Assessing the Costs of Solar Power Plants for the Island of Roatàn

by

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ABSTRACT

This is an analysis assessing the installation costs of different solar power plant technologies and the current commercial availability for installation on the Island or Roatàn. Commercial large-scale power plants have been in use for decades and their technical feasibility has been documented as well as their high installation costs. Roatàn is currently seeking alternatives for powering their island. This thesis explores the initial costs of the solar power options currently available to the island, focusing on the large energy storage requirements needed for the island to be powered entirely off of sunlight.

Thesis Supervisor: Daniel Frey

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BACKGROUND

1.1 Brief History of Solar Power

Humans have made use of direct sunlight as an energy source for millennia. The ancient Greeks in the 3rd Century BC used "burning mirrors" to light ceremonial torches, the Romans used sunlight to heat bathhouses, and the Swiss scientist Horace de Saussure used a solar oven to cook food during expeditions. However it was not until the early 1980's that sunlight was harvested on a larger "utility" scale. In 1982 the installation of a 1-megawatt capacity system in Hisperia California, was the first installation of such a system on what can be considered a utility scale. The Hisperia plant was developed by ARCO Solar and employed photovoltaic cells mounted on 108 separate dual-axis trackers. Despite ultimately being unable to make a profit and eventually closing in 1994, the plant paved the way for the introduction of clean, renewable solar power on a large scale. [1]

Shortly after the construction of the Hisperia plant in 1982 an industry consortium lead by the U.S. Department of Energy constructed a 10-megawatt central-receiver demonstration in plant in California, known as "Solar One". This plant established the feasibility of solar-thermal electric or concentrating solar power systems (CSP). The success of Solar One lead to the construction of larger solar thermal power plants including a collection of plants known as the "Solar Energy Generating Systems" (SEGS), this collection of power plants is located in the Mojave Desert has a combined generating capacity of 354 MW. [2]

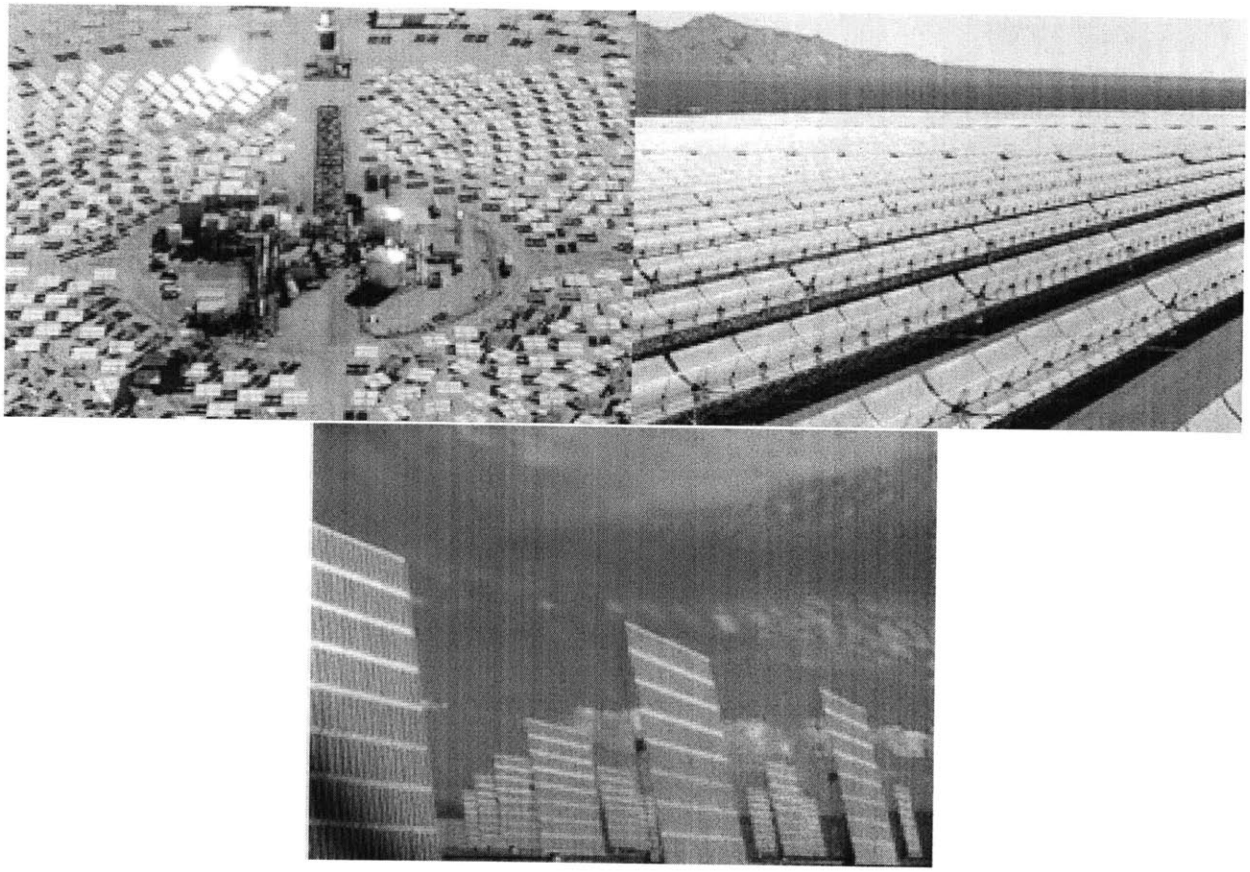

Figure 1: Three operational solar power plants. California's Solar One (top left), SEGS (top right), Hesperia (bottom)
Source: US Department of Energy

The growing demand for renewable energy sources and the early successes of some solar power has led to the significant growth of solar power, with the global capacity increasing by nearly a factor of ten over the past five years, from 2.2 GW in 2004 to 21.7GW in 2009 [1]. This dramatic increase in capacity shows no signs of slowing with many large CSP and Photovoltaic plants planned for construction, within the next 5 years.

[1] Global capacity figures were taken from the publication REN21 GST 2010, more detail is available in the appendix

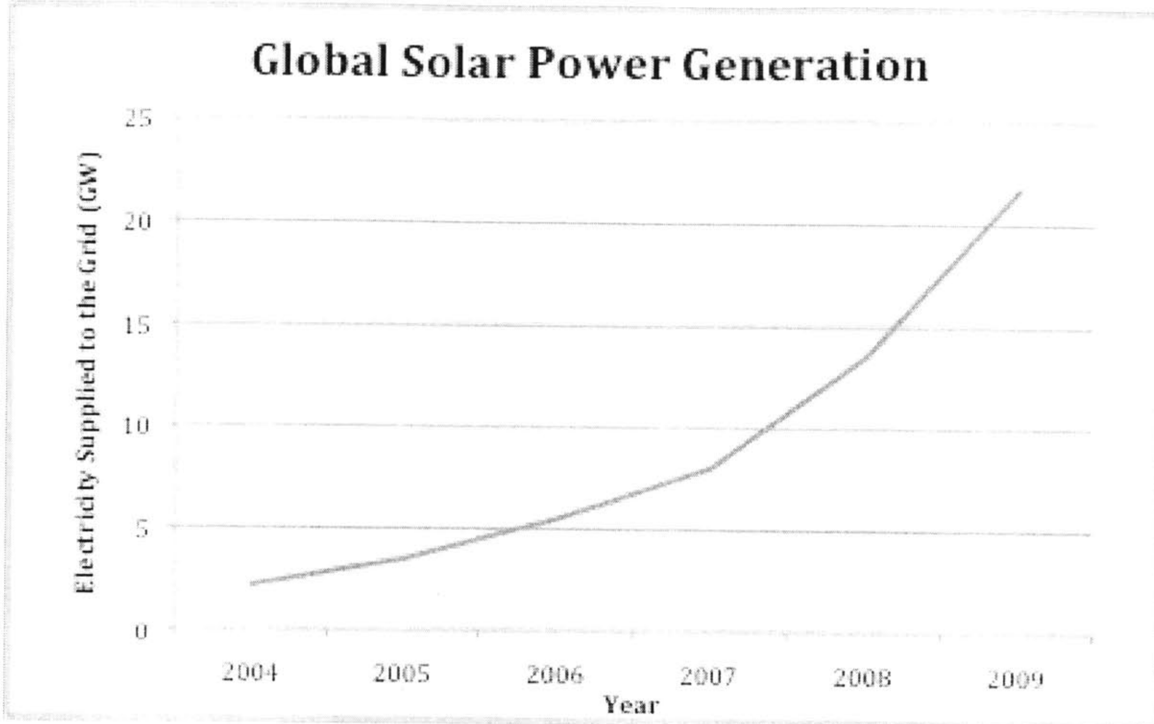

Figure: 2
Source: REN21 GSR 2010

1.2 Current Solar Power Generation Technologies

There are a variety of methods that are currently being used to produce electricity from sunlight on large scales. The simplest of these and the first to be implemented on a large scale at the Hespera site was photovoltaics (PV). PV power plants convert sunlight directly into electricity using solar cells. This direct conversion has the benefit of being mechanically very simple and relatively low maintenance. Continuous improvements in PV technology and new products such as thin-film cells from Nanosolar promise to reduce the cost of solar power. Currently PV panels produce 96% of the world's solar generated electricity. [3]

Concentrated solar power technologies (CSP), differ from PV arrays in that the sunlight is used to heat a fluid that then spins a turbine to generate electricity, much like a coal or nuclear power plant. These solar thermal plants are mechanically more complex than PV plants but installations such as Solar One and SEGS have proven CSP to be an effective means of utility scale electricity generation. The CSP plants in operation use a variety of concentration methods including parabolic dish, parabolic trough, linear fresnel and heliostats, as well as a variety of electricity generation methods including stirling engines and steam turbines.

