

Cost Benefit Analysis of Implementing a Solar Photovoltaic System

Krishpersad Manohar¹, Rikhi Ramkissoon², Anthony Adeyanju³

Senior Lecturer, Department of Mechanical and Manufacturing Engineering, The University of the West Indies,
St. Augustine, Trinidad, West Indies¹

Ph.D. Candidate, Department of Mechanical and Manufacturing Engineering, The University of the West Indies,
St. Augustine, Trinidad, West Indies²

Senior Lecturer, Department of Mechanical Engineering, Ekiti State University,
Ado-Ekiti, Nigeria³

ABSTRACT: An environmental cost benefit analysis (ECBA) was used to determine the feasibility using solar photovoltaic (PV) as an alternative power source. The capital investment cost and the cost of externalities such NO_x and CO₂ emissions from a natural gas power generation process were valued. The environmental impact of treating waste water was valued based on Cost–Benefit Analysis Using Data Envelopment Analysis. The ECBA results indicated that using solar photovoltaic modules is a feasible option and is comparable to the existing conventional grid power mode of operation. The difference between the present value of benefits of using the PV grid tied system and that of using conventional grid power supply was 4.5% for the WWTP. Due to the highly subsidised price of electrical power in Trinidad and Tobago the payback period analysis showed 32.9 years and 86.8 years for the grid tied and standalone PV system, respectively.

KEYWORDS: Solar Energy, Photovoltaic, Cost Benefit Analysis, Waste Water Treatment.

I. INTRODUCTION

Renewable energy can be defined as energy flows which are replenished at the same rate as they are “used” [1]. Types of renewable energy include solar photovoltaic, solar thermal, geothermal, wind and hydro-electric, although different technologies which utilize natural sources are emerging at a rapid pace. In this study, the use of solar photovoltaic systems will be investigated as the main types of renewable energy for powering a waste water treatment plant (WWTP). The island of Trinidad, located 10° 40'N latitude and 61° 30' W longitude, lies very close to the equator. This location affords great potential for harvesting solar energy throughout the year as there is minimal reduction in solar intensity at any time due to seasonal changes. The components, design and installing of a solar photovoltaic system is influenced by the electrical equipment to be powered. Different equipment requires different voltages, current and power. These variables ultimately determine the design and choice of the other components of the system. In this study the advantages and disadvantages of using solar photovoltaic was explored as it pertains specifically to domestic wastewater treatment in Trinidad. Generally, the major advantages of using renewable energy are reduced annual energy costs, reduced environmental impact (since renewable energy technologies usually produce little to no pollutants during their operation) and increased sustainability as a result of fewer pollutants [2]. Major disadvantages include site restrictions, high initial capital investment and limitations on power generation potential. In recent times installations of renewable energy systems can be seen in several areas throughout Trinidad & Tobago. The capacity range from small 10 W PV or wind installations to 5.1 kW residential PV systems [3]. Government-funded pilot projects have also been undertaken such as the 2 kW PV arrays in both the University of Trinidad & Tobago and

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

Trinidad Electricity Commission (T&TEC) compounds [4]. To date, there have not been any installations as large as the system which would be required for the WWTP.

II. PHOTOVOLTAIC SITE OVERVIEW

The wastewater treatment plant (WWTP) at Orangefield, Trinidad, was chosen for this study. Currently this plant treats 309 m³ of domestic sewage from 11,000 persons daily using a Completely Mixed Activated Sludge (CMAS) process. Domestic waste from households and schools within the vicinity flow by gravity to the intake or wet well located next to the treatment plant. Fig.1 shows the wet well of the WWTP. Physical site dimensions measured included length and width of the WWTP compound as well as the height of all buildings, trees and other potential obstructions located on and around the compound.



