THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF JOHN AND WILLIE LEONE FAMILY DEPARTMENT OF ENERGY AND MINERAL ENGINEERING

SOLAR ENERGY TECHNO-ECONOMIC ASSESSMENT IN NORTHWESTERN INDIA

STEVEN PATRICK
SPRING 2014

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degrees in
Energy Engineering and Energy Business and Finance
with interdisciplinary honors in
Energy Engineering and Energy Business and Finance

Reviewed and approved* by the following:

Jeffrey R. Brownson
Associate Professor of Energy and Mineral Engineering
Thesis Advisor

Andrew N. Kleit
Professor of Energy and Environmental Economics
Honors Advisor

Sarma Pisupati
Associate Professor of Energy and Mineral Engineering
Honors Advisor

* Signatures are on file in the Schreyer Honors College.

ABSTRACT

Indian electricity demand has rapidly grown, creating the need for quick sustainable solutions. Solar photovoltaic power plants are potential solutions to India's energy crisis. In order for India to reach their goal of 20,000 MW of grid-connected solar energy by 2022, investors and independent power producers (IPPs) must understand the financial benefits from these projects as well as the risks they must mitigate. The Northwestern cities of Jaipur and Ahmedabad were selected to explore the financial feasibility of these projects. Weather files from 2004 to 2008 were provided by the National Renewable Energy Laboratory (NREL) to analyze the total annual solar output of a 1-megawatt hypothetical solar power plant situated in either Jaipur or Ahmedabad. The performance prediction software, System Advisor Model (SAM), used Perez irradiance modeling to determine the total annual electricity output for each of the five years in each city. Two financial base case simulations were performed for each city, assuming the average electrical output of each year remained constant over the consecutive 25 years.

Net present value (NPV), internal rate of return (IRR), and levelized cost of energy (LCOE) are the three financial metrics used to compare projects. The financial metrics of the base case scenario are considered the most likely outcomes for the solar projects. Multiple simulations were compiled in order to observe how NPV, IRR, and LCOE are affected by changing the solar resource, renewable energy credit (REC) clearance percentage, project leveraging, electricity price escalation rates, and interest rates.

Ahmedabad, which is located 300 miles south of Jaipur, had a higher annual electrical output than the projects based in Jaipur, thus leading to a higher NPV and IRR, and a lower LCOE. An increased REC market clearance percentage resulted in an increased NPV and IRR. A larger equity percentage led to a decreased NPV and an increased LCOE. An increased electricity price escalation rate caused NPV and IRR to both increase. Finally, an increased interest rate caused a decrease in NPV and an increase in LCOE.

It is important for the Indian government and power producers to mitigate financial risks associated with solar projects in order to attract investments for solar photovoltaic systems. Long-term measured weather data would provide a significantly more accurate picture of a solar project's revenue streams and the variability associated with them. The REC market clearance percentage can be increased through government enforcement of recent Renewable Purchase Obligation legislation. Additionally, a stronger estimate of electricity price escalation rates over the next 25 years would assist investors and IPPs in better determining the financial feasibility of these projects. By having a more accurate picture of the future price of electricity, the Indian government can appropriately subsidize solar energy. Solar energy is proving to be one of the major energy solutions in India. This study analyzes the relationship between economics, the solar resource, and government policy in hopes to explain the benefits and challenges of Indian solar energy.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would first like to express my gratitude for Dr. Jeffrey Brownson and Dr. Andrew Kleit for their guidance and assistance on this thesis throughout the 2013-2014 school year. This experience has taught me the true value of a college education and how one is never done learning after college. I cannot thank them enough for teaching me how to be wrong and learn from my mistakes in research. These were valuable lessons that I will take with me wherever I end up. Next, I would like to thank Dr. Sarma Pisupati for being one of the readers on my thesis. I also would like to acknowledge Drew Gardner for his assistance with Indian accounting structures. Finally, I would like to thank my wonderful family and friends for the support they provided to me during my educational career at Penn State. I could not have done it without them.

Chapter 1

Introduction

India, boasting an impressive population of 1.2 billion people, has consistently been plagued by power shortages and insufficient generating capacity to meet growing electricity demand. Supplying this increasing energy demand will strain world resources and cause environmental issues throughout Asia. For these reasons, India has begun to explore and encourage renewable energy alternatives through various initiatives and financial incentives, which will help encourage the development of 20,000 megawatts of grid-connected solar energy by 2022. This 2010 Jawaharlal Nehru National Solar Mission was received as one of the most progressive solar missions in the world; however, concerns have been raised regarding India's commitment to enforcing the new legislation. As one of the largest developing countries, India provides huge potential for investment opportunities from around the world. If the Indian government would like to meet its goal, they must help mitigate financial risks associated with their country to attract investors and independent power producers to finance and operate these projects.

Various simulations were performed in order to determine which parameters the Indian government, IPPs, and potential investors should focus on. Understanding which risks can be mitigated allows for a more attractive solar energy environment, thus increasing investment opportunities for solar power projects. Weather files were provided by the National Renewable Energy Laboratory for the regions surrounding Jaipur and Ahmedabad.

Using System Advisor Model (SAM), the total annual output was calculated for each of the five given years between 2004 and 2008. One base case simulation was run for each city, assuming the average annual electricity output for that specific range of years remained constant over the subsequent 25 years. In addition to the varying solar resource, renewable energy credit (REC) market clearance, project leveraging, electricity price escalation rate, and interest rate were all adjusted to observe their effects on net present value, internal rate of return, and levelized cost of energy.

Each variation affected the financial metrics differently. An increased solar resource increased NPV and IRR and decreased LCOE. Increased REC clearance percentage increased NPV and IRR. Increased equity in the project decreased NPV and increased LCOE. Increased electricity price escalation rates increased NPV and IRR. Finally, increased interest rates decreased NPV and increased LCOE. As seen from the results, the government should increase their focus on enforcing the REC mechanism and provide stronger estimates of electricity price predictions and more weather monitoring stations.

Chapter 2

Background

In order to perform a techno-economic analysis on solar photovoltaic power plants in Northwestern India, certain pieces of information must be collected. It is important to understand the solar resource of the area to better predict revenues for the power producer. Additionally, the effect of local and federal government on solar projects in the region should be explored so that power producers can maximize profit. Finally, it is important to examine the project's net present value (NPV), internal rate of return (IRR), and levelized cost of energy (LCOE), which will be used to compare projects against each other and other electricity generating methods.

2.1 Site Location

2.1.1 Solar Electricity in India

Over the past few decades, India's rapid population growth has led to crippling electricity shortages, which must be solved while focusing on the gradual reduction of the country's carbon footprint. Launched in 2010 in response to the aforementioned energy concern, India became home to one of the world's most aggressive solar missions.

The Jawaharlal Nehru National Solar Mission set out to install 20,000 megawatts of grid-connected solar power by 2022. Through this mission, the country aspires solar energy to reach grid parity, meaning the LCOE of solar energy will be equal to or less than the price of power from the electiricty grid. The Indian government plans to achieve this by lowering solar energy prices to market prices by 2022 through, “(i) long term policy; (ii) large scale deployment goals; (iii) aggressive research and development; and (iv) domestic production of critical raw materials, components, and products'” [4] Currently, grid parity price per kilowatt-hour fluctuates between $0.10 and $0.14, while solar PV is generally priced between \$0.14 and $0.17. [23]

The National Tariff Policy of 2006 was adjusted so that State electricity regulators could mandate utilities and businesses to purchase solar energy. The Renewable Purchase Obligation (RPO) was enacted, which allows states the option to require utilities or other entities to purchase a specific amount of solar electricity. Currently, 0.25% of electricity distributed by utilities must come from solar energy. This percent will be gradually increased to 3% over a 12-year span. [4] One exception pertains to Rajasthan, where only utilities are subject to the RPO. [5]

Solar energy's high generation costs compared to traditional methods like coal or natural gas has made it difficult for independent power producers (IPPs) to sell solar generated electricity. In response to this, the Ministry of Power established a government agency which can enter into preferential power purchase agreements (PPAs) with solar IPPs. The power can be purchased from the government agency by an energy trading company and fed to the grids where voltage is equal or greater than 33 kilo-volts. The IPP must be in accordance with the Central Electricity Regulatory Commission's (CERC) regulations on tariffs and the PPA duration of 25 years. This scheme allows solar energy to be bundled with the non-allocated quota of central stations' electricity which is generated by non-renewable sources. By bundling the more expensive renewable energy with cheaper conventional methods, the gap between conventional prices and solar prices is reduced. Power producers that utilize this method are not eligible for renewable energy credits. [4]

Solar renewable energy credits (REC) were established to complement the RPO so that utilities could purchase and sell certificates to meet their target RPO. [4] A company receives 1 REC for every 1 megawatt-hour generated with solar energy. A company will receive RECs if they do not have a PPA to sell electricity with an obligated entity for the purpose of meeting its RPO. Furthermore they can either sell the electricity to the distribution licensee of the area at the prevailing Average Pooled Power Purchase Cost (APPC), any other licensee or open access consumer at a mutually agreed price, or through a power exchange market.

Additional charges will be incurred when power is sold to a 3rd party such as wheeling charges, distribution charges, and open-access charges. RECs remain valid for 730 days after the date of issuance, and can they also be purchased on a voluntary basis. [6] [7] Many companies currently sell solar energy to a 3rd party purchaser with no RPO. This way, the power producer can receive a high PPA through a mutual agreement with the 3rd party purchaser, but still receive RECs. [9] A company is able to earn RECs when selling at the average pooled purchase cost (APPC) of $0.045/kilowatt-hour, which is the average purchase cost distribution licensees purchase electricity at. Despite being able to recuperate RECs with this method, the price is too cheap for solar companies to agree to because of the low selling price and poor market clearance of the RECs.

Table 1: Charges for REC Mechanism in USD [2]

Accreditation Charges	
Processing Fees (one time)	$83
Accreditation Charges	$490
Annual Charges	$170
Re-validation charges (Every 5 years)	$250
Registration Charges	
Processing Fees (one time)	$17
Registration Charges (one time)	$83
Annual Charges	$17
Re-validation charges (Every 5 years)	$83
REC Issuance Charges	
Fees per certificate	$0.17

Currently Solar RECs have a floor price of $153 and ceiling price of $221. [7] If the RPOs were strictly enforced, more Solar RECs will be cleared on a day-to-day basis. Additionally, as solar energy production increases in India, the government must take steps to increase the RPO so that the market is not flooded with uncleared RECs. Currently, only 20% of RECs are cleared on the market, which has resulted from India's poor enforcement of RPOs. [8] Additionally, the floor price for RECs is supposed to decrease every five years to reflect increasing prices of electricity, which have been estimated to be around 8% nominally per annum to reflect increasing prices on domestic and imported coal along with the transportation of it. [17] The Indian government believes solar will be more economically feasible as electricity prices increase so REC prices will be expected to halve every five years. [9] This indicates that solar energy will be competitive without subsidies in the near future.

2.1.2 Sambhar Lake, Rajasthan

The first solar photovoltaic plant, depicted in figure 2.1, will be located in the region surrounding Jaipur, in Rajasthan India. Located only 96 kilometers south west of Jaipur, Sambhar Lake provides cheap land and access to water to generate electricity near Rajasthan's largest city.

