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An Economic Basis for Littoral Land-Based Production of Low Carbon Fuel from Renewable Electrical Energy and Seawater for Naval Use: Diego Garcia Evaluation

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14. ABSTRACT

The Naval Research Laboratory (NRL) was challenged to determine the maximum size and configuration of a fuel producing process on the remote island of Diego Garcia using electricity from renewable sources such as wind and solar. Data from renewable site assessments of Diego Garcia conducted by the National Renewable Energy Laboratory (NREL) and the Naval Facilities Engineering Command (NAVFAC) have been used in this report to support an economic basis for the littoral production of low carbon fuel from carbon dioxide (CO_2) and hydrogen (H_2) in seawater. Diego Garcia represents one of the most difficult challenges to the U.S. Navy for the future production of low carbon fuel from renewable electrical energy from photovoltaic (PV) arrays and wind turbines due to its extremely small land area and Class II wind classification. This study uses this remote base as a detailed example of the many possible sites and scenarios that could be utilized for the proposed littoral land-based process. The maximum size and configuration of a fuel producing process on Diego Garcia using electricity from renewable sources such as wind and solar is detailed.

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EXECUTIVE SUMMARY

NRL was challenged to determine the maximum size and configuration of a fuel producing process on the remote island of Diego Garcia using electricity from renewable sources such as wind and solar. Data from renewable site assessments of Diego Garcia conducted by NREL and NAVFAC have been used in this report to support an economic basis for the littoral production of low carbon fuel from carbon dioxide (CO_2) and hydrogen (H_2) in seawater.

NRL has estimated that 320 MW of electricity is needed to produce the 47 million gallons of fuel delivered annually to Diego Garcia. Using published capital cost estimates and a range of solar and wind renewable electrical energy scenarios, costs ranging between $3.76 and $5.12 per gallon are calculated for producing 129,000 gallons per day of fuel. It is possible to supply up to 100% of the fuel now imported to the tiny foot-print of Diego Garcia. Current real total costs of this imported fuel is about $6.60/gallon. This provides policy analysts with a reasonable economic rationale and justification for planning and designing a new littoral energy conversion process to provide low carbon jet and diesel fuel for naval operations at sea.

A graphic depiction illustrates how a fuel process could be configured on the island of Diego Garcia. This remote base represents the most difficult challenge for using wind and PV arrays due to its extremely small land area (10 square miles, of which only about 6 square miles is actually available) and Class II wind classification. Larger area potential sites of strategic naval importance such as Guam, Cuba, Djibouti, and Hawaii could be constructed at lower capital costs and therefore achieving lower per gallon prices than Diego Garcia.

AN ECONOMIC BASIS FOR LITTORAL LAND-BASED PRODUCTION OF LOW CARBON FUEL FROM RENEWABLE ELECTRICAL ENERGY AND SEAWATER FOR NAVAL USE: DIEGO GARCIA EVALUATION

1.0 BACKGROUND

SECNAV has set forth Navy goals for alternative energy use which require that 50 percent of DON energy requirements **at sea** and **on shore** be derived from alternative (non-petroleum) sources by 2020 [1]. The five ambitious energy goals involve energy efficient acquisition, sailing the "Great Green Fleet" by 2016, reducing non-tactical petroleum use by 50% by 2015, increasing alternative energy ashore, and increasing alternative energy so that by 2020, 50% of total navy energy consumption will come from alternative sources. These goals seek to enhance combat capabilities and to provide greater energy security [1].

In pursuit of these ambitious energy goals, the US Navy has enlisted the National Renewable Energy Laboratory's (NREL) technical assistance in the evaluation of 22 Navy installations. One of these installations is located on the remote island of Diego Garcia [2]. The Naval Support Facility Diego Garcia is one of the most strategically important U.S. military installations. Located over 2,750 miles south of Iraq and Afghanistan, the base has served as a critical refueling station during the Persian Gulf War, Operation Desert Fox, and the Afghanistan war. Due to its location in the middle of the Indian Ocean, the base relies solely on petroleum based resources to provide power and electricity to the island [3]. In addition the base relies on petroleum based resources to support all naval operations in, around, and from the installation. The island's potential renewable resources, extremely small land mass, and its importance in US military operations provides one of the most challenging cases for assessing how these resources could be exploited and used to ensure its maximum energy security and strategic importance for the US Navy.