Fig. 1. Wet well (intake) of the Orangefield waste water treatment plant

III. ELECTRICAL POWER REQUIREMENT

Presently, the WWTP is powered 100% from the grid. The main power consumption apparatus in the plant are pumps and blowers. In the wet well, 2 horizontal centrifugal pumps, each powered by 1 US Electric 7.5 horsepower motor, automatically alternate to transfer wastewater to the aeration chamber. The pumps are controlled by a waterproof electrical switch installed in the water intake well which floats on top of the wastewater. When the water reaches a pre-determined height, raising the float with it, the level system automatically switches on 1 of the pumps which transfers the wastewater to the aeration chamber in the WWTP approximately 30m away. In the aeration chamber, oxygen is introduced into the raw sewage by means of 2 Roots Model U-RAI 56 Rotary Lobe Blowers (Fig. 2), each individually powered by 1 Westinghouse 20 horsepower motor [5]. The blowers also provide the necessary vacuum suction to transport the undigested organic settled solids (the Return Activated Sludge) from the clarifier chamber to the aeration chamber [5]. All other auxiliary power needs such as lighting and potable water pumps were also supplied from the grid. Therefore, using the average readings of energy consumption from the bimonthly Trinidad and Tobago Electricity Commission (T&TEC) bill over a one year period proved to be the most accurate way to determine the overall energy consumption of the WWTP. This data was essential for predicting the energy requirements for an alternative power system before doing an upgrade. The average bimonthly consumption (60 days) was calculated as 10,500 kWh and the average bimonthly cost including all taxes was TT\$ 5000 or TT\$ 0.476 per kWh. This is a highly

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

subsidise price and is one of the lowest rate in Latin America [6]. For a 24 hour period the power consumption for the WWTP was 175 kWh



Fig. 2. Inside of the blower house, showing blower #2 and the air outlet pipe leading to the treatment plant

IV. AVAILABLE SOLAR ENERGY

At the site location the average daily temperature was recorded using an *Ambient Weather WS-2080* Weather Station. The thermometer of the *WS-2080* was compared to a calibrated thermometer to ensure accurate readings were obtained. Data was recorded at 1 hour intervals by a data-logger stored on site and retrieved weekly [7]. Average daily and monthly temperatures were then calculated. A pyranometer on a flat surface and voltmeter were used to record irradiance readings at 5-minute intervals over a 24-hour period for one month. Fig.3 shows a sample graph of the variation in insolation measured at the site. On this day the insolation at the site was 5.41 kWh/m^2 . The insolation data was compared to values based on readings from the USA's National Aeronautics and Space Administration's (NASA) satellites for central Trinidad over the same time period (the month of May). The monthly insolation values were within 3% of the average NASA readings collected from 1983 – 2005 for central Trinidad (Table 1) [8].

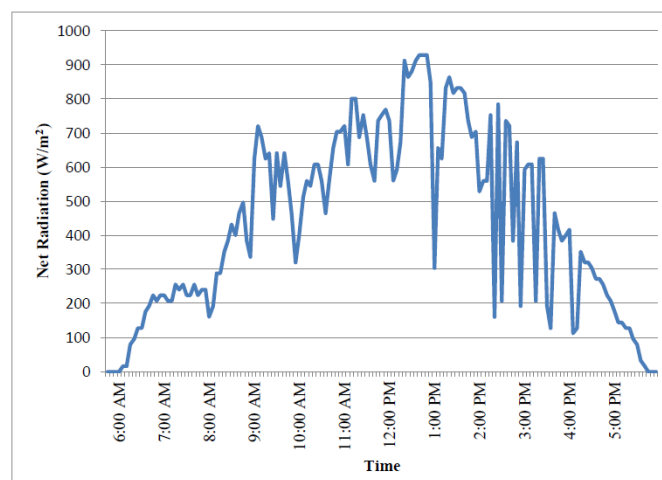


Fig.3. Graph Showing Site Irradiance Values at the Orangefield WWTP

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

Table 1: Summary of Monthly Insolation Values

| Month | Insolation (kWh/m ² /day) | |
|-----------|---|----------|
| | NASA | Adjusted |
| January | 6.3 | 5.73 |
| February | 6.38 | 5.81 |
| March | 6.27 | 5.71 |
| April | 5.88 | 5.35 |
| May | 5.89 | 5.36 |
| June | 5.51 | 5.01 |
| July | 5.73 | 5.21 |
| August | 5.73 | 5.21 |
| September | 5.68 | 5.17 |
| October | 5.73 | 5.21 |
| November | 5.49 | 5 |
| December | 5.89 | 5.36 |

