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Cost Effectiveness of Renewable Energy Policy on Military Installations

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Abstract

In 2007, the United States government issued the National Defense Authorization Act, and Section 2852 mandates that the Department of Defense (DoD) meets 25% of its energy needs from renewable sources by 2025. This paper investigates the production decisions that the DoD faces when increasing its share of renewable energy to meet this objective. A linear programming model is created to solve for the cost-effective renewable energy portfolio mix for each military base to meet its production target of renewable energy. The renewable sources utilized in each base's energy portfolio include solar, wind, geothermal, and renewably-sourced energy from the grid, each of which entails its own capital and marginal cost structures that the model incorporates when computing total cost. The model allows for detailed analysis of numerous sets of constraints and scenarios of interest to policymakers, including an alternative policy in which the DoD-operated facilities must each meet the 25% target instead of the Department's aggregate objective. Later scenarios reveal how the DoD can meet this mandate while also complying with additional policies pertaining to renewable energy production. The cost comparisons between these scenarios demonstrate how the model and framework developed in this paper yield lessons for policy makers designing renewable energy production thresholds.

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I) Background

In the centuries since the Industrial Revolution, the world has achieved impressive material and population growth on a foundation of fossil fuels. The incredible abundance of these resources precipitated advancements in manufacturing and transportation, and as a result touched virtually all sectors of the economy. Fast forward approximately 250 years and the global energy landscape appears far less optimistic. Rising concerns about scarcity, price fluctuations, climate change, pollution, and numerous other issues demonstrate the true costs to an economy dependent on fossil fuels. The year 2014 in particular served as a powerful reminder of the risks that the United States faces when it relies largely on oil imports from tumultuous parts of the world. Disagreement amongst the members of OPEC and major independent oil players, such as Saudi Arabia, Iraq, and Libya, resulted in an oversupply of oil in the midst of a low demand environment. Basic economic theory of supply and demand then explains the 40% decline in oil prices in the second half of 2014 (The Economist, 2014). While placing more money in the hands of US consumers, the glut in oil supply also places immense strain on US oil-producing companies, which are burdened with higher production costs than their Middle Eastern counterparts. Due to its capital-intensive nature, the US oil production is at further risk if the Federal Reserve elects to raise interest rates (Luft, 2014). As one means of combating this uncertainty around oil, the US has in recent years begun to promote diversified energy portfolios through the utilization of renewable energy.

From a cost standpoint, fossil fuel and renewable industries are complete opposites. The former benefits from many years of support and investment that afford it optimized and efficient installations. As a result, upfront capital expenditures for fossil

fuel energy tend to be relatively low. At the same time, oil companies must continuously scour for increasingly-elusive resources and deposits in order to ensure their continued existence. When a utility invests in a renewable system, it must pay heavy construction and installation fees because in many cases the most cost effective technology has yet to be fully engineered (Bockris, 65). Since non-renewables are easy to build and exploit, they appear attractive when short term solutions are considered. Renewable energy systems, once installed, provide cheap, independent energy decades into the future.

Markets failing to internalize the negative externalities of fossil fuels when determining energy prices widens the cost gap between renewable and non-renewable energies. In economic theory, an externality can be defined as a cost or benefit imposed on someone as a result of another person's decision to purchase some good or service. The commonly cited externalities of fossil fuel derived energy are the various forms of pollution that result from their usage. Owen (2006) argues that some renewables, such as wind, may already have a social cost advantage over fossil fuels after augmenting the price for non-renewable energy according to these externalities. Fossil fuels are inherently volatile and vulnerable to acute supply shocks, whereas renewables benefit from virtually unlimited supply using resources such as wind and sunlight. As engineers design ways to more effectively store and transmit renewable energy, incorporating such volatility into energy prices will frame renewables as a more competitive energy source (Owen, 2006).

Individual states within the US have instituted Renewable Portfolio Standards (RPSs) in order to hasten the country's transition to renewable energy systems. Lyon and Yin (2010) find that states with organized and sophisticated electricity markets are more

likely to adopt an RPS, as are those states with high concentrations of renewable resources. While the proponents of such policies claim that these standards stimulate sustainable job and industry growth, Lyon and Yin (2010) find that the political pressures often compel a state to adopt an RPS. Although politically popular, an RPS adoption is often inferior from a cost standpoint to an energy tax or some form of cap-and-trade system. The independently crafted renewable standards within each state give way to discrepancies between what contributes to an RPS in one state versus another, thereby making cooperation difficult (Lyon and Yin, 2010).

The United States has not, however, attempted a national RPS, which Michaels (2007) argues could unify mandate details between states and reduce administrative costs of monitoring dozens of distinct policies. Support at the national level would legitimize the country's commitment to a renewable future. However, widespread failure at the state level may also suggest deeper complications if the federal government were to increase the scale of such a policy. Another concern from Michaels (2007) centers on the notion that some states may produce exclusively non-renewable energy and simply purchase renewable energy from more resource abundant states, leading to significant pollution imbalances in some parts of the country. While more promising than the individual RPS approaches, a national RPS comes with its own host of complications and further demonstrates the difficulty in mandating renewable energy production.

II) Research Question and Motivation

Commanding an 80% share of all federal energy usage, the DoD is the single largest energy consumer in the US public sector (ACORE, 2012). The energy that the

DoD uses falls broadly into two broad categories: operational and installation. The former is necessary to train, transport, and maintain DoD troops and weapons systems whereas the latter powers non-tactical vehicles and some 300,000 buildings across the Department's numerous bases worldwide (Schwartz, Blakeley, and O'Rourke, 2012). In fiscal year 2011, the cost that the DoD paid to power these bases was approximately $4.1 billion, comprising 26% of their total energy expenditure (Holland et. Al, 2013). With the majority of the DoD's energy being sourced from large utility grids, their bases and therefore centers of command are exposed to colossal risks in the event of a mass blackout.

In the last decade, the Department, through Congressional mandate, has turned its attention towards utilizing renewable energy as a means of bolstering their energy security and mitigating the risks inherent in operations dependent on fossil fuels. The Energy Policy Act of 2005 (EPAct) serves as the first formal requirement that DoD installations offset their heavy electricity consumption with certain target amounts of renewable energy. From 2013 onward, the DoD must meet 7.5% of its energy needs through renewables (Andrews, 2009). This policy represents a shift in attitude away from nearly 40 years of focus on energy efficiency and reduced consumption to a more active role in securing America's energy security.

The year 2007 proved to be a crucial time for the progression of military goals and the long term adoption of sizable renewable energy production that serves as the central focus of this paper. Title XXVIII, Subtitle E, Section 2852 of Public Law 109 declared the National Defense Authorization Act for 2007, which contains within it the following provision in regard to the DoD's goals:

> ‘‘(1) to produce or procure not less than 25 percent of the total quantity of electric energy it consumes within its facilities and in its activities during fiscal year 2025 and each fiscal year thereafter from renewable energy sources”
>
> ‘‘(2) to produce or procure electric energy from renewable energy sources whenever the use of such renewable energy sources is consistent with the energy performance goals and energy performance plan for the Department…’’

With these proclamations, the Department is committed in the long term to supporting and adopting renewable energy technologies in order to meet increasingly stringent requirements related to energy security. The target of 25% renewable energy builds upon the previous EPAct goals and has since presented the military with a daunting challenge. Not an innately utility-oriented entity, the DoD missed its EPAct objective of 7.5% renewable by 2013, instead falling in at only 5%. Some components have fared better than others at making the transition to renewable systems. For example, both the Air Force and Marine Corps surpassed the EPAct requirements with approximately 8% and 12% renewable energy shares in 2013, respectively, while the Army lagged behind at only 1% (Annual Energy Management Report, 2013).

An additional policy enacted in 2007 by President Bush is Executive Order 13423. This mandate augments the requirements set forth in EPAct 2005 by requiring that half of the renewable energy credited towards this goal originate from new renewable systems (Andrews, 2009). Since EPAct called for 7.5% of energy to be sourced from renewables, this Executive Order demands that the Department obtains at least 3.75% of its energy via new, onsite production of renewable energy. By emphasizing investment in onsite production, the Executive Order reveals the government’s devotion towards achieving energy security. This paper therefore models the costs and consequently production decisions that the DoD faces in order to comply

with these mandates in the most cost effective manner. Data and specifications relevant to the model are the topics of Sections III and IV.

III) Data Summary

The data manipulated in this paper are drawn from a variety of US agencies and organizations and drawn together in order to construct and present an intuitive model of how the Department of Defense can, in the most cost-effective manner, satisfy the requirements of the policies discussed in Section II. In total, 555 DoD facilities are used to study the decisions relating to these mandates. The data are broken down into three broad categories: installation-level data from the Department of Defense, the availability of renewable energy resources throughout the US, and relevant financial data needed to estimate the costs of the renewable energies considered in this paper.

a) Department of Defense Installation Data

Each year, the Department of Defense publishes an Annual Energy Management Report detailing the DoD's progress towards achieving various energy targets in conservation and production. These reports also comment generally on consumption and provide energy breakdowns by military component. Of particular interest to this study, however, are the appendices that supply installation level data for DoD operated bases. Appendix G of the FY2012 report contains estimated annual renewable energy production, and Appendix E of the FY2013 report provides total consumption values for each base. Since the 2012 report tabulates technical potentials of all military bases, these numbers are based on physical factors such as natural resource abundance that do not

change on an annual basis. Therefore, to provide the most current data, consumption from 2013 was paired with technical potentials from 2012 to determine production constraints for the linear programming model developed in Section IV.

