Seasteading Energy Study:

Evaluation of Sustainable Energy Options for a Small City-on-the-Sea

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June 15, 2012

Our Mission: To further the establishment and growth of permanent, autonomous ocean communities, enabling innovation with new political and social systems.

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Seasteading Report

Energy Study

Abstract

The purpose of the Seasteading Institute is to promote the establishment of permanent, autonomous communities in the ocean in order to develop a new generation of governance. The purpose of this document is to estimate and compare the energy costs in USD/kW and installation cost for ocean thermal energy conversion, solar, wind, and wave systems. Diesel generators were used as a baseline comparison. While it is not yet possible to design a specific seastead, the goal is to determine the feasibility of utilizing the aforementioned renewable energy sources on a seastead housing up to 1,000 people. While diesel energy costs roughly $0.46/kWh, ocean thermal energy conversion (OTEC) costs $0.75-$1.00/kWh. Unsubsidized solar power costs $1.10/kWh and wind power costs $0.18-$0.20/kWh depending on the location of the wind turbine.

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Introduction

The Seasteading Institute was founded to establish new autonomous communities in the open ocean as a means of developing new governments with political and social systems different than that of the United States and other countries. Due to the growth of offshore industry over the past 50 years, there are already several methods of living at sea. This research was initiated to design a more permanent living space in comparison to houseboats, offshore drilling rigs and cruise ships.

There are many challenges in forming a permanent community on open waters. This paper will address the issue of generating and storing energy through the use of renewable resources. Being located on the ocean offers several renewable energies that have not typically been utilized on a large scale without subsidies.[1] One exception to this is offshore wind farms, which are becoming increasingly popular in Europe. These sources include tidal and solar power. Subcategories of solar power include wind, wave, ocean thermal energy conversion (OTEC), and photovoltaic power. The feasibility of using these resources depends greatly on the location of the seastead. A location study done by the Seasteading Institute has analyzed ideal locations based on political and economic climates, wind speeds, temperatures, and other factors.[2] Based on these weighted variables, the location was narrowed down to coastal regions off the U.S., southwest of Japan, the Baltic Sea, Portugal, and the Sydney region of Australia.[2] Estimates for wave heights, water temperatures, sun coverage, and average wind speeds will be based on these locations when calculating energy productions.

One concern that must be taken into account when determining the feasibility of new energy generators is environmental effects. While OTEC may be capable of producing massive amounts of energy even with an efficiency of 3%, it can also result in water temperature changes that affect the local flora and fauna.[3] Methods of mitigating these harmful effects will be explored to make the seastead as green as possible.

In addition to being safe, the energy generators must also be capable of powering a retired oilrig that can house up to 1,000 people. 40% of the available space will be designated for common areas. It is assumed that at most, the energy load per person is 4.5 kW.[4] On land, people use on average 2.25 kW. With 1,000 people, the power needed is 4.5 MW. To accommodate for any error in this estimate, the cost reported for each energy system will be based on 5 MW plants.

1 Diesel Power – Baseline Conditions for Comparisons

While diesel fuel combustion is not renewable or green, the option is explored here because it might be the most economical and it serves as a basis for comparing the cost per kWh of different energy sources.

1.1 Background

Diesel generators combine a diesel engine with a generator to produce electricity from diesel fuel. Ships often use diesel generators for auxiliary power and also for propulsion. The engine combusts diesel fuel, and this stored chemical energy is converted into mechanical energy. This mechanical energy forces electric charges through the wires of the generator, thus creating a current.

1.2 Calculations and Assumptions

The cost of diesel fuel for a seastead was estimated at $6/gal[1]. This accounts for the cost of the fuel plus the delivery to the seastead.

The lifetime of a generator was taken as 10 years, after which time the generator is resold at some salvage value and a new one is purchased. The yearly maintenance of the generator was taken at 10% of the capital cost.

Caterpillar sells 1010 kW generators, so calculations are based off of five generators with an efficiency of 37%. With an energy density of 39.6 MJ/L,[5] the fuel consumption necessary for generating 5.05 MW is 0.34 L/s. Calculations can be found in Appendix A and the specification sheets for the generator can be found in Appendix B. The cost of diesel electricity estimates at $0.46/kWh.

2 OTEC

Ocean thermal energy conversion (OTEC) is a method by which the natural temperature gradient in ocean water is used to produce energy.

2.1 Background

The concept utilizes a closed Rankine cycle to produce work from the natural 20-25K temperature difference between the ocean surface and deep ocean water. In a closed system, the warmer waters can be used to vaporize pressurized ammonia through an evaporator. This vapor powers a turbine, which generates energy.[3] The cold water from deeper water levels condenses the vapor. In an open system, the surface water is flash-condensed in a vacuum chamber. The vapor is used to power a turbine, and then condensed by the cold seawater.[3] A third option is the hybrid system. Diagrams of the three cycles are shown below.

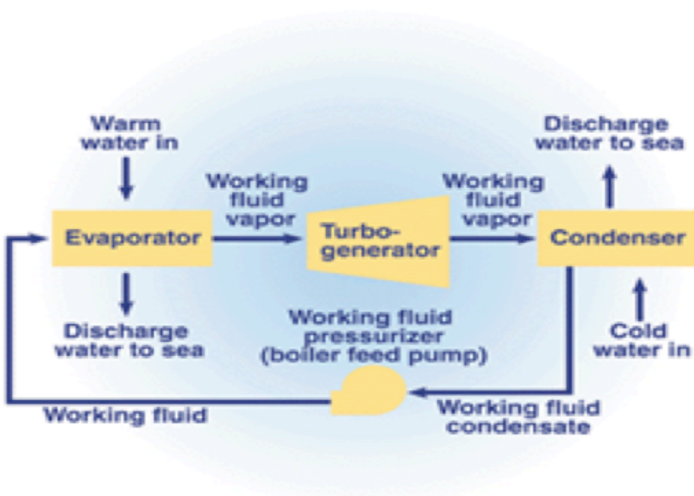

Figure 1: A closed-cycle OTEC plant [6]

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[1] Estimate decided collectively during discussion with George Petrie.

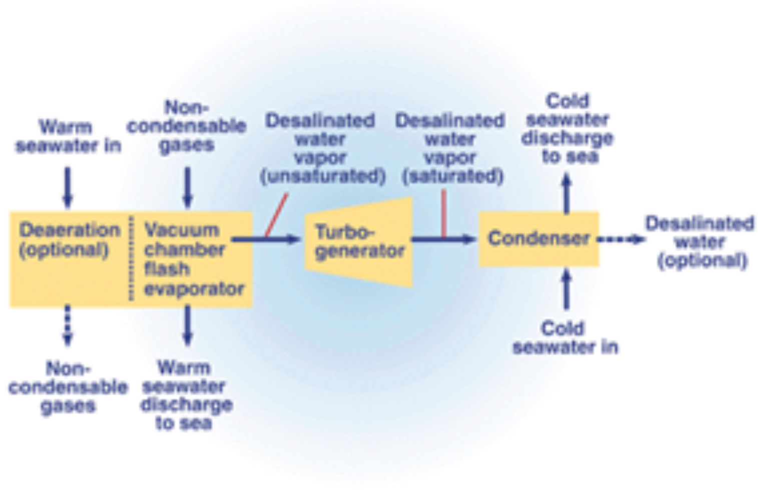

Figure 2: An open-system OTEC plant [6]

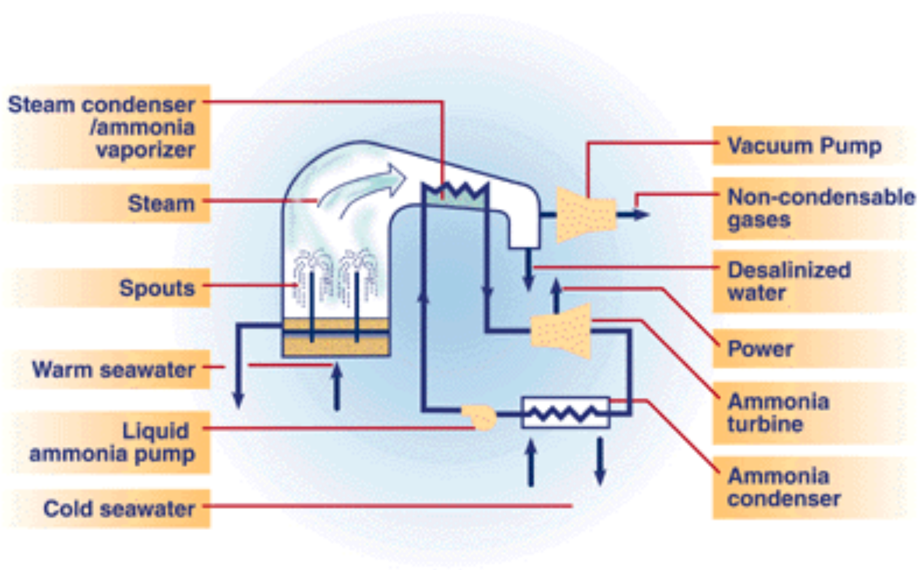

Figure 3: A hybrid OTEC system [6]

One advantage of using OTEC is that it offers a more stable source of energy than wind, solar, or wave power.[7], [8] The process can run continuously and does not require an energy storage system. The cold water stream can also be incorporated into an air conditioning system, whereby the cold water is directed through the walls of buildings so that the excess heat is transferred to the water, thereby cooling the buildings. It also has the potential to replace refrigeration systems.