2.0 INTRODUCTION

NRL was tasked by the Congressional Research Service (CRS) to determine the size, estimated cost, and configuration of a fuel producing process on the remote island of Diego Garcia using electricity from renewable sources such as wind and solar. In November of 2013, NREL performed a net-zero renewable energy site assessment of Diego Garcia and initially estimated the potential amount of wind and solar power that could be generated on site to be used to supply electricity to the island [4]. "Net Zero Energy" means that the renewable energy produced on-site over the period of a given year is equal to the installation's energy demand [5]. The island's average annual electrical production is ~10 MW that is supplied by roughly 20 MW to 25 MW of diesel generators [6]. The prior year NRL published a cost/benefit and energy balance analysis that addresses the critical scientific and technical challenges that impact the economic feasibility of producing jet fuel at sea using CO_2 and H_2 [7]. These data have been used as a starting point by NRL to conduct a reasonable economic analysis to support the rational and justification of planning and designing a new future littoral renewable energy conversion process that provides low carbon jet and diesel fuel for all naval operations at Diego Garcia, including the use of the synthetic hydrocarbon fuel to power the island's electrical grid.

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3.0 RESULTS AND DISCUSSION

3.1 Photovoltaic Renewable Generation On Diego Garcia

Figure 1 is a picture of the island and Table 1 provides the island dimensions relative to the large lagoon it encompasses. In the image, 10 square miles of land (27 km^2) surround a 57 square mile (147 km^2) lagoon [8]. With respect to solar feasibility, NREL used a Preliminary Technical Assessment (PTA) that had already been conducted and published for official use only by NAVFAC in 2011 [6]. The photovoltaic arrays renewable energy estimates are based on the use of roughly 1% of the island's total (~0.27 km^2) dry land area, and this only includes the land that bounds the western side of the lagoon. This side of the island is the one that is occupied by military operations and is home to the island's power stations and the 2.3 to 2.6 mile long airstrip (Figure 2) [8-9]. Ideally the alternative renewable sources should be located as close to the grid they support. Therefore, it is this land that was used in NAVAC's initial assessment for the locations of photovoltaic arrays on Diego Garcia [6].

The total amount of power that could be provided by PV in the 1% of land was reported to be between 15 to 30 MW. NAVFAC reported that additional 3 to 5 MW could be achieved with PV locations on top of selective installations on the island. During NREL's site assessment, they determined that approximately ~2 MW would be the upper limit before serious grid integration measures would be required. The proposed NRL process would use the 15 to 30 MW of solar power to produce liquid hydrocarbon fuel as a drop in replacement for traditional petroleum based JP5 that is currently being used for the power stations. This novel way of storing renewable energy as a liquid hydrocarbon would avoid the need for serious modifications and power integration to the current infrastructure on Diego Garcia.

Sources indicate that 20-25 MW is the average rated size of the JP5 fueled power stations supplying electricity to Diego Garcia [6]. Since this power originates from petroleum based resources, an estimated average of 5.6 million gallons of fuel must be delivered annually to Diego Garcia just to operate the power plants. In FY2014, this Fully Burdened Cost of Fuel (FBCF) is estimated at $37 million dollars.

The FBCF is defined and explained as follows. The Defense Logistics Agency/Energy (DLA/E) reported a fuel price-per-gallon of $3.64 (JP-5) and $3.61 (F-76) in FY2014 [10]. This price does not include the additional costs of logistical storage and delivery of the fuel to naval operational vessels at sea and strategic installations such as Diego Garcia. The Fully Burdened Cost of Fuel (FBCF) is defined as the standard price per gallon diesel or jet paid by the DOD plus the logistical cost to procure, store, and deliver the fuel at sea. The most recent detailed justified FBCF can be found in the 2008 report by the Defense Science Board [11]. The report establishes an FBCF of $4.00/gallon for FY2005. Using data from previous reports ($1.56/gallon procured price) a burden cost of $2.44/gallon was established. This burden cost of fuel can be adjusted for the last 9 years using standard inflation calculators to arrive at an FY2014 value of $2.97/gallon. This gives a FBCF price for FY2014 of $6.61 JP-5 and $6.58 F-76.