After filtering for installations in the United States, Figure 1 was produced in order to understand the spatial distribution of bases (left) and their sizes (right).

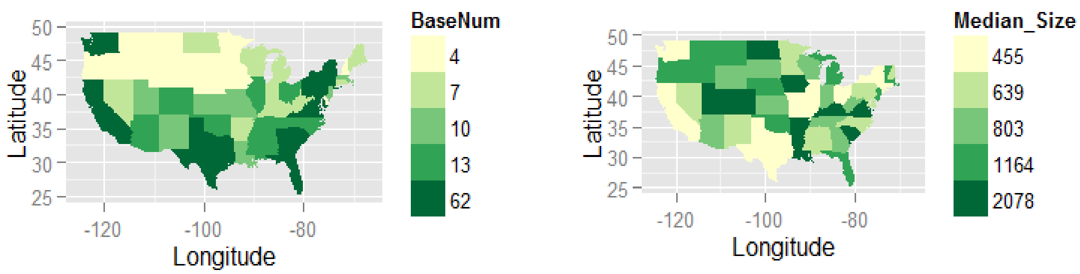


Figure 1. Spatial Characteristics of Contiguous US DoD InstallationsError! Reference source not found.

The legends for these maps were determined using quintiles of the distribution of count and median square footage values. Data on base sizes was also taken from Appendix E of the FY2012 annual report. There appears to be a strong correlation between high base counts and small median square footage. For example, many northern states to the west of the Mississippi contain four or fewer bases yet have some of the largest median base sizes in the US. Specific states such as California, Texas, and New York support this pattern. These observations can be attributed to states that have numerous bases also having a higher concentration of small bases located in more urban areas. The Midwest has enough open space to tolerate larger installations than in New England or other densely populated regions along the east coast.

b) Renewable Resource Data

The National Renewable Energy Laboratory (NREL), based in Golden, Colorado, engineers a number of resources for public education of renewable energy. Among these tools are interactive prospector maps for solar, wind, and geothermal resources. Solar insolation (KWh/m^2/day) measures the daily intensity of sunlight per square meter at collectors spread throughout the country. Figure 2 illustrates the NREL's Solar Prospector tool and reveals rising levels of insolation moving radially towards the southwest, with parts of Nevada and Arizona claiming the most concentrated natural resources.

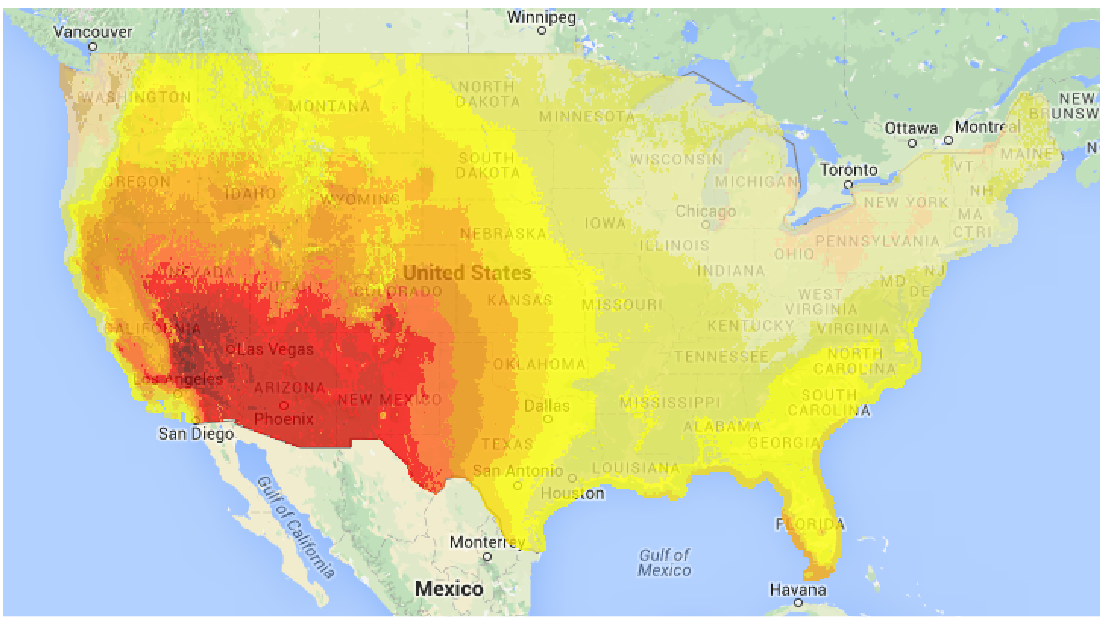


Figure 2. NREL Solar Insolation Map for Contiguous US

The feasibility of wind energy depends on highly variable wind speeds, which the NREL categorizes into wind power classes from 1 to 7 in order of increasing favorability. Regions that receive a power rating of 1 or 2 are generally perceived as not economically feasible locations for generating wind energy. These include inland areas in the southeast as well as some mountainous areas in the west. Offshore wind along the west and east

coasts tends to be where the strongest winds blow, as well as the heart of the Midwest such as North and South Dakota. Figure 3 displays GIS data from the NREL's Wind Prospector.

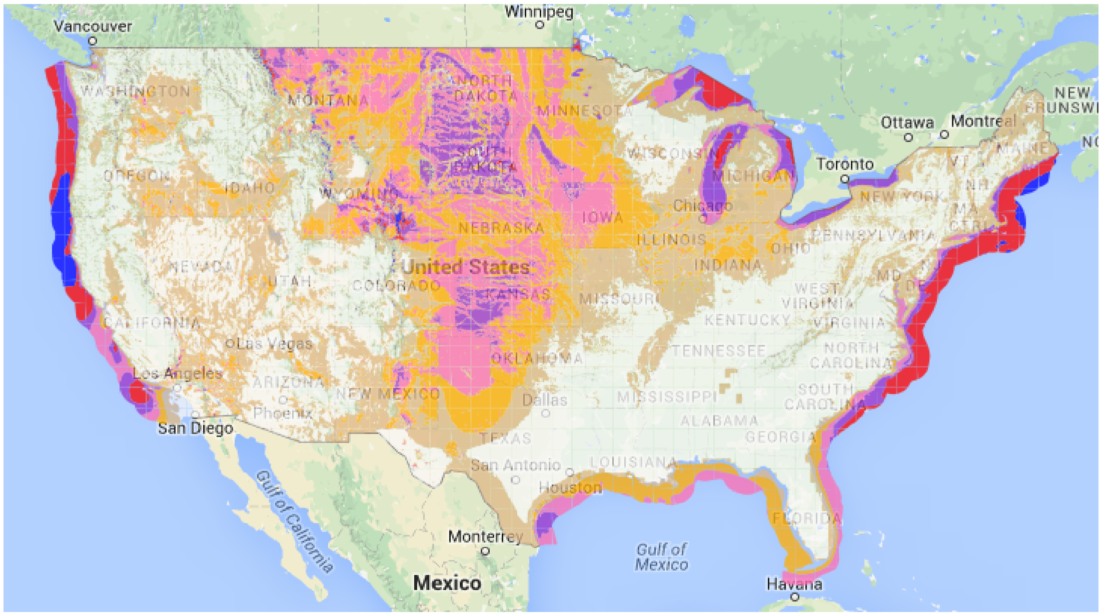


Figure 3. NREL Wind Power Class Map for Contiguous US

The NREL divides geothermal energy into resource classes ranging from 5 being the least attractive and 1 representing regions with the most abundant resources. Based on the Geothermal Prospector image from the NREL in Figure 4, geothermal hotspots tend to fall within Colorado and other mountainous and coastal parts of Idaho and Oregon. There appears to be a slanted line running from North Dakota through part of Alabama that divides a resource plentiful west from a resource poor east in terms of geothermal production potential.

