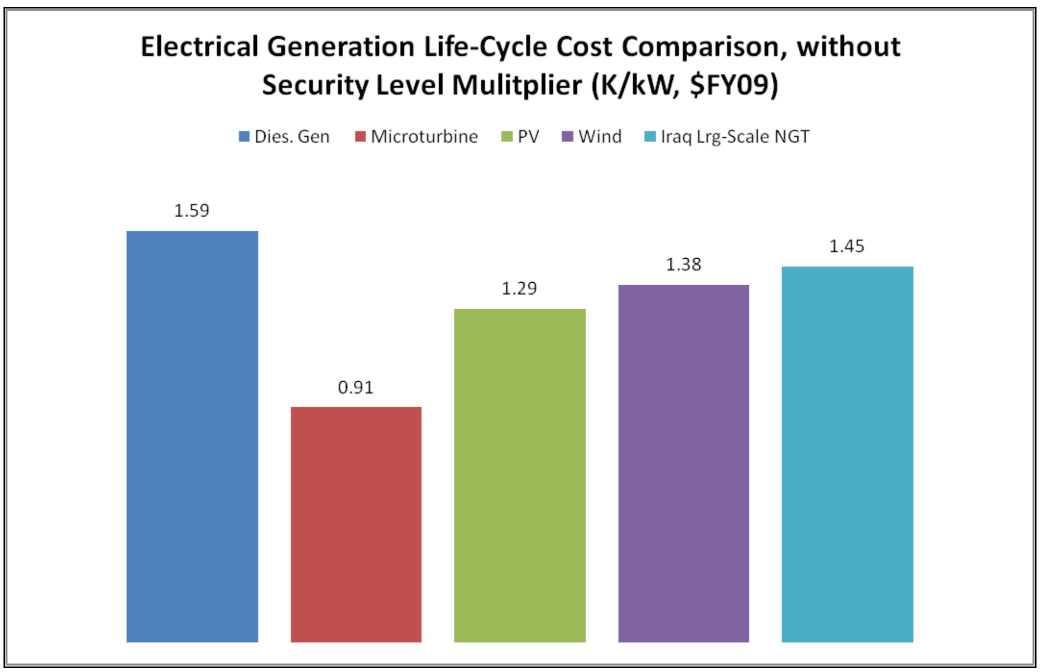

Figure 23: Electrical Generation Cost Comparison without Security Level Multiplier (Average K/kW, $FY09)

G. COMPARISON OF ALTERNATIVES

The next set of observations focuses on the impact that security alone has on the annual levelized life-cycle cost of each system. Figure 24 is a three-parameter bubble chart comparing:

1. LCC, including fuel and SLM, in $K/kW (y-axis).

2. SLM, derived from a site-specific matrix-rating tool that has been generalized to provide a score indicative of a high security threat environment, such as Iraq (x-axis).

3. Pre-SLM costs indicated qualitatively, not quantitatively, by visual inspection of the diameter of each bubble.

Parameter number three is included in order to provide an additional indication of how security affects the cost of production.

Reading the chart is done by observing the vertical position of the ball, which corresponds to the LCC. A ball's horizontal position corresponds to a system's SLM , which was developed following a threat matrix evaluation. In this case, generic site evaluations were conducted for low- and high-security threat environments based on presumed conditions in Iraq. Finally, ball diameter gives a qualitative comparison of what the non-SLM LCC are for each system.

Figure 24 shows that in a high security threat environment, microturbines, while having a higher SLM than PV or wind, at $10.53 million per kW, have a lower LCC. PV systems have the lowest SLM, and the next lowest LCC of $11.34 million per kW. Diesel generators have high SLM and LCC values. The least cost effect, and least secure system is the large-scale natural gas turbine. In a high-threat environment, it rates a LCC of 21.62, and SLM of over 15.

In a high security threat environment microturbines appear to have the edge, despite the slightly higher security risk due to fuel logistics. Wind and PV are quite competitive compared to small diesel generators and large-scale natural gas turbines. If removing the fuel logistics burden is desired, while still being able to provide supply, wind and PV are attractive options. On a pure cost basis, microturbines should be considered.