V. SHADE ANALYSIS

The cost-effectiveness of a PV system depends crucially on positioning its solar array to capture as much sunlight as possible [9]. Shading of a single cell connected in series in a module can cause multiple problems including dissipation of power, cracking, overheating, melting of solder or damage to the encapsulating material [9]. This problem is termed hotspot formation. The same occurs on a larger scale, that is, a single shaded module in an array can cause significant power dissipation from the entire array due to hotspot formation. It is therefore important to reduce the formation of shadows on PV modules, especially shadows caused by permanent objects such as nearby trees and buildings. As such, shade analyses were conducted at potential solar panel locations on the compound. In addition, the available area and average temperature at the site were determined [10].

To determine the potential for recurring shadows, solar shade analyses, including sun charts, were conducted at several locations on the site. Locations were chosen based on available area and potential for shade development by surrounding obstructions. Theodolite surveying software package which allowed measurement of azimuth, horizon angle, elevation angle and photographic capturing of the horizon were employed. The shade analysis conducted revealed a potential loss of 0.35% of insolation due to shading at this location. The site survey showed that 4606m² of land space was available within the compound of the Orangefield WWTP. However, not all of the available land was suitable for placing solar modules due to shading. From the site survey carried out, location A shown in Fig.5 was the most suitable location for placement of the solar PV panels.

Another factor to be considered is the ambient temperature since the performance efficiency and by extension the power generated by a PV panel is temperature dependent. Ambient outdoor temperature at the site had a monthly average of 27.8 °C, with minimum and maximum monthly averages of 26.2 °C and 29.2 °C, respectively. The minimum and maximum daily temperatures recorded were 22.0 °C and 36.1 °C, respectively. Therefore, the design of the system was based on the maximum ambient temperature of 36.1°C.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

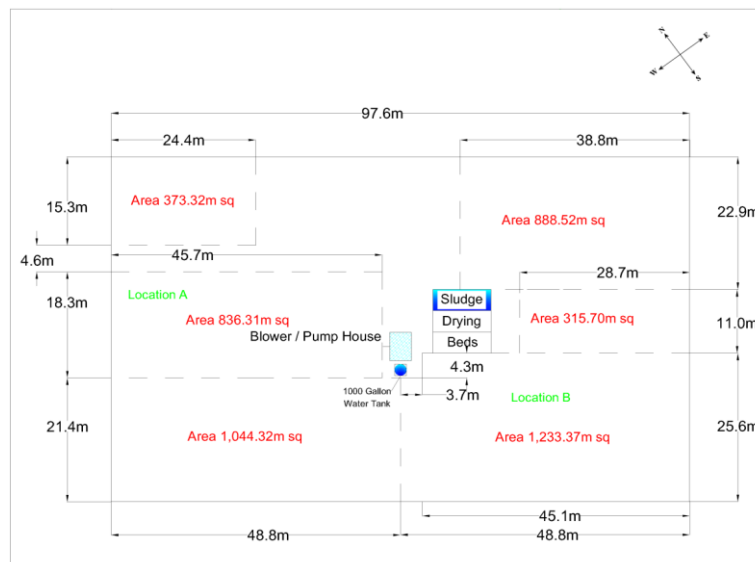


Fig. 5. Plan of Orangefield WWTP Showing Dimensions and Proposed Installation Location of the Solar PV System

VI. PHOTOVOLTAIC (PV) SYSTEM REQUIREMENT

Sizing the PV system was based on the daily energy requirement of 175 kWh and an insolation value of 5.49 kWh/m²/day for a 5 hour period per day. This was the lowest monthly insolation observed in November [8].