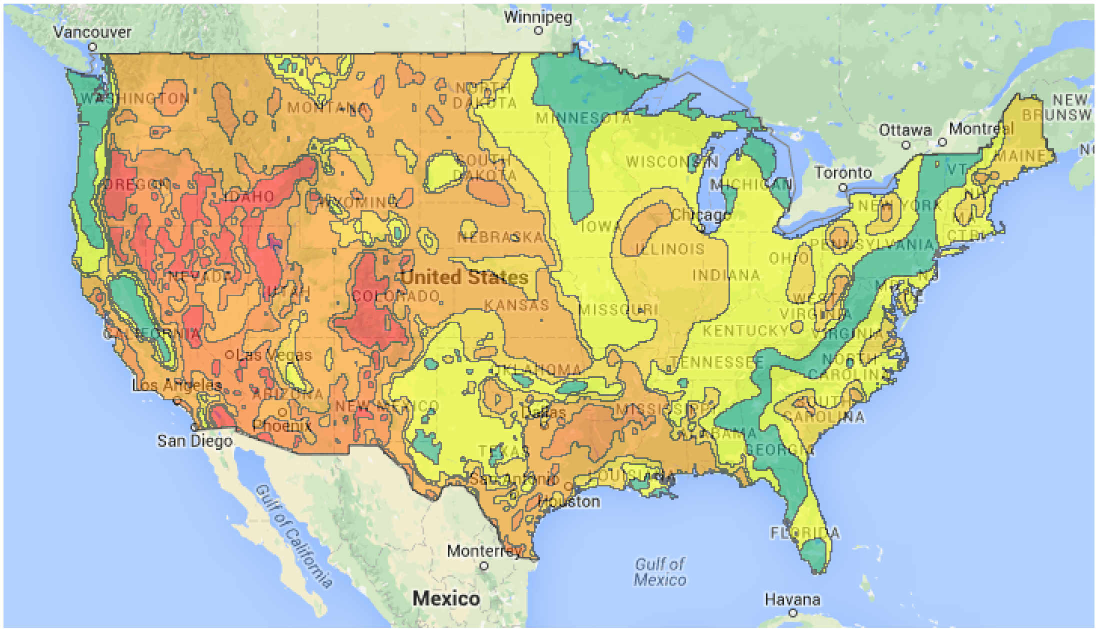


Figure 4. NREL Geothermal Resource Map for Contiguous US

c) Financial Data

The United States Information Administration (EIA) maintains, in cooperation with the NREL, the Transparent Cost Database. This interactive tool scrapes dozens of published articles pertaining to the capital, variable, and fixed costs of renewable energy systems, and displays the distributions of these metrics using box plots. The median values of these financial variables are used to compute levelized cost in Section IV.

IV) Model and Methodology

This section specifies the various components of the linear optimization model that will be solved to analyze the efficiencies of various renewable energy policies.

a) Mathematical Cost Minimization Model

Objective function: $TC = \sum_i \sum_e (P_{i,e} * MC_{i,e})$

Choice variable: $P_{i,e}$ $where\ e \in \{Solar, Wind, Geothermal, Green\ Power\}$

Subject to:

I) $\sum_e \left(P_{i,e}\right) \geq 0.25 *\ E_i\ \ ;\ \ \forall i$

II) $\sum_i \sum_e (P_{i,e})\ \geq\ \sum_i (0.25 *\ E_i)$

III) $P_{i,e}\ \leq\ C_{i,e}\ \ ;\ \ \forall i, e$

IV) $\sum_e (P_{i,e})\ \leq\ E_i$

V) $\sum_e P_{i,e} \geq OS_i\ \ ;\ \ \forall i$

In the above model, total cost (*TC*) serves as the objective function to be minimized. $P_{i,e}$ represents annual production (KWh) at installation *i* of renewable energy *e*. Similarly, $MC_{i,e}$ denotes the marginal cost ($/KWh) of production corresponding to a specific installation and renewable energy combination. This cost is assumed to be constant within bases but varies spatially between them according to the various environmental resources discussed in Section III. $C_{i,e}$ identifies the maximum capacity (KWh) that installation *i* can produce of renewable energy *e*. Seen in many constraints, the variable E_i signifies the total energy (KWh) consumed by installation *i*, and is used to provide renewable energy targets as well as production ceilings. Finally, OS_i refers to the onsite production (KWh) that a base is required to produce in fulfilling the mandates under the Executive Order scenarios. The model highlighted in this section provides a framework for the Department of Defense to minimize their expenditures while achieving their various renewable energy adoption goals.

b) Model Scenarios

The model outlined in the previous section runs for two core objectives: the individual as well as the national; the former being run for the purpose of quantifying the efficiency gained in Congress' decision to implement the National Defense Authorization Act for 2007 at the national level over the individual level. Both goals aim to minimize the same objective function detailed above. The individual objective further divides into completely and partially independent scenarios in order to observe the behavior of DoD bases with varying degrees of renewable capabilities. Recall that installation level data were not available for the DoD, and therefore production values and costs outputted by the model assume an initial installed capacity of zero kilowatt-hours. The model's cost output therefore represents an upper bound to the total cost necessary for the DoD to meet its mandates. The national objective is repeated with an additional constraint reflecting the Executive Order's mandate that bases obtain half of their renewable energy from onsite production. Installations for which this is infeasible simply produce up to their total renewable capacity. Since the DoD is concerned with renewable energy largely to the extent that it can provide energy security, these final scenarios illustrate a more accurate assessment of the cost effectiveness of renewable energy on military installations.

i) Individual Objective

The individual objective examines a hypothetical situation in which bases are each responsible for obtaining 25% of their energy consumed from renewables, as opposed to the Congressional mandate that the DoD as a whole source 25% of its energy

from renewables. Constraints I and III (reproduced below) are used in all runs of the individual models in order to place realistic constraints on variables of interest.

$$\text{I)}\ \ \sum_e \left(P_{i,e}\right) \geq 0.25 * E_i \ \ ; \ \forall i$$

$$\text{III)}\ \ P_{i,e} \leq C_{i,e} \ \ ; \ \forall i,e$$

Constraint I is known as the core constraint when fulfilling the individual objective. This is the mandate that for each base, the sum of all kilowatt-hours produced via renewable energy must exceed 25% of the total energy consumed at that base. Since the marginal costs within installations are assumed to not vary with production, the model will minimize total cost by allocating production to the cheapest resource available. Once that technology has reached its capacity, the model will identify the resource with the next cheapest unit cost and shift production accordingly. Constraint III ensures that each base can only produce at most its technical capacity for each renewable, thereby removing physically infeasible solutions. Naturally, not all military bases are located in areas teeming with renewable resources. Therefore, subsets of the DoD bases in this study are necessary so that the bases used can meet their targets under Constraint I.

A DoD installation is defined as being completely independent if, without any assistance from the grid, that base can produce at least 25% of its energy needs onsite. More explicitly, a base must have solar, wind, and geothermal capacities that when summed together exceed 25% of the total energy consumed at that base. After filtering for this requirement, only 45 installations remain in the model. This observation is not particularly concerning because military bases are built for mission readiness and not for the purpose of having abundant renewable resources. It does, however, suggest that the DoD may have to focus its renewable energy efforts on a handful of high potential bases

in striving to achieve a high level of energy security in the long run. To model using complete independence, the values that energy type, e, can assume initially excludes green power. A second scenario uses these same 45 bases, but offers them the option to also purchase green power, thereby allowing for analysis of substitution effects between renewable energies.

The notion of partial independence relaxes the stringent requirements of complete independence by allowing bases to access renewable energy from the grid. The installations included in this subsample are then those bases capable of meeting 25% of their energy needs through solar, wind, geothermal, and green power. There are 52 bases with no renewable energy potential that are also located in states without established green power systems and another 45 bases with potential yet insufficient resources to meet the 25% target. These 97 installations prevent an analysis of the individual objective using all bases in the sample, since they would yield infeasible solutions in the model. The remaining 458 bases are then modeled using Constraints I and III.

ii) National Objective

At the national level, the production choices that each installation makes are done so in context with the Department's aggregate renewable energy goal. Whereas adhering to the individual objective meant that bases were forced to use the resources or procurement costs available to them, the national objective allows the DoD to utilize the most efficient renewable systems nationwide when making production decisions. Note that the objective function has not changed from the individual objective scenarios.

Constraints II, III, and IV (reproduced below) comprise the restrictions placed on the national model.

$$\text{II)}\ \sum_i \sum_e (P_{i,e}) \geq \sum_i (0.25 * E_i)$$

$$\text{III)}\ P_{i,e} \leq C_{i,e}\ ;\ \forall i, e$$

$$\text{IV)}\ \sum_e (P_{i,e}) \leq E_i$$

Replacing Constraint I from the individual model, Constraint II acts as the core constraint at the national level. This inequality directs the DoD to produce, across all bases and renewable energy types, kilowatt-hours equaling or exceeding 25% of energy consumed on all installations. When a base attempts to minimize DoD costs while individually meeting the 25% target share, it will never produce beyond that goal due to the added marginal costs it would incur. This assumed that regardless of what a given installation chose to produce or procure, that energy would only satisfy itself. At the national level, more efficient bases may (and in fact do) choose meet more than 25% of their energy needs from renewables as a way of compensating for other bases that would have otherwise paid higher energy costs. Constraint IV acts as an overproduction constraint in that it prevents a given base from producing more than it can consume. Since the model assumes that bases cannot trade energy or sell their excesses back to the grid, allowing installations to produce more than they consume would result in unused energy in some bases and a lack of energy in others. This would be counterproductive to the DoD's goal of energy security and is therefore controlled via the overproduction constraint. Constraint III remains the same as in the individual scenarios.

