Determination of Solar Energy Transition Potential of Department of Defense Facilities and Nontactical Vehicles: An Application of Multicriteria Decision Theory Modeling and Simulation Approaches

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The United States (US) Department of Defense (DoD) offers a great opportunity to implement solar energy solutions across its US bases. It is the single largest energy consumer in the federal government and has sufficient land requirements to implement solar energy solutions. By implementing solar energy solutions across its bases in the US, the DoD will be able to realize benefits such as meeting federal policies and mandates, reducing energy intensity from fossil fuel resources (including foreign oil), reducing carbon dioxide emissions, and improving national security and mission readiness. This report describes the current DoD energy landscape for its facilities and nontactical (fleet) vehicles, DoD benefits of implementing solar energy technologies, and research methods and results that will help realize these benefits through the development of a decision model that will augment the implementation of solar energy technologies on DoD bases.

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As of fiscal year 2007, the United States (US) Department of Defense (DoD) occupied more than 577,500 facilities worth over 700 billion dollars, located on more than 5,300 sites on over 32 million acres across the globe (DoD, 2008b, p. 2). Total DoD facility energy consumption in fiscal year 2007 was approximately 217,536 billion British thermal units (Btu) of fossil energy, 8,788 billion British thermal units of renewable energy, and 525.5 billion Btu of other energy sources. Total spending on facility energy consumption for fiscal year 2007 was 3.4 billion dollars (calculations and data from DoD, 2008a, p. 1). The DoD also operated more than 190,000 nontactical vehicles that traveled over 1.5 billion miles in fiscal year 2007. These vehicles consumed more than 101 million gasoline gallons equivalent or 12,717 billion Btu, with fuel costs of approximately 250 million dollars (calculations and data from US General Services Administration, 2008, pp. 11, 13, 14, 73).

The DoD accounted for more than 78% of total government energy consumption in fiscal year 2007 (Figure 1) [US Energy Information Administration (EIA), 2008]. In fiscal year 2007, the DoD relied heavily on fossil fuels as their primary source of energy for facilities and nontactical vehicles. Fossil fuels accounted for more than 96% of the DoD's total energy consumption. Together, facilities and nontactical vehicles accounted for 230,006.03 billion Btu of fossil energy and 28.41 million metric tons of carbon dioxide emissions. Facilities and nontactical vehicles constituted 27.43% of total DoD energy consumption and 21.77% of total government energy consumption (Figure 2) (calculations and data from DoD, 2008a, p. 1).

In fiscal year 2007, the military services accounted for over 90% of total fossil energy consumption in the DoD. As leading consumers, there is an opportunity to target the military services as the leading candidates within the DoD to consider a transition to solar energy technologies. The Army, Air Force, Navy and Marine Corps consumed 33.91%, 32.47%, 19.11%, and 5.06%, respectively, of total DoD facility fossil energy in fiscal year 2007 (Figure 3) (calculated from the US Departments of the Air Force, Army, Navy, and from the Marine Corps, 2008, p. 1). The Army, Air

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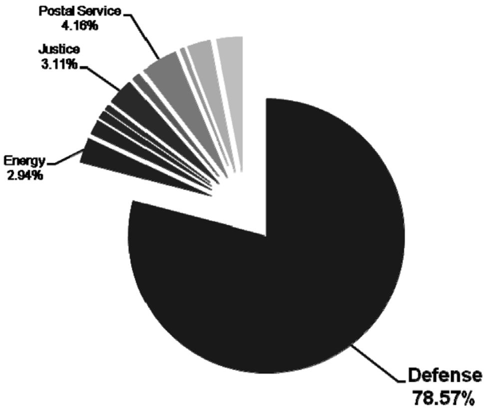


Figure 1. 2007 Government energy consumption, calculated from US Energy Information Administration (2008, 25).

Force, Navy and Marine Corps also consumed 48.91%, 21.52%, 15.25%, and 8.96% of DoD nontactical vehicle total fossil energy in fiscal year 2007 (Figure 3) (calculated from US General Services Administration, 2008, p. 14).

A top-level analysis of DoD solar energy potential revealed that 9,070.37 terawatt hours (TWh) per year of solar energy could be produced by using all available DoD land. This calculation was derived with assumptions that include solar radiation intensity of 2,074.77 kilowatt hours (kWh) per meter squared per year (calculated from National Renewable Energy Laboratory, 1994, pp. 8–242) and a packing factor of 3 at a 10% solar energy efficiency (Zweibel, 2009). Since the total fossil energy requirement for facilities and nontactical vehicles was 67.41 TWh per year in fiscal year 2007 (after the conversion from British thermal units), research results indicate that the DoD would need to set aside 0.74% of its land to meet their fossil energy requirement (Table 1).

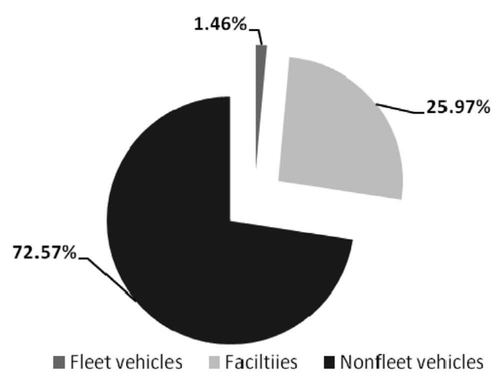


Figure 2. 2007 US Department of Defense energy consumption, calculated from US Department of Defense (2008a, 1).

The technical viability of implementing solar energy on DoD land allows for a discussion on why the DoD would consider implementing solar energy on its bases. The next section of this article discusses the benefits of implementing solar energy technologies on DoD bases.

Background

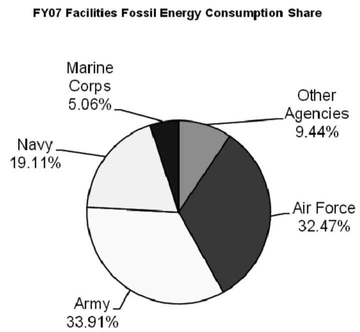
The benefits of implementing solar energy solutions across the DoD includes meeting federal policies and mandates, reducing energy intensity from fossil fuel resources (including foreign oil), reducing carbon dioxide emissions, and improving national security and mission readiness.