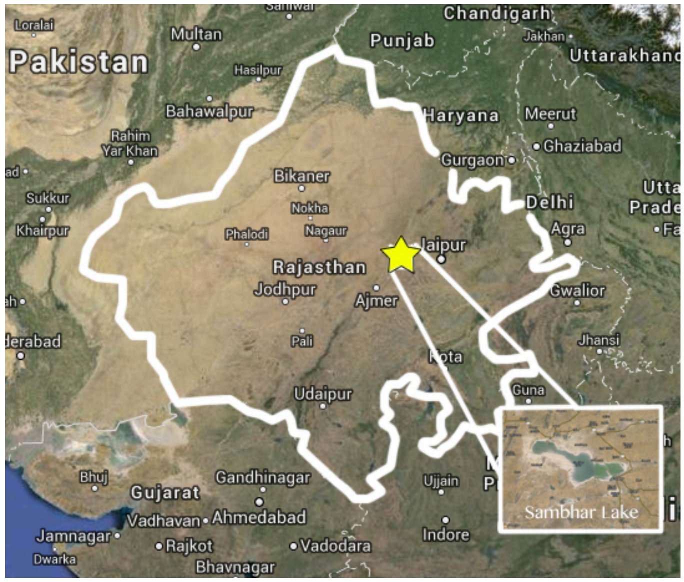

Figure 1.1 Sambhar Lake, Rajasthan India

The region boasts an impressive 300-330 days of sun per year with a solar irradiance of 5-7 kilowatt-hours/m^2 on land that is considered flat and undeveloped. [10] Additionally, the region has access to major cities through India's railway infrastructure, and provides a labor market that is considered 20-30% cheaper than the average Indian pay wage. [10] This high potential for solar generation coupled with cheap and underutilized desert makes this region a prime candidate for solar power generation.

In addition to the favorable conditions for solar energy, the state of Rajasthan has formulated a solar energy policy to promote the development and growth of solar energy within the state. Rajasthan has set a state-specific goal to develop 10,000 to 12,000 megawatts of solar energy in the next decade. To prepare for this, the State Transmission utility has supplied infrastructure to create stronger transmission systems and sub-stations in the desert region. [11]

Permits for land purchases are granted based on the amount of solar energy that will be produced. The permitting agency will allow 2.5 Hect/MW for crystalline solar photovoltaic cells and 3.5 Hect./MW for amorphous solar photovoltaic cells. Any revenue from energy consumed by the solar power producer will be tax-free. Subsidies in Rajasthan are not available for grid-connected photovoltaic plants greater than 500kW capacity. [11]

2.1.3 Ahmedabad, Gujarat

Ahmedabad, situated in Gujarat and pictured in figure 2.2, presents itself as another potential city for solar energy development.

Figure 2.2. Ahmedabad, Gujarat India

As a neighboring state of Rajasthan, Gujarat receives an almost identical amount of solar irradiation. Additionally, Ahmedabad sits as the 5^{th} largest city in India, so there is a substantial demand from utilities for solar energy to meet their RPO.

The State Government of Gujarat also created a solar policy in 2009 in hopes of promoting the production of both solar infrastructure and solar energy. The policy has focused around the development of solar parks, which allow for the construction of solar panels close to where they will be used to generate electricity. This promotes industry within the state while reaching the Indian government's target reduction for carbon emissions. [12]

The solar producers will incur a wheeling charge of 2% of energy fed to the grid. Grid transmission of 66 kilo-Volts and above will be provided by the state utility for electrical distribution. The value added tax (VAT) on electricity is removed for any self-consumption used by the solar power producer in addition to any sale of solar electricity to a 3rd party purchaser or licensee. [12]

Additionally, under the Gujarat Electricity Regulatory Committee (GERC), the megawatt sized photovoltaic projects can sell electricity to the distribution licensees for 25 years under a predetermined PPA. The rate for the first 12 years is set at $0.164/kilowatt-hours, and it drops to $0.115 kilowatt-hours for the remaining 13 years. Entities that opt for this payment scheme are ineligible to receive RECs. [13]

Solar power producers must provide $825 per megawatt capacity at the time of signing a PPA to ensure payment to the bank in case of schedule delays. This money will be refunded if the developer completes construction on time. [12]

2.2 Solar Resource Assessment

In order to assess the feasibility of these projects, the solar photovoltaic components and solar resource must be examined, as these aspects will provide the base understanding of the estimated revenues for any solar power project.

2.2.1 System Components

For this project, a 1-megawatt nameplate capacity plant is used for the analysis. The 1-megawatt represents peak array direct current (DC) power output prior to accounting for efficiency losses. In order to determine the total annual energy output, the nameplate capacity must account for system efficiency losses due to operational losses, temperature-related losses, and inverter losses. Inverters, which convert direct current to alternating current, are sized to handle the amount of electricity generated prior to accounting for inverter efficiency losses. The SunPower solar panel (SPR-305E-WHT-U) characteristics are seen in table 2.. [2]

Table 2: Module Characteristics taken from System Advisor Model [2]

Cell Efficiency	18.7%
Maximum Power	305 W
Maximum Voltage	54.7 V
Maximum Current	5.58 A
Open Circuit Voltage	62.4 V
Short Circuit Current	5.96 A
Temperature Loss Coefficient	-0.118 W/^{o}C

The inverters will also be SunPower products (SPR-10001f-1), and the product specifications are listed in table 3.

Table 3: Inverter Characteristics taken from System Advisor Model [2]

Maximum Alternating Current (AC) Power	9,995 W
Maximum Direct Current (DC) Power	10,423 W
Nominal Alternating Current (AC) Voltage	277.0 V
Maximum Direct Current (DC) Voltage	600.0 V
Maximum Direct Current (DC) Current	46.80 A
Minimum MPPT DC Voltage	230.0 V
Nominal Direct Current (DC) Voltage	330.0 V
Maximum MPPT DC Voltage	500.0 V

After selecting the solar panels and inverters, the array characteristics can be determined, which are shown in table 4.

Table 4: Array Characteristics taken from System Advisor Model [2]

Nameplate Capacity	1 MW
Total Modules	3276 Modules
Panel Degradation Rate	0.50%
Modules per String	6 Modules
Strings in Parallel	546 Modules
Total Module Area	5343 m^2
String Open Circuit Voltage	385 V
String Max Power Voltage	328 V
Land Use	3 acres
Overall Efficiency	86%

2.2.2 Weather Files

The solar resource is the most important parameter when considering the application of solar energy conversion systems. Many costs stay constant over changing geographic regions, but the solar resource can drastically change, which affects the project's revenue stream and overall financial viability.

Additionally, after a plant is installed, the solar resource should continue to be measured in order to track the plant's efficiency throughout its service life. Consistent solar resource data is required to determine if decreased electrical output is caused from weather-related factors or disruptions to system and plant efficiencies. [14]

The National Renewable Energy Laboratory (NREL) has recorded and prepared single-year data over a series of five years in Jaipur and Ahmedabad. These files contain hourly records of the direct normal irradiance (DNI), global horizontal irradiance (GHI), diffuse horizontal irradiance (DHI), latitude, longitude, elevation above sea level, hour of the day, albedo, dry bulb temperature, and wind velocity.

Using NREL's System Advisor Model (SAM), the data can be input to predict hourly performance predictions for the year. The plant's performance can be calculated for the average annual production output for the years that NREL provides data for, obtaining an average system output. [2] This average system output will be used as the total system performance over a 25-year project lifespan. [2] Solar panels will decrease in efficiency over the 25 years as well, so additional costs may be incurred to maintain panels and keep output constant. [22]

Table 5 displays the annual megawatt-hour output for the system facing due south at a tilt of 30^{o}.

Table 5: Annual Electricity Output from a 1MW nameplate capacity solar photovoltaic plant in Jaipur and Ahmedabad

Year	*Jaipur, Rajasthan*	*Ahmedabad, Gujarat*
2004	1711 MWh/year	1721 MWh/year
2005	1715 MWh/year	1741 MWh/year
2006	1702 MWh/year	1708 MWh/year
2007	1700 MWh/year	1736 MWh/year
2008	1678 MWh/year	1689 MWh/year
Average	**1701 MWh/year**	**1717 MWh/year**

2.2.3 Annual Output Modsls

The theory behind the performance calculations in SAM is rooted in solar radiation concepts. The sun emits radiation, which travels through space and then must travel through the Earth's atmosphere. The distance photons travel through Earth's atmosphere depends on the solar zenith angle, which describes the position of the Earth's relation to the sun during the day.

The air mass value is used to explain the variation in solar resource throughout the day. As the solar zenith angle decreases approaching solar noon, the air mass index decreases. This means that at solar noon, photons will travel the shortest distance in a day before reaching the ground. While cloud systems are an obvious impedance to solar energy, the atmosphere also contains gaseous molecules, dust, and particulates that scatter and absorb incoming solar radiation. Additionally, some of the solar radiation will be reflected back into the atmosphere so the reflective properties of the site location must be taken into consideration, as this will add to the performance output. [14] Weather files provided by NREL help to utilize real solar irradiance observations at a given site. The isotropic diffuse sky model and Perez model are commonly used to determine total irradiance on a tilted surface given information collected from the weather file.

Isotropic Diffuse Sky Model

In this method, total irradiance on a tilted solar photovoltaic panel is found by the summation of the direct beam, sky diffuse, and ground diffuse light sources as seen in equation 2.1, where G_t is the total irradiance on a tilted surface and G_{bt}, G_{dt}, and G_{gt} are respectively the beam, diffuse, and ground reflected components, which comprise the total irradiation. [1]

Equation 2.1: Total irradiance on a tilted surface

$$G_t = G_{bt} + G_{dt} + G_{gt}$$

In order to find the total irradiance on the tilted surface, data from the weather files must be utilized. The DNI is the amount of solar radiation centered from the sun that a limited field of view receives. [2] DNI is used to calculate total beam irradiance using equation 2.2, where θ_Z is the solar zenith angle. [1]

Equation 2.2: Direct beam irradiance on a surface based on total DNI and angle of incidence

$$G_b = DNI * \cos(\theta_z)$$

The total amount of beam irradiance on a tilted surface can be determined using equation 2.3, where θ is the angle of incidence on the tilted surface and θ_z is the solar zenith angle. [1]

Equation 2.3: Total irradiance on a tilted surface

$$G_{bt} = G_b \frac{cos(\theta)}{\cos(\theta_z)}$$

Additionally, the amount of diffuse irradiance on a tilted surface can determined using the diffuse horizontal irradiance (DHI), which is the irradiation received at a surface that was scattered by the atmosphere or other molecules or particles in the air. Given the DHI data in the weather file, the total diffuse irradiance on a tilted surface can be calculated using equation 2.4, where β is the tilt of the solar panel. [1]

Equation 2.4: Total diffuse irradiance on a tilted surface

$$G_{dt} = DHI * (1 + \frac{cos(\beta)}{2})$$

Finally, the total reflected ground irradiation on a tilted surface can be determined using equation 2.5, with the albedo (ρ_g) data also coming from the provided weather file. [1]

Equation 2.5: Total ground irradiance on a tilted surface

$$G_{gt} = \rho_g * G_b * DHI * (1 - \cos\frac{\beta}{2})$$

Using that data provided by NREL and selecting a system tilt, a representative annual solar resource can be determined for the project.