Another advantage is that in an open system, a byproduct is desalinated, potable water. The final condensed stream is potable and can be used as drinking water and can reduce platform expenses for fresh water production.[3], [8], [9] The deep-sea water is often nutrient and organism-dense. Drawing up these organisms and nutrients can have a damaging effect on the environment and deep-sea ecology and at the same time could foul the pipes of the plant if chlorine isn't used to prevent it. The cold water discharge (if not used for air conditioning) could also change the water temperature and lead to coral bleaching or other environmental effects. However, the nutrient-dense water can also be used to cultivate crops like lobster, microalgae, and abalone for food and nutritional supplements.[7]

Pilot-scale OTEC plants have performed well, but have yet to be successfully scaled up to a commercial size due to the capital costs and technical problems.[7] Currently, there is a 120 kW OTEC plant on the island of Nauru (Micronesia, South Pacific). The net power output is 30 kW.[7] Hawaii has a mini-OTEC plant with a net output of 18 kW and a second land-based plant with a net output of 103 kW.[7]

2.2 Calculations and Assumptions

Like most renewable energy systems, OTEC requires a costly initial investment. Luis Vega has done extensive research on the implementation of OTEC, including a cost analysis as shown in Figure 4. [3] The graph shows that the cost per kW decreases as the size of the plant increases, meaning that OTEC could be a more competitive option for a larger seastead with greater energy needs. For OTEC to be competitive with conventional energy sources, Vega predicts that for a nominal OTEC plant size of 1 MW, diesel fuel costs need to be above $45/barrel and water expense needs to be above $1.60/m^3. The installation cost for a 5 MW OTEC plant ranges from $300 million to $400 million. This does not take into account the 1% annual maintenance and operating costs [4] or the savings on potable water needs to offset these costs. For the pre-commercial scale 5 MWe plant designed by Luis Vega [3] in Figure 5, 2,300 m^3 of desalinated water can be produced daily.

For a 5 MWe plant with a 20 year lifetime and taking into account depreciation and operating costs, electricity would cost $0.75/kWh based on the lower limit of a $300 million capital investment and not including savings for potable water recovery. For the upper limit of a $400 million capital investment with no potable water recovery, the estimated cost of electricity is $1.00/kWh. Replacing on-board potable water needs at $0.40/m^3 (the cost of current tap-water in parts of the U.S.) would not bring the cost of electricity down. However, compared with the cost of bottled water valued at $1/gal ($264/m^3), then the net savings to the seastead would be

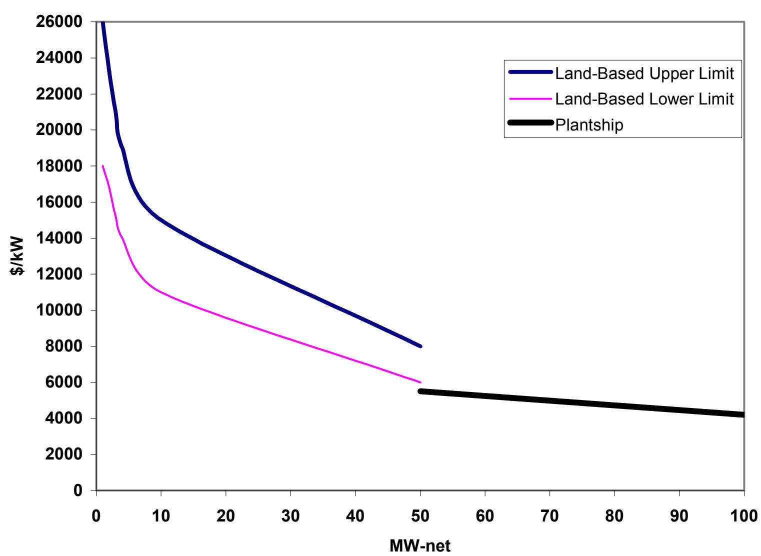

Figure 4: Estimates of capital cost for a single stage OTEC plant [3]

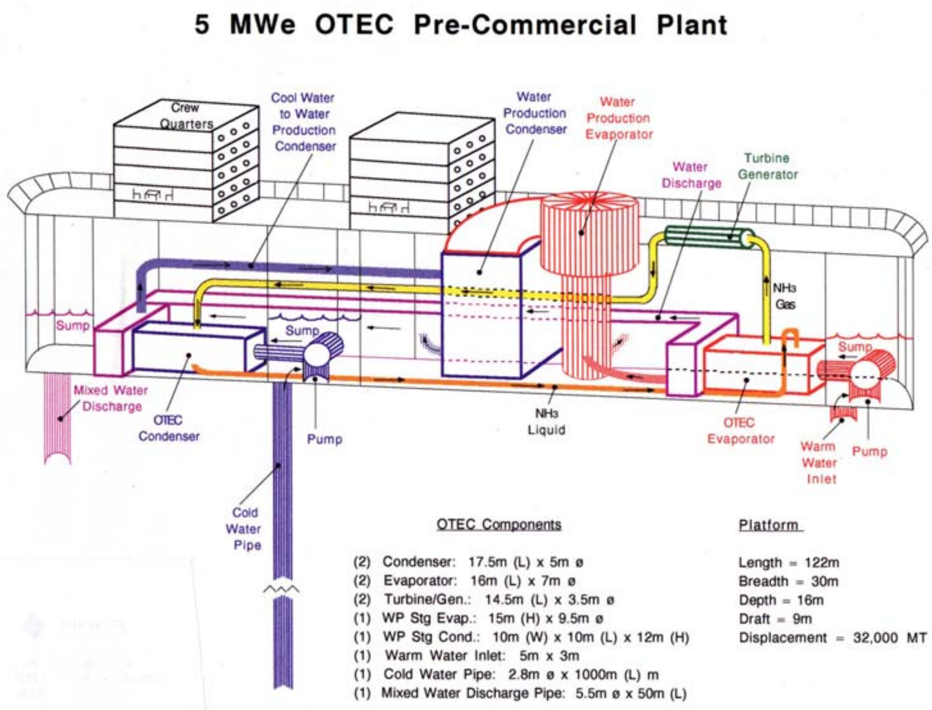

Figure 5: A 5 MW OTEC power plant [3]

roughly $220 million per year. Calculations are shown in Appendix D.

2.3 Conclusions and Recommendations

While OTEC may seem promising as an energy source for a seastead, its use is limited by the location of the plant. To generate more power than is consumed by the pumps, evaporators, etc., the temperature difference between the warm and cold streams must be at least 20°C. The locations meeting this criterion are shown in Figure 6.

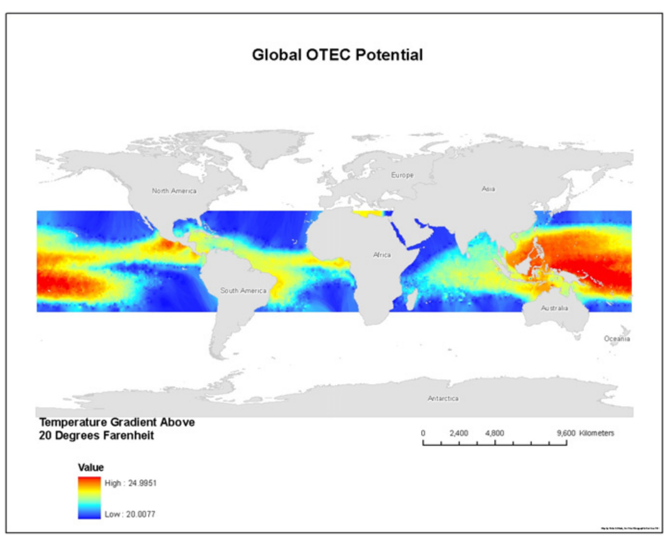

Figure 6: Temperature gradients above 20 C [7]

A major setback is capital cost, but as oil prices and concern for the environment grow, it may be more viable as an alternative energy source for seasteads, remote locations, and developing islands.

3 Photovoltaic Power

Harvesting energy through the use of photovoltaic energy is becoming increasingly popular as the search for a future global energy source continues. Recently, advancements have been made in photovoltaic technology that increase the efficiency of solar cells while decreasing the production costs.

3.1 Background

Solar energy can be converted into electricity by concentrated solar power (CSP) or by photovoltaics (PV). CSP is the use of lenses and mirrors to concentrate light into an intense beam. PV creates an electric current using the photoelectric effect. A solar panel consisting of solar modules uses semiconductors to generate a voltage. When light strikes the surface of the cell, it causes electrons in the semiconductor to jump from a valence energy band to a conduction band, causing the excited electrons to become free charge carriers, as shown in Figure 7.[10] These free carriers become the current in an electrical circuit, while leaving a hole in their places. When p-type and n-type semiconductors are in contact, an electric field is created. The electrons move in the opposite direction of the holes created, thus a current is created from light energy.

These solar cells are currently being used in people's homes and satellites, with predictions for increased use in the future. The efficiency of solar cells is can be calculated using Equation 1:

$$\eta = \frac{P_{electricity}}{P_{light}} \quad \text{Eq. 1}$$

where $P_{electricity}$ is the power generated by the solar cell and P_{light} is the power from the light source.

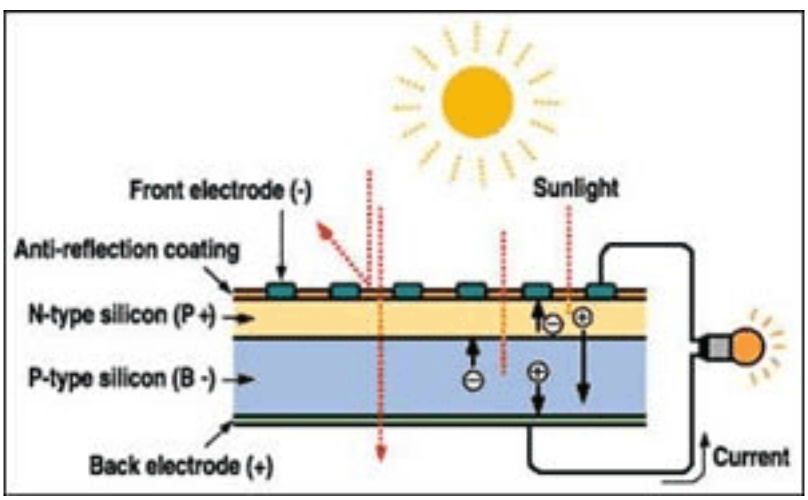

Figure 7: A photovoltaic cell [10]

Solar panels are becoming common on private properties as people look for greener methods of energy production. PV cells produce clean energy with no bi-products or waste and solar power is inexhaustible. While the input (sunlight) is free, the panels are expensive. For private homes and businesses, the cost of installing solar panels can be offset by tax incentives. However, the source of energy is not reliable in many areas and if there is no backup power source, then energy storage systems are another necessary expense.