| | | |
|--|--|------------|
| Required PV Power Capacity | = 175 kWh/5 hours | = 35 kW |
| Adjusted PV Power required for Trinidad location | = 35 kW + (-0.05 x 35 kW) | = 36.75 kW |
| Estimated Solar panel temperature | = 36.1°C x 1.2 | = 43.3°C |
| Power loss due to temperature | = (43.3°C – 25°C) x 0.005 x 36.75 kW | = 3.36 kW |
| Power loss from DC to AC conversion | = 36.75 kW x (1 – 0.9) | = 3.68 kW |
| Mismatch loss | = 36.75 kW x (1 – 0.95) | = 1.84 kW |
| Dust and impurity losses | = 36.75 kW x (1 – 0.93) | = 2.57 kW |
| PV System Size | = 36.75 kW + 3.36 kW + 3.68 kW + 1.84 kW + 2.57 kW | = 48.2 kW |

The number and type of solar panels were sized for a 49 kW non tracking system with a design life of 25 years [11]. Monocrystalline solar panels with a rated efficiency of 17%, 25 years life, 300W STC Rated Power (Factory Standard Test Conditions) and 280 W PTC Rated Power (Photo Voltaic USA Test Conditions) were selected. A total of 175 panels were required at a unit cost of TT\$ 2058 resulting in a capital investment of TT\$ 360150.

A 50 kW inverter rated at 96.7% efficiency at a cost of TT\$ 146737 was selected. Based on the average of three quotations from licensed contractors the cost for installation including material (concrete, electrical material and wiring) was a total of TT\$ 57000. The system was designed to feed into the grid when producing surplus power and feed off the grid when needed. Therefore, the system should have a net zero power consumption from the grid. This design eliminated the need of a battery bank for storage that was estimated at TT\$240000 with battery life of 7 years. However, with a standalone system there will be need for four sets of batteries costing by simple analysis TT\$ 960000. The annual operation and maintenance cost is estimated as 0.2% of the photovoltaic modules cost and increases at a rate of 10% each year for 25 years with an annual discount rate of 8%.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

$$\text{Present value for operation and maintenance for 25 years} = \frac{720.3}{0.02} \left[1 - \left(\frac{1.1}{1.08} \right)^{25} \right] = \text{TT\$ } 20963$$

VII. ENVIRONMENTAL COST-BENEFIT ANALYSIS (ECBA)

Environmental cost-benefit analyses (ECBA) are used for the social evaluation of investment projects and policies that involve significant environmental impacts [12]. The term “environmental impact” is used to include both positive and negative effects of a project. Although difficult, economic valuation of these environmental impacts forms one of the critical steps of ECBA.

An ECBA was used to evaluate the merits of fully powering the WWTP using a Photovoltaic system to generate electricity. This was compared with the existing system of a grid connected power source with electricity generated using natural gas as the fuel source.

Based on the average bi-monthly electricity bill of TT\$ 5000 paid to the Trinidad and Tobago the Trinidad and Tobago Electricity Commission (T&TEC) a yearly power cost of TT\$ 30000 was used. An annual rate of increase in commercial electricity rates was estimated at 4.5%/year based on a recommended increase by the Trinidad and Tobago Regulated Industries Commission in 2011 [6]. Therefore, the present value of grid supplied power for the next 25 years was calculated as;

$$\text{Grid power cost} = \frac{30000}{0.045} \left[1 - \left(\frac{1}{1.045} \right)^{25} \right] = \text{TT\$ } 444846$$

Externality cost associated with power generation from natural gas using a combined cycle power plant include the cost of health care to individuals as well as the mitigation cost of the major pollutants of power generation processes including NO_x, SO_x, PM and CO₂. Based on the findings of Sundqvist [13] an externality cost of \$0.324/kWh of electricity generated and used, was applied to the annual average of 63000 kWh used at the Orangefield plant. Estimating the rate of increase in externality cost as 5% per year for the next 25 years, the present value was calculated as;

$$\text{Externality cost} = \frac{20412}{0.05} \left[1 - \left(\frac{1}{1.05} \right)^{25} \right] = \text{TT\$ } 287686$$

The benefits of a WWTP are the costs associated with environmental decay and health damage to the population from water pollution as well as the possible direct reuse of water for purposes such as irrigation. Based on work done by Hardisty et.al [14] and Molinos-Senante et.al [15], on similar WWTP, a median value of \$6.22/m³ of treated wastewater was used based on the total economic value of water. The Orangefield WWTP was designed to treat 309m³/day of wastewater. Estimating the rate of increase in waste water treatment cost as 5% per year for the next 25 years, the present value was calculated as;

$$\text{Waste water treatment benefit} = \frac{701523}{0.05} \left[1 - \left(\frac{1}{1.05} \right)^{25} \right] = \text{TT\$ } 9887240$$

Using a PV system to power the WWTP has a total cost of TT\$ 584850 for the design operating life of 25 years. The benefits of operating a PV powered system will be the cost of mitigating the externalities of harmful emissions from burning natural gas and the harmful effects on the environment and associated health issues.