Perez Model

The Perez Model is more commonly used in modern software applications. It accounts for horizon brightening, circumsolar, and isotropic diffuse radiation. The algorithm to determine the diffuse irradiance on a tilted surface is shown in equation 2.6. [3]

Equation 2.6: Total irradiance on a tilted surface

$$G_t = DHI * [\frac{(1 - F_1)(1 + \cos(\beta))}{2} + F_1\frac{a}{b} + F_2\sin(\beta)$$

In this equation, the two shape factors, F_1 and F_2, are the circumsolar and horizon reduced brightness coefficients, respectively. They are determined using the equations seen in equations 2.7 and 2.8, respectively, and are directly affected by the atmosphere clearness index. [3]

Equation 2.7: Circumsolar reduced brightness coefficient

$$F_1 = max[0, (f_{11} + f_{12}\Delta + f_{13}\frac{\pi\theta_z}{180^\circ})]$$

Equation 2.8: Horizon reduced brightness coefficient

$$F_2 = f_{21} + f_{22}\Delta + f_{23}\frac{\pi\theta_z}{180^\circ}$$

The delta value in the equations above represents the ratio of diffuse irradiation to total irradiation. It is calculated using the DHI, absolute air mass, and extraterrestrial radiation, as seen in equation 2.9. [3]

Equation 2.9: Delta value measuring the amount of direct horizontal irradiance that passes through the air

$$\Delta = \frac{DHI \cdot AM_a}{E_a}$$

The f coefficients in the equations are defined for a specific range of clearness (ε), which is calculated in equation 2.10, where k is a constant equal to 5.53×10^{-6} for degrees or 1.041 for radians. [3]

Equation 2.10: Sky clearness index

$$\epsilon(clearnessindex) = \frac{(DHI + DNI)/DHI + (\kappa(\theta_z)^3)}{1 + \kappa(\theta_z)^3}$$

Tables 6 and 7 show the Perez model coefficients for irradiance and the corresponding lower and upper bounds based on the bin value, respectively. [3]

Table 6: f coefficient values for Perez model

Bin	**f_{11}**	**f_{12}**	**f_{13}**	**f_{21}**	**f_{22}**	**f_{23}**
1	*-0.010*	*0.60*	*-0.062*	*-0.060*	*0.072*	*-0.022*
2	*0.13*	*0.68*	*-0.15*	*-0.019*	*0.066*	*-0.029*
3	*0.33*	*0.49*	*-0.22*	*0.055*	*-0.064*	*-0.026*
4	*0.57*	*0.19*	*-0.22*	*0.019*	*-0.15*	*-0.014*
5	*0.87*	*-0.39*	*0.30*	*0.23*	*-0.46*	*0.0010*
6	*1.1*	*-1.2*	*0.36*	*0.29*	*-0.82*	*0.056*
7	*1.1*	*-1.6*	*0.41*	*0.26*	*-1.1*	*0.13*
8	*0.68*	*-0.33*	*0.40*	*0.16*	*-1.4*	*0.25*

Table 7: Clearness Index Lower and Upper Bounds

ε (clearness index)	**Lower Bound**	**Upper Bound**
1 (Overcast)	**1.00**	**1.07**
2	**1.07**	**1.23**
3	**1.23**	**1.50**
4	**1.50**	**1.95**
5	**1.95**	**2.80**
6	**2.80**	**4.50**
7	**4.50**	**6.20**
8 (Clear)	**6.20**	**> 6.20**

Finally, a and b depend on the solid angle created by the circumsolar region as seen on a tilted surface. The equations to find a and b are seen in equations 2.11 and 2.12, respectively. [3]

Equation 2.11: Coefficients a, dependent on solid angle created by circumsolar region

$$a = max(0^\circ, \cos(\theta))$$

Equation 12: Coefficient b, dependent on solid angle created by circumsolar region

$$b = max(\cos 85^\circ, \cos(\theta_z))$$

The Perez model will be used in this simulation to estimate total electrical output for the year. The Perez model is used commonly in modern software systems as it is able to account for horizon brightening, isotropic diffuse radiation, and circumsolar diffuse radiation, where the Isotropic model only accounts for the isotropic diffuse radiation. [2]

2.3 Financial Background

Costs and revenues for solar photovoltaic plants must be determined in order to carry out a meaningful project analysis. Costs can be broken up into the following four different categories: capital costs, operation and maintenance, financing, and taxes, while revenues come from sale of electricity and government incentives.

2.3.1 Total Installed Costs

These costs refer to all direct and indirect costs required to build the solar plant. Direct capital costs refer to the physical materials required such as modules, inverters, mounting structures, transformers, cables, and labor for installation. Indirect capital costs refer to items such as permitting, environmental studies, engineering, grid interconnection, land, and land preparation. [2]

Direct costs and indirect costs, shown in table 2.8, combined constitute the total installed costs. Values are taken from System Advisor Model, which updates prices based on market trends. All total installed costs, excluding land costs, are considered depreciable assets. It is important to distinguish which assets can depreciate for tax purposes. The total installed costs are all purchased as one lump sum in the base year of the project.

Table 8: Capital Costs in dollars per watt installed for the system ($/W$_{DC}$)

Modules	$0.62/W$_{DC}$
Inverters	$0.18/W$_{DC}$
Equipment	$0.32/W$_{DC}$
Installation	$0.37/W$_{DC}$
Installer Margin and Overhead	$0.23/W$_{DC}$
Environmental Studies	$0.01/W$_{DC}$
Engineering	$0.01/W$_{DC}$
Grid Interconnection	$0.02/W$_{DC}$
Land	$0.02/W$_{DC}$
Land Preparation	$0.06/W$_{DC}$

2.3.2 Operating and Maintenance

Operation and maintenance costs refer to the costs required to keep the plant running in addition to the costs required to insure the solar plant. People must be hired to clean solar panels, maintain and inspect equipment, and oversee operations. India's Central Electricity Regulatory Commission (CERC) estimates that operation and maintenance costs for 2014 will cost roughly $19,000/MW$_{DC}$ installed and will increase at a rate of 5.72% annually. [6]

2.3.3 Financing

Financing costs refers to the amount of money the power producer must pay back each year to the entity from which it borrowed. This cost is dependent upon the amount of debt incurred by the power producer and the interest rate on the loaned money. In addition to paying back the loaned sum, the power producer must also pay the interest on the remaining balance of the outstanding term loan. In this simulation's base case, 70% of the total installed costs will be financed with a loan, which is the average debt-to-equity ratio for most solar investments. [24]

2.3.4 Taxes

Finally, tax costs refer to the amount of money the power producer must pay to the state and federal government. Solar equipment is exempt from paying the Value Added Tax in India, so the solar power producer will not have to pay this cost. [15] The producer will have to pay the Minimum Alternate Tax (MAT) of 19% once the cumulative profits before taxes is positive. A corporate tax must also be paid once cumulative taxable profits is positive; however, this will not be encountered in this project due to the 2012 Accelerated Depreciation Benefit Solar Tax Law, which allows solar producers to receive 100% accelerated depreciation of solar assets in their first year after purchase in India. [16]

2.3.5 Revenues

Revenues are calculated by determining the total solar output and multiplying it by the agreed price of electricity set by either market driven prices or a mutually agreed upon Power Purchase Agreement (PPA). The simulation base case assumes electricity costs to nominally increase 8% annually based on the Central Electricity Regulatory Commission's report on increasing coal prices.[25] The average Indian inflation rate is around 7%, so an 8% nominal inflation rate would be considered reasonable. [26] Additionally, the PPA is renegotiated at the end of each year.

Revenue streams also come from the salvage value recuperated in the final year of operation and government incentives such as solar renewable energy credits (RECs), which can be sold for additional revenues. [2] Prices for RECs are taken from India's Energy Exchange market which is updated daily. Eligible entities can receive RECs as long as they are selling their electricity at prices driven by the market. Solar producers can choose to sell a portion of their electricity to 3rd party purchaser at an agreed preferential tariff, but they will forgo receiving RECs for that portion of electricity. In this project, the solar energy will be sold to a 3rd party with no RPO at a pre-determined PPA. Therefore, the power producer will retain the RECs but still have a locked in PPA price. [8]

2.3.6 Incentives

In this simulation, RECs will be received per megawatt-hour generated. Currently, RECs are selling at $153, and are expected to decrease 50% each year because of increasing electricity prices. This is the Indian government's way of phasing out RECs as they become more competitive.[17] Lack of RPO enforcement by the Indian federal and state government has resulted in a weak REC market with only 20% of all distributed RECs are cleared on the market [8] On August 8th 2013, Gujarat waived off the shortfall in RPO compliance, allowing utilities that did not meet the preset levels to avoid penalties. Acts like this undermine the seriousness of RPO legislation and hurt REC markets by instilling doubt into non-compliance penalties. [18]

2.4 Economic Metrics

Various economic metrics can be used to compare solar projects against each other or solar projects against other electricity production methods such as coal-fired power plants. Certain assumptions must be made in order to carry out the analysis.

The average cost of equity is estimated to be 15% in India, while the average cost of debt is 12%. For a base case with 70% debt and 30% equity, the weighted average cost of capital (WACC) is 12.9%. The WACC will be used as the project’s nominal discount rate.[27] Discount rates are adjusted to reflect risk, so the power producer may be subject to a higher discount rate based on the project's risk. [19] Table 2.9 shows the various assumptions made for this project in order to carry out the economic metrics.

Table 9: Assumptions made for economic metrics

Project Life [2]	25 years
Inflation Rate [26]	7%
WACC [27]	12.9%
% Equity [24]	30%
% Debt [24]	70%
Debt [24]	12%
REC Average Selling Price [8]	153.0/REC
% of RECs Cleared on Market [8]	20%
Minimum Alternate Tax	19%
Average Electricity Prices [6]	$0.11/kWh
Auxiliary Consumption [2]	0.50%
Transmission Losses [2]	0.50%

2.4.1 Net Present Value

Net Present Value (NPV) examines the cash inflows and outflows by discounting future revenues and costs to determine project profitability. Total revenues and costs, which account for inflation, are summed and discounted with the nominal discount rate for each year using present value analysis. These total discounted values for each year are then added up. A positive value indicates that the project will be profitable, while a negative value indicates that the project's returns would be less than the initial cash outflow. [19]

2.4.2 Levelized Cost of Energy

Levelized cost of energy (LCOE) is used to find the cost required per unit of energy produced. This allows alternative energies like solar to be compared with different scales of operation, investments, and operating periods. The LCOE is found using equation 2.13, where C_n represents the total installed costs, operation and maintenance costs, and capital expenditures for the year and Q_n represents the amount of energy produced each year. The annual costs sums all dollar costs over the given year and discounts it to the base year using present value analysis. [19]

Equation 13: Levelized Cost of Energy

$$LCOE = \frac{\sum_{i=0}^{n} \frac{C_n}{(1+d)^n}}{\sum_{i=1}^{n} \frac{Q_n}{(1+d)^n}}$$

2.4.3 Internal Rate of Return

Internal rate of return (IRR) is the rate that sets the net present value equal to zero. An iterative technique is used to determine the discount rate that sets the NPV to zero. Projects can be compared to one another by comparing this internal rate of return. Ideally, the power producer would select the project with the highest IRR that is also above the original discount rate. [19]

2.4.4 Power Purchase Agreement

Power purchase agreement (PPA) price is the price charged per unit of energy by the power producer. The PPA is a mutually agreed upon price when the power producer is selling to a 3rd party. The PPA in this model will escalate at a constant rate of 8% annually. [9] The market rate currently for electricity in India is $0.10/kWh; however, the average price of electricity from solar power plants is around $0.16/kWh [23]

Chapter 3

Methods

3.1 Find Annual Solar Output

System Advisor Model (SAM) software is used to determine annual solar electrical output for all years with NREL generated weather data. The weather files in this simulation have been developed using weather satellite (METEOSAT) measurement techniques. The SAM file should reflect panels that are facing due south and tilted 30^{o} The SunPower solar panel (SPR-305E-WHT-U) and inverter (SPR-10001f-1) must be specified in the file in order to find total annual output given the panels' and inverters' performance efficiencies. The simulation is then run, and the total annual electrical output in megawatt-hours is recorded. The two cities the simulations will be based out of are Ahmedabad and Jaipur. Ahmedabad is situated roughly 300 miles south of Jaipur so the solar resource will be slightly greater than the solar resource near Jaipur.

3.1.1 Revenues

3.1.1.1 Sale of Electricity

The amount of electricity generated in megawatt-hours must be converted to kilowatt-hours. Electrical output must be decreased by 0.50% each year to reflect panel degradation for the system. An additional 1.0% must be decreased due to auxiliary power consumption used by the plant and transmission losses.[2] This electricity is then multiplied by the price of electricity per kilowatt-hours to find revenues from the sale of electricity. The price of electricity is assumed to start at /kWh in year 1 and escalates at a rate of 8.0%, based off the rate of inflation and increasing prices for electricity generated from coal, for the next 25 years in the base simulation case. [6] [9]

3.1.1.2 Incentives

One renewable energy credit is provided by the Indian government for every megawatt-hour generated by solar energy. The amount of RECs received is found then by converting the amount of kilowatt-hours generated to megawatt-hours after accounting for panel degradation, auxiliary consumption, and transmission losses. This number equals the amount of RECs received from the government. Due to RPO enforcement problems, only 20% of RECs are assumed to be cleared on the market at the floor price of $153. Additionally, the price of RECs is expected to decrease by 50% every five years due to increasing electricity prices. [9]

3.2 Free Cash Flow Model

A cash flow model was created in order to determine changing revenues and costs over the 25-year period. The cash flow for each year is determined by summing the profits after taxes and depreciation and subtracting out any capital expenditures from the year. The free cash flow represents all cash that is left over for both debt and equity holders in the project. The weighted average cost of capital, which reflects the costs of capital and debt determined by the equity and debt holders, is used as the discount rate so the unlevered discounted cash flow represents the enterprise value as opposed to just the equity value. The base-case model assumes a debt-to-equity ratio of 70:30. This section will help guide the process carried out to receive the final cash flow values for the projects

3.2.1 Total Installed Costs

The direct and indirect costs for the photovoltaic plant are based on NREL's price assumptions found in System Advisor Model. They are summed to determine the total installed cost required to build the entire plant. [2] The total installed costs are all incurred in year 0 of the project.