There also exist several commercial-scale solar power plants in the U.S. according to the Solar Energy Industries Association. More than 23,000 utility-scale plants up to 2,700 MW in size are under development while over 1,300 plants up to 75 MW are currently operating.[11]

There are several different types of solar panels available today. The most efficient is a 43.5% efficient concentrated PV cell made by Solar Junction.[10] While efficiency of PV cells is increasing, these have yet to be produced on a large scale. Mono-crystalline silicon panels are currently the most efficient panels at converting sunlight into electricity on the market at roughly 25%.[11] Polycrystalline silicon panels contain less silicon, making them less efficient at 20.4%, but cheaper to produce. Thin film solar panels are made by depositing thin layers of photovoltaic material such as copper indium gallium selenide (CIGS) or gallium arsenide (GaAs) onto a substrate. While less efficient than silicon, the cost of thin film technology is decreasing each year.

3.2 Calculations and Assumptions

The calculations presented below are based on quotes on monocrystalline silicon panels from Helios Solar Works of Milwaukee, WI, a company already manufacturing panels on a large scale. The specifications for their 420 W 9T6 series panels can be found in Appendix E. It should be noted that with advancing technologies, the cost of solar power is predicted to be $0.06/kW-hr by 2020[12]. Efficiencies have reached 43.5% and are continuing to rise while manufacturing costs drop.[13]

It should also be noted that there are roughly five peak hours of sunlight per day in the Caribbean, which was used as a basis for the calculations.[14] These peak hours do not necessarily correspond to the peak hours of energy consumption, so some sort of storage system must be implemented. Different storage options are explored later, but the cost of those systems is not included in the cost of solar energy calculated here.

It is also important to note that the efficiency of the solar panels decreases with temperature. This effect may be detrimental if the panels are used in the Caribbean where the surface temperatures are higher (ca. 35°C). This is due to the temperature dependence of the charge carrier density *n*, where n^2 is proportional to the temperature cubed:

$$n_i^2 = BT^3 \exp\left(-\frac{E_{G0}}{kT}\right) \qquad \text{Eq. 2 [15]}$$

B is a constant dependent upon the material of the semiconductor, E_{G0} is the bandgap of the material linearly extrapolated to absolute zero, *k* is a constant, and *T* is the surface temperature. This is why at the nominal operating cell temperature (NOCT) the power rating of the panel is only 320 W. The NOCT is the surface temperature when there is a wind speed of 1 m/s, 800 W/m^2 insolation, and an ambient temperature of 20°C.[16] Under these normal operating conditions, the surface temperature is 45°C.

The input power, or P_{light} from Eq. 1, is calculated from the following equation:

$$P_{light}[kW] = Irr\left[\frac{kWh}{m^2 day}\right] * A[m^2] * \frac{1}{5}\left[\frac{day}{hr_{sun}}\right] * \eta \qquad \text{Eq. 3}$$

The solar irradiance in Aruba with panels pointing south is on average 6.8 kWh/m^2day.[17] With a 420 W-rated solar panel with a surface area of 2.6 m^2 and efficiency of 15%, the input power is 540 W, which is greater than the power for which the panel is rated Therefore, the number of panels that can fit on a 400’x400’ seastead was multiplied by the power rating of 320 W to obtain a power plant size of 1.8 MW. Calculations can be found in Appendix D.

The maximum power rating of the plant (assuming sunny conditions) is 1.8 MW, which is collected over the peak hours of sunlight per day. Assuming there are 1825 hours of sunlight per year (or 5 hours per day), the capacity of the plant is 3330 MWh/yr. Factoring in the cost of DC to AC inverters, installation costs of $5/W (quoted by Puget Sound Solar), electrical systems, and automation over a 20-year lifetime, the average total cost per year is roughly $1.9 million.

The resulting cost of solar electricity is $1.11/kWh. This is roughly five times the cost of electricity in the United States. While the cost should decrease as the cost of solar panels decreases, this does not include the additional expense of an energy storage system. It should also be noted that at most, 1.8 MW of energy can be generated in the space available on the seastead. Another platform with more solar panels would increase the initial capital investment and require more maintenance.

3.3 Conclusions and Recommendations

One option to improve upon the design is to buy solar panels that track the path of the sun. This will increase the hours of peak sunlight, which can also decrease the cost. Outlined in section 6.2 is the possibility of using organic, flexible, transparent solar panels in place of glass on the seastead. While inefficient, these panels are lightweight and can make efficient use of available space on the seastead.

4 Wind Power

Wind power is a rapidly expanding form of renewable energy. The installed global wind capacity is increasing exponentially each year as more countries invest in this abundant energy source. Offshore windfarms are also becoming more widely used as advancements in offshore engineering are made. Offshore turbines mitigate the problems of the noise and aesthetics that land-based wind farms bring. Germany has been developing offshore wind farms since March 2011.

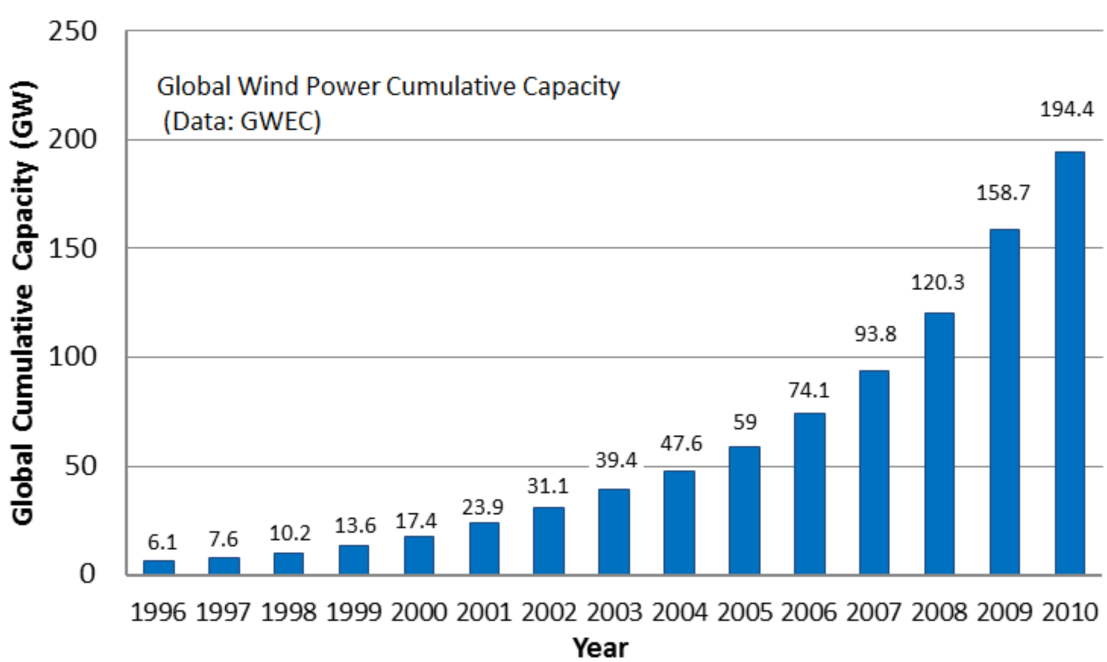

Figure 8: Installed Global Wind Power Capacity [18]

4.1 Background

Wind can be used to drive a turbine and create electricity from mechanical energy. Wind is the result of a thermal gradient caused by solar radiation. When a volume of air is heated, it rises, leaving a gap that is quickly filled by cooler air. This cooler air is wind. When the wind pushes a blade of a turbine, it is converting kinetic energy into mechanical energy.

This paper will explore the costs of horizontal axis wind turbines (HAWTs) as opposed to vertical axis wind turbines (VAWTs). The VAWT is similar in shape to the Gorlov Helical Turbine outlined in Section 6.1. It can operate with wind in any direction at lower average wind speeds while producing less noise and fewer vibrations as a HAWT. However, a VAWT requires twice the amount of space as a VAWT to generate the same amount of power. Since space is of concern on a seastead and because HAWTs are more commonly manufactured, costs and calculations are based on HAWTs.

Wind power is currently one of the most expensive forms of energy available. Until wind turbines can become competitive with fossil fuels in another 15 years, they require government subsidizing for development. Despite this, offshore wind is a new technology becoming more widely used in Europe. Typically, custom-made ships are used to install the turbines, where the steel pile is driven 20 m into the seabed in waters up to 30 m deep. New proposals for floating turbines have been developed for use in deep waters, as shown in Figure 11.[21] Not all of the proposed structures have been thoroughly tested. Only three floating offshore wind turbines have been in existence as of 2011.

Figure 9: A VAWT [20]

Figure 10: A Hyundai HAWT [19]

Blue H Technologies of the Netherlands installed an 80 kW floating turbine 21 km off the coast of Italy. It collected test data for a year before it was decommissioned, though it was never connected to the grid.[22] Similarly, SeaTwirl installed a grid-connected floating turbine off the coast of Sweden, which collected preliminary data for a year before being decommissioned. Hywind installed a floating 2.3 MW Siemens turbine off the coast of Norway in 2009.[22] It is still functional, although the costs associated with the turbine, deployment, and 13 km long transmission cable came to $62 million.