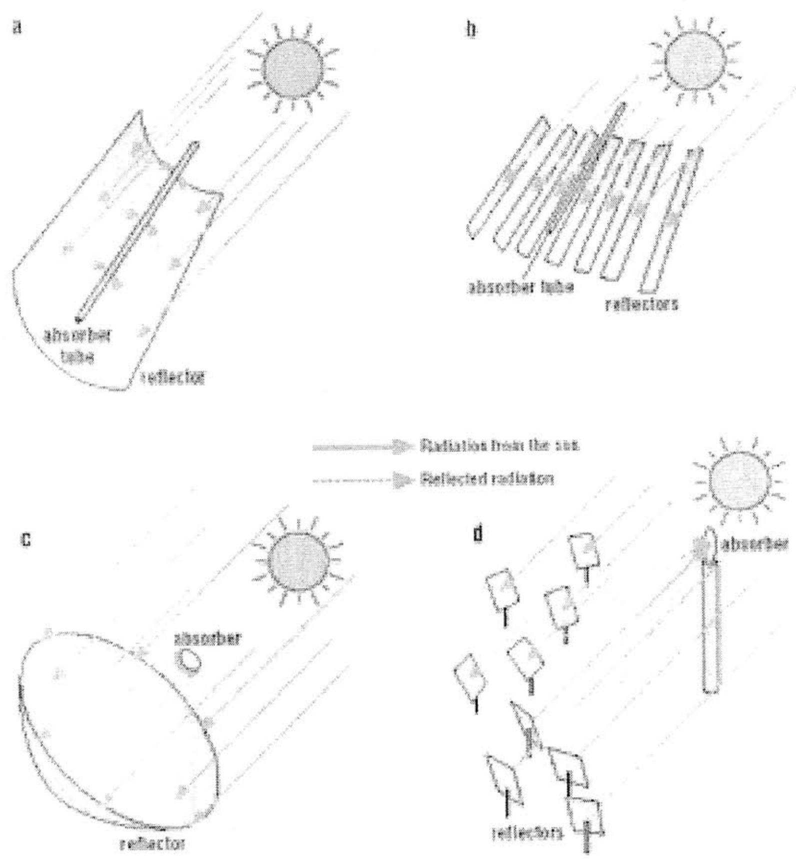

Figure 3: (a) Parabolic Trough, (b) Linear Fresnel, (c) Parabolic Dish, (d) Central Receiver with Heliostats
Source: Renewable Energy World

2. CASE STUDY: ROATÀN HONDURAS

The island of Roatán in Honduras is a member of a group of small islands known as the "Bay Islands." Currently these islands including Roatàn generate their own electricity using a number of large diesel powered generators. The cost of this system is volatile depending largely upon the cost of fuel, with monthly fuel bills costing between $900,000 and $1,000,000, not including maintenance or repair costs. In addition to the cost of fuel, an additional concern with the current power generation system is that of pollution. The primary economic industry on the island is tourism and any damage to the coral reefs and natural environment from a fuel leak or long-term use of the generators would severely damage the island's economy. These concerns have led the island to consider the installation of solar power plants in place of the diesel generators. [4]

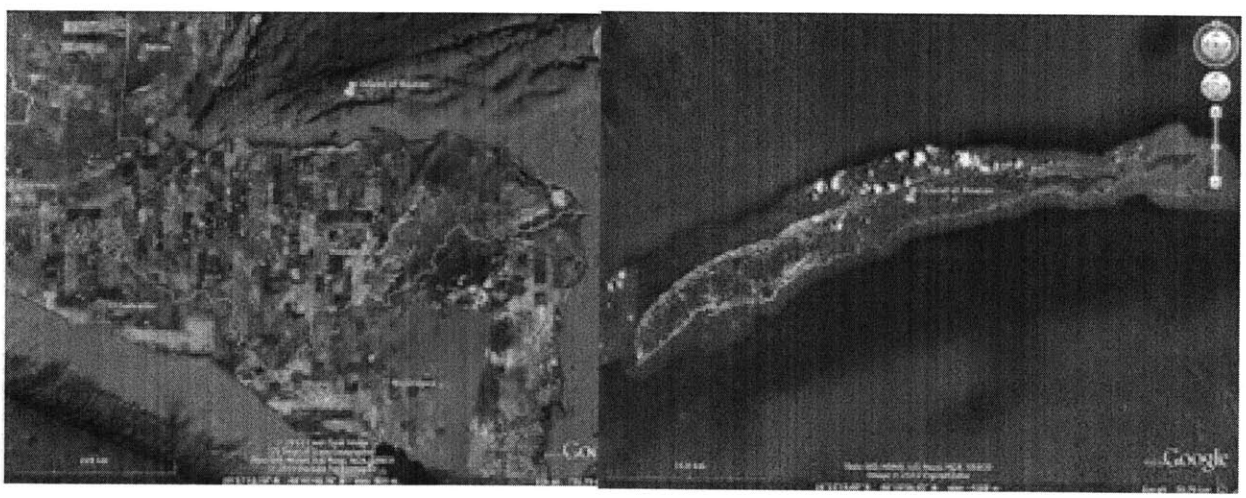

Figure 4: Satellite images of the Island of Roatàn
Source: Google Earth

2.1 Functional Requirements

The island of Roatán is situated off of the coast of Honduras near to the equator. It receives a significant and seasonally consistent amount of direct sunlight with an annual average of 5.46 $kWh/m^2/day$ for a tilted surface, and as a result is a good candidate for collecting solar energy. [6] Some of the functional requirements for a solar power plant that is used as the only source of electrical power on the island are as follows:

1) Power Generation - The island's energy consumption varies with the season and time of day, but peak demand is approx 12 – 13MW during the month of May. This demand peak roughly coincides with peak solar irradiance.
2) Energy Storage – ~48hours of energy storage, enough to provide electricity throughout the night, and during extended cloudy or rainy periods. The old diesel generators will remain as an emergency backup.
3) Scalability – Roatán's electrical distribution infrastructure is at times unreliable and as a result a decentralized approach using several smaller 3-5MW power plants that can be added/expanded as needed is preferred by the council. This indicates that 3-4 plants will be needed to meet the entire island's rising electrical demand. These plants should also be interconnected for redundancy.
4) Space Efficiency – Since the location will be based on an island minimizing the plant's footprint is important.

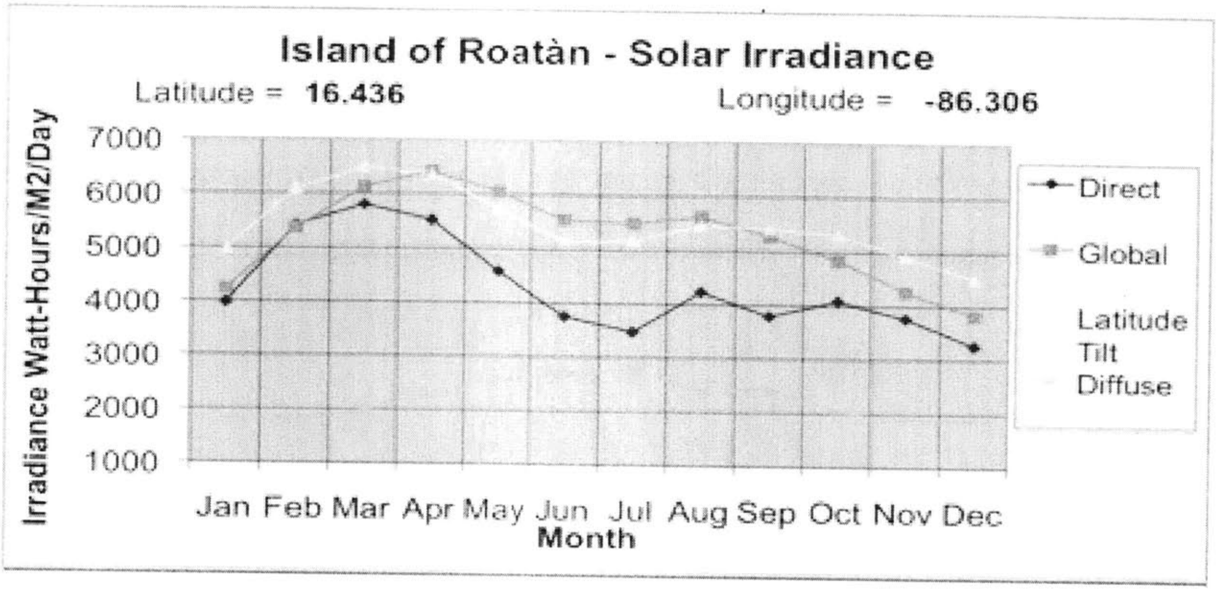

Figure 5: Daily solar irradiance for the Island of Roatàn. "Direct" represents the direct normal solar irradiance on a flat plate parallel with the ground. "Latitude Tilt" represents the direct normal solar irradiance on a flat plate tilted towards the sun.