3.2.2 Operation and Maintenance Costs

Beginning in year 1, annual operation and maintenance costs will be incurred, as the plant will need people to run the plant, inspect equipment, and fix problems. The Central Electricity Regulatory Commission (CERC) predicts operation and maintenance costs to increase at a nominal rate of 5.72% each year. This should be reflected with increasing operation maintenance costs in years 1 to 25. [6]

The WACC will be used to discount the free cash flow at the end. This discount rate accounts for the cost of capital and cost of debt.

3.2.3 Tax Costs

3.2.4.1 Gross Operating Income

The gross operating income is the amount of money available after subtracting operation and maintenance costs from gross revenues. This is commonly referred to as the Earnings Before Interest, Tax, Depreciation, and Amortization (EBITDA).

3.2.4.2 Book Depreciation

All total installed costs except for the land itself is considered a depreciable asset. This means that the value of the assets decrease with time The book value for year 1 is calculated by summing all costs in year 0 except for land costs. The book value will decrease by 15.30% each year over the next 25 years.[9] The15.30% of the remaining book value each year is subtracted from the corresponding gross operating income to obtain the Earnings Before Interest and Tax (EBIT).

3.2.4.3 Tax Rate

The EBIT value is multiplied by the tax rate to obtain the amount of money that must be paid from profits. When the cumulative EBIT is greater than 0, the power producer must pay the minimum alternate tax (MAT) of 19% on the EBIT from that corresponding year. This tax payable is subtracted from the EBIT to obtain the profit after tax.

3.2.4.4 Net Cash Flow

The net cash flow is determined by subtracting any capital expenditures made that year from the after-tax operating income, which is determined by adding book depreciation back to the profit after taxes. A negative net cash flow indicates that cash outflows were greater than cash inflows for the year and more equity would need to be raised.

3.2.4.5 Discounted Cash Flow

The discounted cash flow takes future cash flows and adjusts them to reflect dollar amounts in the base year. The nominal weighted average cost of capital is used to determine the present worth factor for each year to discount the value.

3.3 Economic Metrics

3.3.1 Net Present value

The net present value (NPV) is found by summing the discounted cash flow from each year. A positive NPV is a good indicator to accept the project.

3.3.2 Internal Rate of Return

The internal rate of return is found through an iterative excel technique, where a discount rate is determined that sets the NPV of the net cash flow to 0. A project with an IRR greater than the nominal discount rate is considered favorable.

3.3.3 Levelized Cost of Energy

The levered LCOE is determined by first summing operation and maintenance, interest payment, loan repayment, capital expenditure, and tax payable for each year. Any increases in term loans can be subtracted from that cost summation to receive total cash outflow for the year. The total costs for each year can be discounted using the nominal discount rate to the base year and added together to get the total life cycle costs. Total energy generated in kilowatt-hours must also be discounted using the nominal discount rate. Following this, the total life cycle costs are divided by the discounted amount of generated energy to yield LCOE.

3.4 Variable Changes

Changing variables in the cash flow allow the simulation to reflect different scenarios. The four variations will involve changes with project leveraging, electricity price escalation rates, REC clearance percentage on the market, and the cost of debt. Exploring how these changes affect the various economic metrics will be important to understand the risk associated with solar projects in Northwestern, India. All other assumptions will be kept the same in the simulations.

Chapter 4

Results and Discussion

4.1 Results and Discussion

4.1.1 Base Case Solar Project in Jaipur and Ahmedabad surrounding region

The results of the base cases for the various locations are shown in table 10.

Table 10: Base Case Simulation for 1 MW solar photovoltaic plant

	JAIPUR	**AHMEDABAD**
	1702 MWh/year	*1723 MWh/year*
NPV	$166,200.00	$183,500
IRR	14.00%	14.10%
LCOE	$0.168/kWh	$0.167/kWh

The base case was created using the following assumptions. The average output for each location was found using System Advisor Model (SAM). NREL provided weather files for each location from 2004 to 2008.The total annual electrical output for each year was determined using SAM. The five years of data were averaged to get the average annual output.

Jaipur averaged 1702 megawatt-hours per year and Ahmedabad averaged 1723 megawatt-hours per year. These values were be the assumed annual production output values for the 25-year simulation, prior to accounting for panel degradation, auxiliary losses, and transmission losses. Each year, it was assumed that the system outputs 0.50% less electricity due to panel degradation. An additional 1% of total electrical output was lost due to auxiliary and transmission losses. Accounting for these losses determined the total amount of electricity generated for sale.

In year one of the project, the price of solar electricity was set at $0.10/kWh. The base case model assumes an 8% price increase for the next 25 years. Additionally, the Renewable Energy Credit (REC) clearance percentage on the market was assumed to be 20%, which is the current REC clearance percentage on the market. The power producer received one REC per megawatt-hour generated, which are valued at $153/REC, but the price is expected to halve every five years when the price floor is reset. The plants roughly received 1650 RECs per year; however, only 20% of those were sold to increase revenues. The summation of electricity sold from each plant and REC revenues gives the total revenues for the power producer. Operation and maintenance costs were subtracted from this to obtain the gross operating income. As determined by India’s Central Electricity Regulatory Commission, operation and maintenance costs are assumed to be $18,600 in the first year and increase 5.72% each year.

Depreciation was subtracted out to obtain the earnings before interest and tax (EBIT). The book value depreciation rate is set at 15.30% for each year. When the cumulative EBIT value was positive, the power producer paid the minimum alternate tax (MAT) rate of 19% on the EBIT. The total amount of taxes paid was removed from EBIT to obtain the profit after taxes, which then added back the book value depreciation to obtain the after-tax operating income. The net cash flow was obtained by removing any capital expenditures from the after-tax operating income.

The debt-to-equity ratio was set to 70:30, which reflects similar project leveraging in India. Additionally, the cost of equity was assumed to be 15% and the cost of debt was assumed to be 12%. Using these values, the weighted average cost of capital was determined to be 12.9%, which was used to discount the free cash flow. The discounted free cash flow is the cash flow available to all providers of capital.

The net present value was determined through the summation of the discounted cash flows for each year. The internal rate of return was determined by finding the discount rate that would set the NPV of the project to 0. The levelized cost of energy was determined by dividing the discounted total costs of the system by the discounted amount of energy produced by the system.

Table 11 shows the cash flow model for Jaipur, Rajasthan that was used to find the discounted cash flow of the project, and table 12 shows the cash flow model for Ahmedabad, Gujarat. Additionally, table 13 shows the method used to get the after-tax operating income.

Table 11: Cash flow for Jaipur, Rajasthan - Years 0 -25

YEAR	0	1	2	3	4	5
Annual Production (kWh)	0	1702000	1702000	1702000	1702000	1702000
After Panel Degradation %	0	1702000	1693490	1685022.55	1676597.437	1668214.45
After Auxillary Consumption %	0	1693490	1684980	1676512.55	1668087.437	1659704.45
Net Production (kWh)	0	1684980	1676470	1668003	1659577	1651194
Price per unit ($/kWh)	0	$0.10	$0.11	$0.12	$0.13	$0.14
Rec/Unit (REC/MWh)	0	1684	1676	1668	1659	1651
Rec's Cleared	0	336	335	333	331	330
Price per REC ($/REC)	0	$153.45	$153.45	$153.45	$153.45	$153.45
Total Received from REC's sold	0	$51,559.20	$51,405.75	$51,098.85	$50,791.95	$50,638.50
Total Sale ($/kWh)	0	$220,057.20	$232,464.51	$245,654.67	$259,850.91	$275,281.68
Operation & Maintenance	0	$18,645.00	$19,711.49	$20,838.99	$22,030.98	$23,291.15
Gross operating income	0	$201,412.20	$212,753.02	$224,815.68	$237,819.93	$251,990.53
Depreciation	$-	$275,966.25	$233,743.42	$197,980.67	$167,689.63	$142,033.12
Taxable Income	$-	$(74,554.05)	$(20,990.40)	$26,835.00	$70,130.30	$109,957.41
Income Tax	$-	$-	$-	$-	$13,324.76	$20,891.91
After-tax Operating Income	$-	$201,412.20	$212,753.02	$224,815.68	$224,495.17	$231,098.62
CAPEX	$1,823,701.00					
Increase in Term Loans	$-					
NET CASH FLOW	$(1,823,701.00)	$201,412.20	$212,753.02	$224,815.68	$224,495.17	$231,098.62
DICOUNTED CASH FLOW	$(1,823,701.00)	$178,398.76	$166,912.11	$156,222.92	$138,175.56	$125,987.55

YEAR	6	7	8	9	10	11
Annual Production (kWh)	1702000	1702000	1702000	1702000	1702000	1702000
After Panel Degradation %	1659873.378	1651574.011	1643316.141	1635099.56	1626924.062	1618789.442
After Auxillary Consumption %	1651363.378	1643064.011	1634806.141	1626589.56	1618414.062	1610279.442
Net Production (kWh)	1642853	1634554	1626296	1618080	1609904	1601769
Price per unit ($/kWh)	$0.15	$0.16	$0.17	$0.19	$0.20	$0.22
Rec/Unit (REC/MWh)	1642	1634	1626	1618	1609	1601
Rec's Cleared	328	326	325	323	321	320
Price per REC ($/REC)	$76.73	$76.73	$76.73	$76.73	$76.73	$38.36
Total Received from REC's sold	$25,165.80	$25,012.35	$24,935.63	$24,782.18	$24,628.73	$12,276.00
Total Sale ($/kWh)	$266,554.86	$284,395.53	$303,654.20	$324,277.41	$346,449.29	$358,086.01
Operation & Maintenance	$24,623.41	$26,031.87	$27,520.89	$29,095.08	$30,759.32	$32,518.76
Gross operating income	$241,931.45	$258,363.66	$276,133.31	$295,182.32	$315,689.97	$325,567.25
Depreciation	$120,302.05	$101,895.84	$86,305.77	$73,100.99	$61,916.54	$52,443.31
Taxable Income	$121,629.40	$156,467.83	$189,827.54	$222,081.33	$253,773.43	$273,123.94
Income Tax	$23,109.59	$29,728.89	$36,067.23	$42,195.45	$48,216.95	$51,893.55
After-tax Operating Income	$218,821.87	$228,634.78	$240,066.08	$252,986.87	$267,473.02	$273,673.70
CAPEX						
Increase in Term Loans						
NET CASH FLOW	$218,821.87	$228,634.78	$240,066.08	$252,986.87	$267,473.02	$273,673.70
DICOUNTED CASH FLOW	$105,664.00	$97,787.80	$90,945.09	$84,889.21	$79,495.14	$72,044.31