The percent contribution that each base makes to the national objective is defined relative to the individual 25% renewable goal. Subtracting a base's target production

from its total renewable production provides the shortage or surplus kilowatt-hours. Since an installation's renewable production is bound by 0 and that base's total energy consumption, the contribution that a base can make to the national objective is bound between -100% and 300% of its own objective. A negative contribution suggests that other bases are overcompensating to make up for the resulting deficit. Similarly, a positive value implies that the base is obtaining more than 25% of its energy from renewables. A contribution of 0 indicates that the base is exactly pulling its weight in the national context. This concept is displayed in mathematical form in Equation 1.

$$Contribution_i = \frac{\sum_e \left(P_{i,e}\right) - (0.25 * E_i)}{E_i}$$

Equation 1. National Contributions of Individual Installations

iii) Executive Order Scenarios

The remaining scenarios are intended to address the many demands placed on the military's production of renewable energy. Recall from Section II that Executive Order 13423 mandated that 3.75% of each base's energy needs are met through new renewable energy produced onsite. While this particular policy was intended to augment the EPAct regulations of 2005, explicitly directed production of renewable energy certainly complements DoD interests in energy security. To capture the effects of this policy, a theoretical Executive Order is also constructed for the National Defense Authorization Act of 2007 that parallels Executive Order 13423. Where 3.75% represented half of the 7.5% renewable energy target, this hypothetical policy requires that 12.5% of the renewable energy used to satisfy the Department's goal of 25% share renewable be

derived from new, onsite production. The national objective discussed above is then recalculated for actual and theoretical Executive Orders. For convenience of terminology, Executive Order 13423 will be referred to as EO1 and the theoretical Executive Order will be known as EO2. Constraint V (reproduced below) reflects the requirements of these policies.

$$\text{V)}\quad \sum_e P_{i,e} \geq OS_i \;\; ; \;\; \forall i$$

Recall that OS_i signifies the onsite production target that installation *i* must meet. In the EO1 scenarios, this variable assumes the value 3.75% of base *i*'s total consumption if that base has enough renewable potential to meet that target. Similarly in the EO2 cases, OS_i is equal to 12.5% of base *i*'s annual consumption only if it is feasible for that base to reach such a level. In both Executive Order models, a base without sufficient capacity to meet the relevant target is assigned an OS_i equal to that installation's total renewable capacity. The Appendix in Section VIII contains similar analyses of the Executive Orders as applied to the individual objective scenarios. They are not, however, applied to the completely independent scenario without grid support, because imposing the requirement that bases already producing 25% of their energy from renewable produce at least 3.75% or 12.5% share renewable would yield redundant results.

iv) Benchmarking

The benchmark scenarios consist of DoD bases meeting their individual or national objectives through the exclusive purchase of non-renewable energy provided by the grid in their state. Such a solution affords the results greater context and quantifies the costs incurred by the DoD in complying with their Congressional mandates. Comparing

the cost outcomes of any individual or national objective mentioned thus far with its corresponding benchmark scenario also provides insight into the current cost effectiveness of renewable energy. The separate constraints for each energy type can be simplified in the benchmarking case by limiting the energy sourced from the grid to the total amount of energy used by that base.

c) Cost Estimation

Developing reasonable, spatially sensitive marginal cost estimates of pertinent renewable energy supplies the linear programming model with the information needed to make cost effective decisions and model military production choices. This subsection explains the financial factors used in the model as well as cost estimation methodology for solar, wind, geothermal, and green power.

i) Levelized Cost

Since renewable energy projects span multiple years and last for decades once established, the levelized cost of energy (LCOE) offers an attractive solution to accumulating the cash flows associated with such a financing structure. A levelized cost is a single metric, in dollars per kilowatt-hour, that encapsulates all of the lifecycle costs associated with building and operating an energy producing asset (US Energy Information Administration). This value can be computed using Equation 2, reproduced from NREL documentation.

$$LCOE = \frac{(Overnight\ cost\ *\ Recovery\ Factor) + Fixed\ O\&M}{8760\ *\ Capacity\ Factor} + Variable\ O\&M$$

Equation 2. Levelized Cost of Energy

The overnight cost represents the expenditure ($/KW) that would be necessary to construct a given energy system overnight instead of spreading the cost out over a number of years. The recovery factor is calculated using a separate formula that treats costs as an annuity and converts them into present value terms. Multiplying the overnight cost by the recovery factor therefore yields the present value cost ($/KWh) of installing an energy system overnight. Fixed O&M and Variable O&M are the annual fixed and variable costs ($/KWh) connected to the project. For most renewable systems, the variable costs are assumed to be 0 since they are powered by natural processes. The capacity factor is a measure of the energy system's efficiency, where a value of 0 indicates that the system is dysfunctional and 1 implies that the system is capable of running at maximum capacity indefinitely. Mathematically, it is defined as the ratio of how much energy a certain system can produce in a given time to the maximum amount of energy that same system would generate were it to run at nameplate capacity.

Using the NREL resource mapping tools in conjunction with energy specific research detailed in the following subsections, spatially varied capacity factors were designed for solar, wind, and geothermal energy. Utilizing the EIA's Open Energy Transparent Cost Database, median values were identified for each of the financial variables in Equation 2, including overnight cost, fixed O&M, and variable O&M. The recovery factor was calculated separately using a real discount rate of 3%, as recommended by the NREL Levelized Cost of Energy Calculator tool. Finally, the

methods for determining the capacity factor of each renewable allowed for the usage of spatially varied levelized costs in the resulting model.

ii) Solar Cost

James Anders and Sahan Dissanayake (2013) develop a model framework for estimating the expected output of a solar energy system, as shown in Equation 3.

$$Photovoltaic\ System\ Output = \sum_{t=0}^{24} \frac{Sun_i * R_i * Z_i}{(1+d)^t}$$

Equation 3. Estimated Output of Solar Energy Systems

The mean insolation (KWh/m^2/day) for a base is represented by Sun_i and is the spatially varied component of this equation. The term R_i is known as the derate factor, which Anders and Dissanayake determine to be 0.74 based on an array of factors from the NREL. Due to differences in data and assumptions between Anders and Dissanayake (2013) and this paper, a derate factor of 0.79 was calculated for this study. The variable Z_i signifies the size, or nameplate capacity, of the solar energy system installed and was assumed to be 1,000 KW. A discount rate of 3% (see above) and a lifespan of 25 years round out the assumptions needed to estimate solar output using Equation 3. The resulting figure is all the kilowatts generated by the solar technology over its entire life. Assuming that solar energy systems depreciate linearly, the annual output was then computed and compared to the maximum annual output of 24,000 KWh. The quotient of these values is the capacity factor, which was entered into Equation 2 to determine levelized cost of solar energy.

iii) Wind and Geothermal Costs

Power and resources classes were drawn from NREL Wind and Geothermal Prospector tools, respectively, to obtain the spatial components for the levelized costs of wind and geothermal energy. Since the military invests heavily in both onshore and offshore wind production, the relevant financial data from the Transparent Cost Database was used to calculate weighted average values to use in the model. Without a breakdown of the military's wind usage, equal weights were applied to both forms of wind energy. Mappings from power and resource class into capacity factors were completed using researched figures from Black and Veatch (2012).

iv) Green Power Cost

Green power's close relationship with non-renewable utility energy allows for a simple approach to cost assumptions. Utilities charge a premium over their conventional energy in order to offset the higher costs of supplying energy through an integrated electricity grid. The kilowatt-hour cost of green power is therefore the sum of non-renewable grid energy and the average premium charged. Since utility rates and green power premiums vary across states, these costs are also spatial, but at a higher granularity than solar, wind, and geothermal energies.

V) Scenario Results

This section presents the model outputs for the objectives and scenarios outlined in Section IV. The individual objective, divided into separate analyses of completely and

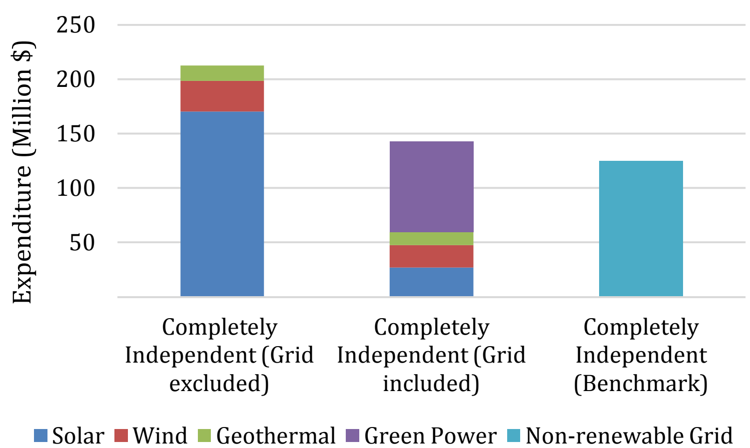
partially independent scenarios is considered first, followed by the national scenario. Next, the national objective is observed a second time with the inclusion of the Executive Order constraint (Constraint V). Tabulated summaries of specific outcomes for solar, wind, geothermal, and green power energies can be found in the Appendix (Section VIII), as can a similar analysis of the Executive Order scenarios under the individual objective.

a) Individual Objective

i) Complete Independence

Figure 5 illustrates the total expenditures made by completely independent DoD installations in achieving 25% of their energy needs through the production of renewables. Taken together, installations choose to spend $170.2 million on solar, $28.4 million on wind, and $14.0 million on geothermal energy for a total expenditure of $212.6 million (rounding may cause calculations to deviate slightly). In this first scenario, solar is a prominent choice for many installations with 77% of bases choosing to produce some quantity of the renewable energy. The DoD's cost per installation when only observing this subset isolated from the grid is $4.73 million.