Implementation of solar energy technologies across DoD bases could assist in reducing fossil fuels and carbon dioxide emissions and in the facilitation of DoD compliance with various policies, including the Energy Policy Act of 2005, Executive Order 13423, and Executive Order 13514. The DoD could directly meet fossil fuel and carbon dioxide emission reduction policies by investing in solar energy technologies. Reducing fossil energy consumption may allow the DoD to meet targets in the Energy Policy Act of 2005 for federal facilities. These reduction targets are based on energy consumption per square foot in federal buildings with a fiscal year 2003 baseline and on a 2% reduction per

Table 1. Solar energy potential for the US Department of Defense (DoD)

Total DoD land (acres)	**32,408,261.70**
Total DoD land (m^2)	131,152,119,250.66
Sunlight energy intensity (kWh/m^2-year)	2,074.77
Conversion efficiency	0.10
Packing factor	3.00
Adjusted sunlight energy intensity (kWh/m^2-year)	69.16
Sunlight energy potential on DoD bases (kWh-year)	9,070,369,130,934.74
Potential energy from DoD bases (TWh-year)	9,070.37
Total facility and non-tactical fossil energy consumption (TWh-year)	67.41
% Land needed to meet fossil energy requirements from solar	0.74%

kWh, kilowatt hours; TWh, terawatt hours.



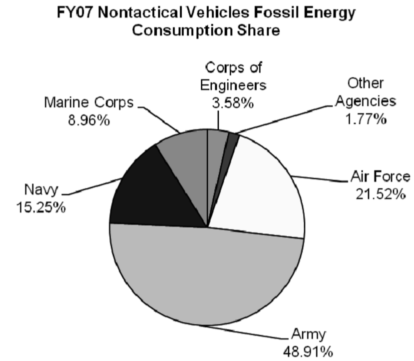


Figure 3. US Department of Defense facilities and nontactical vehicle fossil energy consumption share.

year starting in fiscal year 2006 and ending in fiscal year 2015 (Table 2) (109th Congress, 2005, sec. 102). Further, the Energy Policy Act of 2005 calls on the President to

> ensure that, to the extent economically feasible and technically practicable, of the total electric energy the federal government consumes during any fiscal year, the following amounts shall be renewable energy: (1) not less than 3 percent in fiscal years 2007 through 2009, (2) not less than 5 percent in fiscal years 2010 through 2012, and (3) not less than 7.5 percent in fiscal year 2013 and each fiscal year thereafter. (sec. 203)

Investments in solar energy technologies also could help the DoD meet the current fossil energy and carbon dioxide emission reduction goals of Executive Order 13423 (Table 3). Executive Order 13423 calls for

> the head of each government agency to improve energy efficiency and reduce greenhouse gas emissions of the agency through reduction of energy intensity by 3% annually through the end of fiscal year 2015, or 30% by the end of fiscal year 2015, relative to the baseline of the agency's energy use in fiscal year 2003. (Office of the President, 2007)

In October 2009, President Barack Obama signed Executive Order 13514, "Federal Leadership in Environmental, Energy, and Economic Performance." Executive Order 13514 requires federal agencies to set a 2020 greenhouse gas emission reduction target and includes a 30% reduction target for nontactical vehicle petroleum use by 2020 (Office of the President, 2009).

Reductions in carbon dioxide emissions also could improve the future mission readiness of the DoD. Reducing carbon dioxide emissions and solving climate change issues could positively contribute to the DoD mission. On April 17, 2007, a group of retired generals held a global climate change forum and documented important DoD benefits attributable to reduced climate change issues. Their findings were documented in the report *National Security and the Threat of Climate Change*. According to this report,

Table 2. Energy Policy Act of 2005 federal facilities reduction goals

FY	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
% Reduction	2	4	6	8	10	12	14	16	18	20

From 109th Congress (2005), secs. 651–657.

Table 3. Executive Order 13423 federal energy reduction goals

Fiscal year	2008	2009	2010	2011	2012	2013	2014	2015
% reduction	9	12	15	18	21	24	27	30

From Office of the President (2007).

"Climate change trends pose grave implications for national security that will affect the organization, training, equipping, and planning of the military mission" (Center for Naval Analysis, 2007, p. 1).

In a follow-up report, *Powering America's Defense*, further evidence linked climate change concerns with the DoD mission. The report stated that "destabilization driven by ongoing climate change has the potential to add significantly to the mission burden of the US military in fragile regions of the world" (Center for Naval Analysis, 2009, p. vii). The report further connected energy, security, economics, and climate change and challenged future leaders to think of these parameters as a complex system of systems (p. 16). In this report, a startling characterization of climate change by retired Air Force General Chuck Boyd was that "climate change is about instability. It is a destabilizing activity, with murderous consequences." Climate change consequences resulting from increasing carbon dioxide emissions include disruption of agricultural patterns and water availability, and these cause migratory concerns that lead to competition for resources that impact the DoD military mission (p. 22).

Further, a transition to solar energy technologies could enhance national security benefits by reducing foreign oil expenditures that may contribute to Sunni fundamentalist Islamic movements. Future investments in solar energy technologies would limit DoD dependency on foreign fossil fuel resources, including foreign oil. Solar energy technologies provide electrical power as a substitute for current fossil fuels that power facilities and nontactical vehicles.

Annually, the US pays approximately $160 billion to Saudi Arabia for its oil, of which approximately $3–$4 billion goes to the Wahhabis, supporting Sunni fundamentalist Islamic movements (Woolsey, 2006, notes: p. 5). According to the 9/11 Commission report of 2004, Saudi donors and charities have been a major source of financing to al Qaeda and other extremist groups. It was estimated by the Central Intelligence Agency that it takes approximately 30 million dollars per year for al Qaeda to sustain its operational capabilities (9/11 Commission, 2004, pp. 169–172). However, attacks like those on 9/11 require as little as $400,000–$500,000 to conduct (p. 172).

Further, the 2007 US Department of State report *International Narcotics Control Strategy Report* revealed that al Qaeda was raising money through charities in Saudi Arabia and that these charities had significant Saudi donor sponsorship. The report indicated that a decade before 2002, al Qaeda and other jihadist organizations collected between $300 and $500 million through funds from Saudi charities and private donors (US Department of State, 2007, pp. 355–356). These findings may influence the DoD to increase its attention on the links between foreign oil expenditures and funding to al Qaeda and other jihadist organizations. Since Saudi Arabia's economy relies heavily on oil revenues, future strategies that limit foreign oil expenditures could limit funding to these organizations. In Saudi Arabia, oil revenues historically have accounted for 90% of total Saudi export earnings and state revenues and above 40% of the gross domestic product (EIA, 2011).