YEAR	12	13	14	15	16	17
Annual Production (kWh)	1702000	1702000	1702000	1702000	1702000	1702000
After Panel Degradation %	1610695.495	1602642.017	1594628.807	1586655.663	1578722.385	1570828.773
After Auxillary Consumption %	1602185.495	1594132.017	1586118.807	1578145.663	1570212.385	1562318.773
Net Production (kWh)	1593675	1585622	1577609	1569636	1561702	1553809
Price per unit ($/kWh)	$0.23	$0.25	$0.27	$0.29	$0.32	$0.34
Rec/Unit (REC/MWh)	1593	1585	1577	1569	1561	1553
Rec's Cleared	318	317	315	313	312	310
Price per REC ($/REC)	$38.36	$38.36	$38.36	$38.36	$19.18	$19.18
Total Received from REC's sold	$12,199.28	$12,160.91	$12,084.19	$12,007.46	$5,984.55	$5,946.19
Total Sale ($/kWh)	$383,786.87	$411,447.51	$441,134.42	$473,039.85	$501,382.96	$538,272.16
Operation & Maintenance	$34,378.83	$36,345.30	$38,424.25	$40,622.12	$42,945.70	$45,402.20
Gross operating income	$349,408.04	$375,102.21	$402,710.17	$432,417.73	$458,437.26	$492,869.97
Depreciation	$44,419.48	$37,623.30	$31,866.94	$26,991.29	$22,861.63	$19,363.80
Taxable Income	$304,988.56	$337,478.91	$370,843.24	$405,426.44	$435,575.63	$473,506.17
Income Tax	$57,947.83	$64,120.99	$70,460.21	$77,031.02	$82,759.37	$89,966.17
After-tax Operating Income	$291,460.21	$310,981.22	$332,249.96	$355,386.71	$375,677.89	$402,903.79
CAPEX						
Increase in Term Loans						
NET CASH FLOW	$291,460.21	$310,981.22	$332,249.96	$355,386.71	$375,677.89	$402,903.79
DICOUNTED CASH FLOW	$67,959.78	$64,226.30	$60,778.47	$57,582.70	$53,915.37	$51,215.85

YEAR	18	19	20	21	22	23
Annual Production (kWh)	1702000	1702000	1702000	1702000	1702000	1702000
After Panel Degradation %	1562974.629	1555159.756	1547383.957	1539647.037	1531948.802	1524289.058
After Auxillary Consumption %	1554464.629	1546649.756	1538873.957	1531137.037	1523438.802	1515779.058
Net Production (kWh)	1545955	1538140	1530364	1522627	1514929	1507269
Price per unit ($/kWh)	$0.37	$0.40	$0.43	$0.47	$0.50	$0.54
Rec/Unit (REC/MWh)	1545	1538	1530	1522	1514	1507
Rec's Cleared	309	307	306	304	302	301
Price per REC ($/REC)	$19.18	$19.18	$19.18	$9.59	$9.59	$9.59
Total Received from REC's sold	$5,927.01	$5,888.64	$5,869.46	$2,915.55	$2,896.37	$2,886.78
Total Sale ($/kWh)	$577,933.01	$620,532.29	$666,328.80	$712,605.49	$765,486.34	$822,319.69
Operation & Maintenance	$47,999.20	$50,744.76	$53,647.36	$56,715.98	$59,960.14	$63,389.86
Gross operating income	$529,933.81	$569,787.53	$612,681.44	$655,889.50	$705,526.20	$758,929.83
Depreciation	$16,401.14	$13,891.76	$11,766.32	$9,966.08	$8,441.27	$7,149.75
Taxable Income	$513,532.67	$555,895.77	$600,915.12	$645,923.43	$697,084.93	$751,780.08
Income Tax	$97,571.21	$105,620.20	$114,173.87	$122,725.45	$132,446.14	$142,838.22
After-tax Operating Income	$432,362.60	$464,167.34	$498,507.57	$533,164.05	$573,080.06	$616,091.62
CAPEX						
Increase in Term Loans						
NET CASH FLOW	$432,362.60	$464,167.34	$498,507.57	$533,164.05	$573,080.06	$616,091.62
DICOUNTED CASH FLOW	$48,680.74	$46,290.27	$44,034.48	$41,714.60	$39,714.45	$37,816.79

YEAR	24	25
Annual Production (kWh)	1702000	1702000
After Panel Degradation %	1516667.613	1509084.275
After Auxillary Consumption %	1508157.613	1500574.275
Net Production (kWh)	1499648	1492064
Price per unit ($/kWh)	$0.59	$0.63
Rec/Unit (REC/MWh)	1499	1492
Rec's Cleared	299	298
Price per REC ($/REC)	$9.59	$9.59
Total Received from REC's sold	$2,867.60	$2,858.01
Total Sale ($/kWh)	$883,380.24	$949,002.93
Operation & Maintenance	$67,015.76	$70,849.06
Gross operating income	$816,364.48	$878,153.87
Depreciation	$6,055.84	$5,129.30
Taxable Income	$810,308.64	$873,024.57
Income Tax	$153,958.64	$165,874.67
After-tax Operating Income	$662,405.84	$712,279.20
CAPEX		
Increase in Term Loans		$190,370.10
NET CASH FLOW	$662,405.84	$902,649.30
DICOUNTED CASH FLOW	$36,013.85	$43,468.08

Table 12: Cash flow for Ahmedabad, Gujarat - Years 0 -25

YEAR	0	1	2	3	4	5
Annual Production (kWh)	0	1716000	1716000	1716000	1716000	1716000
After Panel Degradation %	0	1716000	1707420	1698882.9	1690388.486	1681936.543
After Auxillary Consumption %	0	1707420	1698840	1690302.9	1681808.486	1673356.543
Net Production (kWh)	0	1698840	1690260	1681723	1673228	1664777
Price per unit ($/kWh)	0	$0.10	$0.11	$0.12	$0.13	$0.14
Rec/Unit (REC/MWh)	0	1698	1690	1681	1673	1664
Rec's Cleared	0	339	338	336	334	332
Price per REC ($/REC)	0	$153.45	$153.45	$153.45	$153.45	$153.45
Total Received from REC's sold	0	$52,019.55	$51,866.10	$51,559.20	$51,252.30	$50,945.40
Total Sale ($/kWh)	0	$221,903.55	$234,414.18	$247,715.36	$262,030.90	$277,436.41
Operation & Maintenance	0	$18,645.00	$19,711.49	$20,838.99	$22,030.98	$23,291.15
Gross operating income	0	$203,258.55	$214,702.69	$226,876.37	$239,999.92	$254,145.26
Depreciation	$-	$275,966.25	$233,743.42	$197,980.67	$167,689.63	$142,033.12
Taxable Income	$-	$(72,707.70)	$(19,040.73)	$28,895.69	$72,310.29	$112,112.14
Income Tax	$-	$-	$-	$-	$13,738.95	$21,301.31
After-tax Operating Income	$-	$203,258.55	$214,702.69	$226,876.37	$226,260.96	$232,843.95
CAPEX	$1,823,701.00					
Increase in Term Loans	$-					
NET CASH FLOW	$(1,823,701.00)	$203,258.55	$214,702.69	$226,876.37	$226,260.96	$232,843.95
DICOUNTED CASH FLOW	$(1,823,701.00)	$180,034.15	$168,441.69	$157,654.89	$139,262.40	$126,939.05

YEAR	6	7	8	9	10	11
Annual Production (kWh)	1716000	1716000	1716000	1716000	1716000	1716000
After Panel Degradation %	1673526.86	1665159.226	1656833.43	1648549.263	1640306.516	1632104.984
After Auxillary Consumption %	1664946.86	1656579.226	1648253.43	1639969.263	1631726.516	1623524.984
Net Production (kWh)	1656367	1647999	1639673	1631389	1623147	1614945
Price per unit ($/kWh)	$0.15	$0.16	$0.17	$0.19	$0.20	$0.22
Rec/Unit (REC/MWh)	1656	1647	1639	1631	1623	1614
Rec's Cleared	331	329	327	326	324	322
Price per REC ($/REC)	$76.73	$76.73	$76.73	$76.73	$76.73	$38.36
Total Received from REC's sold	$25,395.98	$25,242.53	$25,089.08	$25,012.35	$24,858.90	$12,352.73
Total Sale ($/kWh)	$268,770.61	$286,759.29	$306,100.29	$326,971.12	$349,326.64	$361,007.23
Operation & Maintenance	$24,623.41	$26,031.87	$27,520.89	$29,095.08	$30,759.32	$32,518.76
Gross operating income	$244,147.20	$260,727.42	$278,579.40	$297,876.03	$318,567.32	$328,488.48
Depreciation	$120,302.05	$101,895.84	$86,305.77	$73,100.99	$61,916.54	$52,443.31
Taxable Income	$123,845.15	$158,831.59	$192,273.62	$224,775.04	$256,650.78	$276,045.17
Income Tax	$23,530.58	$30,178.00	$36,531.99	$42,707.26	$48,763.65	$52,448.58
After-tax Operating Income	$220,616.62	$230,549.42	$242,047.41	$255,168.77	$269,803.67	$276,039.90
CAPEX						
Increase in Term Loans						
NET CASH FLOW	$220,616.62	$230,549.42	$242,047.41	$255,168.77	$269,803.67	$276,039.90
DICOUNTED CASH FLOW	$106,530.65	$98,606.70	$91,695.69	$85,621.35	$80,187.82	$72,667.21

YEAR	12	13	14	15	16	17
Annual Production (kWh)	1716000	1716000	1716000	1716000	1716000	1716000
After Panel Degradation %	1623944.459	1615824.737	1607745.613	1599706.885	1591708.35	1583749.809
After Auxillary Consumption %	1615364.459	1607244.737	1599165.613	1591126.885	1583128.35	1575169.809
Net Production (kWh)	1606784	1598665	1590586	1582547	1574548	1566590
Price per unit ($/kWh)	$0.23	$0.25	$0.27	$0.29	$0.32	$0.34
Rec/Unit (REC/MWh)	1606	1598	1590	1582	1574	1566
Rec's Cleared	321	319	318	316	314	313
Price per REC ($/REC)	$38.36	$38.36	$38.36	$38.36	$19.18	$19.18
Total Received from REC's sold	$12,314.36	$12,237.64	$12,199.28	$12,122.55	$6,022.91	$6,003.73
Total Sale ($/kWh)	$386,958.49	$414,808.61	$444,778.71	$476,947.21	$505,496.28	$542,708.41
Operation & Maintenance	$34,378.83	$36,345.30	$38,424.25	$40,622.12	$42,945.70	$45,402.20
Gross operating income	$352,579.66	$378,463.32	$406,354.46	$436,325.10	$462,550.58	$497,306.22
Depreciation	$44,419.48	$37,623.30	$31,866.94	$26,991.29	$22,861.63	$19,363.80
Taxable Income	$308,160.18	$340,840.01	$374,487.53	$409,333.80	$439,688.95	$477,942.42
Income Tax	$58,550.43	$64,759.60	$71,152.63	$77,773.42	$83,540.90	$90,809.06
After-tax Operating Income	$294,029.23	$313,703.71	$335,201.83	$358,551.67	$379,009.68	$406,497.16
CAPEX						
Increase in Term Loans						
NET CASH FLOW	$294,029.23	$313,703.71	$335,201.83	$358,551.67	$379,009.68	$406,497.16
DICOUNTED CASH FLOW	$68,558.80	$64,788.57	$61,318.45	$58,095.52	$54,393.53	$51,672.62

YEAR	18	19	20	21	22	23
Annual Production (kWh)	1716000	1716000	1716000	1716000	1716000	1716000
After Panel Degradation %	1575831.06	1567951.904	1560112.145	1552311.584	1544550.026	1536827.276
After Auxillary Consumption %	1567251.06	1559371.904	1551532.145	1543731.584	1535970.026	1528247.276
Net Production (kWh)	1558671	1550792	1542952	1535152	1527390	1519667
Price per unit ($/kWh)	$0.37	$0.40	$0.43	$0.47	$0.50	$0.54
Rec/Unit (REC/MWh)	1558	1550	1542	1535	1527	1519
Rec's Cleared	311	310	308	307	305	303
Price per REC ($/REC)	$19.18	$19.18	$19.18	$9.59	$9.59	$9.59
Total Received from REC's sold	$5,965.37	$5,946.19	$5,907.83	$2,944.32	$2,925.14	$2,905.96
Total Sale ($/kWh)	$582,676.47	$625,645.66	$671,799.85	$718,471.90	$771,787.88	$829,079.22
Operation & Maintenance	$47,999.20	$50,744.76	$53,647.36	$56,715.98	$59,960.14	$63,389.86
Gross operating income	$534,677.27	$574,900.90	$618,152.49	$661,755.91	$711,827.74	$765,689.36
Depreciation	$16,401.14	$13,891.76	$11,766.32	$9,966.08	$8,441.27	$7,149.75
Taxable Income	$518,276.14	$561,009.14	$606,386.17	$651,789.84	$703,386.48	$758,539.60
Income Tax	$98,472.47	$106,591.74	$115,213.37	$123,840.07	$133,643.43	$144,122.52
After-tax Operating Income	$436,204.81	$468,309.16	$502,939.12	$537,915.84	$578,184.31	$621,566.83
CAPEX						
Increase in Term Loans						
NET CASH FLOW	$436,204.81	$468,309.16	$502,939.12	$537,915.84	$578,184.31	$621,566.83
DICOUNTED CASH FLOW	$49,113.34	$46,703.32	$44,425.94	$42,086.38	$40,068.18	$38,152.87