Figure 5. Complete Independence Energy Decomposition (N=45)



When these same 45 completely independent bases are then offered the option of sourcing their renewable energy from the grid, they dedicate a substantial portion of their renewable energy portfolios to green power. In total, 62% of bases procure energy through green power, the energy from which comprises 60% of the DoD's renewable energy. Including green power decreases the total cost of compliance from $212.63 million to $142.91 million, or approximately 33%. This sizeable decrease can be attributed in part to the efficient transmission of green power from large utility companies having achieved economies of scale and thereby selling energy at a lower cost. Similar to the characteristics of states with Renewable Energy Portfolios, green power is only offered in states whose energy markets have been restructured to allow such a transfer of energy to occur. There appears to be an exchange of solar for green power occurring between these two scenarios, as evidenced by the relative constancy of wind and geothermal expenditure. This observation suggests that green power marginal costs tend to be lower than those for solar at many installations. Since green power by definition is simply the non-renewable grid cost with an added premium, it is not surprising to find that the benchmark case then yields the lowest total cost of $125.1 million.

Figure 6. Complete Independence Cost/KWh (Grid Excluded)

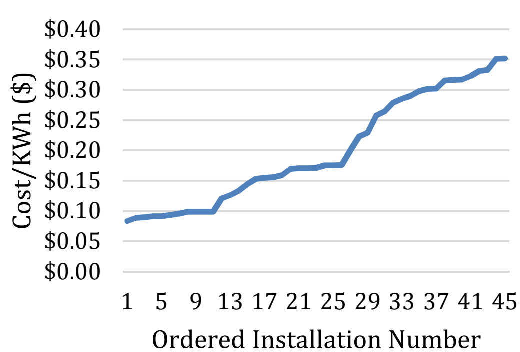
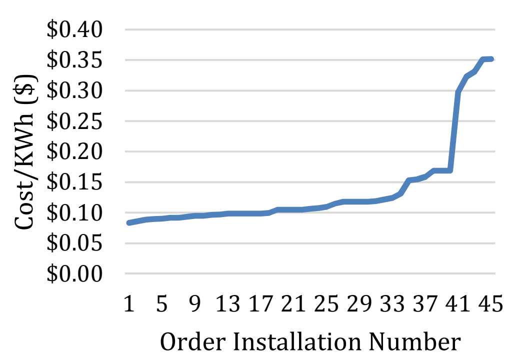


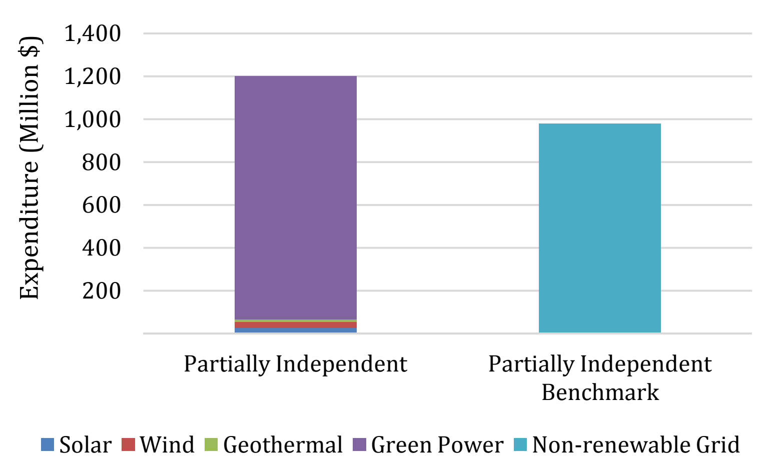
Figure 7. Complete Independence Cost/KWh (Grid Included)



Figures 6 and 7 above illustrate the per kilowatt-hour costs for all 45 bases in this subsample. In the absence of green power, the prices that installations pay across all energy types are well spread over a range of values from $0.08 to $0.35. The small group of bases that pay around $0.10 per kilowatt-hour are those whose renewable energy portfolios contain a high share of wind or geothermal energy, whereas the group between $0.30 and $0.35 are bases in regions of low solar insolation yet high potential capacity. With the introduction of a renewably-sourced grid, however, many bases substitute more expensive solar energy for cheap green power, whose costs tend to fall in the $0.08 to $0.18 range. The remaining high costs in Figure 7 represent those installations located within states that do not offer green power, possess poor insolation, yet have a high technical capacity for solar. As a result, these bases must continue to purchase expensive solar energy to meet the individual mandate imposed in this scenario.

ii) Partial Independence

Figure 8. Partial Independence Energy Decomposition (N=458)

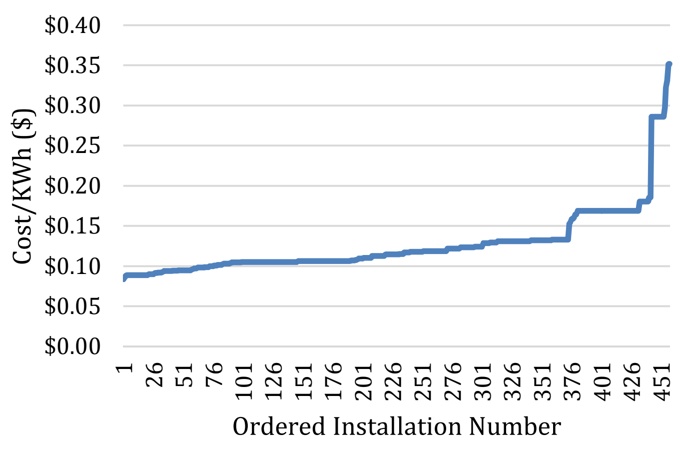


Widening the sample to the partially independent scenario reveals an extreme case of grid reliance among military installations. In particular, green power constitutes 94% of all renewable energy

produced and only 3.7% of bases choose not to import their renewable energy from the grid. Since the model's scope now includes most DoD bases, the cost of $1.2 billion more accurately reflects what the Department might spend on energy in a given year, relative to complete independence. Figure 8 visualizes green power's domination and the marginalization of onsite production under this scenario. On an individual installation basis, the cost of green power outranks the other renewable technologies as the most cost effective solution to increasing the size of the military's renewable energy portfolio. The clear preference for bases to obtain their energy from external sources undermines the Department's commitment to bolstering energy security, but results in a per installation cost of $2.62 million. Additional mandates and constraints in favor of generating onsite production are necessary, however, to ensure that the National Defense Authorization Act achieves its intended goals in the partial independence scenario.

On a cost per kilowatt-hour basis, partial independence behaves similarly to the completely independent scenario with the inclusion of green power. Figure 9 reveals many bases primarily using their state's green power prices to achieve their energy targets as well as the smaller group without access to a renewable-integrated grid. What stands out in Figure 9 that was not present in Figure 7 are the 50 bases all meeting their goal at a

Figure 9. Partial Independence Cost/KWh

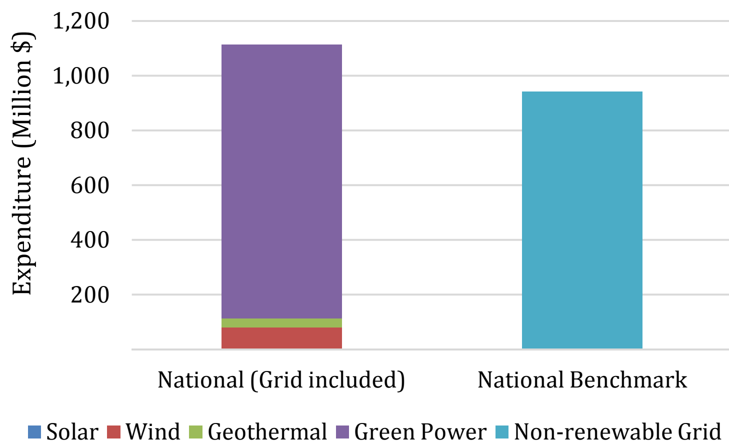


per kilowatt-hour cost of $0.169. These are installations located in California that have no onsite renewable capacity. Similar runs of many bases having the same energy cost create the horizontal portions of Figure 9, and were not included in the complete independence scenario due to their complete reliance on green power.

b) National Objective

The DoD's overall compliance cost decreases with the addition of 97 bases from the partial to the national scenarios, demonstrating that the ability to coordinate across all installations results in a more efficient outcome. Specifically, the total cost of meeting the national objective is $1.11 billion, approximately $100 million less than the partially independent scenario. At the installation level, the national scenario entails spending $2.01 million per base whereas the partial scenario requires $2.62 million per base despite spanning more bases. At the same time, Figure 10 demonstrates that green power continues to dominate other forms of renewable energy from a price standpoint, although perhaps slightly less so in the national than the partial independence scenario. Unless cheaper renewables capture a larger portion of the DoD's renewable portfolio, the benchmark cost will also continue to