Congressional Research Service report RS21985 in 2005 identified government actions needed to protect the fragile electric grid. The electric grid was recognized as vulnerable to outages caused by system operator errors, weather damage, or terrorist attacks. The main risk identified was from a successful terrorist attack (Abel, 2005, p. 1). The grid is highly vulnerable, with many avenues for disruption. For example, it could be severely damaged through a nuclear attack or by a more widespread high-altitude electromagnetic pulse [Defense Science Board (DSB), 2008, p. 55]. Cyber attacks also could disrupt the energy grid, and DoD adversaries are advancing technologies in this arena (Worthen, 2008). There also is evidence that China has started to map the US electric grid (Dignan, 2008). However, we should not dismiss the degree to which the grid is vulnerable to overload and natural events. In April 2004, the US–Canada Power System Outage Task Force released its final report, placing a cause of the August 15, 2003, Canada and Northeast blackout on the failure to manage tree growth adequately in transmission lines (Figure 4). This failure was the common cause of the outage of three FE 345-kV transmission lines and one 138-kV line (US–Canada Power System Outage Task Force, 2004, p. 18).

In the 2008 DSB DoD energy strategy report *More Fight–Less Fuel*, two energy challenges were described in a memorandum to the Under Secretary of Defense for Acquisition, Technology and Logistics:

1. Unnecessarily high, and growing, battle space fuel demand compromises our operational capability and can jeopardize mission success

2. Critical missions at military installations are vulnerable to loss from commercial power outage and inadequate backup power supplies (DSB, 2008, intro memorandum)

Providing for distributed energy operations on DoD bases could help meet electric grid vulnerability challenges, solving the second energy challenge described by the Under Secretary. These bases would be able to sustain distributed

Figure 4. Map, 2003: blackout-impacted areas. Source: http://en.wikipedia.org/wiki/File:Map_of_North_America,_blackout_2003.svg (see Source data).

energy operations, avoid electric grid vulnerability challenges, and provide continuous operational capability. Bases that implement solar energy technologies would be able to maintain improved continuity of operations, thus helping them meet the electric grid vulnerability challenges facing the DoD and promote energy security.

While some distributed energy capability on bases presently exists in the form of generators, these technologies do not seem to allow sufficiently for an adequate level of continuity of operations. These generators do not seem to be sufficient to meet long-term mission demands for 24 hours a day, seven days a week. The 2008 *More Fight–Less Fuel* report, for example, states that

> Backup power systems at these installations are larger, but are still based on diesel generators and fuel supplies sized for only short-term commercial outages and seldom properly prioritized to critical loads because those are often not wired separately from non-essential loads. (DSB, 2008, p. 53)

Figure 5, a graph showing operational gaps as operating hours, depicts issues with current backup generator technologies on DoD bases. The longer that the base generators operate, the more extensive is the maintenance required. This is important because, without power during the maintenance of a generator, a base would not be able to meet mission demands as it operates. It is anticipated that maintenance times will continue to grow as generators operate for extended periods (aggregated from Loehlein, 2007; and Solar Electric Light Fund, 2008).

Further, the exploitation of grid-connected generator technologies could negatively impact DoD critical missions. As already mentioned, generators may not be reliable for long-term operations, and research indicates that they also could be rendered nonoperational by short-term exploitation. This was evident during the Aurora project conducted by the Department of Homeland Security, during which an experimental cyber attack launched by researchers on a generator caused it to self-destruct (Cable News Network, 2007). Figure 6 depicts the generator that was tested and rendered nonoperational during the Aurora experiment

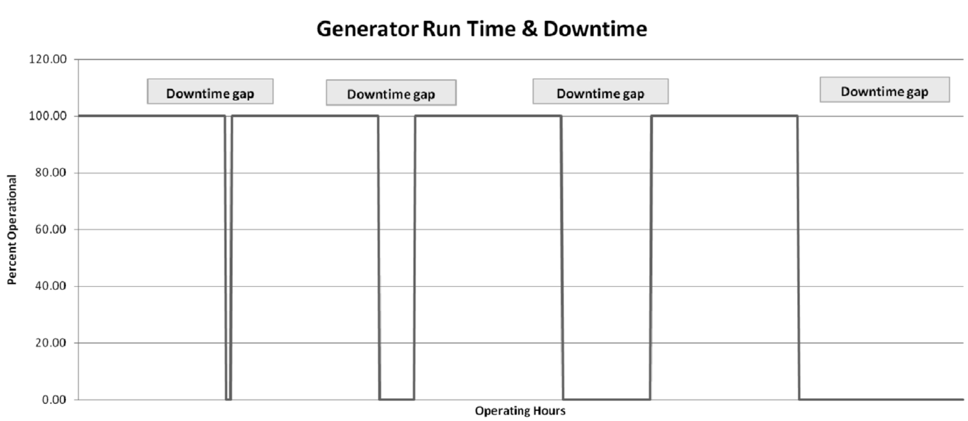


Figure 5. Generator run time and maintenance. Generator downtime gaps increase over time as the complexity of maintenance increases from minor services to major services to major overhauls.

Figure 6. Aurora cyber attack experiment.

(Militaryphotos.net, 2010). It should be noted that military bases that operate generators not connected to the electric grid may be able to overcome exploitation by a cyber attack.

Solar energy technologies could offer a more robust energy solution when coupled with current generator technologies to provide continuity of operations for the DoD. Solar energy technologies could provide distributed energy during clear-day operations, adding to the resiliency of the base and enabling improved continuity of operations. In addition, solar energy technologies coupled with electric or hybrid vehicles could provide an opportunity to store energy for nighttime operations.

Methods

The research summarized in this section has resulted in a decision model that offers the potential to help optimize the implementation of solar energy technologies across DoD bases in the US. The decision model optimizes solar energy implementation by evaluating policy, technical, and mission parameters to achieve the aforementioned benefits. The researchers conducted a system-level study involving facility fossil energy requirements, carbon dioxide emissions, percentage of land necessary to meet the fossil energy requirement, cost of solar implementation, and the number of military personnel on 200 DoD bases in the US. These parameters were selected based on outputs of an energy and environmental subject-matter expert panel composed of industry and former government personnel. These parameters also are important in the realization of the DoD benefits described in the background section of this report.