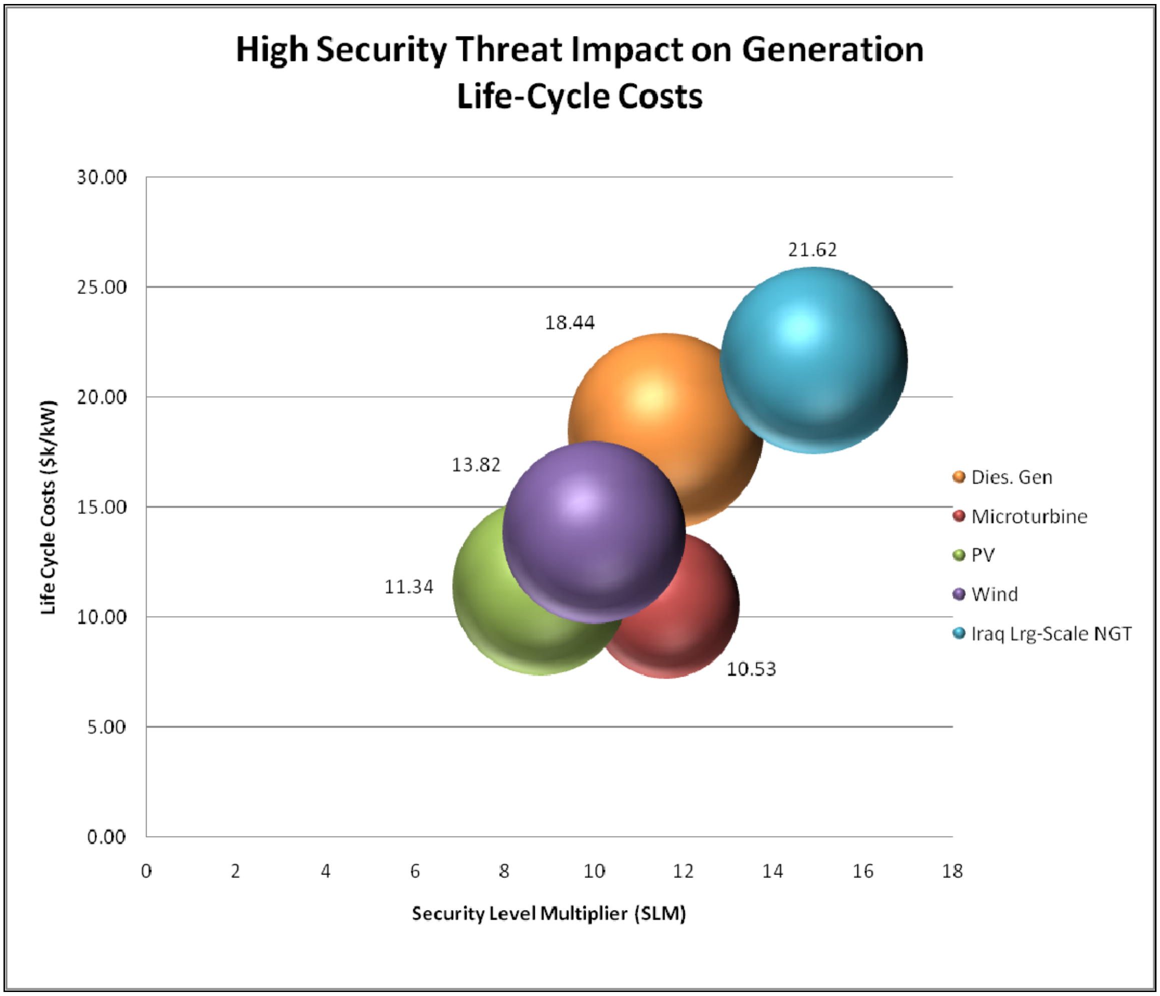

Figure 24: High Security Threat Impact on Generation Life-Cycle Costs

Figure 25 is the same as above except that it compares systems is a generic low-threat environment. Here, the notable observations are that the large-scale system costs nearly three times as much to produce one kilowatt of electricity compared to microturbines. Diesel generators become significantly more attractive, and indeed outperform PV and wind in terms of both SLM and LCC. Microturbines still beat out all of the competition.