Table 2 shows that the 5.6 million gallons of fuel annually to support the power facilities at Diego Garcia is only a fraction (~12%) of the total amount of the 47 million gallons of fuel delivered to the installation a year (129,000 gallons/day) [12]. The other 88% is used to support Naval operations in, around, and from the installation.

NAVFAC and NREL estimate that 15 to 30 MW of power can be produced using photovoltaic renewable generation on 1% of the island [6]. Based on former analysis by the Naval Research Laboratory, 15 to 30 MW of electricity can produce 6,000 gallons/day to 12,000 gallons/day of fuel using CO_2 and H_2 feedstock from seawater [7]. Based on the numbers provided by NAVFAC and further supported by NREL's net-zero renewable energy site assessment, a scenario can be envisioned where an additional 9% to 19% of the land or enclosed water of the island could be used to generate electricity from photovoltaic renewable generation. This would result in the ability to produce from 150 MW to 600 MW of electricity. This electricity would be enough to support the production of 60,000 to 243,000 gallons of fuel per day from CO_2 and H_2 in seawater. However only 320 MW of electricity is needed to support production of the 129,000 gal/day that is used on average at Diego Garcia.

The derivation of solar power generation from photovoltaic systems in a particular geographical location is dependent on a rather large number of variables (solar cell material, altitude, irradiance, ability to track the sun, etc.) that change the overall efficiencies of the systems [6,13]. Therefore it is only reasonable to ascertain a large range of power production for a given amount of area as proposed by NAVFAC for Diego Garcia (15 MW to 30 MW) and verified by NREL. Indeed the difference between the minimum and maximum power production proposed was based on the lowest efficiency solar panels versus the highest efficiency in industry. This large range in power production will greatly impact the footprint and cost, therefore final economic analysis for implementing a photovoltaic system capable of supplying 320 MW of electricity for the production of 129,000 gal/day of fuel needed at Diego Garcia.

NRL uses the solar irradiance for the area around Diego Garcia as a minimum of 5.0 $kWh/m^2/day$ [14-15]. Dividing this number by 24 hours in a day gives a power rating 0.208 kW/m^2 at 100% efficiency of the PV array. Typically PV arrays are approximately 16% to 25% efficient. To derive the lower value for NREL (15 MW on ~1% of Diego Garcia land area), we need to assume 26% efficiency of the solar panels.

Since 320 MW of power is needed to produce all the fuel at Diego Garcia, a ratio is used to derive the size of PV arrays as follows:

$$15 \text{ MW}/275{,}017 \text{ m}^2 = 320 \text{ MW}/x$$

$$x = 5{,}867{,}000 \text{ m}^2 = 5.87 \text{ km}^2, \text{ or}$$

$$x = 63 \text{ million ft}^2 = 2.27 \text{ miles}^2$$

This means we need approximately 5.87 km^2 of arrays that would take up 21.7% of the land mass on Diego Garcia. The cost of the arrays at $4.80/watt installed is $1.54 billion. Table 3 provides the cost breakdown of the various major components (solar PV arrays, the carbon/hydrogen production units, and the FT units) of the littoral land-based solar powered fuel process. These values are used in the estimated capital analysis of the process in Table 4. The total cost to produce 47,085,000 gallons a fuel a year would be $2,090,000,000. The operation and maintenance costs at 5% a year would be $104,500,000 at an expected lifetime of at least 25 years. The capital cost amortized over this 25 year period would be $83,600,000, for a final estimated fuel cost of $3.99/gallon.

