DISTRIBUTED ELECTRICITY GENERATION FROM SOLAR PHOTOVOLTAICS IN CHILE: TECHNO-ECONOMIC ASSESSMENT FOR AN INDUSTRIAL SITE IN SANTIAGO

by

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ABSTRACT

With some of the best solar resources of the world, Chile is positioned to vastly reduce its consumption of fossil fuels and ramp-up the share of renewables for electricity generation. Distributed generation facilities appear particularly attractive as a way to reduce the needs for power transmission capacity. This paper evaluates the technical and economic feasibility of installing a roof-top solar photovoltaic (PV) system on the facilities of a major shipping company in the city of Santiago. A computer based-model estimates hourly electricity generation during the life-time of the solar panels, as well as the expected electricity consumption, and corresponding injections/withdrawals of electricity to/from the main grid, to assess economic benefits. The model is composed of 3 modules: 1) A solar generation module; 2) an Electricity Demand module; and 3) an Economic Assessment model that estimates the costs and benefits associated to the installation of PV solar. Results indicate that under the baseline conditions, the Net Present Value of the project is negative, mainly due to the absence of subsidies to solar installations and to the low electricity prices offered to consumers under the Net Metering policy. However, when lower solar system installation costs, lower discount rates, or a payment for carbon emissions reductions are considered, the Net present value becomes positive.

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CHAPTER 1: INTRODUCTION

Around the globe the energy industry is facing one of the biggest revolutions, like those that happened in the transition from wood to coal and from coal to fossil fuels as dominant sources of energy. Currently, the scientific community has reached consensus that climate change has an anthropogenic nature, due to the carbon dioxide and other green-house gasses that are emitted when fossil fuels are burnt in power plants, vehicles combustion engines, and factory motors[1]. The push to decarbonize the energy to reduce these gas emissions contrasts with the needs of keeping economic growth and providing fuel security. Hence, it is worth to ask: What type of energy we should use to not only continue growing and to provide electricity to most people, but also to have the least footprint on the environment? There is a clear trend and awareness on the population to start switching to a more sustainable energy source. For example, USA and China have increased their renewable energy production 50% and 40% in the last 10 years[2]. Also, on year 2016 many countries signed the historic agreement of the COP 21 in Paris, for the first time in history, a country like Uruguay relied 100% in renewables energies[3], and it was announced that the Santiago Metro system serving more than 2 million passengers per day, signed a power purchase agreement to run 100% on solar energy[4].

In that context, it is worth to look in detail at Chile, a country with high economic and population growth rates but with limited energy resources, and where the challenges to decarbonize the electricity industry are evident. Even though the country imports[5] 95% of the oil and 82% of the gas used, it enjoys abundant renewable energy resources, especially hydro in the south and solar in the north. Tremendous projects have been developed across the country, but since those renewable resources are located far

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[1] (Oreskes, 2014)
[2] (International Energy Agency, 2016)
[3] (Mellino, 2015)
[4] (SunPower Corp, 2016)
[5] (International Energy Agency, 2016)

from the demand areas, there are transmission difficulties. Public and communities' oppositions to large projects have increased the cost and the timing of the big scale hydro, solar, and wind projects. Therefore, it is worth to explore renewable projects at a lower scale and with low dependency on transportation. One example of those attributes is solar distributed generation (DG), which will be examined in this study.

This masters project analyzes the feasibility and prepares the business plan for rooftop PV solar installation in an industrial facility. The case study is focused on one of the major Chilean shipping, logistics and supply chain management companies, which has recently set up a strong environmental plan aiming to reduce GHG (Green House Gasses) emissions and to transform its facilities and distribution centers into smart buildings, supplied with solar energy. Thus, this document will offer the company useful information for the decision on how to accomplish its environmental goals at the lowest cost and without compromising its competitiveness and operations. The case study takes place in Santiago de Chile where the company has one of its warehouses. The following chapters analyze and attempt to quantify the following elements:

- Electricity generated on an hourly basis by a solar system installed in a lar roof of 1,900 sqm.
- Electricity consumed on an hourly basis in the facility analyzed.
- Cost and performance of solar panel, inverter, battery, and controller technologies and products to be used.
- Economic savings due to lower electricity consumption and electricity injection to the distribution grid, and value of using batteries to lower peak and power charges from the utility.
- Financial feasibility, including Net Present Value, Internal Rate of Return and payback period of installing the system.