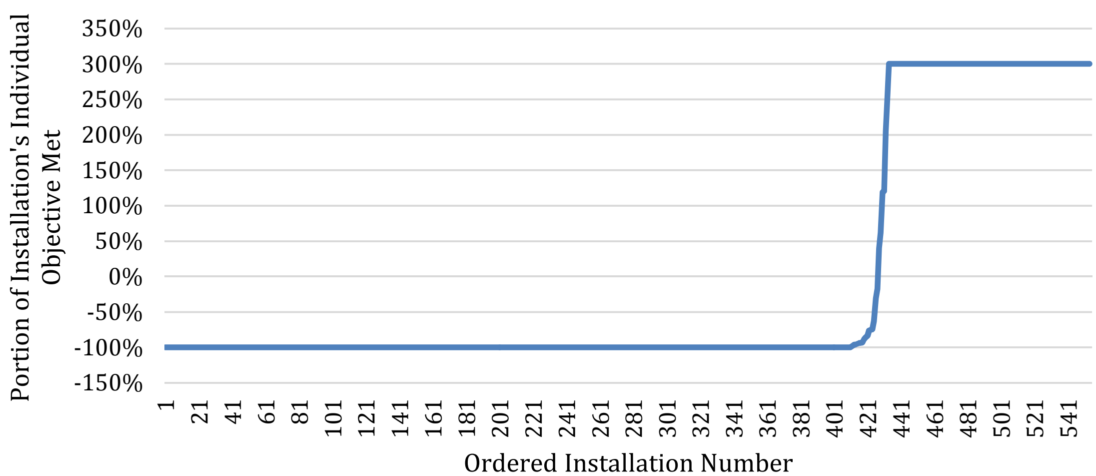
Figure 10. National Objective Renewable Energy Decomposition (N=555)



offer the cheapest source of energy. With renewables grappling for and gaining traction in energy markets today, it may not be many more years before they rival the benchmark costs shown in this section.

Examining all bases working towards a common, cumulative goal of 25% energy provides further insight into the renewable energy decisions that individual bases face. The national objective allows the military to utilize the lowest marginal costs in the country, regardless of installation, before moving to less efficient sources. This contrasts the complete and partial independence scenarios, in which every base utilized resources without regard for where the cost effectiveness of that resource ranked nationally. Figure 11 decomposes the contributions that each base makes towards achieving the national objective.

Figure 11. Installation Contributions to Individual Objective in Fulfilling the National Objective

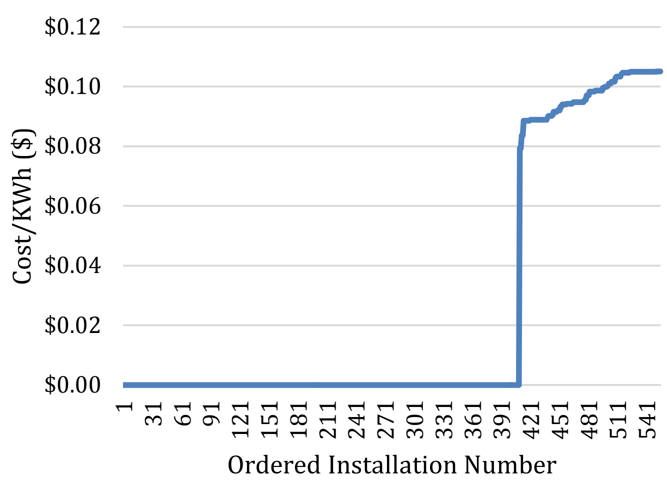


Recall from Section IV that a contribution of -100% represents a base that produces no renewable energy whereas 300% implies that the base acquires all of its energy through renewables. With this in mind, there are 408 installations not contributing, 121 producing as much renewable energy as possible, and the remaining 25 falling on the spectrum in

between. These findings suggest that when pursuing a national objective, the most efficient bases incur the greatest costs as they offset less efficient bases in other locations. A minority of bases producing excessive renewable energy while most ignore the technology altogether may fail to meet the security goals that Congress intended when designing such a mandate. Furthermore, and beyond the scope of this paper, many bases relying solely on fossil fuels while others convert entirely to clean energy would likely pose environmental dangers in locales home to larger installations.

Figure 12 also reflects this dichotomy in production decisions in the horizontal line at no unit energy cost. The bases that do choose to produce renewable energy, however, do so at a much more efficient level than in either scenario under the individual objective. Producing bases in the national model spend between $0.08 and $0.11. Bases that were forced to produce expensive solar in the individual scenarios now simply collect all of their energy from non-renewables while the bases boasting the cheapest wind, geothermal, and green power resources compensate for their share.

Figure 12. National Cost/KWh

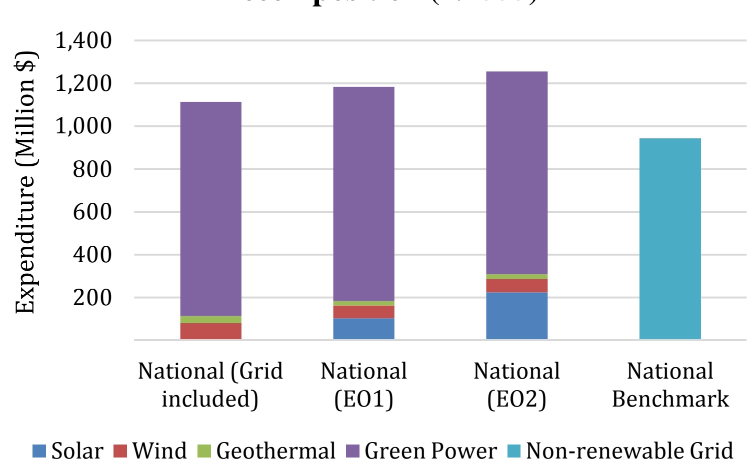


c) Executive Order Models

Adding Constraint V, the provisions from Executive Order 13423 (EO1) and the theoretical application of this mandate to the National Defense Authorization Act for 2007 (EO2), prompts an increased share of onsite renewable energy in the DoD's energy portfolio, albeit at a higher cost. For an analysis of the complete and partial independence cases, refer to the Appendix in Section VIII. Generally speaking, higher costs can be attributed to the mandated production of renewable energy whenever possible before turning to green power in meeting the 25% share target. As a reminder, EO1 requires bases for which it is feasible to produce 3.75% of their energy from renewables and EO2 demands 12.5%. For bases without the physical capacity for this onsite production, the Executive Orders lead them to simply produce as much renewable energy as possible before switching to the grid.

Figure 13 illustrates that in the presence of a minimum percentage of renewable energy, solar becomes relevant and rather sizable in meeting the 25% mandate from the National Defense Authorization Act. Where solar power was entirely substituted out in the prior national model, the EO1 and EO2 cases allocate $103.5 million and $224.6 million of DoD expenditures towards solar energy. These dramatic increases in solar

Figure 13. Executive Order National Energy Decomposition (N=555)



spending reveal a positive correlation between the level of minimum onsite production and the amount of funding directed towards solar energy. At the same time, the effect of a higher renewable energy floor on spending levels among individual bases is negligible between the EO1 and EO2 scenarios. This observation is supported by the comparison of Figures 14 and 15 below. Apart from a very slight differential towards the middle of the distribution, these two plots are identical in most respects. For solar to increase in such a manner, however, suggests a sizable and untapped potential for solar energy on many DoD installations that could be utilized in the event of more demanding onsite production requirements, as in the hypothetical EO2 scenario.

Between Figures 13, 14, and 15 lies an interesting finding: under the national objective, DoD bases are able to collectively increase the Department's investment in solar energy without causing any substantial changes in their own costs per kilowatt-hour. In fact, 265 bases choose to produce some quantity of solar energy in adhering to the EO2 model. The cost burden to the DoD, in the meantime, increases from $1.18 billion to $1.26 billion between EO1 and EO2. These results indicate that bases able to produce solar energy most efficiently do so at a cost comparable to their green power costs. If green power costs were even one cent cheaper than solar, then the model would find the most cost-effective solution by allocating all production into green power. With the minimum renewable requirements imposed by the Executive Orders, however, these cheap solar costs replace the procurement of similarly priced green power. The result is a large adoption of solar energy at only a modest cost to the Department of Defense.