YEAR	24	25
Annual Production (kWh)	1716000	1716000
After Panel Degradation %	1529143.14	1521497.424
After Auxillary Consumption %	1520563.14	1512917.424
Net Production (kWh)	1511983	1504337
Price per unit ($/kWh)	$0.59	$0.63
Rec/Unit (REC/MWh)	1511	1504
Rec's Cleared	302	300
Price per REC ($/REC)	$9.59	$9.59
Total Received from REC's sold	$2,896.37	$2,877.19
Total Sale ($/kWh)	$890,651.77	$956,804.74
Operation & Maintenance	$67,015.76	$70,849.06
Gross operating income	$823,636.01	$885,955.68
Depreciation	$6,055.84	$5,129.30
Taxable Income	$817,580.17	$880,826.38
Income Tax	$155,340.23	$167,357.01
After-tax Operating Income	$668,295.78	$718,598.66
CAPEX		
Increase in Term Loans		$190,370.10
NET CASH FLOW	$668,295.78	$908,968.76
DICOUNTED CASH FLOW	$36,334.08	$43,772.41

Table 13: Example process to obtain after-tax operating income

Years	0	1	2
EABITDA	$ -	$ 203,258.55	$ 214,702.69
Opening Depreciation Balance		$ 1,803,701.00	
Book Value	$ -	$ 1,803,701.00	$ 1,527,734.75
Book Depreciation	$ -	$ 275,966.25	$ 233,743.42
EBIT	$ -	$ (72,707.70)	$ (19,040.73)
Cumulative EBIT	$	$ (72,707.70)	$ (91,748.43)
Tax Payable	$ -	$ -	$ -
Profit after tax	$ -	$ (72,707.70)	$ (19,040.73)
After-tax Operating Income	**$ -**	**$ 203,258.55**	**$ 214,702.69**

Both projects have positive net present values, which show that the investment with the base case parameters would be profitable. Both base case internal rates of return are around 14%, which is higher than the WACC demonstrating that return on investment is greater than the cost of capital required. Additionally, the levelized costs of energy for both base case projects is roughly $0.19/kWh.

4.1.2 Deviation from Base Case

4.1.2.1 Effect of Solar Resource on NPV, IRR, and LCOE

The results in all cases show how projects in regions with higher solar resources will have a higher NPV and IRR, and a lower LCOE. A higher solar resource meant that the power producer was able to sell more electricity, which increased the cash flow outlay leading to a higher NPV and IRR. Additionally, LCOE decreased as more electricity was produced so the overall dollars to kilowatt-hour metric decreased. While the two sites have similar solar resources, it is still clear to see the impact that a better solar resource will have on a project's financial feasibility.

4.1.2.2 Effect of REC Percentage on NPV, IRR, and LCOE

REC clearance percentage on the Indian Exchange Market was adjusted in this model to simulate different financial outcomes. REC clearance percent was adjusted from 0% to 100% in increments of 20%. The results for the Jaipur and Ahmedabad sites are displayed in tables 13 and 14, respectively.

Table 14: Effect of REC clearance percentage on NPV, IRR, and LCOE in Jaipur, Rajasthan

	JAIPUR, RAJASTHAN		
REC % Cleared	1702 MWh/year		
	NPV	IRR	LCOE
0%	($39,400)	12.70%	$0.168/kWh
20%	$166,200	14.00%	$0.168/kWh
40%	$372,400	15.40%	$0.168/kWh
60%	$575,100	16.90%	$0.168/kWh
80%	$774,000	18.50%	$0.168/kWh
100%	$973,000	20.20%	$0.168/kWh

Table 15: Effect of REC clearance percentage on NPV, IRR, and LCOE in Ahmedabad, Gujarat

	AHMEDABAD, GUJARAT		
REC % Cleared	1716 MWh/year		
	NPV	IRR	LCOE
0%	($22,400)	12.80%	$0.167/kWh
20%	$184,000	14.10%	$0.167/kWh
40%	$392,000	15.50%	$0.167/kWh
60%	$595,967	17.10%	$0.167/kWh
80%	$797,000	18.70%	$0.167/kWh
100%	$998,000	20.40%	$0.167/kWh

From the results, it is observed that NPV increased with increasing REC clearance on the market. As more RECs cleared, power producers received more revenue from the state for producing renewable energy. Additionally, the IRR increased as REC clearance increased from 0% to 100%. Finally, the LCOE stayed constant since costs and energy output were not adjusted.

4.1.2.3 Effect of Project Leverage on NPV, IRR, and LCOE

Changing project leverage refers to altering the amount of equity invested by the power producer into a project. The cost of capital is generally higher than the cost of debt, so increasing equity in a project will decrease project profitability. Usually, a lending agency prefers an entity to invest some equity into a project. In tables 15 and 16, equity is adjusted from 0% to 40% in 10% increments in order to view its effect on NPV, IRR, and LCOE.

Table 16: Effect project leveraging has on NPV, IRR, and LCOE in Jaipur, Rajasthan

	JAIPUR, RAJASTHAN		
Equity %	1702 MWh/year		
	NPV	IRR	LCOE
0%	$325,300	14.00%	$0.161/kWh
10%	$269,600	14.00%	$0.163/kWh
20%	$216,200	14.00%	$0.166/kWh
30%	$166,200	14.00%	$0.169/kWh
40%	$116,000	14.00%	$0.178/kWh

Table 17: Effect project leveraging has on NPV, IRR, and LCOE in Ahmedabad, Gujarat

	AHMEDABAD, GUJARAT		
Equity %	1716 MWh/year		
	NPV	IRR	LCOE
0%	$345,000	14.10%	$0.159/kWh
10%	$289,000	14.10%	$0.162/kWh
20%	$235,000	14.10%	$0.165/kWh
30%	$184,000	14.10%	$0.167/kWh
40%	$134,000	14.10%	$0.170/kWh

The results show that NPV decreased with a higher equity percentage. This is because more money is required to cover the cost of capital. The results also show how IRR remained constant as equity increased for a given project. LCOE also increased as equity increased because the cost of capital is larger than the cost of debt.

4.1.2.4 Effect of Electricity Prices Escalation Rate on NPV, IRR, and LCOE

The escalation rates on electricity prices were adjusted from 6% to 9% in increments of 1%. The effect on NPV, IRR, and LCOE are seen in tables 17 and 18. This is an important parameter, as it is rather difficult to predict what energy prices will do over the next 25 years. Understanding the variation in financial results due to changing electricity prices is important to energy project investors.

Table 18: Effect electricity price escalation rate has on NPV, IRR, and LCOE in Jaipur, Rajasthan

	JAIPUR, RAJASTHAN		
Electricity Price Escalation Rate	1702 MWh/year		
	NPV	IRR	LCOE
6%	($106,000)	12.10%	$0.168/kWh
7%	$25,000	13.10%	$0.168/kWh
8%	$166,200	14.00%	$0.168/kWh
9%	$332,300	14.90%	$0.168/kWh

Table 19: Effect electricity price escalation rate has on NPV, IRR, and LCOE in Ahmedabad, Gujarat

	AHMEDABAD, GUJARAT		
Electricity Price Escalation Rate	1716 MWh/year		
	NPV	IRR	LCOE
6%	($90,000)	12.20%	$0.167/kWh
7%	$42,000	13.20%	$0.167/kWh
8%	$184,000	14.10%	$0.167/kWh
9%	$352,000	15.01%	$0.167/kWh

The NPV increased because the amount of revenue over the 25 years increased. IRR increased because a larger discount rate would be needed to discount a larger cash outlay in years 1 through 25. LCOE is independent of electric price escalation rate.

4.1.2.5 Effect interest has on NPV, IRR, and LCOE

Tables 19 and 20 show the effect that interest rates have on project NPV, IRR, and LCOE. A larger interest rate increases the weighted average cost of capital for the project. This will affect NPV and LCOE.

Table 20: Effect interest rate has on NPV, IRR, and LCOE in Jaipur, Rajasthan

	JAIPUR, RAJASTHAN		
Interest Rates	1702 MWh/year		
	NPV	IRR	LCOE
11%	$288,000	14.00%	$0.162/kWh
12%	$166,200	14.00%	$0.169/kWh
13%	$53,600	14.00%	$0.176/kWh
14%	($47,000)	14.00%	$0.182/kWh

Table 21: Effect interest rate has on NPV, IRR, and LCOE in Ahmedabad, Gujarat

	AHMEDABAD, GUJARAT		
Interest Rates	1716 MWh/year		
	NPV	IRR	LCOE
11%	$307,000	14.10%	$0.161/kWh
12%	$184,000	14.10%	$0.168/kWh
13%	$71,000	14.10%	$0.174/kWh
14%	($31,400)	14.10%	$0.181/kWh

NPV decreased as interest rates increased due to a larger WACC. LCOE increased for the project as interest rates increased also because of the increased WACC.

4.2 Discussion

4.2.1 Renewable Purchase Obligation Enforcement and its Effect on Project Feasibility

As seen from the results, REC percentage clearance increases yield a significantly higher NPV and IRR. As outlined in the Jawaharal Nehru National Solar Mission, India aims to install 20,000 MW of grid-connected solar power by 2022. If the country is serious about reaching this goal, then it needs to enforce renewable purchase obligations. By enforcing this policy, demand for RECs will increase leading to more investments in solar energy around the country. In 2013, the state of Gujarat waived off the shortfall RPO compliance, sending uncertainty about the enforcement of the RPO legislation through the industry.

The regulatory environment in India is always changing and many of their policies are not transparent or implementable. [24] The implementation of the RPO is significantly more difficult to manage because the states oversee the implementation of the obligations and they each have their own approach. Acts like the one seen in Gujarat undermine the work India, investors, and power producers have put into solar energy.

Furthermore, it is necessary for states to increase RPOs for utilities in the coming years in order to meet the nation's solar goal. If RPO requirements are not increased, RECs will continue sell at low prices. The Indian government appears to want large investments in the solar market, and their best chance at achieving this is to make solar power project investments look attractive by enforcing RPOs to drive REC trading markets.

The government expects REC prices to decrease in the coming years to reflect the increasing electricity prices. While solar producers will receive less government support, this is still a positive indicator that solar will reach grid parity soon in India. [28]

4.2.2 Potential Risks to Financial Feasibility

Variation in the escalation rate for electricity prices is one of the main concerns for many investors. The World Institute for Sustainable Energy predicts a nominal growth rate around 6%; however, a slight change in this estimate could drastically alter a project's financial feasibility. [17] Most PPAs are renegotiated throughout the project's life to better reflect the market prices, which is why this escalation rate is important in the analysis. India's government offers various payment schemes to lock in set payment rates; however, many power producers opt to work with a 3rd party purchaser because rates will typically be higher.