Table 2 shows a breakdown of the ECBA and the net present value of the PV system as compared with the present grid powered system.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

VIII. PAYBACK PERIOD

A simple payback-time analysis was conducted with an estimated life period of 25 years for the photovoltaic system. The payback period was analysed for a grid tied PV system and a standalone PV system with respect to the cost of operating the WWTP with power from the grid. The present value setting-up and running the grid tied and standalone PV system was TT\$ 584850 and TT\$ 1544850, respectively. The present value of operating the WWTP with power from the grid was TT\$ 444846. This resulted in a payback period of 32.9 years and 86.8 years for the grid tied and standalone PV system, respectively.

Table 2. Environmental Cost Benefit Analysis and Net Present Value

| | Conventional Grid Power (present value over 25 years) | | Photovoltaic Generated Power (present value over 25 years) | |
|-------------------------------------|---|--------------|--|--------------|
| COST | Grid power cost | TT\$ 444846 | PV panels cost | TT\$ 360150 |
| | Externality cost from emissions | TT\$ 287686 | Inverter cost | TT\$ 146737 |
| | | | Installation cost | TT\$ 57000 |
| | | | Maintenance cost | TT\$ 20963 |
| | | | Batteries | TT\$ 960000 |
| BENEFITS | Waste water treatment benefit | TT\$ 9887240 | Waste water treatment benefit | TT\$ 9887240 |
| | | | No externality cost from emissions | TT\$ 287686 |
| Present Value Cost (grid tied) | TT\$ 732532 | | TT\$ 584850 | |
| Present Value Cost (with batteries) | | | TT\$ 1544850 | |
| Present Value Benefits | TT\$ 9887240 | | TT\$10174926 | |
| Net Present Value (grid tied) | TT\$ 9154708 | | TT\$ 9590076 | |
| Net Present Value (with batteries) | | | TT\$ 8630076 | |

IX. DISCUSSION AND CONCLUSION

The ECBA showed that powering the Orangefield WWTP by an array of solar photovoltaic modules is a feasible option and is comparable to the existing conventional grid power mode of operation. However, using standalone systems with battery banks for the storage of power proved to dramatically increase the capital investment cost and makes this option least feasible. Including the monetary costing of the environmental and health effects caused by

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 12, December 2015

emissions from power generation as well as the positive monetary evaluation of wastewater treatment on the environment is an essential aspect of the ECBA. Although the initial cost of purchasing the PV system is high, the cost associated with environmental and health damage avoided by using a PV system is also significant. The difference between the present value of benefits of using the PV grid tied system and that of using conventional grid power supply was 4.5% for the WWTP. As global warming increases, the value of reducing greenhouse gas emissions will also increase with some estimates of monetary value up to US\$59/ton CO₂ equivalent [16]. This will undoubtedly increase the environmental benefits of using a PV system and thus increase the economic feasibility of using such systems in Trinidad.

The payback period analysis showed payback periods of 32.9 years and 86.8 years for the grid tied and standalone PV system, respectively. This analysis showed that PV systems are not feasible since the life cycle calculations were based on 25 years.

One of the major drawbacks for investing in renewable energy technology in Trinidad and Tobago is the low cost of electricity from T&TEC. Comparisons to other Caribbean islands show Trinidad & Tobago's commercial price of electricity at present is TT\$0.42/kWh (US\$0.065/kWh), which is the lowest in the region and is 82% lower than the next closest rate of TT\$0.76/kWh in Guadeloupe [17]. This low electricity cost was reflected in the long payback period for the PV system. The payback period for countries with higher energy cost will be proportionally lower. Significant depletion of Trinidad & Tobago's natural gas reserves has been reported by Ryder Scott in their last analysis [18]. This served as a catalyst for the development and investment in renewable energy resources and technology in Trinidad & Tobago [4].