The main model to accomplish these objectives will estimate the electricity generated by the solar panels on an hourly basis, as well as the electricity consumption per hour in the facility, which then will allow to calculate how much electricity should be purchased to the distribution company, how much of it can be injected to the grid, and how feasible is the usage of storage units. To assess the energy generated, this model considers the site size in squared meters, the tilt, orientation and efficiency of the solar panels, the efficiency of the inverters, potential losses due to temperature, and the irradiance hitting the tilted surface. Similarly, to estimate the hourly electricity consumption, the model considers the operating hours of the plant, the break-down of annual electricity consumption between the main activities and components, and the seasonality of the consumption within a day, week, and year. The data of this model was collected from the Ministerio de Energía de Chile, Universidad de Chile, National Renewable Energy Laboratory (NREL), solar calculation research papers, technical specifications of the different solar panel and inverter technologies, and from the company operations team and the company Energy Audit.

Complementary to the main model, another model estimates the economic performance metrics of the solar power system developed. It takes information on the electricity generated and consumed to estimate a monetary value of the project. Monthly electricity charges for energy, power and peak usage, as well as the solar panel system installation cost and other capital expenditures are used to calculate savings and revenues and operating costs. With that information, it was possible to estimate the project cash flows, net present value, return, and time to recover the investment or payback period. The electricity price information is taken from the distribution company, operating in the facility region, monthly electricity tariffs. The system cost information is based on product and price quotations of solar panel, inverters, cables, and mounting system manufacturers.

CHAPTER 2: METHODS

To assess the economic feasibility of the project, three models were integrated and used to build a master model (see Figure 1 The models are based on different assumptions and data and are all implemented in Microsoft Excel.

The first model is the Solar Generation Model, which calculates the potential solar energy on the site by taking 15-year hourly data of the irradiance, temperature, and cloudiness on the location analyzed, and considering the site roof characteristics. This model allows a detailed analysis of the solar resource available on the site location (Chapter 3).

Then, the Electricity Demand Simulation Model estimate the hourly electricity consumption of the company. To construct the model, it was necessary to revise the electricity tariff offered by the utility, and to analyze the electricity bills and hourly consumption information, gathered by the company in an energy efficiency audit in September 2014.

The third model is the Revenue Calculation Model which estimates the revenues of the solar PV system depending on whether the company chooses a Net Metering approach or a Grid Interconnection to Mid Voltage approach. These two approaches were identified after revising similar case studies in the globe, and analyzing the cases of US C&I Solar developers.

Finally, the Solar Generation Model and the Electricity Demand Model are integrated into one model named Economic Assessment Model. This model is a 25-year forecast of the electricity generation, consumption, revenue, and costs (installed system and the operation ones), which will ultimately allow the calculation of the Net Present Value or NPV (see Figure 2) of the project. By considering the two revenue models it makes possible to compare the NPV, the size of the investment, the time to recover the investment, the amount of carbon offsets, and the break-even values for system costs, carbon price and other uncertain. Moreover, the model provides a sensitivity analysis that considers the solar system cost, the price per carbon offset, the price of electricity, the solar resource, and the orientation, on the NPV and returns results.

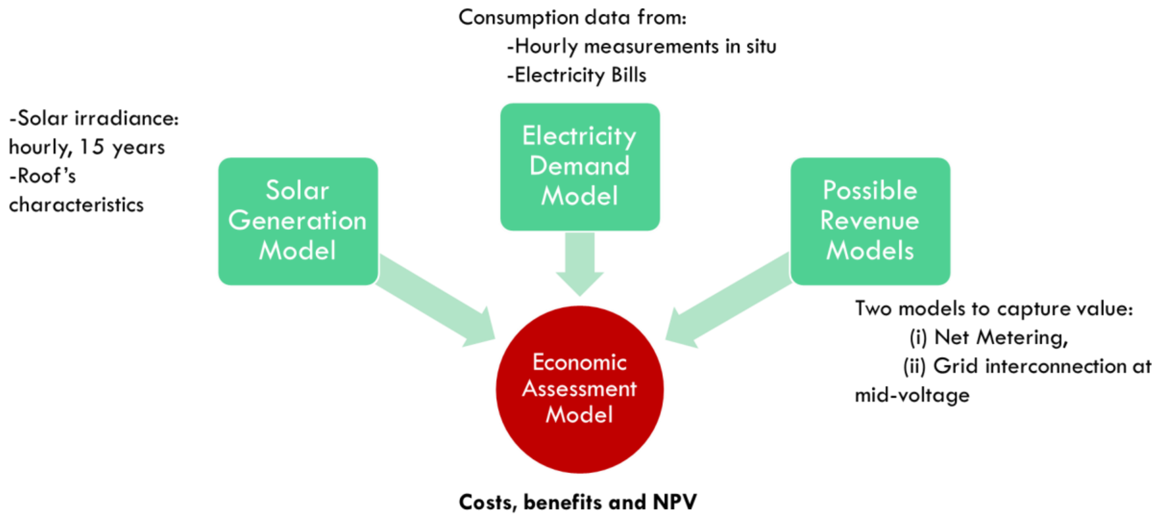

Figure 1: Model composition. Three modules for solar generation, electricity demand simulation, and revenue calculation