Another risk involved with solar energy is the solar resource itself. Most Indian solar resource data is satellite compile data, which can have a margin of error up to 10% for some locations. Recently, ground measuring stations have been installed throughout India; however, more data needs to be collected from the stations. [24] It is important to gather significantly more weather data in order to minimize any uncertainty associated with the solar resource at a specific site. Single-year weather files were used in this simulation. These files help to show variation in the solar annual output from year to year; however, many more years should be collected. Another option is with Typical Meteorological Year (TMY) data, which is comprised of hourly typical solar irradiance values. These files can help when estimating a solar resource over a long period of time, but they do not show the variance of annual production values. Therefore, it would be inappropriate to use TMY data for risk assessment purposes. [20]

4.2.3 Coal Industry's Future for Electricity Production in India

Coal is solar energy's primary competitor in the region. India's proven coal reserve is estimate to contain around 40.62 billion tons, and they are expected to reach peak production by 2030. [17] The coal mined in India is a low quality coal, so India imports large quantities of coal from neighboring countries. Blended domestic and imported coal generated electricity costs roughly $0.069/kWh; however, this price does not factor in subsidies and externality costs. When factoring in these additional costs, domestic coal generated electricity is reported to cost roughly $0.260/kWh while imported coal costs $0.297/kWh. [17] Increased solar energy would decrease investments for coal infrastructure such as railways and ports. Additionally, little water would be needed for these solar projects and minimal harm would be done to the environment. Emissions would decrease from less coal combustion so air quality would also improve throughout the state. [17]

Chapter 5

Conclusion

Solar photovoltaic plants in Northwestern India have large potential to be great investment opportunities. Both base case simulations in Jaipur and Ahmedabad for years had positive net present values of $166,000 and $183,500, respectively. The internal rates of return were roughly 14% for both sites which is larger than the weight average cost of capital calculated for the base case. The levelized cost of energy for these solar projects was $0.168/kWh, which is higher than conventional sources like coal-fired power plants. The Indian government will decrease REC prices in the coming years, which indicates that they believe solar will soon be competitive with traditional generation methods without government aid.

Various simulations were carried out to demonstrate how changing solar resource, REC clearance, project leveraging, electricity price escalation rates, and interest rates effected the project's NPV, IRR, and LCOE. Ahmedabad, located 300 miles south of Jaipur, had a larger solar resource, and therefore greater NPV and IRR, and a lower LCOE on projects. The weather variability causes uncertainty and potential risk for investors as unpredictable weather can affect a project's revenues.

Increased REC clearance on the market caused NPV and IRR both to increase. REC clearance percentage can be increased through government enforcement of the RPO legislation established in the 2010 Jawaharlal Nehru National Solar Mission. Increased equity with projects caused NPV to decrease and LCOE to increase, as less more costs were incurred due to the higher weighted average cost of capital. Increased electricity price escalation rates caused NPV and IRR to increase due to a larger cash flow outlay in years 1 through 25. Finally, increased interest rates caused NPV to decrease and LCOE to increase.

These simulations highlight important aspects that the Indian government and investors should focus on to develop solar energy projects in Northwestern, India. Understanding how these various parameters affect project feasibility will help power producers, the Indian government, and investors learn what risks they can help mitigate in order to secure financing and government incentives for solar power production.

Appendix A

Background on Solar Energy

A.1 Solar Photovoltaic Theory

A.1.1 Sun-Earth Relationship

Electromagnetic radiation in the shortwave energy band (250nm < λ < 3000nm) is emitted by the sun and travels to Earth where it will be transmitted (refracted), reflected, or absorbed. [1] The amount of extraterrestrial radiation incident on the Earth's atmosphere fluctuates throughout a given year due to the tilt of the Earth. After reaching Earth, the light must then travel through the atmosphere either as total beam irradiance or diffuse irradiance. [21] An atmosphere factor of 1.5 is generally used to simulate a clear sky within the Earth's atmosphere. The light is most intense when it travels the least amount of distance in the Earth's atmosphere, which occurs at solar noon when the sun is highest in the sky for a given day. [1]

Irradiance, depicted in figure A.1, is measured in [W/m^2] and refers to the radiant flux incident upon Earth's surface. By integrating irradiance over time, irradiation can be calculated in [J/m^2]. [1]

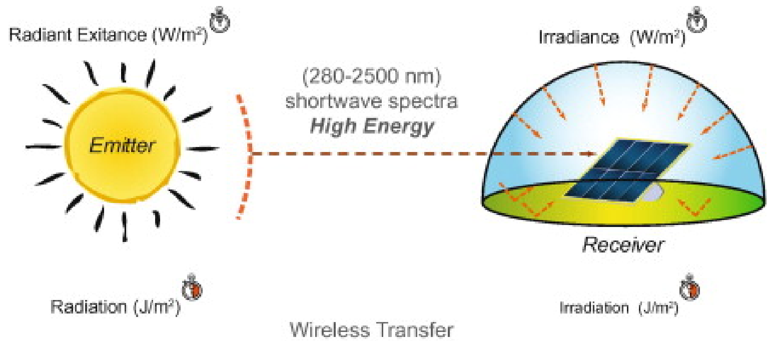

Figure A.3: Sun-Earth Relationship of radiation and irradiation [1]

The Inverse Square Law of Radiation tells us that the intensity of the Sun's radiant exitance [W/m^2] decreases in a manner that is inversely proportional to the squared distance between the emitter and receiver. Note that the electromagnetic radiation is not getting weaker, but that it is being distributed over a larger area so the intensity decreases. [1]

Figure A.2 depicts how photons incident on regions closer to the poles are less dense, making these regions impractical for photovoltaic systems. Light intensity is inversely proportional to the cosine of the angle of incidence, so it is important to try to minimize the angle of incidence on any photovoltaic system so that the maximum amount of photons can reach the solar energy conversion system throughout the year. [1]

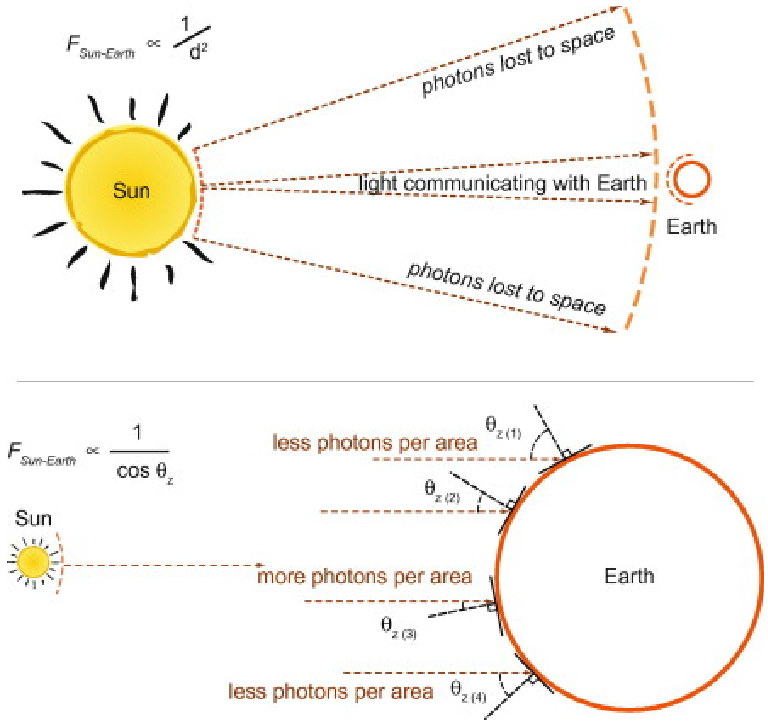

Figure A.4: Depiction of the cosine effect, which explains how the angle of irradiance affects light intensity [1]

Earth-Sun geometric angles are incredibly important to the resource assessment models for solar energy conversion systems. The Sun's position is described by the solar altitude (α_s) and solar azimuth (γ_s) The solar altitude angle is found between the horizontal and the direct beam of the sun, while the solar azimuth angle is found between the projection of the beam radiation on the horizontal plane and due south. Additionally, the zenith angle is used to describe the angle of incidence on a horizontal surface and is measured as the angle between the vertical and the central beam of the Sun or ($90^o - \alpha_s$) Figure A.3 depicts these angles in order to contextualize the Sun-Earth relationship that creates them. [1]

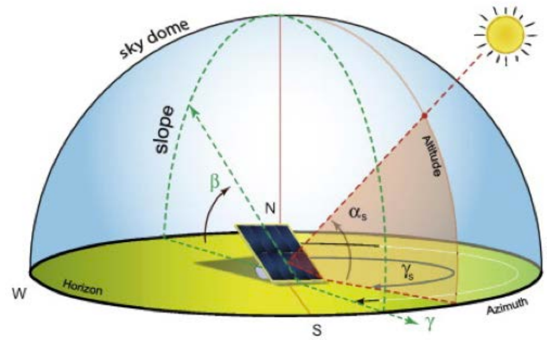

Figure A.5: The geometric angles used to depict earth and its relationship with the sun [1]

Solar declination (δ) is the Earth's tilt, which varies between +23.45^o and -23.45^o throughout the year as it rotates around the Sun. The solstices occur when declination is either +23.45^o or -23.45^o, while the equinoxes occur when declination equals zero. Declination can be calculated by equation A.1, where n refers to the day number out of 365. [1]

Equation A.1: Solar declination

$$\delta = 23.45^\circ * \sin\frac{(360)(284+n)}{365}$$

Hour angle (ω) is the angle of the Sun with respect to a location's longitudinal point on Earth. When the sun is at its highest point in the sky during the day (solar noon), the hour angle is 0^o incrementing 15^o for every hour past that. [1]

Latitude (ϕ) is used to specify the horizontal coordinate component of the solar energy conversion system.

The declination, hour angle, and latitude are all used to calculate information like the solar altitude and solar azimuth angles, which help determine the performance of solar energy applications.

By understanding the angles, the various forms of light projected by the sun can be better predicted. Direct Beam Irradiance (G_B) and Diffuse Irradiance (G_D) alter in intensity at Earth's surface at a given latitude and longitude depending on the time of year and time of day.

The normal global irradiance is calculated by equation A.2, which gives us the amount of irradiance incident upon Earth's atmosphere for that given time of day and year. In the equation, G_{SC} is the solar constant of 1367 W/m^2, which is the amount of radiation Earth’s atmosphere receives per meter squared. [1] [21]

Equation A.2: Total irradiance of a specific location based on the day of the year

$$G_0 = G_{sc}[1 + 0.033 \cos \frac{360n}{365}][\sin \phi \sin \delta + \cos \phi \cos \delta cos\omega]$$

Prices of electricity and demand for electricity both can change throughout the day. Therefore, it is helpful to know how irradiance changes on a given day for an hourly basis when designing a solar energy conversion system. The hourly solar irradiance on a plane perpendicular to the normal radiance is determined using the aforementioned angles and values in the equation A.3. In equation X, ω_1 represents the hour angle at the start of the measurement and ω_2 represents the hour angle one hour later. Additionally, I_o represents the hourly AM0 irradiation in MJ/m^2. [1]

Equation 14: Hourly irradiation of a specific location

$$I_0 = \frac{12 * 3600}{\pi} G_{0n}[\frac{\pi}{180}(\omega_2 - \omega_1) \sin\phi \sin delta + \cos\phi \cos\delta(\sin\omega_2 - \sin\omega_2)]$$

These values represent the maximum irradiance a given locale will have throughout the year, not taking meteorological factors into account.

The angles related to a solar energy conversion systems are described by the slope of system (β) the horizontal coordinate (γ) and the angle of incidence (θ). When the slope of the panel is 0^o the panel is horizontal, while a slope of 90^o positions the system completely vertical. For fixed tilts, an optimum angle can be found to minimize the angle of incidence throughout the year for the system. The horizontal component value of a solar energy conversion system will also affect output. A system facing due south (in the northern hemisphere) will receive more irradiation throughout the year. An angle of 0^o indicates that the panel is facing due south, while -180^o and $+180^o$ indicate that the panel is facing due East and due West, respectively. [1]

Lastly, the angle of incidence is an important angle in solar energy applications as it refers to the angle between the normal of the panel's plane and the projection of the Sun's central beam. Minimizing the angle of incidence maximizes the intensity of the irradiation on the photovoltaic cell as shown by equation A.4. The tilt of the system can be easily adjusted to minimize the angle of incidence. [1]

Equation 15: Angle of incidence

$$\begin{aligned}\cos\theta &= \sin\phi\sin\delta\cos\beta - \cos\phi\sin\delta\sin\beta\cos\gamma \\ &+ \cos\phi\cos\delta\cos\beta\cos\omega \\ &+ \sin\phi\cos\delta\sin\beta\cos\gamma\cos\omega \\ &+ \cos\delta\sin\beta\sin\omega\sin\gamma\end{aligned}$$

A.1.2 The Photovoltaic Cell

Energy exists in different band gaps. A certain threshold of energy must reach the photovoltaic system in order to successfully generate electricity. Photons are released by the sun carrying energy proportional to the radiation frequency. Shorter wavelengths emitted by the Sun contain a larger amount of energy than longer wavelengths. Photons are absorbed by the photovoltaic panels, which excite the energy level of electrons in the semiconducting material into a higher band gap. Certain semi-conducting materials have an intrinsic energy band gap, which must be matched with an equal or greater photon energy level to create a hole-electron pair. [1]

A hole is an absence of an electron due to semiconductor doping, and is considered a positive charge carrier. When an electromagnetic wave with sufficient amount of energy interacts with the photovoltaic cell, an electron from the outer shell of the semi-conductor material is released.