While it may be feasible to utilize approximately 22% of the island for solar arrays, it is not necessarily a practical solution with respect to preserving and maintaining the island's ecology. Reports indicate that the eastern half of the island is a restricted zone that remains much as it was in the late 1800s and early 1900s (Figure 2) [8]. Visitors can obtain a pass to tour the remains of what was once a coconut plantation located on the East side of the island at East Point. As a result of limited land availability for this assessment, NRL has spent time investigating the use of Diego Garcia's 57 square mile lagoon (147 km^2) that could be home to floating structures such as barges or modular floats made from high density polymer HDP (Jet Dock and Versa Dock). These floats could support the entire solar PV array process and occupy only 4% to 6% of the lagoon depending on configuration with a minimum impact of the ecology of the lagoon and land. Interestingly enough these materials have a similar life expectancy to that of the PV arrays (~25 years). An additional row in Table 3 accommodates the capital costs associated with the HPD floats. Individual quotes from both companies indicate the cost will be roughly $\$100/m^2$ and that as the size increases the overall cost per/m^2 will be expected to decrease. In this analysis we used the worst case scenario of $\$100/m^2$. When this cost is accounted for in the second column in Table 4, the cost of the fuel increases from an estimated $3.99/gallon to $5.11/gallon.

3.2 Wind Renewable Generation On Diego Garcia

Since the island is situated 7 degrees south of the equator, its average yearly wind speed is 12.5 miles per hour [16]. This is just barely high enough to receive a Class II wind classification (200 W/m^2) as shown in Table 5 [17]. NREL's PTA team met with environmental and planning personnel to determine suitable locations for wind turbines. The locations were determined to be feasible for both 275 kW and 1 MW turbines [18]. While NREL is still in their preliminary state of determining the feasibility of wind vs PV, they have found that wind is more cost effective by a factor of 2 over PV and that wind is much easier to integrate into the electrical grid then PV [4].

NREL also proposed that the wind farm should be located at the south-eastern part of the island just after the u-bend in the island between the T-site and GEODSS Gate (Figures 1 and 2) [18]. The estimated NREL power from wind generation is between 15 to 19 MW. NREL is in the process of collecting on-site wind data using a Triton Sodar unit. This is far short of the 320 MW of electricity needed for fuel production on the island [18].

To achieve any significant wind power generation above 19 MW, NRL investigated the use of the commercial Vestas V164 wind turbines [19]. Each wind turbine has the maximum nameplate output of 8 MW. Given the class II winds, the maximum per Vectra generator on the island is 2.1 MW. These wind generators have rotor diameters of 164 meters and swept areas of 21,000 m^2 and are located on towers of about 100 m in height and about 50% conversion efficiency. Given the size of the generators, it is envisioned that they would be configured in a single row, 2 per kilometer (2 per 0.6 miles = 2 per 3000 feet), beginning approximately 2 to 3 kilometers south of the airstrip. Thus it is only possible to efficiently position up to 26 windmills for a total of 52 MW of electricity before the restricted area is reached.

Since the capital cost of the wind turbines is half that of the solar PV per Watt ($2.40/watt), the total cost installed would be approximately $125 million dollars [4]. A 2011 wind energy report from NREL estimates that a 200 MW land based wind turbine project containing 133 wind turbines each rated at a capacity of 1.5 MW would cost $419,000,000 or $2.10/watt [20]. Another more recent 2013 estimate from NREL suggests it would cost $2.64/watt [21]. Therefore NRL's costs in Table 4 assume a worst case scenario for the inclusion of wind turbines in the renewable energy matrix on Diego Garcia. Table 4 column 3 shows the estimated capital cost of the fuel after replacing 52 MW of the solar panels with windmills and leaving the entire solar array on land. This would reduce the size of the arrays from 5.87 km^2 to 4.9 km^2. The capital cost of the arrays on land would be reduced from $1.5 billion to $1.3 billion. The cost of the fuel would be reduced from $3.99/gallon to $3.76/gallon. If the arrays remained in the water the price of fuel would increase to $4.70/gallon. From these estimates it can be determined that the cheapest price per gallon of fuel would be obtained by maximizing the use of wind turbines and PV on the available island.