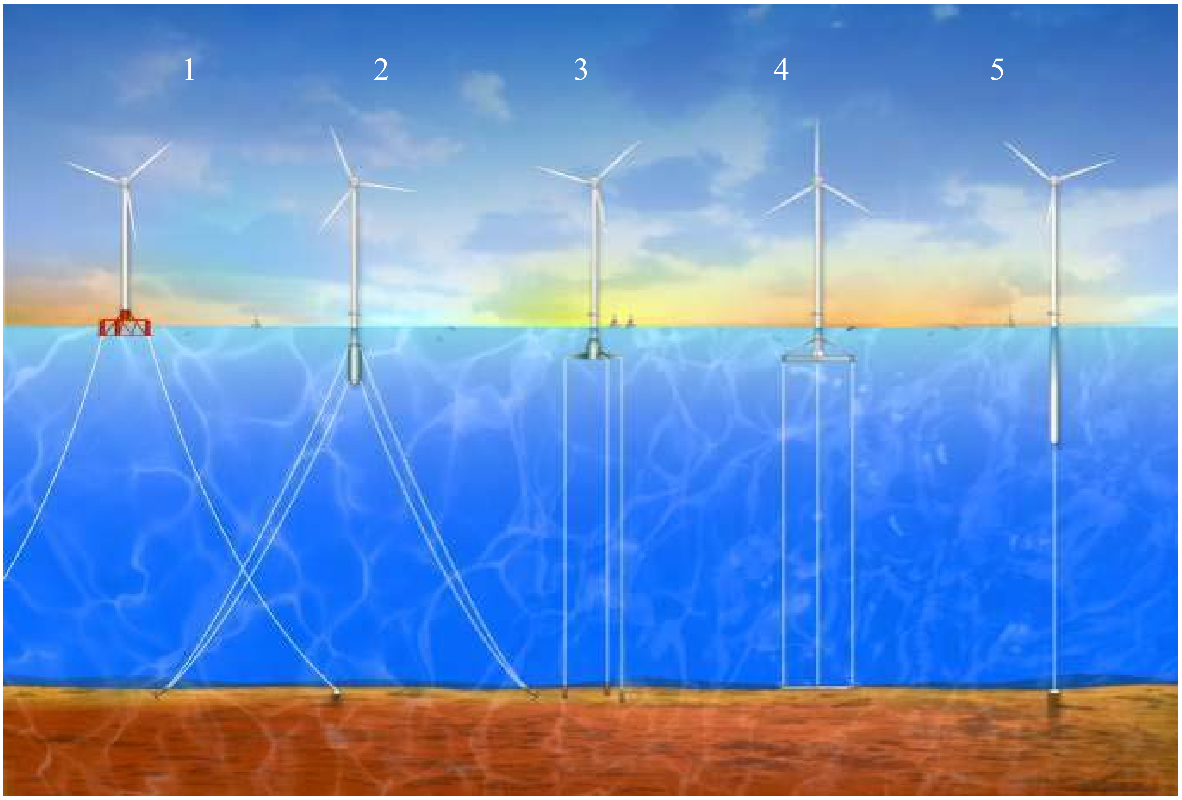

Figure 11: (1) Semisubmersible Dutch tri--floater; (2) spar buoy with two tiers of guy wires ; (3) three-arm mono-hull tension-leg ; (4) concrete TLP with gravity anchor; (5) deepwater spar [21]

4.2 Calculations and Assumptions

As mentioned above, the cost of installing one floating turbine costs $62 million. Adding in the depreciation and yearly operating and maintenance costs (1% of the fixed capital investment) over a 20 year lifetime, the cost of electricity is $5.01/kWh if the turbine produces 9 GWh. However, the installation cost per kW for large projects decreases as the size of the project increases as it does for OTEC, and with this particular project there were additional engineering challenges to be addressed. This estimate does not accurately predict what the cost of wind power is.

The power generated by a wind turbine is given by:

$$P = \frac{1}{2}\rho A v^3 C_p \qquad \text{Eq. 4 [23]}$$

The power is in units of Watts, ρ is the density of air in kg/m^3, *A* is the swept area based on the length of the blades in m^2, *v* is the wind speed in m/s, and C_P is the capacity factor of the turbine. At most, the capacity factor is 59.3%, otherwise known as the Betz limit.[23] This has to do with the nature of the wind turbine and losses due to wind passing through the turbines or pooling in front of the turbine. In reality, the efficiency of the turbine itself must also be taken into account, and the capacity factor will be closer to 30%.[23] Based on this equation, the power produced by a turbine is heavily dependent on wind speed, and therefore location. Because the wind does not blow at a constant rate 24 hours per day, a net export of 38% was used for calculations to account for when the wind is not blowing.

If 5 MW are needed, then the rated installed capacity with a 38% net export should be 13.2 MW. United Kingdom offshore wind studies estimate the cost of offshore wind to be between $4700 and $5790 per kW rated installed with operating costs at $123k per MW per annum. Based on these estimates, the cost of offshore wind is roughly $0.18-$0.20/kWh.

4.3 Conclusions and Recommendations

Like OTEC and solar systems, using wind turbines would also limit the locations of the seastead. A study done at Stanford University on global wind speed at 80 m shows that the places were wind speed averages are above 9.4 m/s are the Arabian Sea, near Georgetown in the Atlantic Ocean, off the coast of Argentina, near Antarctica, and the North Sea.[25] There is some flexibility with location due to the dependence of wind speed on the blade length of the turbines. Choosing an appropriate turbine size can increase the power obtained.

Another concern is that installing a wind turbine to the seastead itself would require mooring. With the force of the wind on the turbine, the extra energy required for dynamic positioning might outweigh the benefits of using wind. The vibrations and sound from the turbines may also make living uncomfortable on the seastead. The sight and sound of turbines has made it difficult for companies to get permits for installation near residential areas for this reason.

Since the wind is not always blowing and because there is no grid to store excess energy produced, an energy storage system is required to store energy from peak hours for later use. The other option is to fuel the turbine with diesel fuel during off-peak hours to keep the turbine running continuously. This has been done in one of Germany's recent offshore wind projects, although residents of a nearby island are complaining of the smell diesel fumes.

Like solar power generation, floating wind power generation requires more development before it can be considered a cost-efficient energy source for seasteading.

5 Energy Storage

There exists a need for alternative energy sources today to replace the use of fossil fuels. While renewable energies such as solar and wind power are clean, one drawback is that these sources are not available 24 hours per day in that the sun does not always shine and the wind is not always blowing. The energy sources also do not always respond to changing energy demands quickly. To overcome this problem, an energy storage system is necessary.

5.1 Pumped-storage Hydroelectricity

Pumped-storage hydroelectricity is a method of storing energy through the conversion of gravitational potential energy to electricity and vice versa. As shown in Figure 12, water is pumped from a low-level reservoir when there is surplus electricity being generated to a higher reservoir.[26] When the demand for energy exceeds the energy available from the renewable energy source, the water is released from the high reservoir back to the low reservoir and drives a turbine to meet this demand.

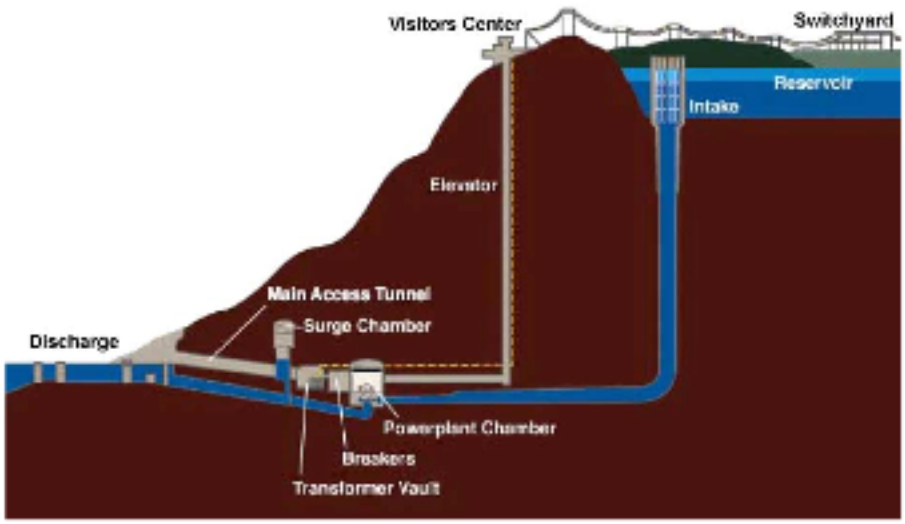

Figure 12: Pumped-storage hydroelectricity plant**[16]**

This storage system has been implemented in several areas, as shown in Table 1. While most produce over a gigawatt of power, the plants typically utilize natural height differences between large, natural bodies of water.

Table 1: Pumped-storage hydroelectricity plants in the U.S.[27]

Name	Location	Year	Capacity (MW)
Muddy Run Pumped Storage Facility	Drumore Township, PA	1966	1071
Northfield Mountain Station	Northfield, MA	1972	1080
Ludington Pumped Storage	Ludington, MI	1973	1872
Blenheim-Gilboa Pumped Storage Power Project	North Blenheim, NY	1973	1160
Jocassee Pumped-Storage Generating Station	Pickens County, SC	1973	610
Raccoon Mountain Pumped Storage Plant	Marion County, TN	1978	1532
Bath County Pumped Storage Station	Bath County, VA	1985	2772
Bad Creek Pumped-Storage Generating Station	Oconee County, SC	1991	1065
Rocky Mountain Hydroelectric Plant	Rome, GA	1995	780

A potential platform for the seastead is an oil drilling platform. These platforms are stabilized by four large columns in each corner roughly 30.5 m long and 9.1 m in diameter.18.3 m of the column are submerged in water. We examined below a suggestion to utilize these columns for pumped-storage hydroelectricity systems inside them.

5.2 Calculations and Assumptions

It is assumed that the reservoir tanks are cylindrical in shape with a 9.1 m diameter. The height difference is 30.5 m and the water temperature is 20°C with a 3.5% salinity, giving it a density of 1025 kg/m^3. Assuming the tanks are installed on top and bottom of the column (and therefore not using any of the 30.5 m available), then using 10 m high tanks seems reasonable.

Using a simplified Bernoulli equation, we find that the potential energy available is:

$$PE = \frac{\dot{m}\, g \Delta h}{g_c} \qquad \text{Eq. 4[28]}$$

Therefore, the total potential energy from one column is 298m J/kg. The mass flow rate depends on the power from the pump, which is powered by the renewable energy source such as solar panels or wind turbines.