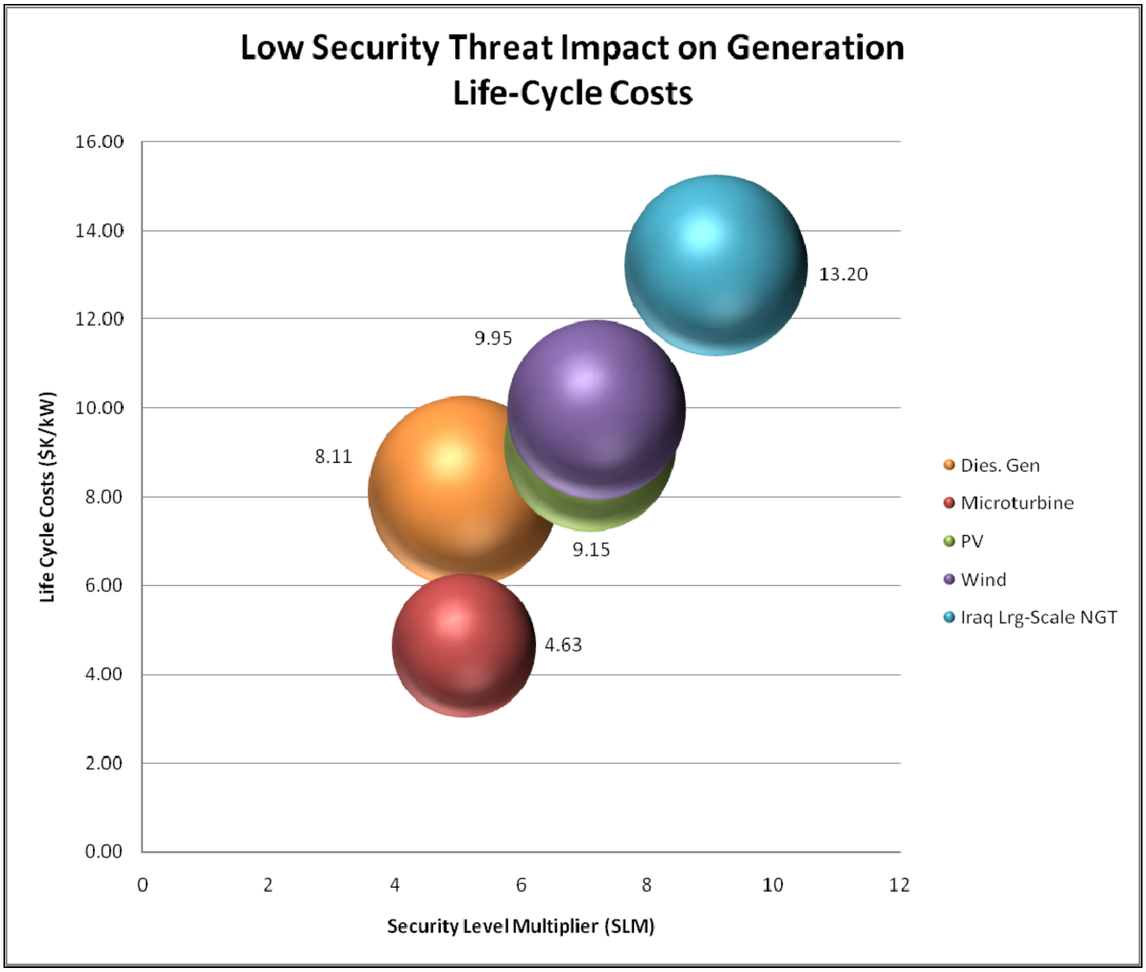

Figure 25: Low Security Threat Impact on Generation Life-Cycle Costs

H. SENSITIVITY AND RISK ANALYSES

Figure 26 includes the data in Figure 24 above, but compares it to the fuel consuming technologies (microturbines, DG diesel generators, and large-scale NG turbines) if fuel were to rise by 2000% in a high security threat environment. As previously explained, 2000% was chosen because it increases the January 2009 price of diesel fuel from approx. $2.29/gal, to $48.11/gal, a figure validated in a briefing by Deputy Director Tindal.