In this assessment, the possibility of putting wind turbines offshore was not consider due to the cost estimates that suggest that it is 2 times more expensive (~$5.60/watt) than land [21] and in some instances may be up to 3 times more expensive. These costs will most certainly be increased by the number of wind turbines that will be needed because Diego Garcia has wind speeds that are just high enough to receive a Class II wind classification (Table 5). This could also perhaps be the most ecologically problematic approach to renewable energy on Diego Garcia, as the turbines must be installed by pile driving them into the seabed.

3.3 Estimated Size of the Fuel Process on Diego Garcia

It is estimated that 573,000 m^3/day of CO_2 and 1400 m^3/day H_2 is needed for a synthetic hydrocarbon fuel process to produce 129,000 gal/day of jet fuel on Diego Garcia. Anticipated future large scale NRL carbon capture modules (18 gpm seawater) have been conceptually designed, scaled up, and configured on the basis of current NRL small carbon capture prototypes (process 0.5 gpm of seawater). The conceptual module design along with the pumps and the infrastructure needed to move the water were used to estimate the total square footage needed for the carbon capture process on Diego Garcia. NRL estimates the total size of the carbon capture process would be 285,000 ft^2 and the total volume would be 5,000,000 ft^3. To take into consideration the fuel process, an additional 570,000 ft^2 is needed at a volume of 17,000,000 ft^3. The entire process would take 855,000 ft^2 or 0.08 km^2 and a total volume of 22,000,000 ft^3. The significant increase in volume of the whole process is due to the height needed for the modular chemical reactors.

Approximately 0.3% of the land mass of Diego Garcia is needed to fit the entire carbon capture and fuel production part of the process. The modular nature of the chemical reactors and carbon capture modules mean that the square footage of the process could easily be configured to fit on the island near the south power plant or on the eastern side of the island near the transmitter site as shown in Figure 2. Figure 3 is a graphic depiction that illustrates how NRL would envision the entire fuel process configured on the island of Diego Garcia for to make the 129,000 gal/day needed for operations.

4.0 CONCLUSIONS

This analysis focuses on determining the size, cost, and configuration of a low carbon fuel producing process on the remote island of Diego Garcia. The amount of fuel (nearly 8% of all Navy operational fuel at sea) that is delivered and utilized on this island along with the extremely small land area, and potential environmental restrictions represent just a few of the many challenges of taking advantage of the renewable energy on the island for producing drop in low carbon fuel. This analysis provides a variety of scenarios that show it is possible to supply up to 100% of all the power and energy needs of Naval Support Facility Diego Garcia without importing any fuel for the foreseeable future. Furthermore, it is shown that through various potential combinations of renewable energy including land based wind, land based PV arrays, and floating PV arrays that this can be done with favorable economics for the Navy when compared to current FY14 FBCF. Finally, it is obvious that on all other potential land based littoral sites that the cost of siting, building, operating, and resulting cost/gallon of final fuel produced will be much lower than projected for Diego Garcia as an actual fuel producing site due to the fact that much higher proportions of wind energy can be utilized on the much larger land footprints

5.0 RECOMMENDATIONS

NREL and NAVFAC estimate that 15 to 30 MW of electricity, could be produced from PV on 1% of the island without restriction. NRL would instead propose to use this electricity as a first step toward demonstrating the feasibility of a fuel process on the island. The 30 MW of PV could be used to produce up to 12,000 gallons/day of the 15,000 gallons/day currently imported to supply power to Diego Garcia. This novel approach to storing renewable energy as a high energy density low carbon fuel would eliminate the costs associated with all the modifications needed to integrate any renewable energy into the existing grid on Diego Garcia. This type of demonstration would provide future policy makers with many more choices as to the future of naval energy resources.