A water turbine has a required power equal to:

$$P = \frac{\dot{m} g h}{\eta} \qquad \text{Eq. 5[29]}$$

where h is the pump head in m, and is equivalent to the height of the column. η is the pump efficiency, and is 80% for the purpose of these calculations. Since not all energy must be stored due to decreased energy between midnight and early morning, P is 0.5 MW per column. With these numbers, the mass flow rate possible is 1300 kg/s. Plugging this mass flow rate into Eq. 3, the potential energy per column is 0.4 MW, for a total energy storage of 1.6 MW. The calculations are shown in Appendix H.

1.6 MW assumes that the water can flow constantly. While this might be true for facilities with large reservoirs, this setup is limited by the size of the water tanks. With a height of 10 m and a diameter of 9.1 m, the mass of water in the system is 666 tonnes (1 tonne =1,000 kg). At the flow rate of 1300 kg/s, this tank would empty in just over 8 minutes, giving 200 MJ of energy per column. Assuming that this is then consumed at 5 MJ/s (or 5 MW), this would only last 40 seconds. In addition, the energy density is only 300 J/kg in comparison to 47 MJ/kg from gasoline or 9 MJ/kg from a lithium battery.

5.3 Conclusions and Recommendations

While this energy storage method could be easily implemented, its low energy density makes it a very expensive and inefficient method of storing energy. If pumped-storage hydroelectricity is used, a much larger volume of water is necessary to provide sufficient energy.

6 Possible Alternatives

Other alternative technologies exist for generating energy from renewable resources. This section reviews several more promising alternatives.

6.1 Gorlov Helical Turbine

The Gorlov helical turbine (GHT) is a water turbine developed by Alexander Gorlov.[2] As shown in Figure 5, the blades of the turbine are unique in that they are shaped like a double helix. The design is meant for free flowing, low head water in rivers, straights, ocean currents, discharge from dams, and tidal currents.[30] While the turbine produces clean energy and can be easily scaled to meet energy needs, the water must be flowing at at least 1.5 m/s. On the open ocean, currents reach these speeds only in the Gulf Stream. However, this location is not ideal for a seastead due to the choppy waters.

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[2] Professor Emeritus and Director of Hydro-Pneumatic Power Laboratory at Northeastern University in Boston, MA

One benefit to the GHT is that the power increases as a function of the water flow raised to the third power while the efficiency stays constant.[31] It is also a source of hydroelectric power that does not cause flooding or kill fish. In 2007, the estimated cost for a hydropower plant using GHT in Virginia would provide power at $1,500 per kW, which is the same cost as Danish wind turbines.[32] The cost greatly depends on the average velocity of water flowing through the turbine.

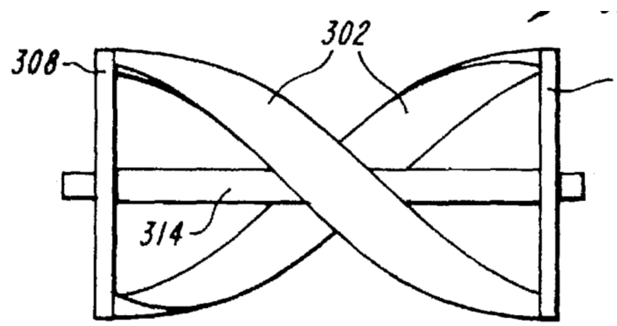

Figure 13: Gorlov Helical Turbine**[33]**

6.2 Organic Power Plastic® Photovoltaic Panels

Konarka Technologies of Lowell, MA has developed an organic, thin, flexible, transparent solar panel that may be viable for use on a Seastead as they are made more efficient. While operating efficiencies are only in the single digits, the panels convert energy over longer hours than a typical silicon panel. They are also cheaper in $/kg, although not in terms of $/W. The advantage of using these panels is that they can coat windows and buildings, not only maximizing the use of space, but also keeping buildings cooler by absorbing solar irradiance.

6.3 Wave Power

Wave power is another potential option for the Seasteading Institute, as was reported in *Floating Breakwaters and Wave Power Generators* by Elie Amar and Jorge Suarez. Generators have been developed to convert wave energy into electricity through the use of attenuators, point absorbers, or terminators since the square of the amplitude of a wave is proportional to the energy stored in the wave.

Attenuators, or hinged control devices, float atop and ride waves. Point absorbers are also floating devices that sit on the surface of the water where the energy density is the highest. They are tethered to the ocean floor and collect energy from waves moving in any direction by converting the relative movement between the water surface and ocean floor.

Terminators are devices that physically intercept waves through their orientation perpendicular to the waves. Terminators are typically used onshore or near shore and work by absorbing or reflecting wave power, which is given in Eq. 6:

$$P = \frac{\rho g^2}{64\pi} H_{m0}^2 T \qquad \text{Eq. 6}$$

Here, P is the energy flux of the wave per unit of wave-crest length, ρ is the density of water, g the gravitational acceleration constant, H_{m0} is the wave height, and T is the period of the wave.

While there exist thousands of patents for devices that harvest wave energy, only several are currently showing promise for commercial scale use.

7 Conclusions and Recommendations

Table 2 summarizes the estimates made for diesel, OTEC, solar, and wind power in this paper.

Table 2: Summary of cost of different energy sources

Energy	Cost ($/kWh)
Diesel	$0.46
Ocean Thermal Energy Conversion	$0.75-$1.00
Solar - Photovoltaic	$1.10
Wind - Offshore	$0.18-$0.20

While offshore wind is the cheapest option, the estimates made here are for turbines that are design for shallow waters, which would restrict the location of the seastead. Floating offshore wind platforms meant for waters over 50 m deep have yet to be fully developed. OTEC could be effective for a larger seastead, although the 500 m^3 evaporators and condensers require a large footprint on the seastead, if not a separate platform. The sale of potable water and use of cold water for air conditioning or cultivating crops could further reduce the cost of OTEC. Diesel is the simplest and another relatively expensive option. The initial investment is low, and fewer or more generators can be run depending on the needs of the seastead. If diesel fuel becomes more expensive in time, natural gas, or other renewable resources may become more cost effective.

There are many other options to be explored and the above estimates are expected to change as markets and technology change. Future research should focus on energy storage options such as compressed air energy storage, batteries, and supercapacitors.

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9 Acknowledgements

Many thanks to Professor Ron Willey for his time and support throughout the semester. From agreeing to take this on as an extra class, to working through calculations with me, the continuous help has been greatly appreciated.

Thanks to Brian Kuhn of Aeronautica Windpower for the education on wind power and turbine installation, and to Dominic Michaelis of Energy Island for the education on the feasibility of OTEC.

Appendix A: Calculations for Diesel Generators

Table A1: Calculations for a 5.05 MW diesel plant

Caterpillar 1010 kW diesel generators		
Cost of 1 1.01 MW diesel generator=	$615,000	Based on sale of used generators
Cost of 1 L of diesel fuel=	$1.59	$6/gal
Energy density of diesel fuel (MJ/L)=	39.6	
Density of diesel fuel (kg/L)=	0.832	
fuel consumption rate (L/s)=	0.34	$\frac{5.05MW}{\omega_{diesel}[\frac{MWs}{L}]*\eta}$
efficiency=	37%	
Operating hours=	8760	hours per year
Volume of fuel per year (L)=	10869287	
Cost of fuel per year ($)=	$17,232,049	
5 Generators (5.05 MW)=	$3,075,000	
Salvage value of 5 generators=	$1,000,000	
Equipment Costs (26.7% FCI)	$3,075,000	Peters, Timmerhaus, and West. *Plant Design and Economics for Chemical Engineers*, 5th ed., 2004. pp 240. Table 6-3.
Electrical Systems (10% FCI)	$1,153,125	
Installation (40% FCI)	$4,612,500	
Instrumentation and Control (6.7%FCI)	$768,750	
Engineering and Supervision (6.7% FCI)	$768,750	
Contractor's Fee (3.3% FCI)	$384,375	
Contingency (6.7% FCI)	$768,750	
Fixed Capital Investment	**$10,531,250**	Σ(direct costs)-salvage value

The fixed capital investment (FCI) for a 5.05 MW diesel generator power plant is roughly $11.5 million. This costs includes the costs of the five diesel generators, plus the direct costs associated with installation, as outlined in Peters, Timmerhaus, and West pp 240. The salvage cost of the generators after 10 years is $1 million. For installation, a high estimate of 40% of the FCI was used to determine the cost since installing the panels on a ship may pose additional challenges.

The cash flow over the 10 year lifetime of the plant is shown in Table A4. The costs associated with year 0 are the FCI. Each year after that, the plant requires 10% of the equipment costs (the cost of the generators) in maintenance, plus the operating costs outlined in Table A2, plus depreciation and fuel costs. The cost of fuel offsets the small capital investment compared to the solar panels. The depreciation was determined by the Modified Accelerated Cost Recovery System (MACRS) method over a seven year period. In the tenth year, there is no maintenance cost, but the diesel can be sold at the salvage cost and the ten year life cycle starts again.

Table A2: Annual operating costs of a 5.05 MW diesel plant

Number of Personnel	Wage&Ben $ per hr	Annual Operating Costs
2	$27.00	$473,040
1	$39.00	$341,640
Operating Costs (labor):		$814,680

Table A3 uses the total cost over 10 years (the sum of the values in the last row of Table A4) to determine the cost per kWh.