Since consolidated data on these parameters do not exist, a data-calculation exercise was conducted to evaluate the facility fossil energy requirements, carbon dioxide emissions, percentage of land necessary to meet the fossil energy requirement, and the cost of solar implementation. Military personnel data were collected from public source materials reflecting base-specific levels. Other data were estimated by using the 2007 DoD *Base Structure Report* as the primary source document. The parameter data were included in a decision model that could assist in the development of an implementation plan for solar energy technologies on DoD bases. The following discussion provides an overview on the calculation methods used for the five parameters.

Facility fossil energy consumption is an important consideration to help meet current and future DoD policy goals. It was calculated by using facility square-footage data contained in the 2007 DoD *Base Structure Report*. The facility square-footage data were multiplied by regionally adjusted fossil energy consumption factors derived from the DoD fiscal year 2007 *Annual Energy Data Report*[1] (DoD, 2008a), adjusted by Department of Energy 2003 Commercial Buildings Energy Consumption Survey factors from its Table C3 (EIA, 2006). Regional adjustments were made at the following regional levels: New England, Middle Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, and Mountain regions. Billion British thermal units is a common energy unit used for DoD facility energy consumption. This energy unit can be converted to joules, megawatt hours, kilowatt hours, or another appropriate energy unit. The following equation shows the calculation method for the fossil energy consumption parameter:

$$\begin{aligned} &\text{fossil energy consumption}_{\text{base } n} \\ &\quad = \text{square footage}_{\text{base } n} \\ &\qquad \times [\text{billion British thermal units/square footage}]_{\text{region}} \quad (1) \end{aligned}$$

Carbon dioxide emissions also were considered in the research because of the importance of meeting future DoD policy goals related to greenhouse gas emission reductions. As mentioned in the background section of this report, reductions in carbon dioxide emissions could also improve the future mission readiness of the DoD. To estimate carbon dioxide emissions for each DoD base, the regional Environmental Protection Agency 2004 Emissions and Generation Resource Integrated (eGrid) Database was used (EPA, 2007). The database factors selected did not include renewable energy. The 2004 eGrid Database separates regions by state. The research used carbon dioxide emission factors in pounds per megawatt hours, converting fossil energy consumption data from British thermal units to megawatt hours [1 billion Btu = 293.07 megawatt hours (MWh)]. The research analysis also converts pounds of carbon dioxide emissions to metric tons (1 metric ton = 2,204.62 lbs). The following equation shows the calculation method for the carbon dioxide emission parameter:

$$\text{pounds carbon dioxide emissions}_{\text{base } n} = \text{megawatt hours}_{\text{base } n} \times [\text{pounds carbon dioxide/megawatt hours}]_{\text{state}} \qquad (2)$$

The proportion of land necessary to meet a base's fossil energy requirement allows for a base-by-base technical feasibility analysis. Solar energy solutions require land to meet the fossil energy demands of a base, and as land availability increases so does the solar energy potential to fulfill a base's fossil energy requirements. Therefore, the research described herein included a parameter that identifies the percentage of land necessary to meet fossil energy requirements on each of the 200 bases examined. To calculate the percentage of land necessary to meet the fossil energy requirement of a base, a multilayered approach was implemented. The approach taken to calculate the percentage of land necessary to meet a base's fossil energy requirement is explained in Table 4. The assumptions and methods in calculating this parameter are provided after the table.

In the current federal environment, costs are an important determinant in investment and budgetary decisions. Therefore, the cost of implementing solar energy technologies also was considered. To calculate the costs to implement solar energy technologies, average cost factors for photovoltaic and concentrating solar power were used. The photovoltaic cost factors were $2.50 per watt (W), $3.50/W, $3.20/W, $2.65/W, and $2.60/W for cadmium telluride, amorphous silicon, copper indium gallium (di)selenide, multisilicon, and monosilicon, respectively (Figure 7) (George Washington Solar Institute, 2009). The concentrating solar power cost factors used were $3.50 for a concentrated solar power trough and $3.85 for a concentrated solar power

Table 4. Rationale for percentage of land necessary to meet a base's fossil energy requirement

Questions	Approach
1. How much land is available at a base?	Fiscal year 2007 DoD *Base Structure Report* acreage data converted to square meters for a base (land available$_{\text{base } n}$ = $\text{m}^2_{\text{base } n}$)
2. How much solar radiation is available on a base for energy?	Regional solar radiation measured in kilowatt hours per meters squared per year in a region: solar radiation = $[\text{kWh} \div \text{m}^2\text{-year}]_{\text{region}}$
3. What are current solar cell efficiencies?	Measured in percent (%) of total solar radiation convertible to energy; average efficiency of a solar cell = 10%
4. What is a sufficient packing-factor assumption?	The packing factor is the fraction of land the solar panel modules cover within the deployed system; a packing factor of 3 will be assumed for incorporation into the research that reduces efficiencies by 10% ÷ 3
5. What is my solar energy potential on a DoD base?	$\text{Solar potential}_{\text{base } n} = \text{land available}_{\text{base } n} \times (\text{solar radiation} \times [\text{efficiency} \div \text{packing factor}])_{\text{region}} = \text{m}^2_{\text{base } n} \times (\text{kWh} \div \text{m}^2\text{-year} \times [10\% \div 3])_{\text{region}}$
6. What percentage of land is needed to meet a base's current fossil energy consumption?	Percentage of land necessary to meet fossil energy requirement = fossil energy consumption$_{\text{base } n}$ ÷ solar energy potential$_{\text{base n}}$

DoD, US Department of Defense; kWh, kilowatt hours.
Assumptions and methods:
—Acreage data: included in fiscal year 2007 DoD (2008b, appendix) *Base Structure Report*; conversion to square meters is 1 acre = 4,046.87 m²; land available is assumed as total owned acreage since obstructed land (roads, airfields, etc.) on a base is minimal and roughly 1%–5% (Aimone, 2010).
—Regional solar radiation metrics were used from the National Renewable Energy Laboratory's (1994, pp. 8–242) *Solar Radiation Data Manual for Flat-plate and Concentrating Collectors*, by city and state, reflecting base solar radiation.
—Assume one-axis tracking flat plates at 0 tilt with a packing factor of 3 and panels operating at 10% efficiency from George Washington University Solar Energy Institute subject-matter expert committee member interview (Zweibel, 2009)