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Figure 1: Image of Diego Garcia

Figure 2: Schematic of Diego Garcia

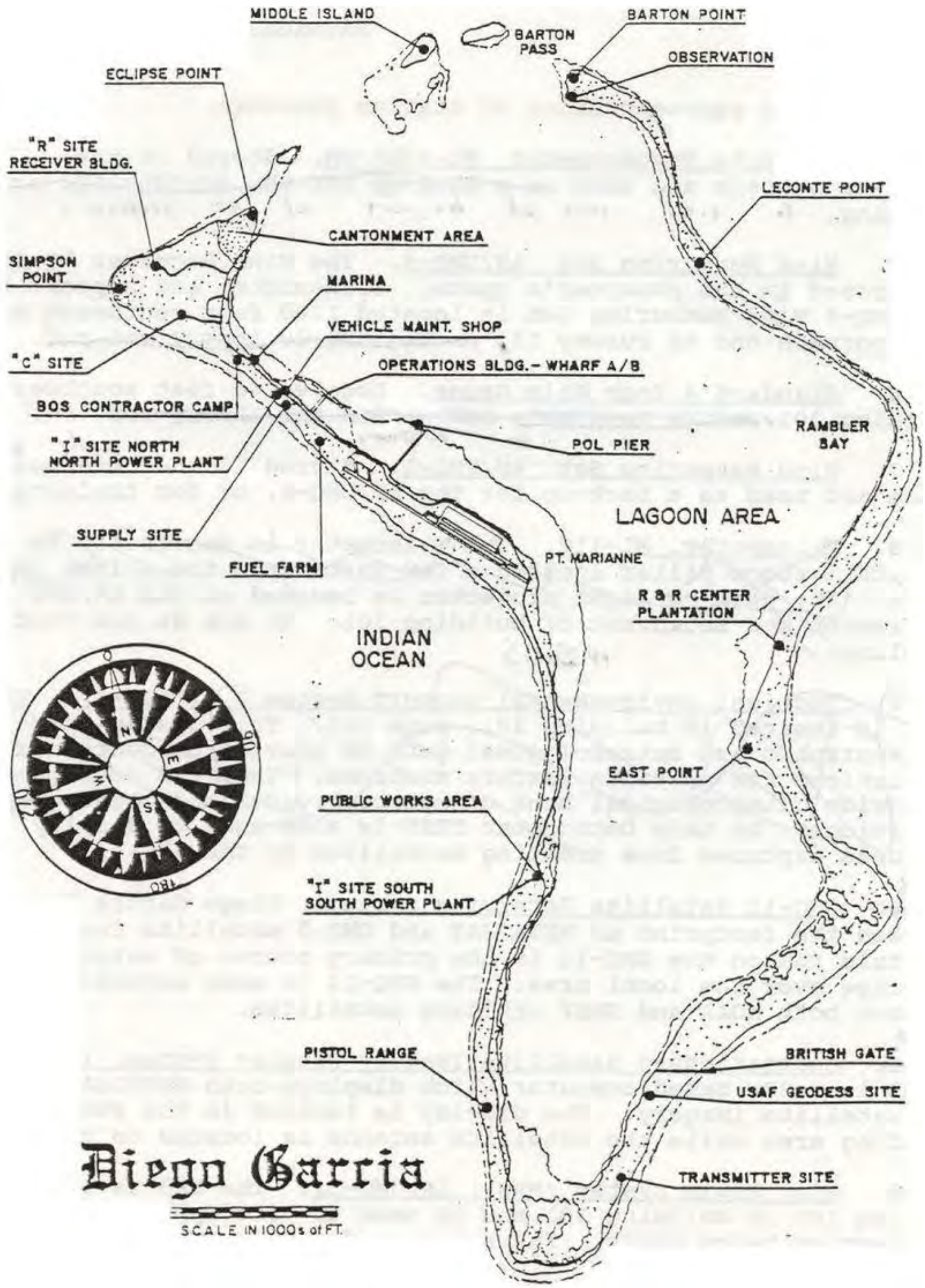

Figure 3: Graphic Depiction of Solar PV And Wind Renewable Energy Configured For A Fuel Process On The Island Of Diego Garcia

Table 1: Land and Sea Areas

Locations	**km^2**	**miles^2**
Land	27	10
Lagoon	147	57
Land + Lagoon	174	67

Table 2: Fuel Delivered and Used at Diego Garcia

Location of Fuel Used at Diego Garcia	**Type of Fuel**	**Amount of Fuel**	**FBCF FY14 ($)6.61**
Total Fuel Used to Supply Power to Diego Garcia	JP5	5.6 million gallons/year	$37 million
Total Fuel Used to Support Operations	JP5, F76, MUM, RME	41.4 million gallons/year	$273 million
Total Fuel Delivered to Diego Garcia	JP5, F76, MUM, RME	47 million gallons/year	$310 million

Table 3. Estimated capital cost of jet fuel synthesis process.