Table A3: Installed cost per kWh of a 5.05 MW diesel plant

Total Cost=	$ 204,297,294	From Table A4
Annual Cost=	$ 20,429,729	Total Cost/Lifetime
Cost per kWh=	$0.46	$\frac{\$/yr}{1000\frac{kW}{MW}*\frac{hr_{operating}}{yr}*Capacity[MW]}$

Table A4: Cost analysis of a 5.05 MW diesel plant

Time (years)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Capital Investment	**$11,531,250**										**-$1,000,000**
Maintenance (10% capital cost)		$307,500	$307,500	$307,500	$307,500	$307,500	$307,500	$307,500	$307,500	$307,500	$0
Fuel cost		$17,232,049	$17,232,049	$17,232,049	$17,232,049	$17,232,049	$17,232,049	$17,232,049	$17,232,049	$17,232,049	$17,232,049
Operating Cost		$814,680	$814,680	$814,680	$814,680	$814,680	$814,680	$814,680	$814,680	$814,680	$814,680
MACRS (7 year)		14.29%	24.49%	17.49%	12.49%	8.93%	8.92%	8.93%	4.46%	0.00%	0.00%
Depreciation		$1,504,916	$2,579,103	$1,841,916	$1,315,353	$940,441	$939,388	$940,441	$469,694	$0	$0
Total Cost:	$11,531,250	$19,859,145	$20,933,333	$20,196,145	$19,669,583	$19,294,670	$19,293,617	$19,294,670	$18,823,923	$18,354,229	$17,046,729

Appendix B: Diesel Generator Specifications

CONTINUOUS 1010 ekW 1263 kVA

60 Hz 1800 rpm 480 Volts

CAT

SPECIFICATIONS

CAT GENERATOR

Cat Generator
Frame size.. 1424
Excitation...Internal Excitation
Pitch...0.6667
Number of poles..4
Number of bearings..................................... Single bearing
Number of Leads...006
Insulation....................... UL 1446 Recognized Class H with tropicalization and antiabrasion
Insulation......Class F with tropicalization and antiabrasion
- Consult your Caterpillar dealer for available voltages
IP Rating..IP23
Alignment... Pilot Shaft
Overspeed capability..125
Wave form Deviation (Line to Line)........................... 002.00
Voltage regulator.............3 Phase sensing with selectible volts/Hz
Voltage regulation...........Less than +/- 1/2% (steady state)
Less than +/- 1% (no load to full load)
Telephone influence factor..............................Less than 50
Harmonic Distortion..Less than 5%

CAT DIESEL ENGINE

3512 TA, V-12, 4-Stroke Water-cooled Diesel
Bore... 170.00 mm (6.69 in)
Stroke.. 190.00 mm (7.48 in)
Displacement..51.80 L (3161.03 in^3)
Compression Ratio.. 13.5:1
Aspiration..TA
Fuel System.. Direct unit injection
Governor Type.. Woodward

CAT EMCP 4 SERIES CONTROLS

EMCP 4 controls including:
- Run / Auto / Stop Control
- Speed and Voltage Adjust
- Engine Cycle Crank
- 24-volt DC operation
- Environmental sealed front face
- Text alarm/event descriptions

Digital indication for:
- RPM
- DC volts
- Operating hours
- Oil pressure (psi, kPa or bar)
- Coolant temperature
- Volts (L-L & L-N), frequency (Hz)
- Amps (per phase & average)
- ekW, kVA, kVAR, kW-hr, %kW, PF

Warning/shutdown with common LED indication of:
- Low oil pressure
- High coolant temperature
- Overspeed
- Emergency stop
- Failure to start (overcrank)
- Low coolant temperature
- Low coolant level

Programmable protective relaying functions:
- Generator phase sequence
- Over/Under voltage (27/59)
- Over/Under Frequency (81 o/u)
- Reverse Power (kW) (32)
- Reverse reactive power (kVAr) (32RV)
- Overcurrent (50/51)

Communications:
- Six digital inputs (4.2 only)
- Four relay outputs (Form A)
- Two relay outputs (Form C)
- Two digital outputs
- Customer data link (Modbus RTU)
- Accessory module data link
- Serial annunciator module data link
- Emergency stop pushbutton

Compatible with the following:
- Digital I/O module
- Local Annunciator
- Remote CAN annunciator
- Remote serial annunciator

CONTINUOUS 1010 ekW 1263 kVA

60 Hz 1800 rpm 480 Volts

TECHNICAL DATA

Open Generator Set - - 1800 rpm/60 Hz/480 Volts	DM8229	
Low Fuel Consumption		
Generator Set Package Performance		
Genset Power rating @ 0.8 pf	1262.5 kVA	
Genset Power rating with fan	1010 ekW	
Coolant to aftercooler		
Coolant to aftercooler temp max	82 ° C	180 ° F
Fuel Consumption		
100% load with fan	275.4 L/hr	72.8 Gal/hr
75% load with fan	214.1 L/hr	56.6 Gal/hr
50% load with fan	154.7 L/hr	40.9 Gal/hr
Cooling System[1]		
Air flow restriction (system)	0.12 kPa	0.48 in. water
Air flow (max @ rated speed for radiator arrangement)	1614 m^3/min	56998 cfm
Engine Coolant capacity with radiator/exp. tank	286.8 L	75.8 gal
Engine coolant capacity	156.8 L	41.4 gal
Radiator coolant capacity	130.0 L	34.3 gal
Inlet Air		
Combustion air inlet flow rate	94.5 m^3/min	3337.2 cfm
Exhaust System		
Exhaust stack gas temperature	457.8 ° C	856.0 ° F
Exhaust gas flow rate	241.6 m^3/min	8532.0 cfm
Exhaust flange size (internal diameter)	203.2 mm	8.0 in
Exhaust system backpressure (maximum allowable)	6.7 kPa	26.9 in. water
Heat Rejection		
Heat rejection to coolant (total)	656 kW	37307 Btu/min
Heat rejection to exhaust (total)	1053 kW	59884 Btu/min
Heat rejection to aftercooler	145 kW	8246 Btu/min
Heat rejection to atmosphere from engine	118 kW	6711 Btu/min
Heat rejection to atmosphere from generator	49.8 kW	2832.1 Btu/min
Alternator[2]		
Motor starting capability @ 30% voltage dip	3430 skVA	
Frame	1424	
Temperature Rise	105 ° C	189 ° F
Lube System		
Sump refill with filter	310.4 L	82.0 gal
Emissions (Nominal)[3]		
NOx g/hp-hr	9.4 g/hp-hr	
CO g/hp-hr	.94 g/hp-hr	
HC g/hp-hr	.27 g/hp-hr	
PM g/hp-hr	.144 g/hp-hr	

[1] For ambient and altitude capabilities consult your Cat dealer. Air flow restriction (system) is added to existing restriction from factory.

[2] UL 2200 Listed packages may have oversized generators with a different temperature rise and motor starting characteristics. Generator temperature rise is based on a 40°C ambient per NEMA MG1-32.

[3] Emissions data measurement procedures are consistent with those described in EPA CFR 40 Part 89, Subpart D & E and ISO8178-1 for measuring HC, CO, PM, NOx. Data shown is based on steady state operating conditions of 77°F, 28.42 in HG and number 2 diesel fuel with 35° API and LHV of 18,390 btu/lb. The nominal emissions data shown is subject to instrumentation, measurement, facility and engine to engine variations. Emissions data is based on 100% load and thus cannot be used to compare to EPA regulations which use values based on a weighted cycle.

Appendix C: Calculations for a 5 MW OTEC Plant

The capital investment for a 5 MW OTEC plant is between $300 million and $400 million. These two values were taken as the fixed capital investment (FCI) for the lower and upper estimates, respectively. This cost includes equipment and installation for an offshore plant.

The cash flow over the 20 year lifetime of the plant is shown in Tables C2-C3. There are multiple charts based on the upper and lower estimates for the FCI and for the different sales prices of the 2231 m^3 of potable water per day generated during the process. The costs associated with year 0 are the FCI. Each year after that, the expenses are depreciation and the maintenance and operating costs, which are 1% of the FCI. The depreciation was determined by the Modified Accelerated Cost Recovery System (MACRS) method over a 15 year period.

Table C1 uses the total cost over 20 years (the sum of the values in the last row of Tables C2-C3) to determine the cost per kWh for each estimate shown in Tables C2-C3.

Table C1: Installed cost per kWh of a 5 MW OTEC plant

Energy	Cost ($/kWh)
OTEC - lower estimate	$0.75
OTEC - upper estimate	$1.00

Table C2: Cash flow analysis for an OTEC plant with a FCI of $300 million and no sale of water

Capital Cost	$300,000,000										
Time (years)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Capital Investment	**$300,000,000**										
Maintenance & Operating (1% capital cost)		$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000
MACRS (15 year)		5.00%	9.50%	8.55%	7.70%	6.93%	6.23%	5.90%	5.90%	5.91%	5.90%
Depreciation		$15,000,000	$28,500,000	$25,650,000	$23,100,000	$20,790,000	$18,690,000	$17,700,000	$17,700,000	$17,730,000	$17,700,000
Total Cost:	$300,000,000	$18,000,000	$31,500,000	$28,650,000	$26,100,000	$23,790,000	$21,690,000	$20,700,000	$20,700,000	$20,730,000	$20,700,000
Time (years)	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Totals**
Capital Investment										**$0**	
Maintenance & Operating (1% capital cost)	$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	
MACRS (15 year)	5.91%	5.90%	5.91%	5.90%	5.91%	2.95%	0.00%	0.00%	0.00%	0.00%	100.00%
Depreciation	$17,730,000	$17,700,000	$17,730,000	$17,700,000	$17,730,000	$8,850,000	$0	$0	$0	$0	$300,000,000
Total Cost:	$20,730,000	$20,700,000	$20,730,000	$20,700,000	$20,730,000	$11,850,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	**$660,000,000**
										per year ($):	$33,000,000
										cost per kWh:	$0.75

Table C3: Cash flow analysis for an OTEC plant with a FCI of $400 million and no sale of water

Capital Cost	$400,000,000										
Time (years)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Capital Investment	**$400,000,000**										
Maintenance & Operating (1% capital cost)		$4,000,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000
MACRS (15 year)		5.00%	9.50%	8.55%	7.70%	6.93%	6.23%	5.90%	5.90%	5.91%	5.90%
Depreciation		$20,000,000	$38,000,000	$34,200,000	$30,800,000	$27,720,000	$24,920,000	$23,600,000	$23,600,000	$23,640,000	$23,600,000
Total Cost:	$400,000,000	$24,000,000	$42,000,000	$38,200,000	$34,800,000	$31,720,000	$28,920,000	$27,600,000	$27,600,000	$27,640,000	$27,600,000
Time (years)	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Totals**
Capital Investment										**$0**	
Maintenance & Operating (1% capital cost)	$4,000,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000	
MACRS (15 year)	5.91%	5.90%	5.91%	5.90%	5.91%	2.95%	0.00%	0.00%	0.00%	0.00%	100.00%
Depreciation	$23,640,000	$23,600,000	$23,640,000	$23,600,000	$23,640,000	$11,800,000	$0	$0	$0	$0	$400,000,000
Total Cost:	$27,640,000	$27,600,000	$27,640,000	$27,600,000	$27,640,000	$15,800,000	$4,000,000	$4,000,000	$4,000,000	$4,000,000	**$880,000,000**
										per year ($):	$44,000,000
										cost per kWh:	$1.00

Appendix D: Calculations for Solar Panels

$$P_{light}[kW] = Irr[\frac{kWh}{m^2 day}] * A[m^2] * \frac{1}{5}[\frac{day}{hr_{sun}}] * \eta$$ Eq. D1

As a base line, Irradiance in Aruba is 6.8 kWh/m^{2}day over 5 hours of peak sunlight per day was selected for this analysis. The efficiency is 15% and the surface area of the panels is 2.6 m^2. The theoretical P_{light} from Eq. D1 is 540 W, which is greater than the rated maximum power of the panels. Therefore, Eq. D2 was used instead:

$$P_{total}[MW] = P_{\max}[W] * n * \frac{1MW}{1{,}000{,}000W}$$ Eq. D2

In this case, n is the number of panels that can fit in a 400'x400' area and P_{max} is the rating of the panel based on operating conditions, which for these calculations is 320W.