Source: SWERA

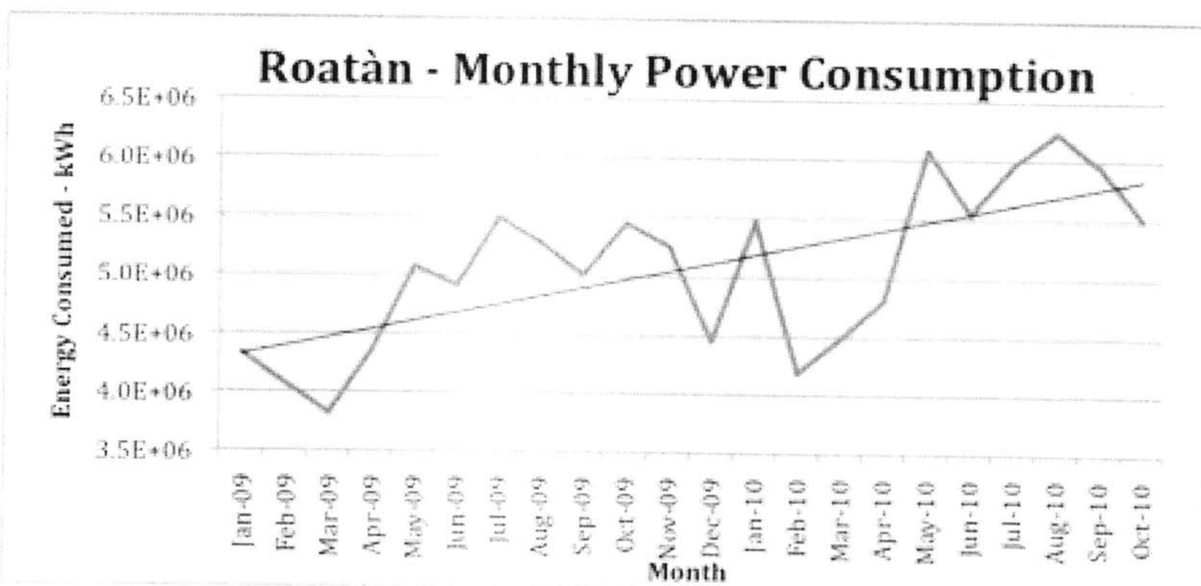

Figure 6: Total monthly power consumption on the Island of Roatàn since 2009. The trend line highlights an overall increase in power consumption.

Source: National Energy Commission (Honduras)

3. Technology Analysis

3.1 Solar Power Plants

There are many potential designs that could be considered to meet these requirements, some technologies to be considered are Photo-Voltaics (PV) and Concentrated Solar Power (CSP) designs including, Dish-Stirling, Central Receiver, Parabolic Trough, and Linear Fresnel.

3.1.1 Photo-Voltaic System (PV)

PV systems have the advantage of directly converting solar radiation into electricity; this combines the collection and conversion step reducing the overall complexity of the system. The primary large components needed for a PV power plant include: Encapsulated PV cells, DC to AC solar inverters, and single axis stands to track the sun's movement.

All of these components are readily available with many companies such as Suntech, SunPower, and Nano Solar supplying silicon solar panels optimized for utility scale applications. High-power, (>500 kW) DC to AC solar inverters are also marketed by a number of companies including General Electric, Solectria, and Satcon. With many site dependant variables, the overall cost of large scale PV system is variable and companies are reluctant to comment on prices, but Beaumont Solar CO. an installer based in the Boston area listed estimates for a turnkey (installed and grid ready) 5kW system as $39,000 and a scaled up 100kW system as $700,000. [8] Assuming a linearly scaled reduction in price due to economies of scale, this translates very roughly into $20.9

million for a 3MW system and $34.8 million for a 5MW PV plant. At least three of the 5MW plants would be needed to power the entire island at a total cost of approximately $104 million.

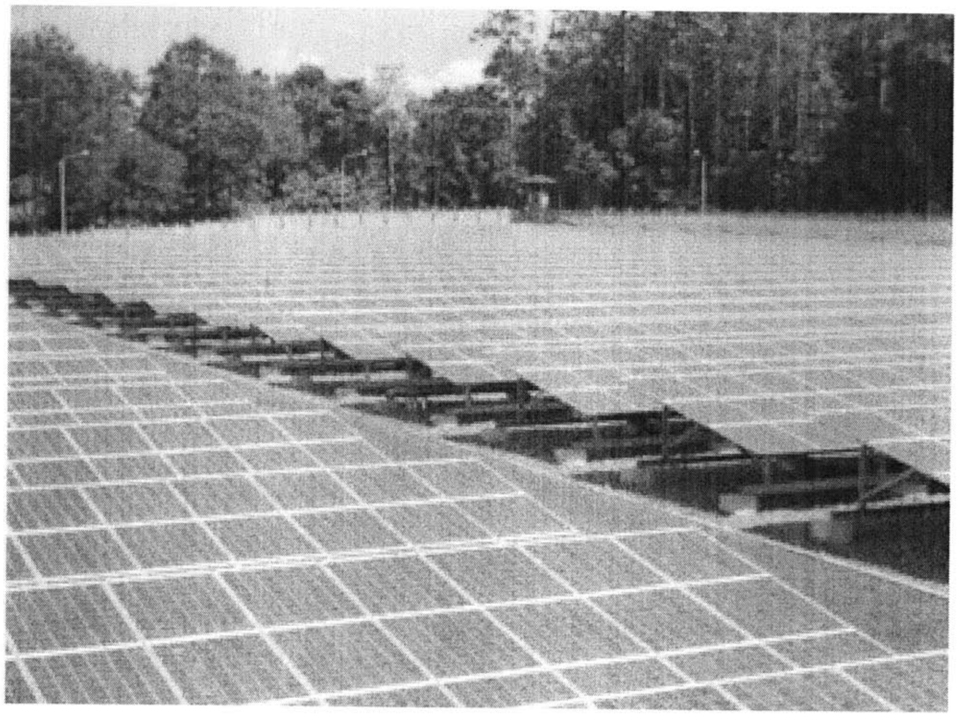

Figure 7: Photo of a large scale PV power plant.
Source: Department of Energy (United States)

PV solar power plants have the advantage of being mechanically quite simple with few moving parts and little maintenance and upkeep required. They also benefit from being very modular; expansion can easily be accomplished by simply adding more panels and inverters. The downsides to this technology are that PV panels are still expensive when compared to other technologies, and the lack of an energy storing medium means that for large-scale off grid applications such as the island of Roatàn expensive energy storage methods such as batteries or mechanical flywheels must be used and the cost of which would have to be added into the cost of the PV system.

3.1.2 Dish-Stirling System

Dish-Stirling systems are a form of concentrated solar power where a parabolic dish is used to concentrate sunlight onto a small absorber/heat exchanger. The energy absorbed by this heat exchanger is then used to run a stirling engine which powers a generator producing electricity for the electrical grid. Such a system is already being produced and installed by companies such as Stirling Energy Systems (SES). SES produces a 25kW solar dish stirling concentrating solar power system that has already been installed into a 1.5MW Power Plant In Maricopa County Arizona. Even though SES is not releasing cost figures a company representative claims that the installation's cost per kilowatt-hour over the plant's expected lifetime is competitive with California's Market Price Referent (MPR). [9] This means that overall lifetime cost of the electricity from the plant should be in the range of $0.10 - $0.12 per kWh, or roughly equivalent to the cost of owning and operating a new base load combined cycle gas turbine (CCGT) power plant as determined by the state of California. [10]

Dish-Stirling systems such as those supplied by SES take advantage of the high thermodynamic efficiency of the Stirling cycle with SES boasting the highest solar energy to grid peak conversion efficiency of any solar technology at 31.25%[2]. The compactness and scalability of the dish-stirling unit is also an advantage. With expansion the of an existing power plant consisting of simply installing more units. The disadvantages however include increased system complexity compared to a PV power plant and similar to the PV power plant, an installation on the island of Roatàn

[2] Peak conversion efficiency represents the conversion of direct normal solar irradiance into electrical output, as claimed by Stirling Energy Systems.

requiring significant energy storage is a challenge, since electricity generation is performed at each dish. An external energy storage system would add considerable cost to the system, and as of January 2011 the dish-stirling systems designed by SES were not available for installations outside of the US. [9]