Figure 14. National EO1 Cost/KWh

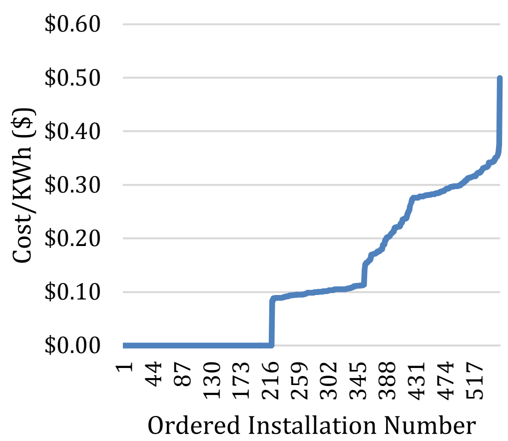
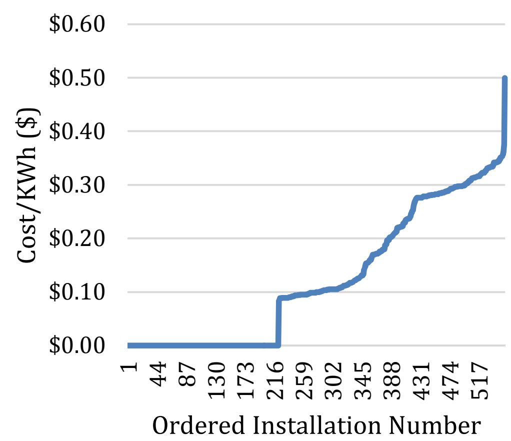


Figure 15. National EO2 Cost/KWh

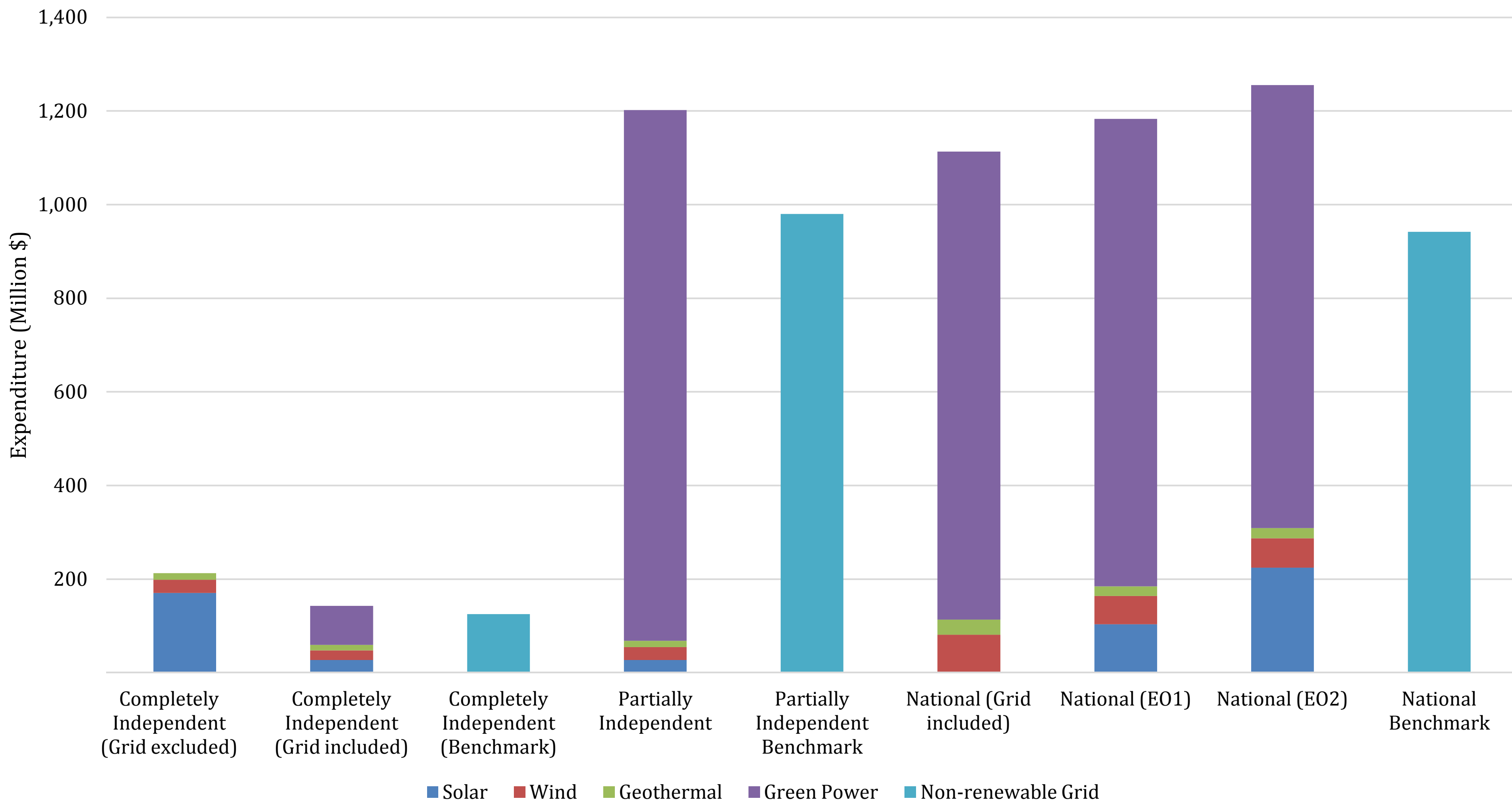


d) Summary

The total expenditure by the DoD in achieving the individual and national objectives in the variety of scenarios highlighted in this paper are summarized in Figure 16. In order to facilitate the comparison between these various scenarios, which include varying numbers of bases, Table 1 summarizes the aggregate and per installation costs associated with each outcome. Although the partially independent cases involve fewer installations (N=458) than the national level (N=555), the costs associated with converting to a 25% share of renewable energy are lower. This suggests that the Congressional decision to implement the National Defense Authorization Act as a Department-wide mandate is indeed more cost-effective assigning each base to individually meet the same goal.

Table 1. Cost Aggregation Across Scenarios			
Objective	**Scenario**	**Total Cost**	**Cost Per Installation**
Individual	Completely Independent (Grid excluded), N=45	$212,629,324.09	$4,725,096.09
Individual	Completely Independent (Grid included), N=45	$142,907,222.61	$3,175,716.06
Individual	Completely Independent Benchmark, N=45	$125,082,378.57	$2,779,608.41
Individual	Partially Independent, N=458	$1,201,878,094.86	$2,624,187.98
Individual	Partially Independent Benchmark, N=458	$980,159,141.11	$2,140,085.46
National	National (Grid included), N=555	$1,113,561,895.71	$2,010,039.52
National	National (EO1), N=555	$1,182,896,911.94	$2,135,192.98
National	National (EO2), N=555	$1,255,401,250.22	$2,266,067.24
National	National Benchmark, N=555	$942,135,770.39	$1,700,606.08

Figure 16. Renewable Energy Decomposition Summary (All Scenarios)



VI) Conclusion

This paper has established a framework grounded in mathematical programming that allows for detailed analysis of renewable energy installation. Using data drawn from the Department of Defense, this model was used to determine the cost efficiency of Congressional mandates concerning the amount of renewable energy that the Department produces. In particular, the National Defense Authorization Act was studied both from the perspective of individual bases as well as the Department as a whole working towards satisfying a 25% renewable energy target. This paper finds that, in terms of total DoD spending, the national level policy saves $88 million in energy expenditures. On a per installation level, however, the savings are more dramatic owing to the exclusion of 97 bases in the partial independence scenarios. The difference in cost between the national and individual objectives reveals the latter to be 31% more expensive than the former.

To further develop the model, additional scenarios were generated using the provisions of Executive Order 13423 and a theoretical Executive Order based on this mandate. As the minimum portion of renewable energy produced onsite versus procured from an external utility increased, the differential between national and individual policies decreased. When this floor was 3.75%, the cost differential was $64 million with a difference in per installation costs of 27%. Raising the floor to 12.5% to mimic Executive Order 13423 on the National Defense Authorization Act yielded an aggregate differential of $41 million, which corresponded to an installation level cost gap of 25%.

Throughout these cost analyses, implications for the overarching mission of energy security are evident. Renewable energy as a whole today is not at a price point that can consistently compete with grid rates. There are certainly areas with favorable

enough wind and geothermal resources that allow for competitiveness on a levelized cost basis, yet capacity constraints prevent a complete takeover. Research and innovation in the coming years will continue to apply downward pressure to these costs, thereby hastening their adoption around the globe. In the United States, these coming gains in efficiency represent opportunity for the Department of Defense to seize control of its energy security. From the battlefields to the home bases that support them, reliable sources of energy are vital to the success of DoD missions everywhere. Over the course of the last decade in particular, Congress and the DoD have both begun to realize the important role that renewable energy can play in bolstering America's energy security. With its vast array of resources and dominant share of government consumptions, the Department of Defense is further poised to set the stage for nationwide adoption of renewable energy in the United States.