REFERENCES

- [1] Godfrey Boyle, "Renewable Energy", 2nd ed. USA: Oxford University Press, 2004
- [2] Randy Maurice, "Renewable Energy and Energy Efficiency Policy Trends and Initiatives in T&T", Third National CDM Capacity Building Workshop, Carlton Savannah Hotel, St Anns, Trinidad, September 12-13, 2012.
- [3] Ian Boon, "T & T's Experience with Renewable Energy Technologies to Date", <http://www.energy.gov.tt/content/203.pdf>, 2012.
- [4] Trinidad & Tobago Ministry of Energy and Energy Affairs (TTMEEA), "Framework for Development of a Renewable Energy Policy for Trinidad and Tobago. Renewable Energy Committee", MEEA, 2011.
- [5] David Benny, (Deputy General Manager of the Water and Sewerage Authority of Trinidad and Tobago, Wastewater Division). Interview by author, 7 August. Chaguana, Trinidad and Tobago, 2012.
- [6] Trinidad & Tobago Regulated Industries Commission (TTRIC), "TTEC Business Plan 2011-2016", Regulated Industries Commission. <http://www.ric.org.tt/home/publications/TTEC%20Business%20Plan%202011-2016.pdf>, 2011.
- [7] California Energy Commission (CEC), "A Guide to Photovoltaic (PV) Systems Design and Installation", http://www.energy.ca.gov/reports/2001-09-04_500-01-020.PDF, 2012.
- [8] NASA (National Aeronautics and Space Administration), "NASA Surface meteorology and Solar Energy", <http://eosweb.larc.nasa.gov/sse>, 2013.
- [9] Paul Lynn, "Electricity From Sunlight: An Introduction to Photovoltaics", West Sussex, UK: John Wiley & Sons Inc., 2010.
- [10] University of Oregon Solar Radiation Monitoring Laboratory, "Sun Path Chart Program", <http://solardat.uoregon.edu/SunChartProgram.html>, 2012.
- [11] NREL (National Renewable Energy Laboratory), "Energy Payback for PV Systems", <http://www.nrel.gov/docs/fy04osti/35489.pdf>, 2004.
- [12] Timo Kuosmanen, and Kortelainen Mika, "Valuing Environmental Factors in Cost-Benefit Analysis Using Data Envelopment Analysis." Ecological Economics Vol. 62, No. 1, pp. 56-65, 2007.
- [13] Thomas Sundqvist, "What Causes the Disparity of Electricity Externality Estimates?" Energy Policy, Vol. 32, No. 15, pp. 1753-1766, 2004.
- [14] Paul E. Hardisty, Mayuran Sivapalan, and Robert Humphries, "Determining a Sustainable and Economically Optimal Wastewater Treatment and Discharge Strategy." Journal of Environmental Management, Vol. 114, pp. 285-292, 2013.
- [15] M. Molinos-Senante, F. Hernández-Sancho, and R. Sala-Garrido, "Cost-Benefit Analysis of Water-Reuse Projects for Environmental Purposes: A Case Study for Spanish Wastewater Treatment Plants." Journal of Environmental Management, Vol. 92, No. 12, pp. 3091-3097, 2011.
- [16] William D. Nordhaus, "Economic Aspects of Global Warming in a Post-Copenhagen Environment." Proceedings of the National Academy of Sciences, Vol. 107, No. 26, pp. 11721-11726, 2010.
- [17] CARILEC (Caribbean Electric Utility Services Corporation), "CARILEC Tariff Survey Among Member Electric Utilities 2010", <http://carilec.com/services/Tariff2010.pdf>, 2012.
- [18] Ryder Scott Company, "Trinidad & Tobago Gas Reserves Certifications Year End 2011", http://www.energy.gov.tt/content/The_Presentation_Of_The_Results_Of_The_Ryder_Scott_Gas_Audit_For_The_Year_End_2011.pdf, 2012.