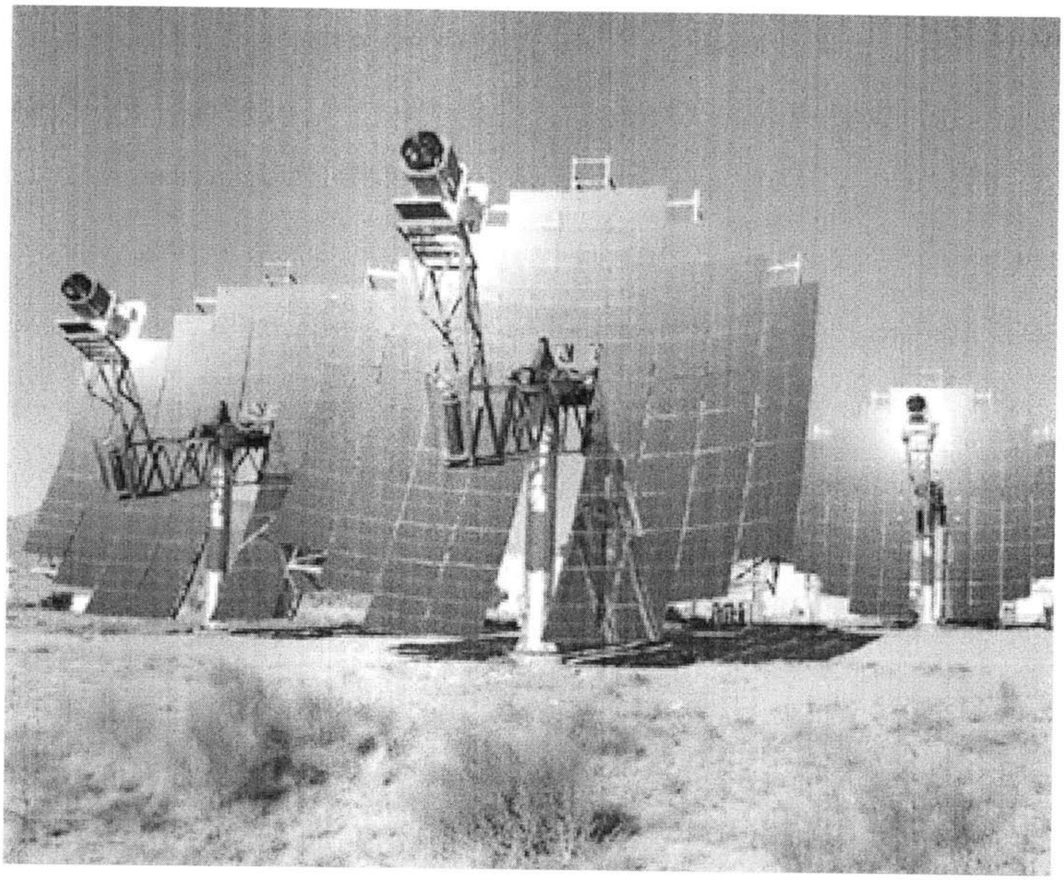

Figure 8: Picture of Stirling Energy System's parabolic dish/stirling engine system.
Source: Stirling Energy Systems

3.1.3 Concentrated Solar Thermal Power Plants

CSP technologies differing from dish-stirling such as linear fresnel, parabolic trough, and central receiver are closely related in that they all utilize steam turbines in their thermal to electric energy conversion step. The use of steam turbines to generate the electricity in power plants is common, with Nuclear, Coal, and Gas power plants all using similar thermodynamic processes to generate the electricity. The primary difference between each of these plants, and CSP solar plants is simply the heat source.

The common use of the steam turbine in power generation means that the technology has been well optimized, and is well understood. CSP plants using steam turbines also benefit significantly from economies of scale with the cost per kW decreasing as the size of the plant increases. Centralized electrical generation is also an advantage where large-scale energy storage is needed. Due to the thermal energy being pumped through a single stream to power the turbines, diverting and storing that energy, as heat, is conceivably cheaper and simpler than with a multitude of smaller storage units. Some of the drawbacks to a plant using centralized steam turbine are the lack of easy scalability; increasing capacity may mean replacing expensive components such as the turbines, instead of simply adding more units. Despite of their many similarities in how they produce electricity, CSP plants differ primarily in how they harvest energy from the sun.

3.1.4 Parabolic Trough

Trough collectors are still the most proven design for CSP power plants. With the installation of SEGS I in 1984 and later with 5 more SEGS installations the technology has been proven reliable and effective. With a long parabolic trough focusing light onto a long, vacuum insulated receiving tube, the support structures needed for the trough are smaller, less complicated, and a single long trough can cover a larger illuminated area than other forms of solar concentrators. Tracking of the sun can also be accomplished using a single axis.

Some drawbacks to this design are that the mirrors shaped as a parabolic trough can be difficult/expensive to manufacture and install, and the heat transfer fluid receiving the thermal energy must travel through a lot of piping before being used to generate steam. This adds to systemic losses with more power needed to pump fluids, thermal losses through the insulation, and more costs associated with the vacuum insulated tubes used to absorb the solar energy. Trough CSP plants also have a relatively low concentration ratio when compared to other CSP designs. This translates to a lower fluid working temperature (typically ~350degrees centigrade) and the use of the Rankine cycle with thermal efficiencies of ~40%. [12]

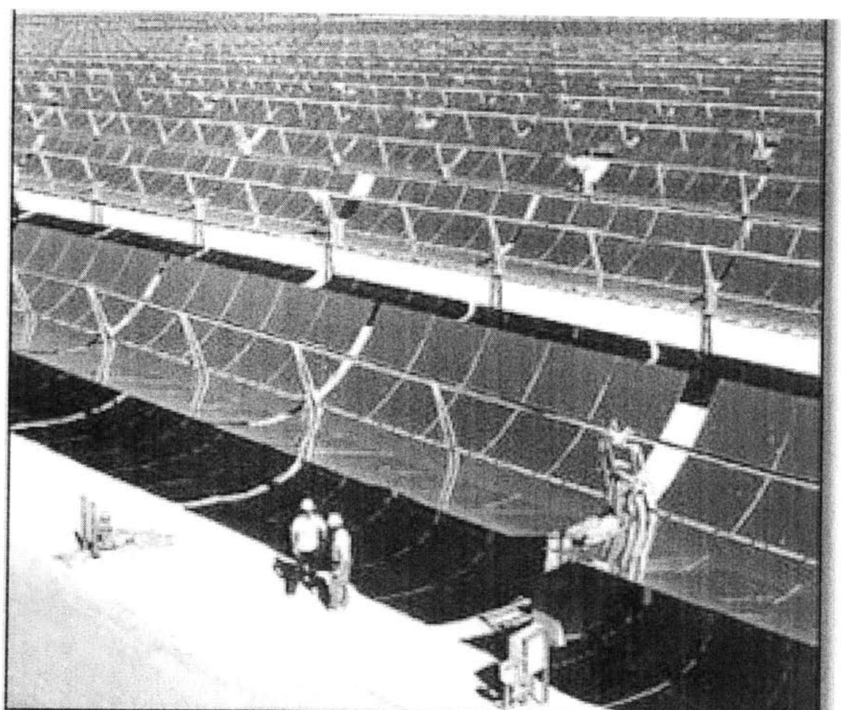

Figure 9: Picture of the parabolic collectors at an SEGS installation
Source: Department of Energy (United States)

Due to many different factors, the costs associated with parabolic trough concentrators can very significantly depending on the systems and installation sites used. Studies conducted for the World Bank[3] have shown an estimated total plant cost of $2971 per kW of total plant output for a 30 MW Rankine cycle trough concentrated solar power plant, installed in a developing country. These numbers are broken down further in figure 10.

Component	30 MW Rankine STPP	200 MW Rankine STPP	30 MW ISCCS (130 MW Total)
Site Works	158	57	156
Solar Field	1534	1184	1467
HTF System/Boiler	282	234	134
Power Block	493	279	247
Balance of Plant	287	162	287
Services	275	192	244
Land	11	10	10
Contingency	454	316	402
Total (U.S. plant)	3495	2384	3093
Discount in Developing Countries	-524	-365	-464
Total	2971	2026	2629
O & M Cost (¢/kWh)	2.3	1.1	1.15

Figure 10: Estimated Current Costs of Parabolic Trough CSP Plants (in $/kW of total plant output.)
Source: Enermodal Engineering Ltd./Marbek Resource Consultants Ltd.

[3] The World Bank hired Enermodal Engineering Ltd./Marbek Resource Consultants Ltd. To conduct the study to evaluate current and future cost reductions in solar thermal power technologies.

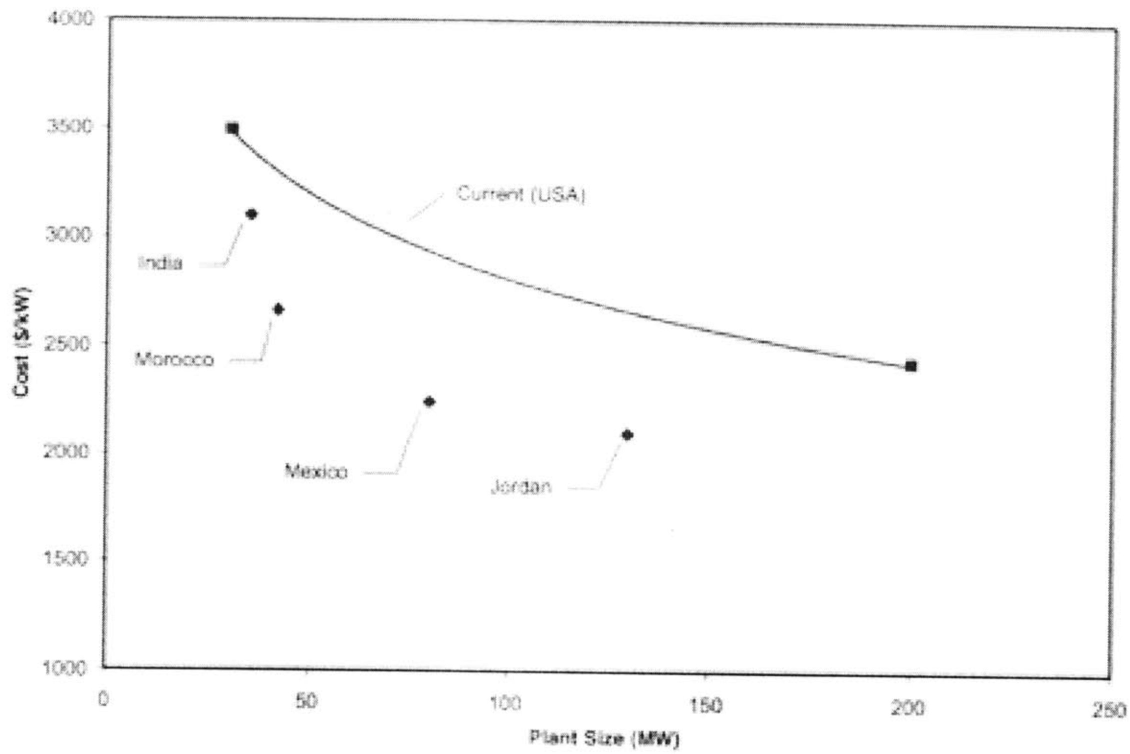

Figure 11: Estimates of Rankine-Cycle Solar Plant Specific Cost
Source: Enermodal Engineering Ltd./Marbek Resource Consultants Ltd.