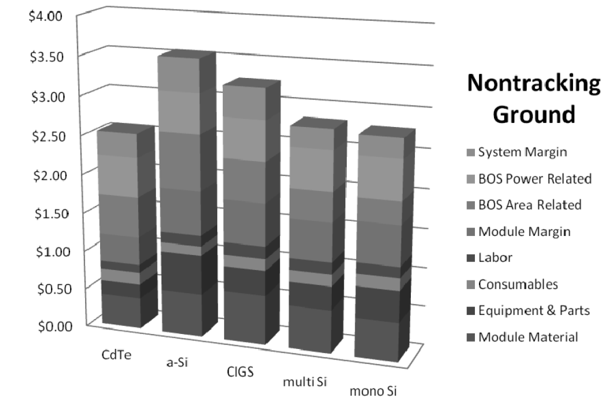


Figure 7. Solar photovoltaic implementation costs. BOS, balance of system.

tower when using midterm 2010 projections (National Renewable Energy Laboratory, 2003, Tables 4-4 and 5-3). An average of these costs (approximately $3.00/W) was applied to the solar system energy requirements needed on each individual base to offset its fossil energy requirement. The average cost factor was applied to the solar energy system requirement. The research assumes total energy delivered is equal to 78% (95% × 91% × 90%). Total energy delivered includes photovoltaic energy delivered as a percentage of the manufacturer's rating × energy delivered after wiring and power tracking losses × the inverter efficiency. Other research assumptions include a solar rating baseline of 4.8 KWh per meters squared per year for the Washington, DC, area, and 365.25 days in a calendar year (Find-solar.org, 2010). The following equations show the calculation method for the solar energy system requirement and the cost to implement solar energy technologies:

$$\text{solar energy system requirement}_{\text{base } n} = \text{fossil energy requirement}_{\text{base } n} \div [\text{total energy delivered} \times \text{solar rating} \times \text{days per year}] \quad (3)$$

$$\text{cost to implement solar technology} = \$ \text{ per watt}_{\text{average of 6 solar technologies}} \times (\text{fossil energy requirement}_{\text{base } n} \div [\text{total energy delivered} \times \text{solar rating} \times \text{days per year}]) \quad (4)$$

Military personnel is an important mission parameter since it is necessary for the DoD to provide forces quickly and efficiently during contingency operations:

> A contingency operation is a military operation that is designated by the Secretary of Defense as an operation in which members of the Armed Forces are or may become involved in military actions, operations, or hostilities against an enemy of the United States or against an opposing force, or is created by definition of law. (Thefreedictionary.com, 2010)

RAND's *Preparing the U.S. Army for Homeland Security: Concepts, Issues, and Options* reinforces military personnel as a critical mission parameter. Mission critical facilities for the Army are ranked by deploying soldiers in this report (Larson and Peters, 2001, p. 267). Hence, the parameter selected for the research consisted of levels of military personnel that are reported by base in the fiscal year 2007 DoD *Base Structure Report* and does not require a calculation method. A mission parameter such as military personnel allows for the identification of critical bases that could be targeted for solar energy technologies.

Military personnel is not the only mission parameter that could be evaluated in a decision model. Command, control, communications, computers, intelligence, surveillance and reconnaissance, and strategic deterrence are other important mission parameters. The *More Fight–Less Fuel* report provides another reference supporting this statement: "Installations with substantial Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance and military strategic deterrence missions have higher mission criticality and greater power requirements" (DSB, 2008, p. 53). This consideration should be noted on bases that may conduct critical missions but do not have a large number of military personnel, such as base depots. However, the research did not include these mission parameters in the decision model since the information is not readily available in public source documents.

Results

The parameter estimates resulted in 200 individual data elements for each of the five parameters under consideration: facility fossil energy requirements, carbon dioxide emissions, percentage of land necessary to meet the fossil energy requirement, the cost of solar implementation, and the number of military personnel on 200 DoD bases. Table 5 depicts a snapshot view of the resulting parameter data used to develop the decision model.

The results across the 200 sampled DoD bases indicate production of 34.1 million MWh per year of fossil energy and 28.5 million metric tons per year of carbon dioxide emissions. The cost to implement solar energy technologies that offset 100% of the 200 bases' fossil energy requirement is 82.2 billion dollars. Further, meeting 100% of the

Table 5. Snapshot of parameter estimates

Base identification number	Fossil energy consumption, regionally adjusted (MWh-year)	Carbon dioxide emissions, regionally adjusted (metric tons-year)	Land needed to meet base fossil energy requirement via solar energy technology, regionally adjusted (%)	Average cost to meet 100% of fossil energy requirement via a solar energy technology, regionally adjusted (US$)	Military personnel (no. of military personnel)
177	886,550.47	801,156.17	65.80	$2,133,384,957.72	67,568
109	771,345.77	676,339.37	1.31	$1,856,157,680.34	45,608
117	537,437.50	410,759.56	0.87	$1,293,283,487.98	50,999
49	623,143.64	566,809.27	31.71	$1,499,525,765.75	6,619
173	30,764.18	23,512.84	2.75	$ 74,030,566.38	—

MWh, megawatt hours.

200 bases' fossil energy requirements would require 0.82% of the total land area of the bases. Finally, a total of 1.2 million military personnel are stationed on the 200 DoD bases sampled.

At the aggregate level, these results indicate the potential to reduce a substantial amount of fossil energy and carbon dioxide emissions at the 200 bases. The results also indicate that land availability to implement solar energy technologies does not seem to be a deterrent. The cost provides for the scope of budgetary resources required to meet 100% of the fossil energy currently produced at each base. The results for the military personnel parameter indicate that a few select bases have critical missions.

The statistical distribution of each parameter yields interesting results. These results are presented at Figure 8. The approach taken to develop the parameter distributions was an equal-bin-width method (10 equal bins). Each of the parameters analyzed yielded a chi-squared (χ^2) distribution.