If the solar panels are not tracking the movement of the sun, then little maintenance and supervision is required. The operating costs (the cost of manual labor) is summarized in Table D1.

Table D1: Operating costs for 1.8 MW PV plant

Number of Personnel	Wage&Ben $ per hr	Annual Operating
2	$27.00	$98,550
1	$39.00	$71,175
Operating Costs (labor):		$169,725

Table D2: Calculations for a 1.8 MW PV plant

Panel rating (W)	320	
Price ($)	$731	
$/W	$2.28	price/watts per panel
Installed cost ($/W from Puget Sound Solar)	$5.00	quote from Puget Sound Solar
Intalled-panel cost ($/W)	2.715625	
Watts:	1800000	
Installation cost ($)	$4,888,125	
Total panel cost ($)	$4,111,875	
Cost of 5 DC to AC inverters=	$750,000.00	[20]
Surface Area of 1 panel (m^2)=	2.6	Helios Solar Spec Sheet, 11Aug2011
Panels per 400^2 ft^2=	5700	400^2 ft^2/Surface Area of Panel[ft^2]
Total power output (MW)=	1.8	#Panels*420W/(1,000,000 W/MW)
Operating hours yearly=	1825	Hours of Peak Sunlight*365 days/yr
Yearly output (MWh/year)=	3329	Operating hours*Power Output
Plant Lifetime (years)=	20	Helios Solar Spec Sheet, 11Aug2011
Cost of panels + installation + inverters ($)=	$9,750,000	
Electrical Systems (10% FCI)	$14,695,940	Peters, Timmerhaus, and West. *Plant Design and Economics for Chemical Engineers*, 5th ed., 2004. pp 240. Table 6-3.
Instrumentation and Control (6.7%FCI)	$2,437,500	
Engineering and Supervision (6.7% FCI)	$2,437,500	
Contractor's Fee (3.3% FCI)	$1,218,750	
Contingency (6.7% FCI)	$2,437,500	
FCI	$32,977,190	

The fixed capital investment (FCI) for a 2.4 MW PV power plant is roughly $18.5 million. This costs includes the costs of the solar panels and DC to AC inverters, plus the direct costs associated with installation, as outlined in Peters, Timmerhaus, and West pp 240. For installation, a high estimate of 40% of the FCI was used to determine the cost since installing the panels on a ship may pose additional challenges.

The cash flow over the 20 year lifetime of the plant is shown in Table D4. The costs associated with year 0 are the FCI. Each year after that, the plant requires 5% of the equipment costs (the cost of the inverters and panels) in maintenance, plus the operating costs outlined in Table D1, plus depreciation. The depreciation was determined by the Modified Accelerated Cost Recovery System (MACRS) method over a 15 year period.

Table D3 uses the total cost over 20 years (the sum of the values in the last row of Table D4) to determine the cost per kWh.

Table D3: Installed cost per kWh of a 1.8 MW PV plant

Total Cost=	$73,255,161	From Table B4
Cost per year=	$3,662,758	Total Cost/Lifetime
Cost per kWh=	$ 1.11	$\frac{\$/yr}{1000\frac{kW}{MW} * \frac{hr_{operating}}{yr} * Capacity[MW]}$

Table D4: Cost analysis of a 1.8 MW PV plant

Time (years)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Capital Investment	**$32,977,190**										
Maintenance (5% capital cost)		$205,594	$205,594	$205,594	$205,594	$205,594	$205,594	$205,594	$205,594	$205,594	$205,594
Operating Cost		$169,725	$169,725	$169,725	$169,725	$169,725	$169,725	$169,725	$169,725	$169,725	$169,725
MACRS (15 year)		5.00%	9.50%	8.55%	7.70%	6.93%	6.23%	5.90%	5.90%	5.91%	5.90%
Depreciation		$1,648,860	$3,132,833	$2,819,550	$2,539,244	$2,285,319	$2,054,479	$1,945,654	$1,945,654	$1,948,952	$1,945,654
Total Cost:	$32,977,190	$2,024,178	$3,508,152	$3,194,868	$2,914,562	$2,660,638	$2,429,798	$2,320,973	$2,320,973	$2,324,271	$2,320,973
Time (years)	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Totals**
Capital Investment										**$0**	
Maintenance (5% capital cost)	$205,594	$205,594	$205,594	$205,594	$205,594	$205,594	$205,594	$205,594	$205,594		
Operating Cost	$169,725	$169,725	$169,725	$169,725	$169,725	$169,725	$169,725	$169,725	$169,725	$169,725	
MACRS (15 year)	5.91%	5.90%	5.91%	5.90%	5.91%	2.95%	0.00%	0.00%	0.00%	0.00%	100.00%
Depreciation	$1,948,952	$1,945,654	$1,948,952	$1,945,654	$1,948,952	$972,827	$0	$0	$0	$0	$32,977,190
Total Cost:	$2,324,271	$2,320,973	$2,324,271	$2,320,973	$2,324,271	$1,348,146	$375,319	$375,319	$375,319	$169,725	**$73,255,161**
										yearly cost ($):	$3,662,758
										cost per kWh:	$1.11

Appendix E: Solar Panel Specifications

HELIOS
SOLAR WORKS

Manufactured in Milwaukee, WI

9T6 SERIES

- High-performance solar modules offering higher efficiency, lower installation costs
- 96 high-quality mono-crystalline cells per module
- Tested to UL 1703 and CEC with a Class C fire rating
- 25-year linear performance warranty
- Manufactured end-to-end in Milwaukee, Wisconsin (USA) using Helios Solar Works advanced, automated platform

Helios Solar Works manufactures high-performance mono-crystalline solar modules for solar electric systems. We use only high-quality components and an advanced, automated manufacturing platform to offer modules that deliver higher efficiency, lower installation costs, and a smaller system footprint.

Helios Solar Works is headquartered in Milwaukee, Wisconsin. We manufacture our modules using materials sourced from regional and U.S. suppliers whenever possible.

CATEGORY

Mono-crystalline Solar (96 Cell)

CHARACTERISTICS

Dimension:	1,976 mm x 1,310 mm (77.8" x 51.57")
Area:	2.58 m^2 (27.77 Sq Ft)
Thickness:	40 mm (1.58")
Weight:	34.66 kg (76.41 lbs)

OUTPUT CLASSES

420, 415, 410, 405, 400, 395, 390

WARRANTY

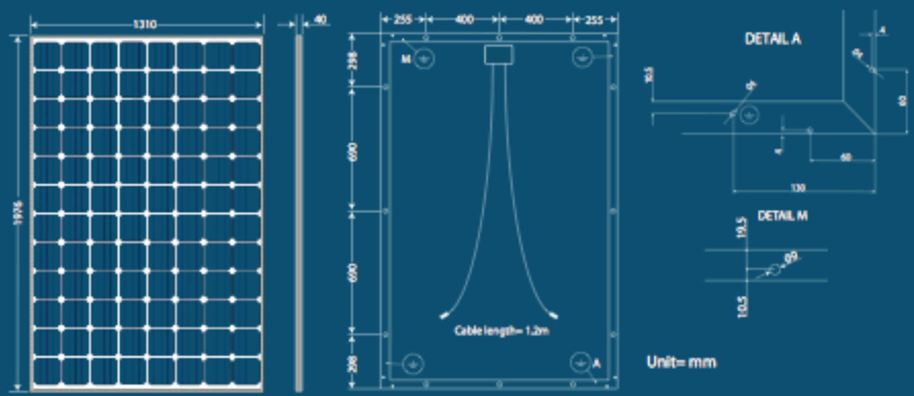
25-year linear performance warranty delivering 80% power at STC

10-year workmanship warranty

Helios USA, LLC
1207 W. Canal Street, Milwaukee, WI 53233
www.heliossolarworks.com

sales@helios-usa.com
877.443.5467

9T6 SERIES



ELECTRICAL DATA STC		9T6 420	9T6 415	9T6 410	9T6 405	9T6 400	9T6 395	9T6 390
Rated Power PMPP (W)	=	420	415	410	405	400	395	390
MPP Voltage (V)	=	49.53	49.23	48.98	48.68	48.43	48.17	47.91
MPP Current (A)	=	8.48	8.43	8.37	8.32	8.26	8.2	8.14
Open Circuit Voltage (V)	=	60.55	60.40	60.25	60	59.8	59.5	59.3
Short Circuit Current (A)	=	9	8.95	8.9	8.86	8.82	8.67	8.62

Measured at (STC) Standard Test Conditions 25° C, insolation 1,000 W/m^2, AM 1.5.