Plant Component	PV $4.80/w Wind $2.40/w
Capital Cost Solar PV Arrays	1,540,000,000
Capital Cost Carbon/Hydrogen Units (Jet Fuel)	330,000,000
Capital Cost of Fischer-Tropsch Unit (Jet Fuel)	220,000,000
Capital Cost Solar + Jet Fuel	2,090,000,000
Capital Cost of VERSA DOCK	$587,000,000
Capital Cost Solar + Jet Fuel + VERSA DOCK	2,680,000,000
Capital Cost of Wind Turbine (52 MW maximum)	124,800,000
Capital Cost of Solar + Jet Fuel + Wind Turbine	1,965,000,000
Capital Cost of Solar + Jet Fuel + VERSA DOCK + Wind Turbine	2,457,000,000

Navy Scenarios:
Table 4. Estimated cost of fuel produced by Navy PV array and/or wind processes.

Cost and Energy Requirements for Platform and Renewable Electricity/Jet Fuel process	**Navy 129,000 gpd Jet Fuel process by PV on Land**	**Navy 129,000 gpd Jet Fuel process by PV on Versa Dock**	**Navy 129,000 gpd Jet Fuel process by PV and Wind on Land**	**Navy 129,000 gpd Jet Fuel process by PV on Versa Dock and Wind on Land**
Capital Costs	2,090,000,000	2,677,000,000	1,965,000,000	2,457,000,000
Capital Cost Amortize 25 years @ 0% per year	83,600,000	107,080,000	75,592,000	98,272,000
Operation and Maintenance @ 5% per year	104,500,000	133,850,000	98,240,000	122,840,000
Capital Costs + O&M per	188,100,000	241,000,000	177,000,000	221,000,000
Output	320 MW	320 MW	320 MW	320 MW
MWhr @ 1day	7,680	7,680	7,680	7,680 MW
MWhr @ 365 days	2,803,000	2,803,000	2,803,000	2,803,000 MW
Operational days per year	365	365	365	365
Gallons of Synthetic Fuel per day	129,000	129,000	129,000	129,000
Gallons of Synthetic Fuel per year	47,085,000	47,085,000	47,085,000	47,085,000
Total Cost	$3.99/gallon	$5.12/gallon	$3.76/gallon	$4.70/gallon

*A system life of 25 years and built by budgeted tax dollars (not borrowed)

Table 5: Net Usable Name Plate Energy Definitions from NREL/DOE for Wind Generators

Wind Power Class	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density (W/m^2)	Speed m/s (mph)	Wind Power Density (W/m^2)	Speed m/ (mph)
1	0 - 100	0 - 4.4 (0 - 9.8)	0 - 200	0 - 5.6 (0 - 11.4)
2	100 -150	4.4 - 5.1 (9.8 - 11.5)	200	5.6 - 6.4 (12.5 - 14.3)
3	150 - 200	5.1 - 5.6 (11.5 - 12.5)	300	6.4 - 7.0 (14.3 - 15.7)
4	200 - 250	5.6 - 6.0 (12.5 - 13.4)	400	7.0 - 7.5 (15.7 - 16.8)
5	250 - 300	6.0 - 6.4 (13.4 - 14.3)	500	7.5 - 8.0 (16.8 - 17.9)
6	300 - 400	6.4 - 7.0 (14.3 - 15.7)	600	8.0 - 8.8 (17.9 - 19.7)
7	400 - 1000	7.0 - 9.4 (15.7 - 21.1)	800	8.8 - 11.9 (19.7 - 26.6)