Figures 10 and 11 show how the cost of a parabolic trough CSP power plant can vary significantly depending upon the plant's size and location. Extrapolating from the data given here it and assuming an exponential trend in cost per kW as the plant size decreases, it can be estimated that a small-scale parabolic trough solar plant using a steam turbine would cost approximately $18 million for a 3MW plant, $26 million for a 5 MW plant, and $55 million for a single 15 MW plant. This analysis shows the benefit of scale with the cost per kW decreasing significantly with size. The 3 MW plant costs $6167 per kW, the 5 MW $5258 per kW, and the 15 MW plant $3709 per kW. For 15

MW of each plant size, this translates into a total cost for the island of $93 million, $79 million, and $55 million respectively.

3.1.5 Linear Fresnel

Linear Fresnel collectors function in much the same way as the parabolic trough collectors except that instead of using a one large curved mirror to concentrate onto a receiving pipe, many smaller, flat or slightly curved, mirrors reflect sunlight onto a receiving pipe, or a smaller secondary parabolic reflector which then focuses the sunlight onto an insulated pipe. The proposed benefits are that the flatter mirrors can be cheaper to manufacture, and can be more tightly packed together allowing for a more efficient use of ground area as well as a higher concentration ratio.

The disadvantages to a system of this type are that the greater number of reflectors increases the complexity of the system, with each facet of the reflectors having to track the sun differently in order to focus onto the pipe or secondary reflector, and the need of a secondary reflector to help concentrate the sunlight decreases the optical efficiency of the system. Overall Linear Fresnel systems are still in the theoretical/experimental phase with a few small test installations having been installed by companies such as Asura Inc. Due to their developmental nature cost estimates are not yet available. A picture of one of their experimental setups is shown in figure 12.

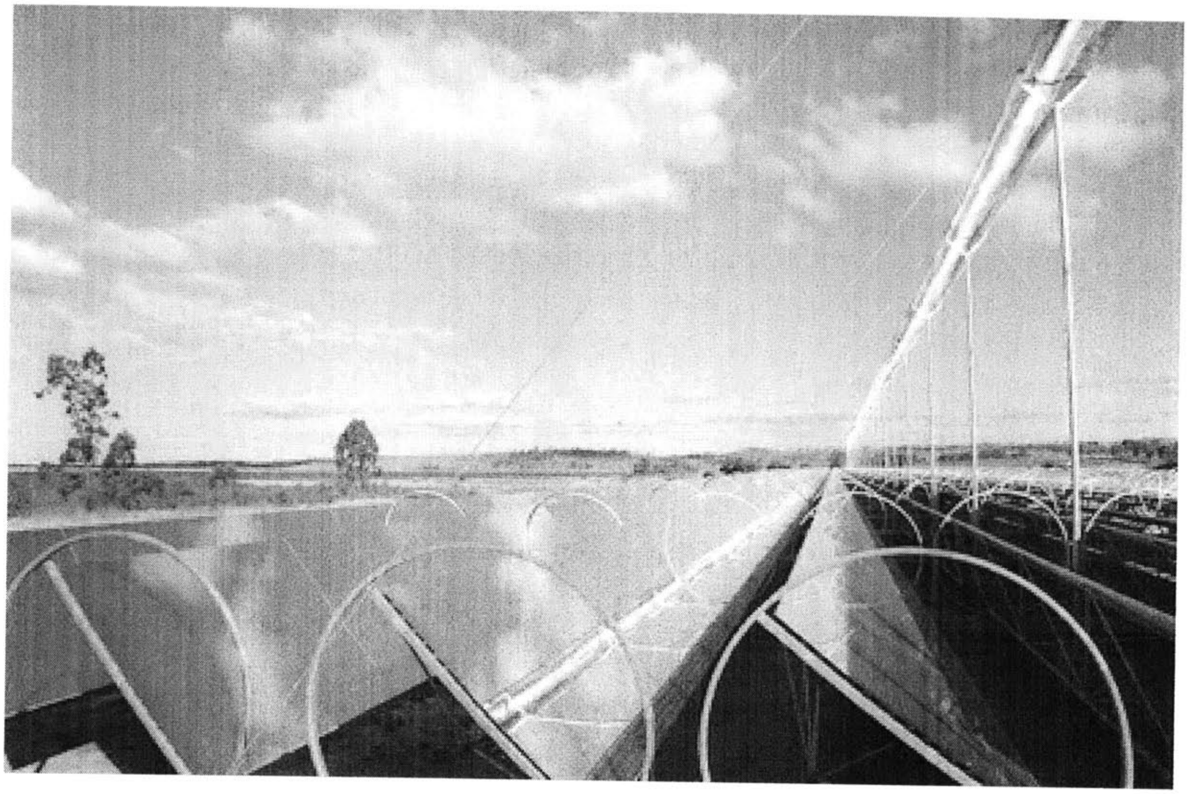

Figure 12: Linear Fresnel Solar Collectors
Source: Asura Inc.

3.1.6 Organic Rankine Cycle

Another technology that may have application for Roatàn but has not been used for solar power is that of organic rankine cycle turbines. These are turbines that are similar in principle to the steam turbines used in the current solar power plants, but instead of using water/steam as the working fluid, organic (hydrocarbon) compounds are used. The benefit is that the system can operate at lower temperatures and pressures. This translates into lower capital costs since less costly piping, valves, and turbine components can be used. The disadvantage is that the thermal efficiency decreases slightly. Organic rankine cycle systems are commonly used in geothermal systems where temperatures and power outputs are lower. No currently operational solar thermal power plants use this system to produce electricity, but it may have a cost advantage for the 3-5MW sized power plants that is preferred for this application. Further analysis and study is needed to confirm this but is it likely that at the 15MW scale the cost benefits will be outweighed the losses in efficiency. [4]

3.1.7 Central Receiver (aka "Power Tower")

The central receiver, also known as "Power Tower," has also seen some limited success with implementation at California's experimental Solar One and a new 11MW commercial installation in Seville Spain. The central receiver design consists of a field of mirrors mounted to individual heliostats designed to reflect the sunlight onto a central receiver placed near the top of a large central tower. By reflecting onto a single central point, the thermal and pumping losses of the fresnel and trough designs are reduced, and higher levels of concentration are achievable. The main difficulty associated with this concept is that the heliostats are very costly, they must very precisely track the sun through two axis to maintain focus on the tower, and dust or other airborne particles can reduce the optical efficiency of the heliostats reflecting light onto the receiver tower.

The tower is the structure that houses the receiving absorber and transmits the thermal energy to the rest of the plant's components. The thermal tower plants currently in operation convert their thermal energy into electrical energy using the same rankine cycle that the parabolic trough plants use. However, the higher concentration ratios achievable with the thermal towers allow for a higher temperature in the heat transfer fluid (up to 1000°C instead of 350°C). This helps to increase the plant's solar to electrical energy conversion efficiency with peak efficiencies reaching up to 23-25% (compared to 20% in parabolic trough plants). [14] These higher temperatures might also allow for an even greater increase in plant efficiency if the hot gas can first be used to power a brayton cycle turbine before the "waste heat" is used to create steam and run a rankine cycle turbine. Such a combined cycle plant, (similar in concept to current combined cycle gas power), is still in the experimental phase but a small combined cycle plant is currently being build by Abengoa Solar at the Seville site for testing.

The cost of a small thermal tower designed for the island of Roatàn is difficult to estimate due to the small number of such plants in operation. However, the World Bank cost study[4] lists the cost of building a 100MW central receiver power plant as $3,270 and 19% lower at $2,660 in developing countries. The break down of the estimated costs involved in a 30MW central receiver power plant is shown in Figure 14. Extrapolating from these two estimates we can roughly estimate that the installation costs of a central receiver solar thermal power plant using the rankine cycle with the capacities of 3MW, 5MW, and 15MW are $4,806 per kW, $4762 per kW, and $4541 per kW respectively. For 15 MW of each plant size, this translates into total costs of, $14

[4] The World Bank hired Enermodal Engineering Ltd./Marbek Resource Consultants Ltd. To conduct the study to evaluate current and future cost reductions in solar thermal power technologies.

million, $24 million, and $68 million respectively. Using this method to calculate the costs of an 11MW plant gives an estimate that is within 5% of the actual estimated costs for the PS10 plant in Seville Spain[5]. It should also be noted that the estimates include the cost of approximately 6.5 hours of thermal energy storage.