The distributions for the fossil energy and carbon dioxide parameters reveal that only a few bases produce large quantities of fossil energy and carbon dioxide emissions (Figure 8a and b). The land parameter distribution reveals that many DoD bases gave the potential to implement solar energy—the left of the distribution represents the binning of those bases that require less land to meet their fossil energy requirements via solar energy technologies (Figure 8c). The cost parameter distribution is skewed to the right, revealing that many bases are grouped to the less costly side of the distribution (Figure 8d).

The mission parameter chart represents the distribution of the sampled DoD bases based on military personnel. The military personnel results indicate that there are only a few mission critical DoD bases (Figure 8e). Since there are only a few critical bases, these bases could be considered influential drivers in the implementation of solar energy technologies. As an important decision parameter, military personnel could be evaluated separately for the implementation of solar energy technologies on critical bases and their infrastructure. Evaluating the mission parameter also could help target specific critical bases and their infrastructure for future solar energy technical feasibility analysis and pilot-scale projects.

To analyze these parameters holistically, a decision model was used to rank the 200 DoD bases for solar energy implementation. To rank the bases, ordinal and cardinal scales were evaluated. The research resulted in a decision model that uses a ratio scale as the cardinal scale to assign the importance of each data element across the five parameters. *Ratio scales* accurately reflect the ratio between two quantifiable elements and provide for an objective ranking of the outcomes. For example, since 67,568 military personnel are 1.48 times more than 45,608 military personnel, in the decision model, a base housing 67,568 military personnel would be considered 1.48 times more critical in terms of implementing a solar energy technology because of the higher number of military personnel. The parameters for fossil energy, carbon dioxide, and military personnel also have greater preferences for higher numbers, whereas the land and cost parameters have greater preferences for lower numbers.

Since comparisons cannot be made across the five parameters since each has a different unit scale, a ratio-scale transformation (normalization) is required to standardize the data. Therefore, to standardize a ratio scale and to

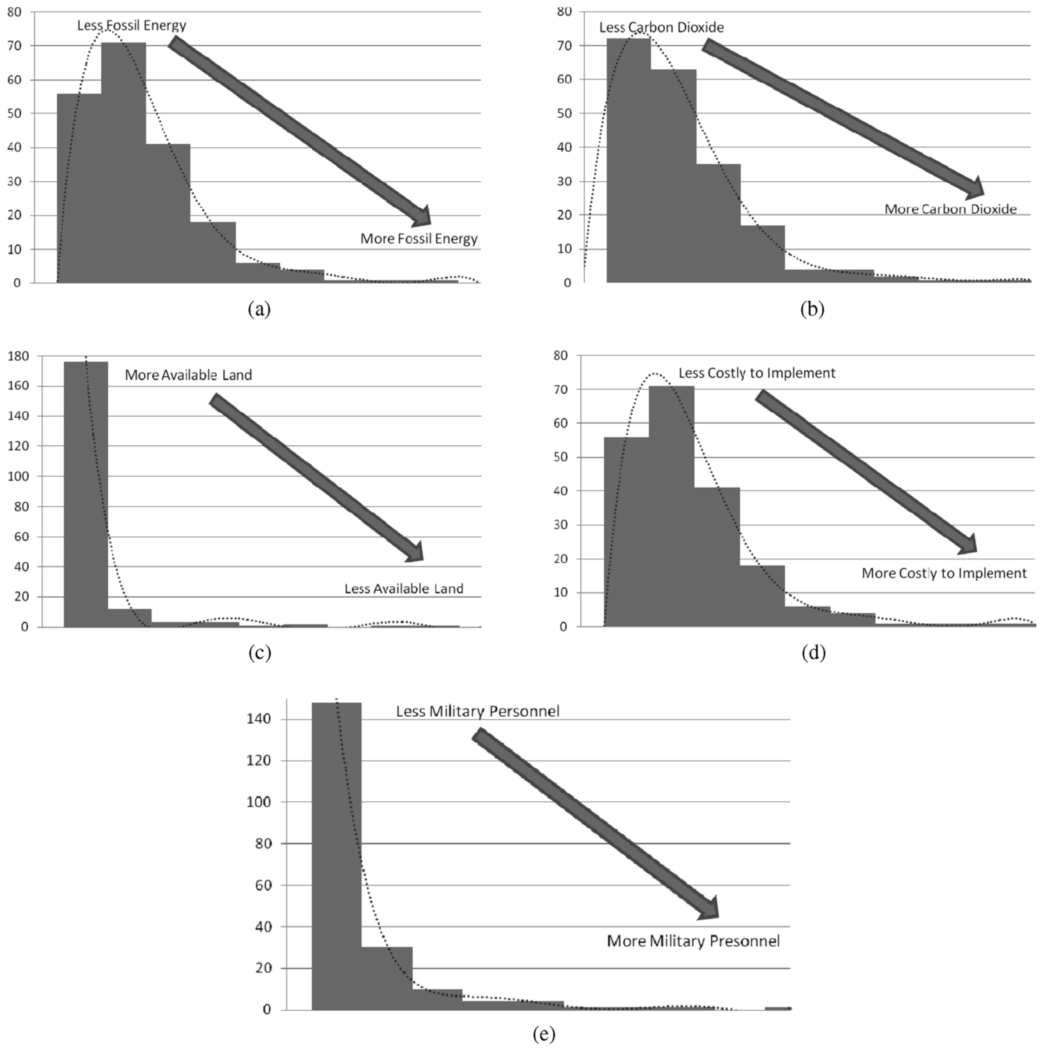


Figure 8. Distribution results for sampled data by parameter: (**a**) fossil energy parameter, (**b**) carbon dioxide parameter, (**c**) land parameter, (**d**) cost parameter, and (**e**) mission parameter.

make comparisons across each parameter, the units were converted to percentage transformations to help develop base rankings. To transform the original units to percentages, the minimum or maximum value of each parameter (depending on optimal value) was used. For example, 67,568 military personnel was considered the optimal value for the mission parameter. Optimal values yield a 100% transformation.