An increase in fuel prices by this amount makes production costs of fuel consuming systems (circled in red) uncompetitive compared to the unaffected wind and PV system.

Of note is that DG sized diesel generators are significantly more expensive than natural gas burning microturbines and large-scale gas turbines. In all three cases, *wind and PV systems appear to be the more attractive choice, with PV edging out wind turbines.*

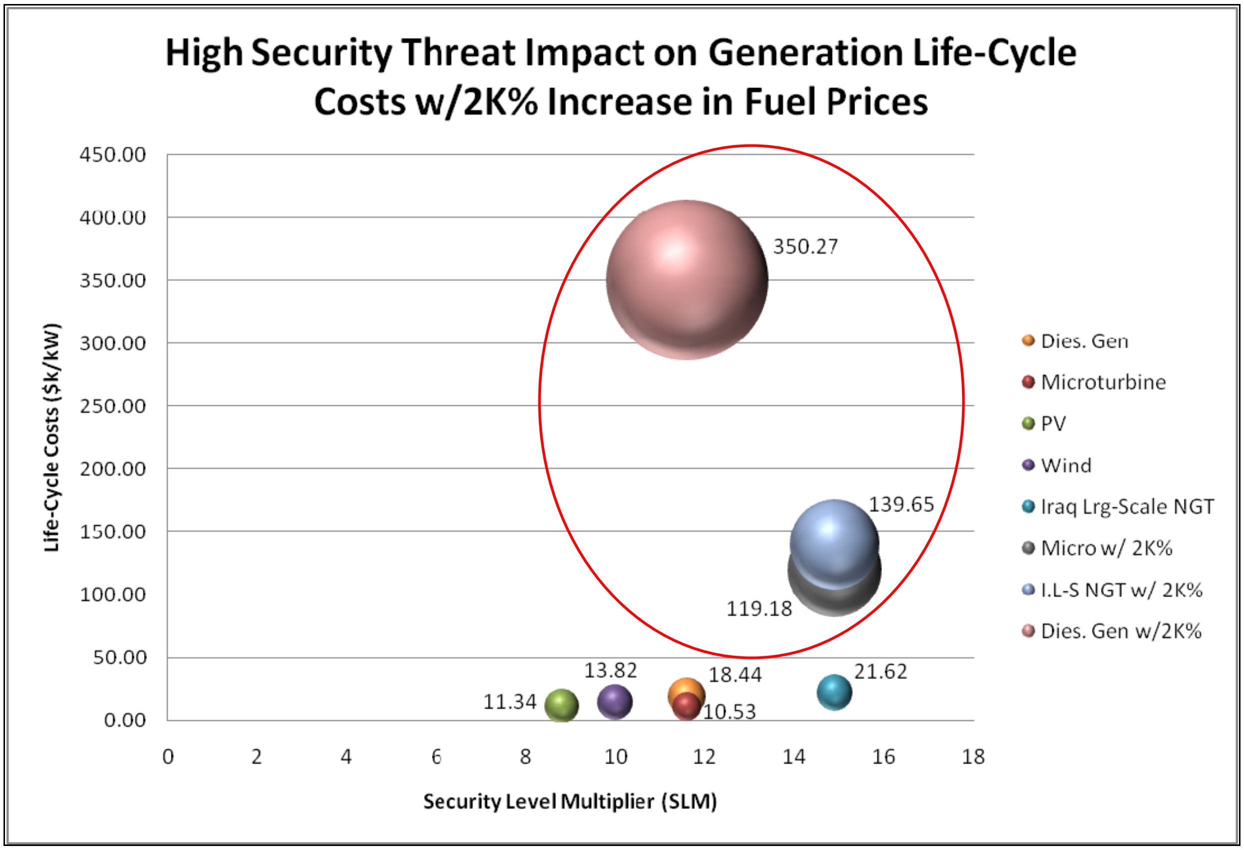

Figure 26: High Security Threat Production Costs with a 2000% Increase in Fuel Prices