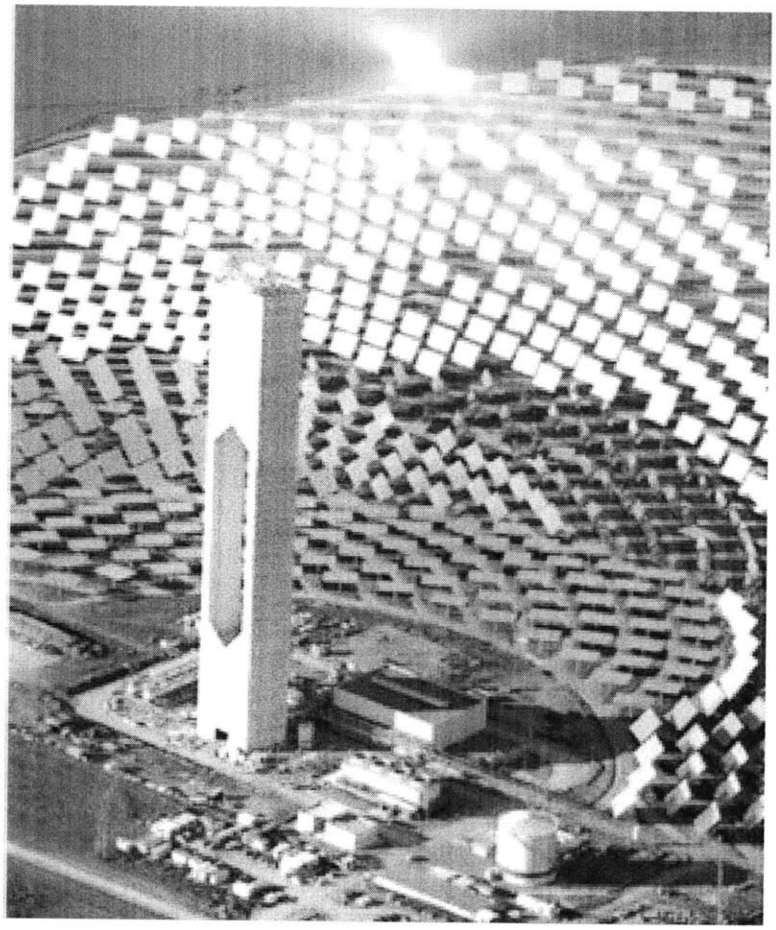

Figure 13: Photo of the PS10 installation in Seville Spain.
Source: Abengoa Solar

[5] I estimated the installation cost of an 11MW central receiver plant to be $50 million; actual cost was 35 million euros [15]. Using the conversion rate of 1.36 euro to dollar, from the end of 2004 (when the plant was completed), gives an estimated error of 4.8%.

Component	30 MW C.R. Rankine SEGS	30 MW C.R. ISCCS (130 MW Total)
Site Works	117	117
Heliostats & Tower	2267	2267
Thermal Storage	420	420
HTF System/Boiler	177	177
Power Block/ Balance of Plant	933	450
Services	391	343
Land	11	10
Contingency	646	566
Total (U.S. plant)	4950	4339
Discount in Developing Countries	-744	-650
Total	4209	3689
O & M Cost (¢/kWh)	2.6	1.6

Figure 14: Break down of estimated costs for a 20 MW central receiving solar thermal power plant.
Source: Enermodal Engineering Ltd./Marbek Resource Consultants Ltd.

3.2 Energy Storage

Large-scale multi-day energy storage, as is needed for the Island or Roatàn, is a design challenge that has not been addressed within national power grids. Most power grids meet demand primarily by throttling fossil fuel powered plants to meet demand and using some short term energy storage methods to help smooth fluctuations in demand. Examples of these short-term energy storage methods include the large Ni-Ca battery banks in Fairbanks Alaska that are designed to supply 27MW for 15 minutes and the practice of pumping water into a reservoir to be used during off peak hours.

For solar power to be used as the only source of electrical power generation the storage capacity of a solar power plant must be very large relative to its generation capacity to continue to output power throughout the night and during extended periods of cloudy or poor weather. There are countless different technologies that can be used to store large amounts of energy but for this evaluation, a few of the most promising will be evaluated. Two forms for large-scale energy storage that might pair well with a decentralized PV or dish-stirling solar plant on the island of Roatàn are mechanical (flywheel) and electro-chemical (battery) storage.

3.2.1 Electrochemical Systems

3.2.1.1 Lead Acid

There are a number of battery chemistries that might be used as an energy buffer to supply power throughout the night and during periods of low solar insulation. The most common of which are lead acid batteries. Commonly used in car batteries, the cost of energy storage in lead acid batteries currently hovers at around $150 per kWh[6]. For a first order estimate the Island of Roatàn would need to store at least 12 hours worth of electricity to power the island day and night off of solar energy alone. On average this works out to storing about 82MWh, at a price of approx $12.3 million.

This number may not be unreasonable, but it assumes a 100% discharge of the pack. Discharging lead acid batteries to this level adversely affects their life span, at a near 100% discharge the life span of a lead acid battery is only a mere ~350 cycles. Meaning the batteries would need to be replaced on a yearly basis. To avoid this the pack would need to be oversized. If the pack was oversized by a factor of 4 allowing for 2 days worth of energy storage and a typical nightly discharge of about 25% the life span would increase to nearly 2000 cycles or ~5.5 years. At a cost of nearly $50 million and

[6]Commercially available quotes from http://www.alibaba.com

needing to be replaced every approximately 5.5 years (which works out to about $272 million if the plant has a 30 year lifespan) lead acid batteries are not an attractive means of utility scale energy storage when relatively deep discharge cycles are needed.

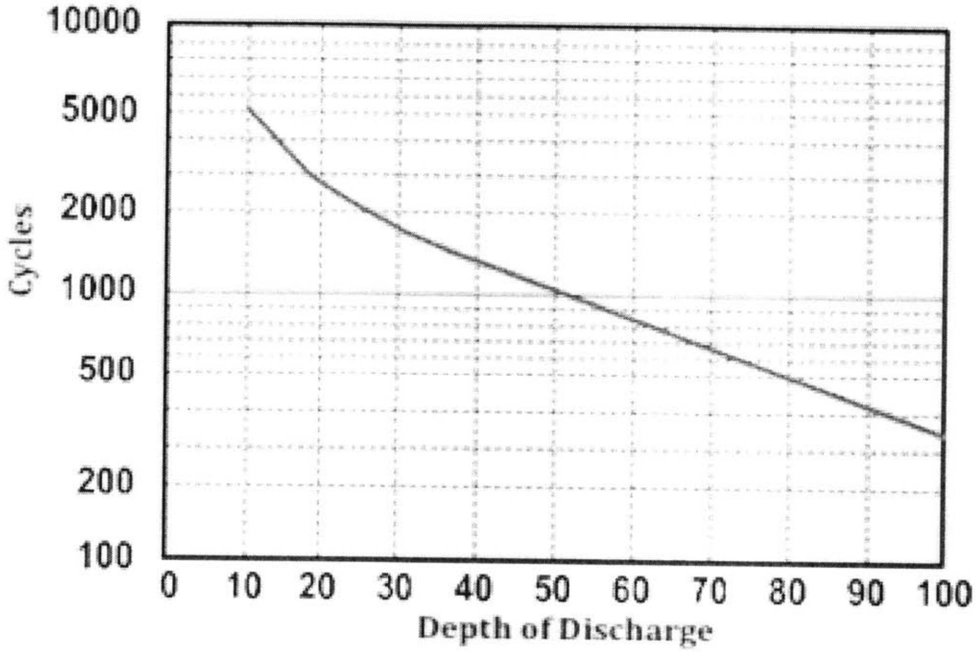

Figure 15: Cycle life of lead acid batteries vs. depth of discharge
Source: http://www.windsun.com/Batteries/

3.2.1.2 LiFeP04

A second battery chemistry that might be better suited to this application is that of Lithium Ion batteries, specifically LiFeP04. Lithium Iron Phosphate batteries can have cycle lives in the thousands with little reduction in cell capacity. The cycle life shown in the chart is that of a 3.2V 200Ah prismatic battery made in china by the Shandong HiPower Energy Group. This cell is currently available from online retailers at the price of $367 per kWh[7]. This is the quoted price for small quantities through retailers; an

[7]Commercially available quotes from http://www.evequipmentsupply.com

order of the quantity needed for this application would almost certainly come with a price reduction. Assuming that the price is $300 per kWh, and with the same 2 day capacity 25% nightly discharge, a pack made from these cells would cost $98 million.

High cycle life data beyond 1000 - 2000 cycles on LiFeP04 cells is very limited, but assuming a roughly linear depreciation in capacity, the cells should have a life span of nearly 15000 cycles before being unable to store enough energy to power the entire island through a 12 hour period. This estimate is also conservative since the pack is initially only being discharged to 25% depth of discharge instead of the 100% depth of discharge used in the test. This translates into a lifespan of nearly 40 years of daily charge/discharge cycles, bringing the per year cost of the batteries to $2.3 million.