The ratio-scale transformations used to develop the percentages were the following:

$$\text{Minimum is optimal value: min value}_{\text{of 200 bases}}/\text{value}_{\text{base } n} \quad (5)$$

$$\text{Maximum is optimal value: value}_{\text{base n}}/\text{max value}_{\text{of 200 bases}} \quad (6)$$

Transforming unit scales to percentages is an acceptable approach as "a pair of ratio scales are equivalent if and only if each can be transformed into the other by multiplying all values by some positive constant $[f^{i}(x) = k \times f(x)]$ (Peterson, 2009, p. 27)." From the research results, 45,608 military personnel divided by 67,568 yields 67.50%, and 100.00% divided by 67.50% maintains the equivalent constant ratio value of 1.48. This approach allows for the standardization of data across the five parameters and, more importantly, the comparison of data for the decision model (Table 6).

The next step in the decision model development was to apply subject-matter expert weightings to each of the five parameters under consideration. A surveying approach to solicit subject-matter expert weights for the five param-

Table 6. Snapshot of parameter transformation standardized data

Base identification number	Fossil energy: importance based on ratio analysis	Carbon dioxide: importance based on ratio analysis	Land: importance based on ratio analysis	Cost: importance based on ratio analysis	Military personnel: importance based on ratio analysis
177	100.00%	100.00%	0.02%	0.38%	100.00%
109	87.01%	84.42%	0.93%	0.43%	67.50%
117	60.62%	51.27%	1.40%	0.62%	75.48%
49	70.29%	70.75%	0.04%	0.53%	9.80%
173	3.47%	2.93%	0.44%	10.83%	0.00%

eters was conducted, and the average weights collected were 15.0%, 11.7%, 18.3%, 19.2%, and 35.8% for the parameters fossil energy, carbon dioxide, land, cost, and military personnel, respectively. By applying these weights to the transformed percentage data, final scores were derived for base rankings. The output of the decision model was an ordinal ranking of the 200 DoD bases (Table 7).

These results assume a 100% fossil energy offset for each parameter, excluding military personnel. Future analyses could be conducted to determine each base's sublevel requirements and their potential fossil energy offsets. A sublevel-adjusted decision model could provide specific technical insight into optimal solar energy technology designs at each base. The decision model in this report provides a quantifiable decision framework to select the bases to target for sublevel technical feasibility analyses and pilot-scale solar projects.

Conclusion

There seems to be an opportunity for the DoD to consider a broad solar energy implementation strategy. By considering implementation of solar energy technologies, the DoD could realize many benefits, which include meeting federal policies and mandates, reducing energy intensity from fossil fuel resources (including foreign oil), reducing carbon dioxide emissions, and improving national security and mission readiness. The decision model results indicate that the DoD has substantial land available to consider a solar energy implementation and that a few critical bases could warrant immediate consideration. Critical bases also could be evaluated separately for a solar energy implementation due to the importance of protecting critical bases and their critical infrastructure.

Use of a decision framework such as that described in this article could facilitate identification of priorities for implementation of solar energy technologies across DoD bases. The decision model described in this report revealed that a base-by-base implementation strategy could be developed for solar energy. The ranking results in the decision model could assist with the selection of bases for solar energy technology considerations, and for further technical feasibility analysis and pilot-scale projects. The continued use of a decision framework inclusive of important

Table 7. Snapshot of final score and base rank

Base identification number	Fossil energy: importance based on ratio analysis	Carbon dioxide: importance based on ratio analysis	Land: importance based on ratio analysis	Cost: importance based on ratio analysis	Military personnel: importance based on ratio analysis	Final score	Rank
177	100.00%	100.00%	0.02%	0.38%	100.00%	62.58%	1
109	87.01%	84.42%	0.93%	0.43%	67.50%	47.34%	2
117	60.62%	51.27%	1.40%	0.62%	75.48%	42.50%	3
49	70.29%	70.75%	0.04%	0.53%	9.80%	22.42%	4
173	3.47%	2.93%	0.44%	10.83%	0.00%	3.02%	200

parameters could assist the DoD in implementing solar energy technologies, enabling this large agency to realize wide-reaching benefits across its facilities and nontactical vehicle fleet.

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Note

1. Renewable and nuclear energy consumption removed from DoD factor before adjusting by Department of Energy factors.

References

9/11 Commission. 2004, July 22. *9/11 Commission Report*. 9/11 Commission, Washington, DC, 578 pp. Available at http://govinfo.library.unt.edu/911/report/index.htm (accessed July 8, 2011).

109th Congress. 2005, August 8. Energy Policy Act of 2005. Public Law 109–58. *Congressional Record* 151, 551 pp. Available at http://doi.net/iepa/EnergyPolicyActof2005.pdf (accessed July 8, 2011).

Abel, A. 2005. *Government Activities to Protect the Electric Grid*. Congressional Research Service (CRS), Washington, DC, 6 pp. Available at http://www.fas.org/sgp/crs/homesec/RS21958.pdf (accessed July 8, 2011).

Aimone, M. 2010, March 12. Interview by Ariel S. Castillo. Washington, DC.

Cable News Network (CNN). 2007. *Sources: Staged Cyber Attack Reveals Vulnerability in Power Grid*. Turner Broadcasting, Atlanta, GA. Available at http://articles.cnn.com/2007-09-26/us/power.at.risk_1_generator-cyber-attack-electric-infrastructure?_s=PM:US (accessed April 15, 2010).

Center for Naval Analysis (CNA). 2007. *National Security and the Threat of Climate Change*. CNA, Alexandria, VA, 69 pp. Available at http://securityandclimate.cna.org/report/ (accessed July 8, 2011).

Center for Naval Analysis (CNA). 2009. *Powering America's Defense: Energy and Risks to National Security*. CNA, Alexandria, VA, 18 pp. Available at http://www.hrp.org/Site/docs/ResourceLibrary/ADM_Nathman-energy_security_brief.pdf (accessed July 8, 2011).

Defense Science Board (DSB). 2008. *More Flight–Less Fuel: Report of the Defense Science Board Task Force on DoD Energy Strategy*. DSB, Washington, DC, 121 pp. Available at http://www.acq.osd.mil/dsb/reports/ADA477619.pdf (accessed July 8, 2011).

Dignan, L. 2008, April 9. *Could Cyber Attackers Bring Down the Electrical Grid?* Tech Republic, Washington, DC. Available at http://www.techrepublic.com/blog/hiner/could-cyber-attackers-bring-down-the-us-electrical-grid/1435 (accessed August 26, 2009).

Find-solar.org. 2010. *My Solar and Wind Estimator*. Energy Matters, Santa Rosa, CA. Available at http://www.find-solar.org/index.php?page=solar-calculator (accessed July 18, 2011).