Figure 27 is the same as Figure 26, except that it is evaluated for a low security threat environment. It again shows that inflated fuel rates make fuel-consuming systems unappealing. While microturbines are more appealing than large-scale and diesel systems, generation costs for all make PV and wind look like the more attractive choice in this case as well.

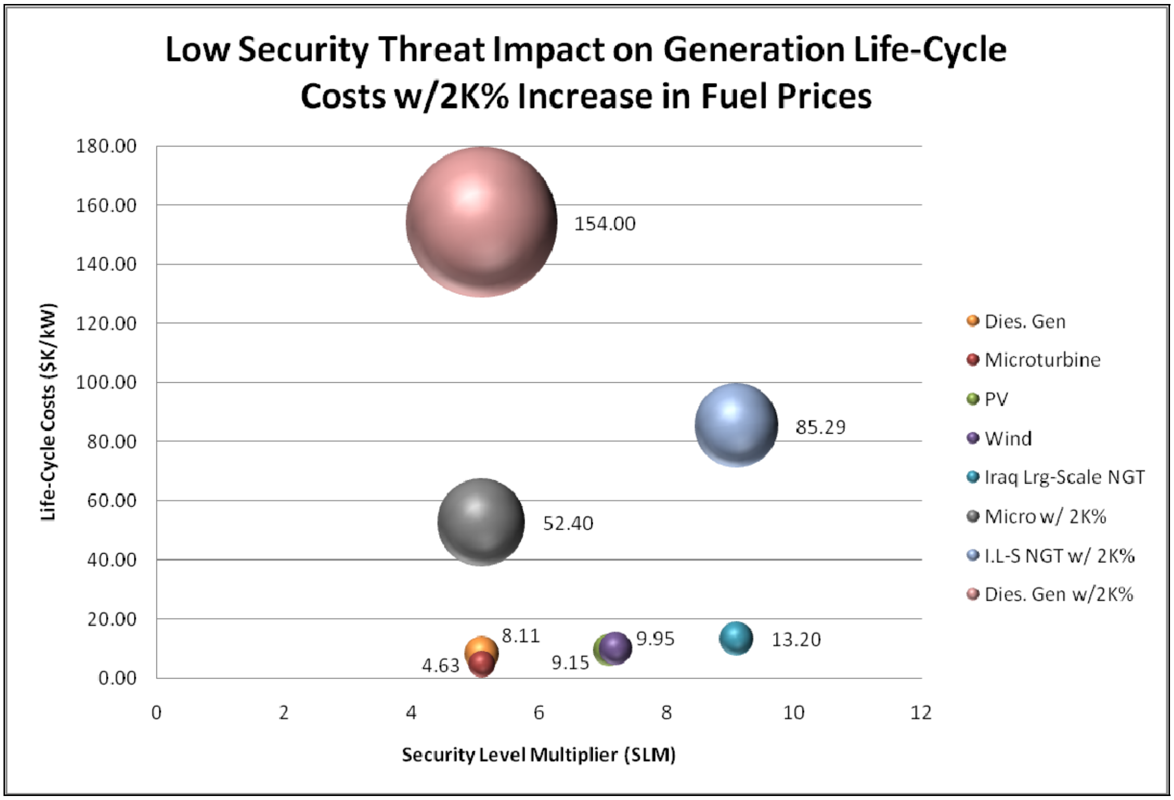

Figure 27: Low Security Threat Production Costs with a 2000% increase in Fuel Prices

I. ANALYSIS SUMMATION

To conclude the analysis portion, a stoplight chart has been devised to indicate possible preferential technology choices given different sets of variables. The decision variables are divided into six areas for each of the five systems evaluated in this research.