ELECTRICAL DATA NOCT		9T6 420	9T6 415	9T6 410	9T6 405	9T6 400	9T6 395	9T6 390
Rated Power PMPP (W)	=	320	315	310	305	300	295	291
MPP Voltage (V)	=	45.78	45.59	45.35	45.15	44.96	44.79	44.59
MPP Current (A)	=	6.99	6.91	6.83	6.75	6.67	6.59	6.51
Open Circuit Voltage (V)	=	56.20	55.98	55.77	55.54	55.31	55.08	54.93
Short Circuit Current (A)	=	7.42	7.35	7.28	7.21	7.14	7.05	6.96

Nominal Operating Cell Temperature (NOCT) values are typical values, 45°C.
Typical cell temperature: insolation 800W/m^2, ambient temperature 20°C, wind speed 1m/s.

OTHER ELECTRICAL PARAMETERS					
System Voltage (V)	=	600/1,000	Temp. Coefficient PMPP (% / °C)	=	-0.41
Temp. Coefficient ISC (% / °C)	=	0.03	Temp. Coefficient UOC (% / °C)	=	-0.32

DESIGN					
Cells	=	96 mono-crystalline, 3 bus bars	Backside	=	Multilayer sheet
Cell Dimensions	=	156 mm x 156 mm, pseudo-square	Frame	=	Anodized aluminum (clear or black)
Front glass	=	4 mm solar glass, highly transparent and anti-reflective	Connection	=	2 x 1.2 m solar cables with MC4 connectors or compatible
Encapsulation	=	EVA - Solar Cells - EVA	Bypass Diodes	=	4 pieces

LIMIT VALUES	QUALIFICATIONS
Module Temperature -40°C to +80°C	IEC 61215, IEC 61730, UL1703, CEC, FSEC, ULC/ORD-C1703-01, TUV

WARRANTY	PERFORMANCE OUTPUT
25 year linear performance warranty. Also 10 years workmanship.	-0/+3 percent

2011_0611

Appendix F: Wind Turbine Calculations

Tables F2 and F3 shows the cash flow analysis for offshore wind based on UK wind data. The net export factor here is 38%, so that the installed rated capacity is 13.2 MW instead of 5 MW. The upper limit is $4700/kW rated installed and the lower limit is $5490/kW rated installed. The operating and maintenance costs are $1,635,425 per year.

The costs associated with year 0 are the FCI. Each year after that, the expenses are depreciation and the maintenance and operating costs. The depreciation was determined by the Modified Accelerated Cost Recovery System (MACRS) method over a 15 year period.

Table F1 uses the total cost over 20 years (the sum of the values in the last row of Tables F2-F3) to determine the cost per kWh for each estimate shown in Tables F2-F3.

Table F1: Installed cost per kWh of offshore wind turbines

Energy	Cost ($/kWh)
Offshore Wind - lower estimate	$0.18
Offshore Wind - upper estimate	$0.20

Table F2: Cash flow analysis for offshore wind turbines at an installation cost of $4700/kW

total output (MW):	5										
total input with 38% net export (MW rated):	13.2										
Capital cost at $4700 per kW rated (USD):	$61,907,895										
Time (years)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Capital Investment	**$61,907,895**										
Maintenance (1% capital cost)		$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425
MACRS (15 year)		5.00%	9.50%	8.55%	7.70%	6.93%	6.23%	5.90%	5.90%	5.91%	5.90%
Depreciation		$3,095,395	$5,881,250	$5,293,125	$4,766,908	$4,290,217	$3,856,862	$3,652,566	$3,652,566	$3,658,757	$3,652,566
Total Cost:	$61,907,895	$4,730,820	$7,516,675	$6,928,550	$6,402,333	$5,925,642	$5,492,287	$5,287,991	$5,287,991	$5,294,182	$5,287,991
Time (years)	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Totals**
Capital Investment										**$0**	
Maintenance (1% capital cost)	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	
MACRS (15 year)	5.91%	5.90%	5.91%	5.90%	5.91%	2.95%	0.00%	0.00%	0.00%	0.00%	100.00%
Depreciation	$3,658,757	$3,652,566	$3,658,757	$3,652,566	$3,658,757	$1,826,283	$0	$0	$0	$0	$61,907,895
Total Cost:	$5,294,182	$5,287,991	$5,294,182	$5,287,991	$5,294,182	$3,461,708	$1,635,425	$1,635,425	$1,635,425	$1,635,425	**$156,524,289**
										yearly cost:	$7,826,214
										cost per kWh	$0.18

Table F3: Cash flow analysis for offshore wind turbines at an installation cost of $5490/kW

total output (MW):	5										
total input with 38% net export (MW rated):	13.2										
Capital cost at $5490 per kW rated (USD):	$72,223,684										
Time (years)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Capital Investment	**$72,223,684**										
Maintenance (5% capital cost)		$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425
MACRS (15 year)		5.00%	9.50%	8.55%	7.70%	6.93%	6.23%	5.90%	5.90%	5.91%	5.90%
Depreciation		$3,611,184	$6,861,250	$6,175,125	$5,561,224	$5,005,101	$4,499,536	$4,261,197	$4,261,197	$4,268,420	$4,261,197
Total Cost:	$72,223,684	$5,246,609	$8,496,675	$7,810,550	$7,196,649	$6,640,526	$6,134,961	$5,896,622	$5,896,622	$5,903,845	$5,896,622
Time (years)	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Totals**
Capital Investment										**$0**	
Maintenance (5% capital cost)	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	$1,635,425	
MACRS (15 year)	5.91%	5.90%	5.91%	5.90%	5.91%	2.95%	0.00%	0.00%	0.00%	0.00%	100.00%
Depreciation	$4,268,420	$4,261,197	$4,268,420	$4,261,197	$4,268,420	$2,130,599	$0	$0	$0	$0	$72,223,684
Total Cost:	$5,903,845	$5,896,622	$5,903,845	$5,896,622	$5,903,845	$3,766,024	$1,635,425	$1,635,425	$1,635,425	$1,635,425	**$177,155,868**
										yearly cost:	$8,857,793
										cost per kWh	0.20

Appendix G: Wind Turbine Specifications

Technical Data AV 928 – 2.5 MW and Power curve

AVANTIS Energy

Performance	
Concept	Gearless
Rated power	2,500 kW
Cut-in wind speed	3 m/s
Rated wind speed	11.6 m/s
Cut-out wind speed	25 m/s
Survival wind speed	59.5 m/s (70 m/s*)
Wind class	IEC IIa

Generator	
Construction	Direct drive PM-generator
Speed range	16 rpm, variable
Size	Ø 5 m x 1.2 m
Rotor	PM, outer
Stator	Water-cooled, internal
Nominal output, Voltage	min. 2,750 kW, 690 V
Main bearing	Taper roller bearing, cylindrical
Protection class	IP 54

Rotor	
Rotor diameter	93.2 m
Swept area	6,822 m^2
Rated speed	16 rpm

Yaw system	Electrical gear motors

Rotor blade	
Material	GRP/Epoxy
Type	AVANTIS AB 92
Length	45.3 m
Weight	10.2 t

Electrical system	
Converter	Full IGBT Rectifier/ Inverter
Frequency	50/60 Hz
Output voltage	690 V
Cooling	Water-cooled

Power regulation	Pitch control
Speed control	Active blade pitch control
Main brake	Individual blade pitch control
Secondary brake	Hydraulic disc brake

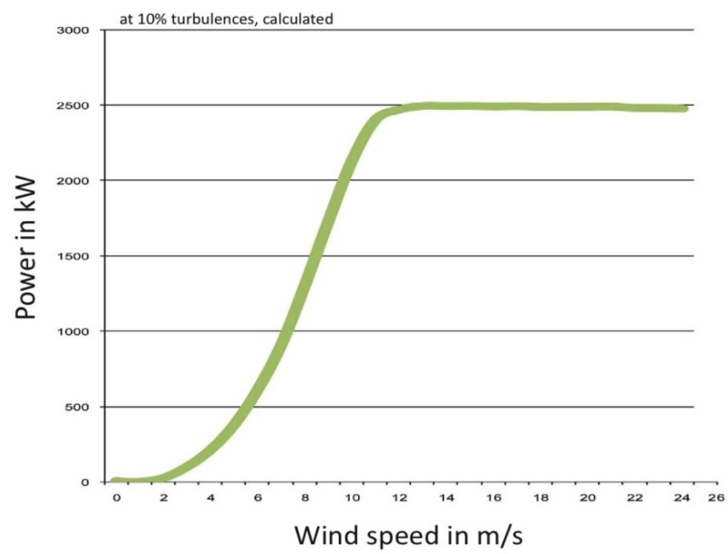
Noise level	
95 % rated power	104.7 dB(A)

Tower	
Hub height	80 m, 99 m
Type	Tubular steel tower

Operating temperature range	-40° C to +40° C

* AV 928 T (Typhoon)

All data subject to change



Appendix H: Calculations for Pumped-Storage Hydroelectricity

$$PE = \frac{\dot{m} g \Delta h}{g_c}$$ Eq. H1[14]

$$P = \frac{\dot{m} g h}{\eta}$$ Eq. H2[15]

Table H1: Pumped storage hydroelectricity calculations

variable	value	units	description	equation
Δh	30.4	m	height of column	
d	9.1	m	diameter of column	
r	4.55	m	radius of column	
g	9.8	m/s^2	gravitational acceleration	
g_c	1	Ns^2/kgm	proportionality constant	
V	650.4	m^3	volumn of each tank	$h\pi r^2$
ρ	1025	kg/m^3	density of water	
m	666648	kg	mass of water in one tank	Vρ
P	0.5	MW	power input of one pump	
h	30.4	m	head of pump	
η	0.8	---	efficiency	
$\dot{m}$	1343	kg/s	mass flow rate per column	$\frac{P\eta}{hg}$
PE	400000	W	potential energy per column	$\frac{\dot{m} g \Delta h}{g_c}$
Total PE	1.6	MW	total potential energy	4PE
t	8.3	min	time for flow	$\frac{m}{\dot{m}}$
E	199	MJ	energy produced per column with one tank of water	$PE * t * 60 \frac{\sec}{\min}$
Energy density	298	J/kg	energy provided per kg of water	$\frac{E}{m}$