George Washington Solar Institute (gwsolar). 2009. *Is CIGS Turning the Corner? Solar Review*, November 16. Available at http://thesolarreview.org/2009/11/16/is-cigs-turning-the-corner (accessed November 29, 2009).

Larson, E.V., and J.E. Peters. 2001. *Preparing the U.S. Army for Homeland Security: Concepts, Issues, and Options*. RAND, Washington, DC, 344 pp.

Loehlein, T.A. 2007. *Maintenance Is One Key to Diesel Generator Set Reliability*. Cummins Power Generation, Minneapolis, MN, 4 pp. Available at http://www.cumminspower.com/www/literature/technicalpapers/PT-7004-Maintenance-en.pdf (accessed May 15, 2010).

Militaryphotos.net. 2010. *AURORA Test Validated Fears of Dept. of Homeland Security*. vBulletin Solutions, El Segundo, CA. Available at http://www.militaryphotos.net/forums/showthread.php?121081-AURORA-test-validated-fears-of-Dept-of-Homeland-Security (accessed April 30, 2010).

National Renewable Energy Laboratory (NREL). 1994. *Solar Radiation Data Manual for Flat-plate and Concentrating Collectors*. NREL, Golden, CO, 256 pp. Available at http://www.nrel.gov/docs/legosti/old/5607.pdf (accessed July 8, 2011).

National Renewable Energy Laboratory (NREL). 2003. *Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts*. NREL, Golden, CO, 340 pp. Available at http://www.nrel.gov/docs/fy04osti/34440.pdf (accessed July 8, 2011).

Office of the Deputy Under Secretary of Defense: Installations and Environment [DUSD(I&E)]. 2008. *Facility Energy Directorate* [Overview]. DUSD(I&E), Washington, DC. Available at http://www.acq.osd.mil/ie/energy/ (accessed January 5, 2009).

Office of the President. 2007, January 24. *Executive Order 13423: Strengthening Federal Environment, Energy, and Transportation Management*. *Federal Register* 72(17):3919–3923. Available at http://edocket.access.gpo.gov/2007/pdf/07-374.pdf (accessed July 15, 2011).

Office of the President. 2009, October 5. Executive Order 13514: Federal Leadership in Environmental, Energy, and Economic Performance. *Federal Register* 74(194):52117–52127. Available at http://www1.eere.energy.gov/femp/pdfs/eo13514.pdf (accessed July 15, 2011).

Peterson, M. 2009. *An Introduction to Decision Theory*. Cambridge Introductions to Philosophy. Cambridge University Press, New York, 328 pp.

Solar Electric Light Fund (SELF). 2008. *A Cost and Reliability Comparison between Solar and Diesel Powered Pumps*. SELF, Washington, DC, 13 pp. Available at http://www.self.org/SELF_White_Paper_-_Solar_vs_Diesel.pdf (accessed May 15, 2010).

Thefreedictionary.com. 2010. s.v. *Contingency Operation*. Farlex, Huntingdon Valley, PA. Available at http://www.thefreedictionary.com/contingency+operation (accessed May 29, 2010).

US–Canada Power System Outage Task Force. 2004. *Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations*. Natural Resources of Canada and the US Department of Energy, Washington, DC, 238 pp. Available at https://reports.energy.gov/ (accessed July 8, 2011).

US Department of Defense (DoD). 2008a, January. *Annual Energy Data Report: Fiscal Year 2007*. DoD, Washington, DC.

US Department of Defense (DoD). 2008b. *Base Structure Report: Fiscal Year 2007 Baseline—A Summary of DoD's Real Property Inventory*. DoD, Washington, DC, 217 pp. Available at http://www.defense.gov/pubs/bsr_2007_baseline.pdf (accessed July 8, 2011).

US Department of State. 2007. *International Narcotics Control Strategy Report*, volume 2, *Money Laundering and Financial Crimes*. Washington, DC. Available at http://www.state.gov/p/inl/rls/nrcrpt/2007/vol2/ (accessed July 8, 2011).

US Department of the Air Force. 2008, January. *Annual Energy Data Report: Fiscal Year 2007*. DoD, Washington, DC.

US Department of the Army. 2008, January. *Annual Energy Data Report: Fiscal Year 2007*. DoD, Washington, DC.

US Department of the Navy. 2008, January. *Annual Energy Data Report: Fiscal Year 2007*. DoD, Washington, DC.

US Energy Information Administration (EIA). 2006. *2003 Commercial Buildings Energy Consumption Survey*. EIA, Washington DC. Available at http://www.eia.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html (accessed July 16, 2011).

US Energy Information Administration (EIA). 2008. *Annual Energy Review 2007*. EIA, Washington, DC, 409 pp. Available at ftp://ftp.eia.doe.gov/multifuel/038407.pdf (accessed July 8, 2011).

US Energy Information Administration (EIA). 2011. *Saudi Arabia* [Country Analysis Brief]. EIA, Washington DC. *2003 Commercial Buildings Energy Consumption Survey*. EIA, Washington DC. Available at http://www.eia.gov/cabs/saudi_arabia/Full.html (accessed July 18, 2011).

US Environmental Protection Agency (EPA). 2007. *Emissions & Generation Resource Integrated Database for 2006*. EPA, Washington DC. Available at http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html (accessed July 16, 2011).

US General Services Administration (GSA). 2008. *Federal Fleet Report, Fiscal Year 2007*. GSA, Washington, DC, 77 pp. Available at http://www.gsa.gov/graphics/ogp/FFR2007_508.pdf (accessed July 8, 2011).

US Marine Corps. 2008, January. *Annual Energy Data Report: Fiscal Year 2007*. DoD, Washington, DC.

Woolsey, J. 2006, March 27. *James Woolsey on Renewable Energy and National Security*. Office of Force Transformation Seminar. Office of Force Transformation (OFT), Washington, DC. Available at http://solarpowersolarenergy.info/james-woolsey-on-renewable-energy-and-national-security/ (accessed July 15, 2011).

Worthen, B. 2008. Wide Cyber Attack Is Linked to China. *Wall Street Journal*, March 30, A18. Available at http://online.wsj.com/article/SB123834671171466791.html (accessed August 26, 2009).

Zweibel, K. 2009, April 10. Interview by Ariel S. Castillo. Washington, DC.

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