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VIII) Appendix

a) Renewable Energy Production Summaries

Table 2. Solar Decomposition by Scenario					
Objective	Scenario	Expenditure	Bases Producing	Bases Producing (%)	Portfolio Share
Individual	Completely Independent (Grid excluded)	$170,221,983.91	35	77.78%	61.83%
Individual	Completely Independent (Grid included)	$26,981,258.61	8	17.78%	10.40%
Individual	Partially Independent	$27,066,638.33	10	2.18%	1.31%
National	National (Grid included)	$0.00	0	0.00%	0.00%
National	National (EO1)	$103,515,561.39	260	46.85%	3.30%
National	National (EO2)	$224,563,186.17	265	47.75%	7.40%

Table 3. Wind Decomposition by Scenario					
Objective	Scenario	Expenditure	Bases Producing	Bases Producing (%)	Portfolio Share
Individual	Completely Independent (Grid excluded)	$28,393,137.28	9	20.00%	25.34%
Individual	Completely Independent (Grid included)	$20,607,591.47	8	17.78%	18.71%
Individual	Partially Independent	$27,831,328.01	27	5.90%	3.20%
National	National (Grid included)	$59,008,630.67	34	6.13%	5.63%
National	National (EO1)	$60,176,462.54	35	6.31%	5.74%
National	National (EO2)	$62,901,403.58	35	6.31%	5.98%

Table 4. Geothermal Decomposition by Scenario					
Objective	Scenario	Expenditure	Bases Producing	Bases Producing (%)	Portfolio Share
Individual	Completely Independent (Grid excluded)	$14,014,202.90	8	17.78%	12.83%
Individual	Completely Independent (Grid included)	$11,898,924.33	7	15.56%	10.89%
Individual	Partially Independent	$13,584,814.22	10	2.18%	1.56%
National	National (Grid included)	$20,613,176.75	10	1.80%	1.99%
National	National (EO1)	$20,942,179.83	11	1.98%	2.02%
National	National (EO2)	$21,709,853.70	11	1.98%	2.09%

Table 5. Green Power Decomposition by Scenario

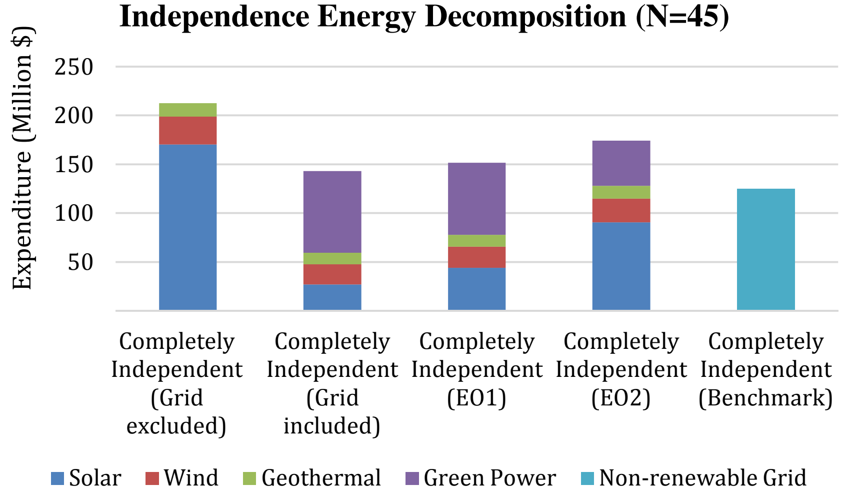
Objective	Scenario	Expenditure	Bases Producing	Bases Producing (%)	Portfolio Share
Individual	Completely Independent (Grid excluded)	$0.00	0	0.00%	0.00%
Individual	Completely Independent (Grid included)	$83,419,448.20	28	62.22%	60.00%
Individual	Partially Independent	$1,133,395,314.30	441	96.29%	93.93%
National	National (Grid included)	$1,038,901,878.09	119	21.44%	92.38%
National	National (EO1)	$998,262,708.17	119	21.44%	88.95%
National	National (EO2)	$946,226,806.77	112	20.18%	84.53%

b) Executive Orders under the Individual Objective

This section provides analysis corresponding to that of Section V, Subsection c, where the national model was evaluated with the addition of Constraint V for the Executive Orders EO1 and EO2. Across all individual objective scenarios, there is an increase in cost as the minimum share of renewable energy produced onsite increases from 0% in the previously considered models to 3.75% under EO1 and ultimately 12.5% under EO2.

Beginning with the completely independent scenario, Figure 17 reproduces the primary scenarios alongside the results from adding EO1 and EO2. The progression from the original complete independence case (second bar from the left) to the EO1 and EO2 scenarios drives total Department expenditures from $142.9 million to $151.4 million to $174.2 million, respectively.

Figure 17. Executive Order Complete Independence Energy Decomposition (N=45)



These higher costs are accompanied by more than a threefold increase in solar expenditure between the National Defense Authorization Act and EO2 models. This observation combined with the constancy of wind and geothermal expenditure suggests that significant solar capacity is the primary reason that these installations can boast complete independence from the grid in meeting their energy goals. Figures 18 and 19 below provide a deeper, installation-level look at the price scaling that occurs with heightened minimum renewable energy production targets. Military bases with only access to expensive solar remain at the high end of these cost per kilowatt-hour plots, and the installations at the lower extreme are identical as well. The gradient between these minima and maxima, however, is steeper in the EO2 model than in the EO1 model. These in turn are both steeper than the original complete independence scenario (grid included) without a minimum renewable energy share (see Figure 7). Increasing cost with a higher mandated share of renewables can be explained by the immense untapped solar potential that bases substituted with green power.

Figure 18. Complete Independence EO1 Cost/KWh

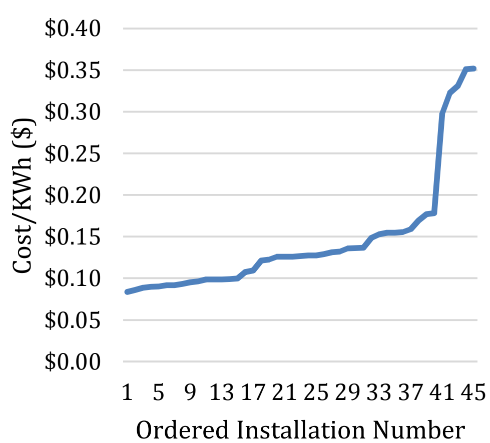
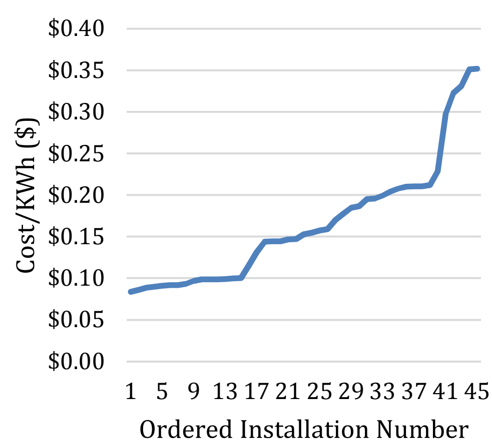


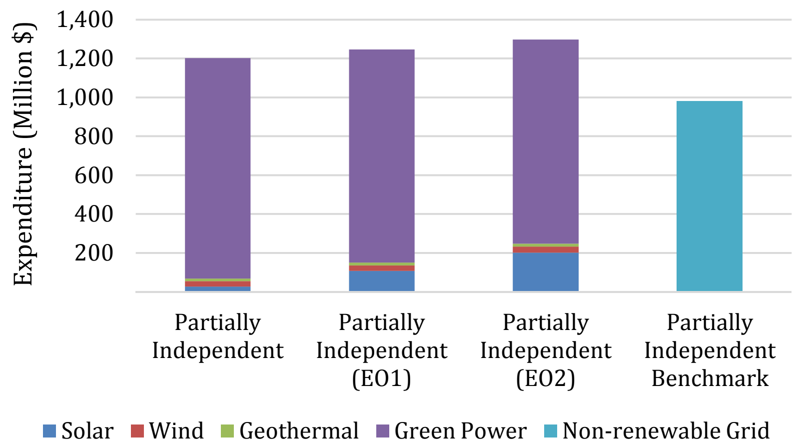
Figure 19. Complete Independence EO2 Cost/KWh



While energy procured from the grid

continues to outpace that produced onsite in the partially independent case, the introduction of minimum renewable requirements increases funds allocated to renewables. Figure 20 compares partially independent EO1 and EO2 scenarios with previous outcomes and finds, similar to complete independence, that solar expenditure rises markedly between these models. Specifically, solar expenditure increases from $27.1 million originally to $107.2 million in EO1, and ultimately to $201 million under EO2. Total expenditure moves upward by approximately $100 million between the original and EO2 partially independent scenarios; a reflection of what amounts to substitution of green power for solar. Whereas the completely independent scenarios indicated that wind and geothermal were operating at maximum capacity, Figure 20 shows a modestly rising share of geothermal between EO1 and EO2. It may therefore also be possible for the DoD to tap into underutilized technologies besides expensive solar under these Executive Orders. The unit energy costs in Figures 21 and 22 afford similar results as those observed in Figures 18 and 19 for the complete independence Executive Order scenarios. In particular, the slope of this curve steepens between the implemented and hypothetical

Figure 20. Executive Order Partial Independence Energy Decomposition (N=458)



Executive Order outcomes, although at a lower magnitude than in the completely independent EO scenarios.

Figure 21. Partial Independence EO1 Cost/KWh

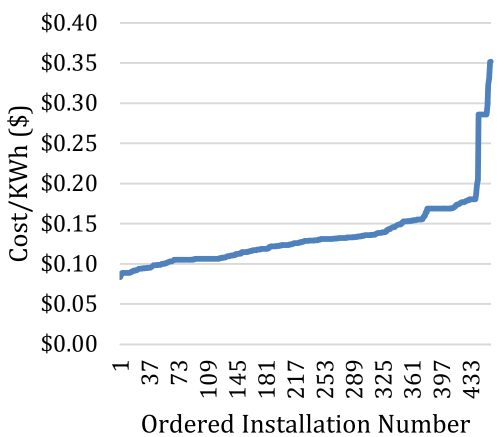


Figure 22. Partial Independence EO2 Cost/KWh