1. Fuel at base-line price and no threat.
2. Fuel at base-line price and low-threat.
3. Fuel at base-line price and high-threat.
4. Fuel at 2000% of base-line price, no threat
5. Fuel at 2000% of base-line price, low-threat
6. Fuel at 2000% of base-line price, high-threat

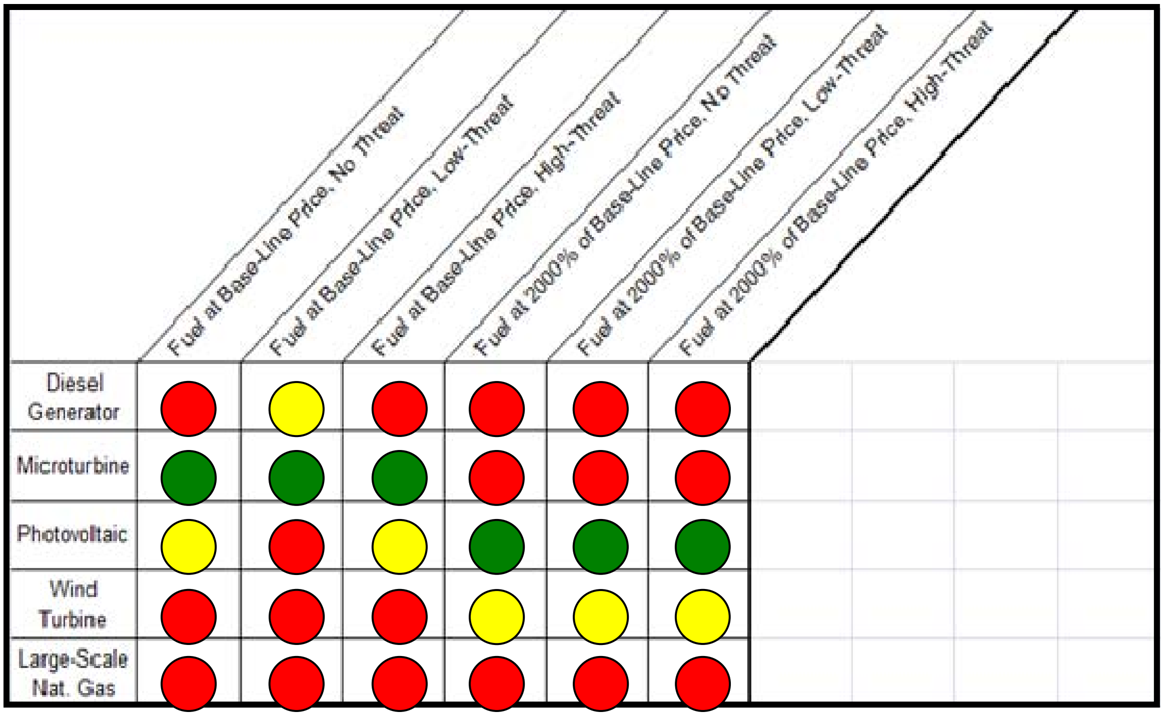

Figure 28: System Fuel v. Security Preference Stoplight

Figure 28 shows that at baseline fuel prices ($2.29 FY09) and no security constraints, microturbines would be a preferred choice with the lowest annual levelized LCC. The next preferred choice would be PV. The other three systems offer more expensive life-cycle costs, and therefore, a decision based on costs would have to eliminate these systems from consideration.

At a baseline fuel price, and low security threat level, microturbines and diesel generators become preferred choices. In this case, security considerations drive down costs on the diesel generator.

At a baseline fuel price and high security threat, microturbines followed by PV again become the preferred system choices.

Once fuel reaches a 2000% increase over the baseline price, systems that consume fuel lose their advantage, regardless of security constraints. At this point, wind and PV become the preferred system choices.

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IV. CONCLUSIONS

The analysis shows that when fuel prices are low, regardless of the security constraints as projected in Chapter III, microturbines have the potential to provide the most cost effective way of supplying the electricity required to make up the current deficit in Iraq. The combination of low natural gas prices, and the security benefits of decentralized electricity production, give microturbines a distinct advantage over its competitors.