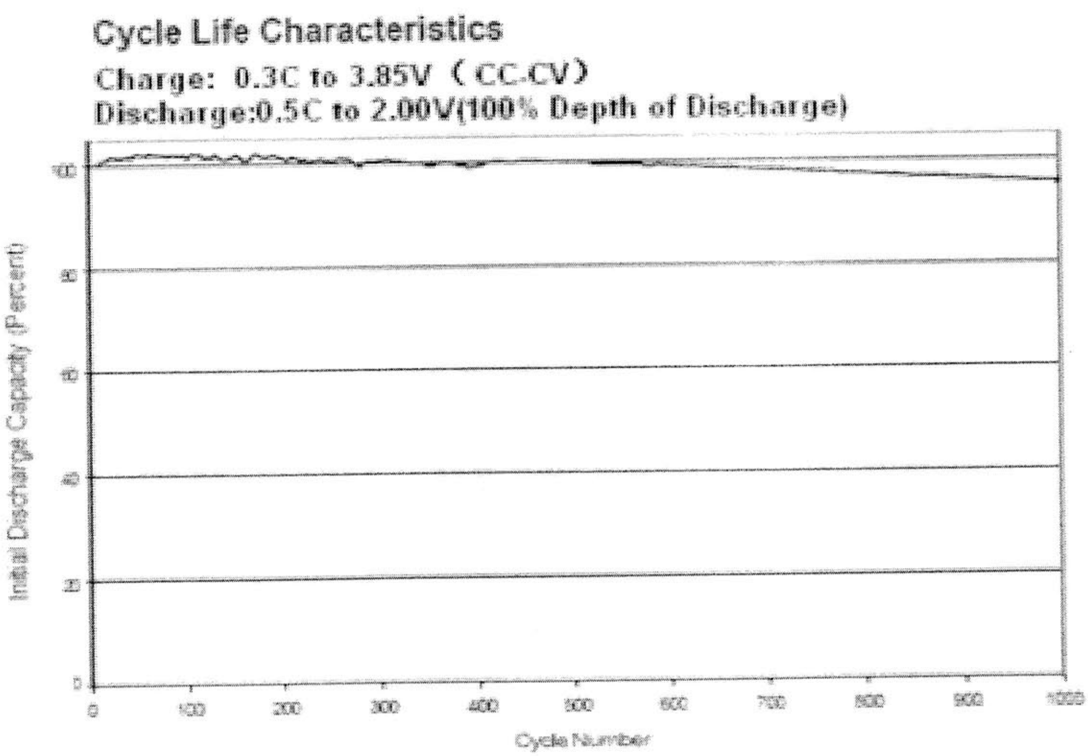

Figure 16: Cycle life of a 200Ah LiFeP04 prismatic cell battery.
Source: Shangdon HiPower Energy Group

3.2.1.3 Flow Batteries

Flow batteries are a means of energy storage similar in principle to lead acid and lithium ion batteries, with the exception that their chemical reactants are stored in separate tanks and pumped through a separate electrochemical cell where the chemical reaction takes place allowing the release of electricity. The external storage of the reactants allows for great economies of scale, the tanks can simply be sized up for greater storage capacity, or similarly the reactive cell can be sized up for greater power output. The physical separation of the reactants also prevents self-discharge over time and aids in increasing the life of the battery. There are a number of companies building and marketing utility scale flow battery systems including the Premium Power Corporation and the ZBB Energy Corporation.

Currently the flow battery providing the most economical means of large-scale energy storage is that of Zinc-Bromide (ZnBr) Flow Batteries. ZnBr flow batteries are relatively inexpensive and can provide energy storage at the cost of approximately $230 per kWh and $300 per kW [16], while having a no limits to the number of cycles the system can withstand during its estimated 30 year lifetime. These estimates include estimated costs for balance of the system and accessory components needed for their operation. Additionally, not having a limited cycle life, and the decoupling of the reactant storage and the electrochemical cell, allows the system to be sized appropriately for the demand at hand without the need for extensive reserve capacities. Using these estimates a system capable of supplying the island with enough electricity for an

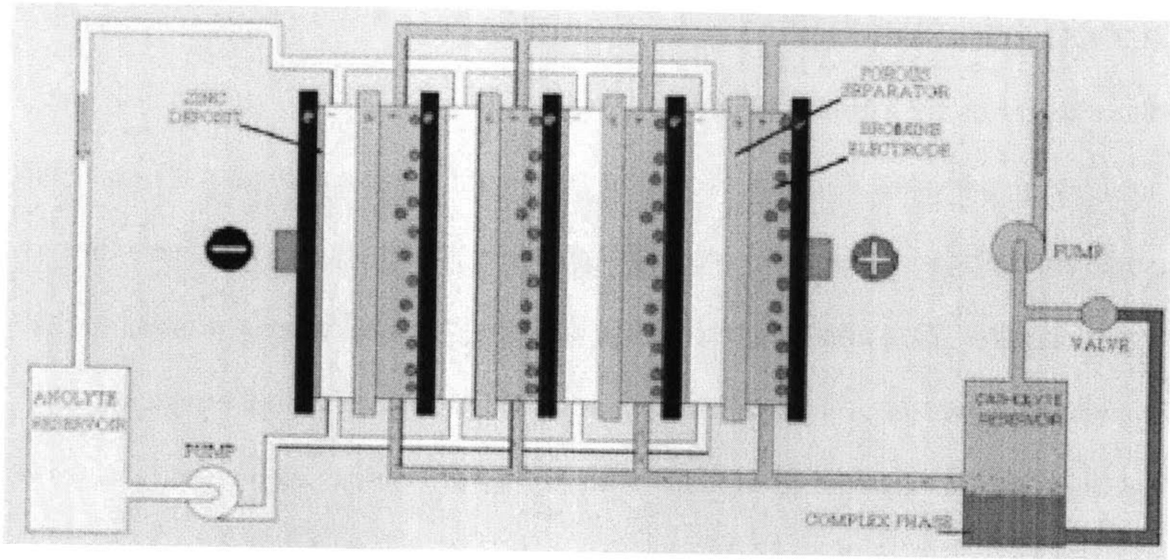

Figure 17: Example diagram of a ZnBr Flow battery system.
Source: http://www.zbbenergy.com/

average two-day period at a peak demand of 15MW[8] would cost approximately $80 million.

3.2.2 Mechanical Systems

Mechanical energy storage systems function by storing energy in the form of kinetic (flywheels) or potential energy (pumped hydro). The island of Roatàn lacks any large mountains or water reservoirs and as a result the only mechanical system that is technically feasible for the island is that of mechanical flywheels. Flywheels are commonly and very effectively used as a form of short-term energy storage and grid support. Companies such as the Beacon Power Corporation, supply and support farms that supply utility scale short-term utility scale energy storage, but high capital costs

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[8] 15MW is an over estimate, allowing for future growth and providing power during peak demand. A system primarily used to provide power at night could get by with significantly less.

and energy losses associated with longer-term energy storage (~24hrs) [11] with these systems means that they are not a viable option for the Island of Roatàn.

3.2.3 Thermal Energy Storage Systems

Unlike, PV or Dish-Stirling power plants, CSP power plants operate using a centralized rankine cycle generator. In these systems all of the thermal energy collected by the plant must be transferred to the steam turbine using a heat transfer fluid. This has the potential to provide a very inexpensive means of energy storage. By simply diverting the hot fluid and storing it in thermally insulated tanks the energy can be stored in the form of heat with minimal investment in storage systems. Thermal energy storage has already been tested at a number of solar power plants including the SEGS locations and the newer power plants in Seville Spain.

The SEGS and Seville systems utilized a two-tank system where cold fluid is stored within one tank before being pumped through the collector array and being stored inside a different insulated tank until it was needed to generate steam. These systems are capable of providing enough thermal energy storage for two hours of plant operation in the SEGS system and up to six hours of operation at the Seville installations. Their success has proven the feasibility of such concepts and demonstrated a thermal efficiency of greater than 99%. [17] The integration of thermal storage is relatively straightforward with the energy capacity being dependant upon the tank size, fluid heat capacitance, and fluid temperature, with higher temperatures giving a greater energy capacity for a given tank size, but often requiring a more expensive thermal storage fluid that can withstand the sustained higher temperatures.

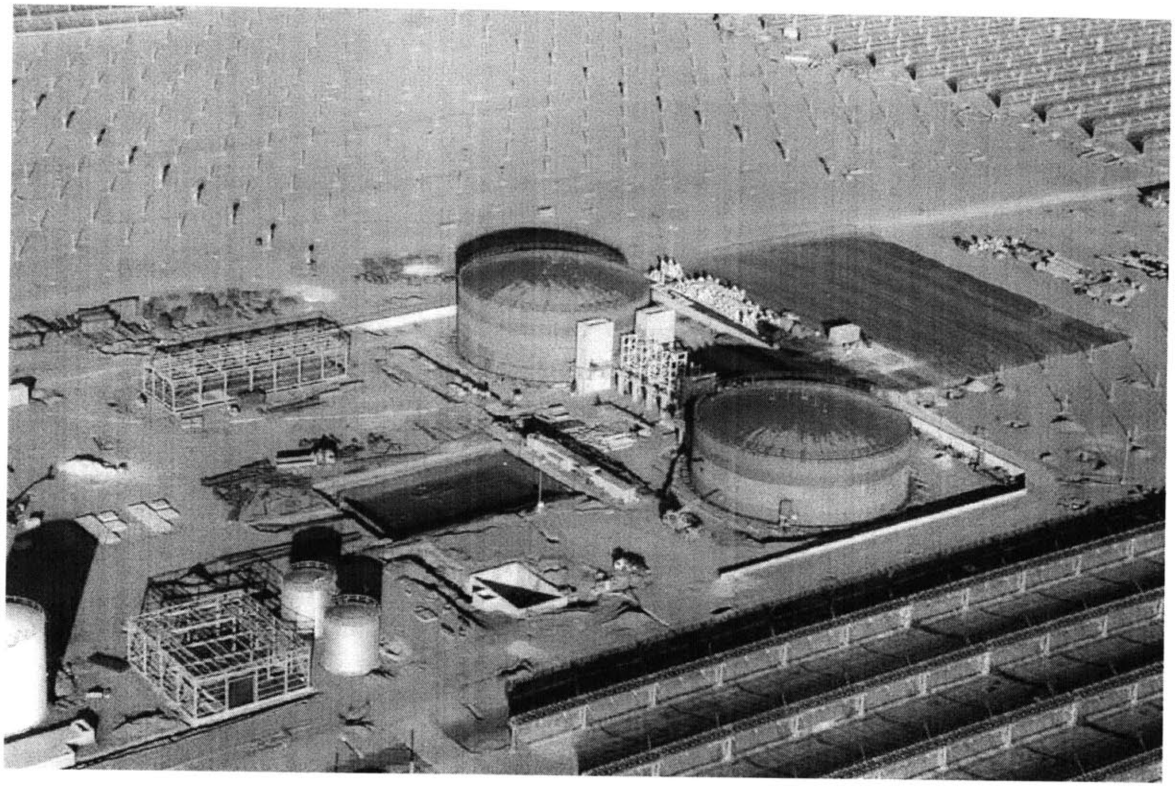

Figure 18: Picture of the two molten salt storage tanks at the Andasol solar power plant.
Source: Scientific American Magazine