Photovoltaic cells are designed so that two semi-conductors are stacked on one another, but are separated by a junction so that electrons and holes cannot recombine immediately. One cell is doped with boron to form p-silicon, which is electron deficient. The other cell is doped with phosphorus to form n-silicon, which has excess electrons in its outer shell. Electrons cannot migrate back to the p-silicon through the junction, so an external circuit connects the two cells through which the electron can flow after being excited by the photon. Figure A.4 depicts the components found in a solar cell, and helps to explain how electricity is generated. [21]

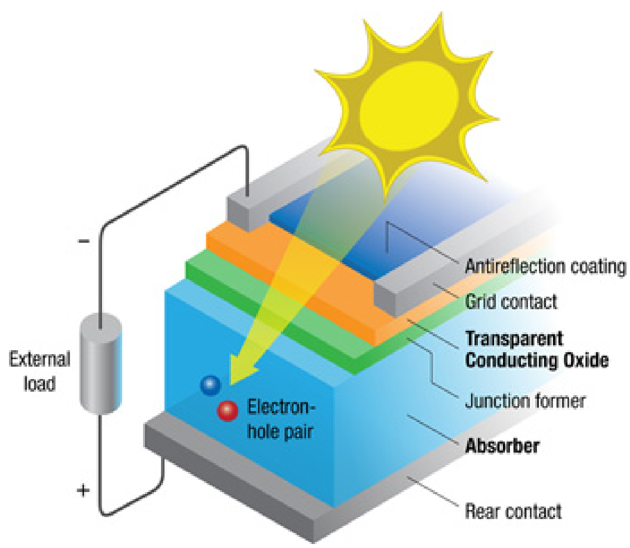

Figure A.6: Depiction of the components found in a solar cell, which allow the sun's emitted radiation to create an electron-hole pair to generate electricity [1]

The intensity of the solar irradiation is crucial to solar energy development because areas that receive less wattage per meter squared will produce less electricity with solar applications. Additionally, not all photons will reach an electron to excite it to generate electricity. The maximum theoretical efficiency of silicon cells, which are the most common, is roughly 23%. [22]

The current-voltage characteristic describes all possible power outputs given a specific solar irradiance and cell temperature. [22] The I-V curve demonstrates all possible voltage and current operating points for the photovoltaic device. The electrical load is what determines where it operates along that curve. The open-circuit voltage (V_{OC}) is described as the operating point under infinite load, while the short-circuit current (I_{SC}) is the point at which there is no load. The maximum power point is a position on the I-V curve between (V_{OC}) and (I_{SC}). The fill factor (FF) represents the performance quality of the PV device. A higher FF indicates the maximum power point is closer to (V_{MP}) and (I_{MP}). Equation A.5 represents how fill factor is determined, where (P_{MP}) is maximum power. Additionally, figure A.5 shows the relationship between current and voltage in order to produce maximum power. [22]

Equation 16: Solar cell fill factor

$$FF = \frac{P_{mp}}{V_{oc}} I_{sc}$$

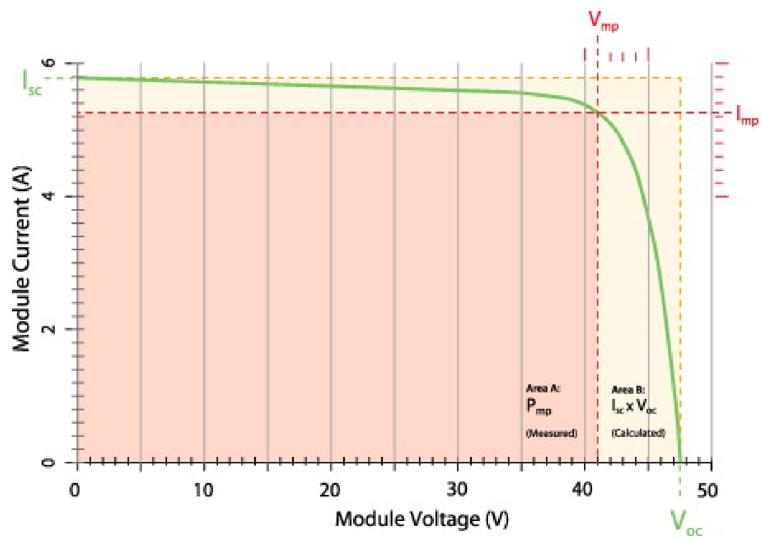

Figure A.7: IV curve for photovoltaic cell, which shows short-circuit current, open circuit voltage, and the max power point [1]

The efficiency is also able to be determined after determining max power. Efficiency in solar cells is expressed as the ratio of power output to the solar irradiance times the area of the photovoltaic device. [22]

In addition to the photovoltaic panels, electrical equipment is required to distribute the energy produced. Modules output DC power that must be converted to AC power using inverters prior to being introduced to the electrical grid. Additionally, as photovoltaic systems produce varying amounts of electricity at any given time based off the solar irradiance, a Power Conditioning Unit must be incorporated to maximize the power output. Inverter efficiency to convert DC power to AC power is estimated to be around 90-95%. [22]

Inverters are the main unit of the PCU. They convert DC power to AC power, and are classified by their power source, power ratings, input and output voltages, waveform, power quality, and power conversion efficiency. [22]

As temperature, irradiance, and system load changes, the voltage and current can adjust to output the maximum amount of power for the given conditions. Cells should be designed to operate at the maximum power point under the IV curve. A maximum power point tracker (MPPT) can be used in conjunction with the solar cells to change the load resistance or input voltage so that the cells can operate at max power for that time of day. The MPPT also then delivers any output voltage required by the load. [22]

Cells can be mounted in modules, which are combined to create an array. Modules can be connected in series to increase the voltage or parallel to increase the current. When a network of modules is installed, it creates what is known as an array. [21]

When photovoltaic systems are tied to the grid, fewer components are needed so systems costs are much cheaper. It is always important to consider the size of the plant based off of the electricity demand in the region for solar energy. One should first determine the desired output needed and then selected the inverters and arrays needed to meet that demand. The predetermined nameplate capacity is divided the module power output to determine the total number of modules. Following this, the correct amount of inverters must be purchased in order to convert the electricity to alternating current. [22]

Some concerns arise when photovoltaic plants supply electricity to the grid. Electricity supplied by solar power producers must have the same power quality as the electricity being supplied by the utility companies. This ensures that the voltage, frequency, and phase of grid electricity are synchronized to the same parameters required by electrical devices. If this condition is not met, damage can be done to the electronic devices using the electricity. Another concern is islanding, which occurs during a power outage. In this instance, workers can be injured because power is still being supplied to the grid. Inverters must be able to identify outages and shut off power transfer immediately. [22]

BIBLIOGRAPHY

[1] BROWNSON, L. (2013) *Solar Energy Conversion Systems*, Elsevier

[2] National Renewable Energy Laboratory (2010), *System Advisor Model*

[3] PEREZ, R. R. STEWART, R. SEALS, and T. GUERTIN (1988), "The Development and Verification of the Perez Diffuse Radiation Model," Atmospheric Sciences Research Center.

[4] (2010), "Jawaharlal Nehru National Solar Mission Towards Building Solar India," Government of India Ministry of New and Renewable Energy, http://www.mrne.gove.in/filemanager/USerFiles/mission_document_JNNSM.pdf

[5] (2011), "Analysis of state-wise RPO Regulation across India" Government of India Ministry of New and Renewable Energy, http://mrne.gov.in/filemanger/UserFiles/Solar

[6] (2013), "Determination of Benchmark Capital Cost Norm for Solar PV power projects and Solar Thermal power projects applicable during FY 2013-2104," Central Electricity Regulatory Commission, http://www.cercind.gov.in/2013/order/SO242.pdf

[7] (2010), "Frequently Asked Questions," Renewable Energy Certificate Registry of India, http://recregistryindia.nic.in

[8] (2014), "India Energy Exchange," Online Market, http://www.iexindia.com/marketdata/areaprice.aspx

[9] (2014), "Madhursi PRK, CCO Halo Energie Pvt Ltd.".

[10] (2013), "Solar Energy", Rajasthan State Industrial Development and Investment Corporation, http://eng.riico.co.in/upload/Solar_Energy.pdf

[11] (2011), "Rajasthan Solar Energy Policy," Government of Rajasthan Energy Department, http://www.rrecl.com/PDF/Solar%20Policy.pdf

[12] (2009), "Solar Power Policy," Government of Gujarat Energy and Petrochemicals Department, http://geda.gujarat.gov.in/policyfiles/SolarPowerpolicy2009.pdf

[13] JOSHI, D. P. (2002), “Grid Connected and Rooftop Power in Gujarat,” Gujarat Energy Development Agency, http://mnre.gov.in/filemanager /UserFiles/presentationspwcworkship06092012/GED.pdf

[14] STOFFEL, T., D. RENNE, D. MYERS, S. WILCOX, M. SENGUPTA, R. GEORGE, and C. TURCHI (2010) *Concentrating Solar Power Best Practices Handbook for the Collection and Use of Solar Resource Data,* National Renewable Energy Laboratory

[15] BANDYOPADHYAY, S. (2013), “Tax Exemptions in India,” Center for Budget and Government Accountability.

[16] (2012), “Accelerated Depreciation Solar Benefit Tax Law,”.

[17] (2013), “Future of Coal Electricity in India and Sustainable Alternatives,” World Institute of Sustainable Energy.

[18] (2013), “RPO Enforcement,” ReConnect Energy

[19] SHORT, W., D. PACKEY, and T. HOLT (1995) *Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies,* National Renewable Energy Laboratory

[20] GUEYMARD, C. and S. WILCOX (2009) *Spatial and Temporal Variability of the Solar Resource,* American Solar Energy Society

[21] DUFFIE, J. and W. BECKMAN (2013), *Solar Engineering of Thermal Processes*, John Wiley & Sons, Inc.

[22] Dunlop, J. (2010) *Photovoltaic Systems,* American Technical Publishers

[23] (2012), “The Rising Sun: Grid parity gets closer – A point view on the Solar Energy sector in India,” KPMG Energy and Natural Resources.

[24] (2013), “Bankability and Debt Financing for Solar Projects in India,” Bridge to India

[25] (2013), “Explanation for the Notification on Escalation Factors and Other Parameters,” Central Electricity Regulatory Comission.

[26] (2014), “Current India Inflation,” Worldwide Inflation Data

[27] (2013), “India’s cost of capital: A survey,” Ernst and Young

[28] (2011), “Determination of Forebearance and Floor Price for the REC framework to be applicable 1st April 2012,” Central Electricity Regulatory Commission.

ACADEMIC VITA

Steven Patrick
356 Futurity Dr. Camp Hill, PA 17011 / ssp5097@gmail.com

Education

Pennsylvania State University, 2014, University Park PA

College of Earth and Mineral Sciences

- Bachelor of Science in Energy Business and Finance
- Bachelor of Science in Energy Engineering
- Spanish Minor
- Environmental Engineering Minor

Honors

- Schreyer Honors College
- Skull and Bones Senior Honor Society
- Dean's List all semesters

Council on International Education Exchange Study Center, Seville Spain

- Studied advanced Spanish linguistics and Spanish history

Leadership

Skull and Bones Senior Honor Society – President, March 2013 – March 2014

Special Interest Association – Co-Founder, September 2013 – April 2014

Atlas – President, March 2012 – 2013

Atlas – Fundraising, Chair 2011 – 2012