The advantages of microturbines are wiped out when fuel prices increase beyond $5.50/MMBTU (FY09). At that point, despite the technology's high capital and storage costs, PV holds a clear advantage in that it is not impacted by fuel price volatility. PV also has potential security advantages due to its low target profile and ability to be decentralized. What is unknown is how balance of system costs would affect the LCC bottom line.

Diesel generators offer decentralization, which gives it an advantage in a low security threat environment. However, fuel costs and logistic constraints make it a poor choice in every other scenario. Since this type of system is currently the primary means of making up the electricity deficit in Iraq right now, it begs the question; how much money is being wasted in maintaining the capability? As noted in Chapter I, officials recognize that this is a problem.

Wind turbines offer similar benefits to PV, including the lack of a fuel requirement, and ability to be decentralized. However, they have twice the O&M costs, and offer a large target profile. Thus, wind turbines fall short of being a cost effective solution.

Finally, large-scale natural gas turbine plants fall short in every category of this analysis. They are expensive to build, hard to secure, and fall prey to fuel logistics problems. Like the other two fuel consuming systems, as fuel prices increase, large-scale generation becomes even more unattractive.

According to the Joint Publication on Multi-Service Concept for Irregular Warfare, long-term stability and commitment to rebuilding and investment are required to acquire and hold the trust of the population (United States Marine Corps Combat Development Command and U.S. Special Operations Command Center for Knowledge and Futures 2006). Just as there has recently been a call for a change in the way we fight wars, there is an equally compelling reason to call for a change in the way in which the United States' invests in reconstruction. Distributed generation technologies, such as microturbines and solar panels, appear to hold the potential to provide a rapid, cost effective way to rebuild and expand electrical infrastructure in war-ravaged regions. It stand to reason that the faster the U.S. can rebuild infrastructure, the faster the U.S. can win the hearts and minds of the civilian population, and negate the acidic effects of irregular warfare efforts by the enemy.

V. RECOMMENDATIONS FOR FOLLOW-ON WORK

There are several possible avenues for follow-on work. The following is list of some potential topics.

- There are several types of distributed generation technologies that were not covered in this research. Investigating how additional technologies may, or may not, change the results would enrich the potential value of this work. The following are some system recommendations that may be feasible for this type of application:
    - Small-scale concentrated solar.
    - Natural gas burning, reciprocating engine, generators.
    - Differentiating amongst various thin-film and traditional PV technologies.
    - Small-scale hydro
    - Mini-turbines
- Energy storage is a vast and complex subject in its own right. It is also going to be a key component to a functioning microgrid system. While it was considered, energy storage should be given a more comprehensive analytical treatment in order to develop a more accurate model of how it affects the total LCC.
- Afghanistan suffers from similar problems as Iraq in terms of the electrical infrastructure being in disrepair and under attack, and most certainly not being able to keep up with demand. However, unlike Iraq, Afghanistan never had a comprehensive generation and grid network. It also presents different meteorological conditions than those in Iraq. Therefore, it is probably true that Afghanistan presents a unique rebuilding challenge that may have requirement different technologies.

- Rebuilding infrastructure means that governments contract out the work to civilian companies. Anecdotally, it seems that companies that specialize in traditional power plant construction receive preferential access to those contracts. It would be interesting to include some sort of quantitative measurement of this phenomena (if it exists) in order to see how it affects the costs associated with constructing new plants.

- Balance of system (BOS) (i.e., complete network architecture) data is not included in the LCC calculations in this paper. It is recommended that in further work on this topic, an attempt is made to gather data on BOS equipment, such as inverters, converters, specific storage requirements, and connection technologies (wiring).

- Security threat evaluations were conducted to test the impact of security constraints on each system's LCC. As noted, the values assigned for each threat to a specific system was somewhat arbitrary. It would be useful if a simulation model was created that could derive a wider base of SLM values that could be used in site planning.

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