The recently installed Andasol solar power station, which went online in 2009, is a 50MW parabolic trough solar power plant that was designed to utilize a twin tank thermal energy storage system. It uses molten salt to store up to 1,010MWh_t of thermal energy. At the time of construction it cost roughly $50 per kilowatt-hour to install, according to NREL's Glatzmaier. [7] Using this estimate and a predicted steam to electricity conversion efficiency of 37%,[9] the expected cost of a thermal storage system

[9] 37% is the approximate steam to energy conversion efficiency experienced by the SEGS Solar Parabolic Trough power plants. [17]

being added onto a parabolic trough CSP plant with enough capacity to power Roatàn for two average days would cost around $13million, and store 267 MWh_t of energy.

4. Conclusions

A summary of the cost estimates for all of the currently commercially available technologies solar power generation technologies is shown in Figures 19 and 20.

Cost Estimates ($ Millions)			
Power Plant Type	**3MW**	**5MW**	**15MW**
Photo Voltaics	20.9	34.8	70
Parabolic Trough	18	26	55
Central Receiver	14	24	68
Energy Storage Type	**Cost of 2 Day Capacity**	**Notes:**	
Lead	272	30 year lifespan	
LiFeP04	98	40 year lifespan	
ZnBr	80	30 year lifespan	
Thermal (2 Tank Molten Salt)	13	N/A	

Figure 19: Chart of estimated installation costs for commercially available solar power generation technologies, and large-scale energy storage.

This first order analysis shows that there is a significant difference in the cost of implementing the varyous energy storage methods. For the use of photovoltaics, ZnBr flow batteries are potentially the best means of storing enough energy to run the Island off of solar power alone. Especially since the number used to calculate the costs of the LiFeP04 cells does not include any balance of system or structural costs while the numbers quoted for the ZnBr system do.

The significantly lower cost of the thermal energy storage system, reletive to the other systems, indicates that regardless of other factors which may have been excluded in this analysis, a concentrated thermal power system is the most cost effective method to choose to generate power for Roatàn. All of the technologies evaluated here are technically capable of meeting the functional requirements for the island, and when connected to a large established grid it seems that on the small to medium sized scales evaluated here, that the three technologies are on a relatively even playing field. The 3-15MW power range is very small when compared to most operational parabolic trough power plants, which are most economical in the 100's of MWs. For Roatàn's application it is the large amount of energy storage needed that makes the thermal power plants the most feasible option.

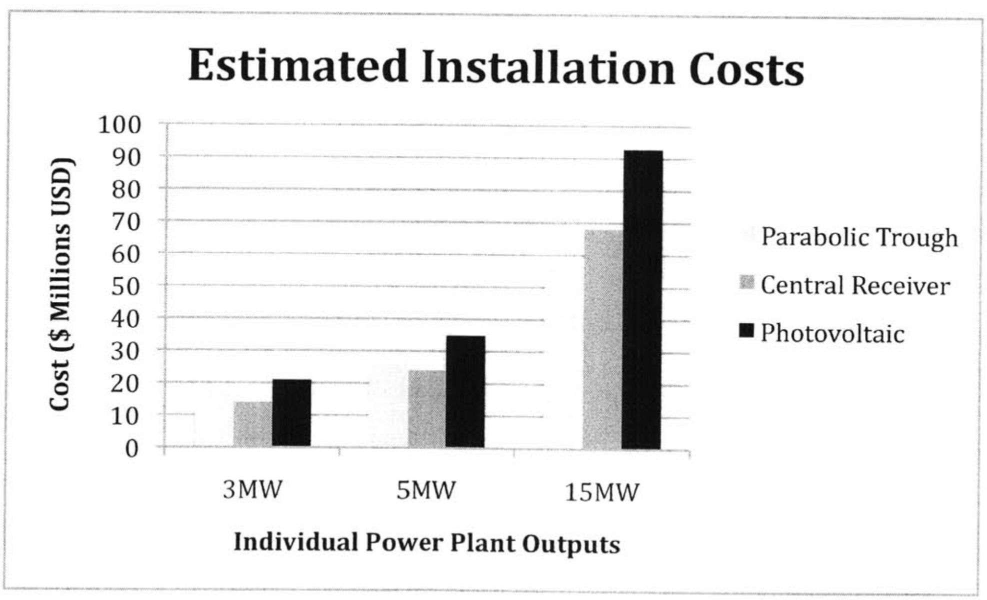

Figure 20: Comparison of the three commercial technologies evaluated.

The results of this analysis show that the design should continue with one of the solar thermal concepts. Since, both are relatively close in terms of costs a more detailed analysis of component specific costs will need to be conducted. It may also be beneficial to include some of the newer experimental components such as using linear fresnel reflectors, organic rankine cycle turbines, and potentially new thermal storage ideas such as single-tank thermocline systems. The experimental components present opportunities for increased efficiencies and reduced costs but incorperate greater risks and may require a partnership with the companies exploring these technologies.

Another insight to take away from this analysis is that for thermal solar power plants capacity matters significantly, with the 15MW plants costing significantly less per kW than multiple 3 or 5MW plants. This indicates that, if the finances can be raised and Roatàn's final goal is to be completely solar powered, it would be most beneficial to use a centralized 15MW plant instead of several dispersed plants and invest the saved money into improving the grid. This will also save costs in yearly operations and maintinence bills, as more parts and operators will be needed to operate and service multiple small plants as opposed to a single larger installation.

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Appendix:

Table 1: Global Solar Power Generation

	Solar PV (Grid-Connected)	Solar Thermal (CSP)	Total Capacity
2004	1.8	0.4	2.2
2005	3.1	0.4	3.5
2006	5.1	0.4	5.5
2007	7.6	0.44	8.04
2008	13	0.5	13.5
2009	21	0.7	21.7
	Rounded to nearest .1GW		

Table 2: Comparison of Solar Thermal Plant Technologies

	Parabolic Trough	Power Tower	Dish Engine
Size	30-320 MW*	10-200 MW*	5-25 kW*
Operating Temperature (°C/°F)	390/734	565/1,049	750/1,382
Annual Capacity Factor	23-50%*	20-77%*	25%
Peak Efficiency	20%(d)	23%(p)	29.4%(d)
Net Annual Efficiency	11(d')-16%*	7(d')-20%*	12-25%*(p)
Commercial Status	Commercially Available	Scale-up Demonstration	Prototype Demonstration
Technology Development Risk	Low	Medium	High
Storage Available	Limited	Yes	Battery
Hybrid Designs	Yes	Yes	Yes
Cost			
$/m^2	630-275*	475-200*	3,100-320*
$/W	4.0-2.7*	4.4-2.5*	12.6-1.3*
$/W$_p$ †	4.0-1.3*	2.4-0.9*	12.6-1.1*

* Values indicate changes over the 1997-2030 time frame.

† $/W$_p$ removes the effect of thermal storage (or hybridization for dish/engine). See discussion of thermal storage in the power tower TC and footnotes in Table 4.

(p) = predicted; (d) = demonstrated; (d') = has been demonstrated, out years are predicted values

Table 3: Power Demands – Roatàn

Year	Month	Peak hour	Max (KW)	Monthly Consumption (KWh/Month)
2008	January	19:00	9,630	N/A
	February	19:00	9,760	N/A
	March	19:00	9,760	N/A
	April	15:00	9,540	N/A
	May	19:00	10,050	N/A
	June	19:00	11,220	N/A
	July	19:00	10,780	N/A
	August	19:00	11,350	N/A
	September	19:00	11,200	N/A
	October	19:00	10,210	N/A
	November	19:00	9,844	N/A
	December	19:00	10,501	N/A
2009	January	19:00	10,580	38,352
	February	19:00	10,040	38,383
	March	12:00	11,580	38,411
	April	19:00	11,807	38,442
	May	19:00	11,750	38,472
	June	13:00	12,030	38,503
	July	14:00	11,800	38,533
	August	14:00	11,390	38,564
	September	19:00	12,295	38,595
	October	19:00	11,400	38,625
	November	19:00	11,100	38,656
	December	18:00	11,940	38,686
2010	January	19:00	10,981	38,717
	February	12:00	11,800	38,748
	March	19:00	11,950	38,776
	April	14:00	13,292	38,807
	May	19:00	12,450	38,837