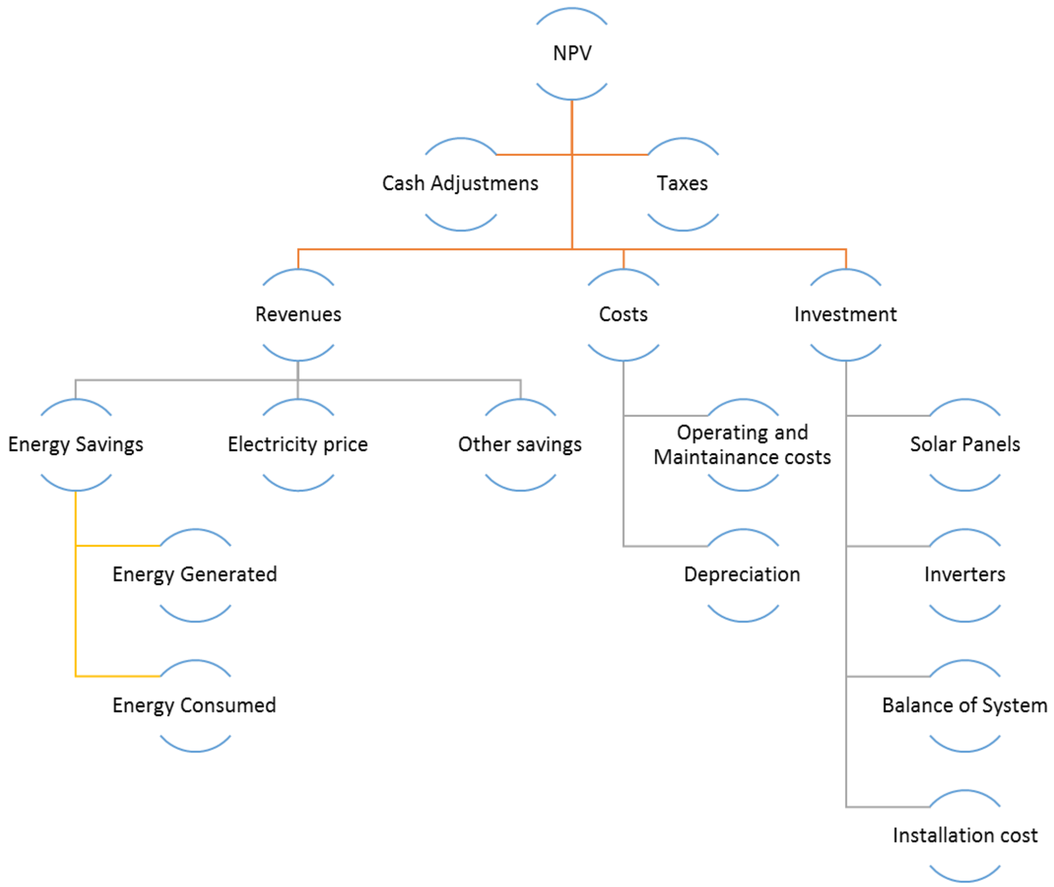

Figure 2: NPV calculation components diagram

CHAPTER 3: THE SOLAR RESOURCE

The Site

The site where the solar resource will be analyzed and where the solar system will be installed is located in an industrial area in the suburbs of Santiago, Chile, with geographical coordinates 33° south and 70° west. This complex contains an administrative office and three warehouses (3) of a local logistic and distribution company. The main warehouse, tagged as "Warehouse 1", holds most of the rooftop area with 2,800 square meters and also in it the major operational activities take place, including the sorter, and shipping. Warehouse 1 has a gable roof with 20° inclination on both sides and therefore the usable area for installing solar panel systems is reduced to approximately half. Additionally, there is a component of roof that is lost due to spaces required for operation and maintenance activities. With all these considerations, the usable surface on the building is approximately 1,400 square meters. Finally, the building orientation or azimuth is 35° towards the west, meaning it receives more sunlight at the afternoon hours than a north oriented roof. The other 2 warehouses have approximately the same tilt as the warehouse 1, and they 3 have the same orientation. The details of the last 2 warehouses are specified on the Table 1and Figure 3.

On the other hand, the Administrative Office accounts for 450 square meters of rooftop and contains most of the Selling and General Administrative functions. This building is the only one that counts with HVAC systems and also it is the one where the server room resides. The Administrative Office building has a shed roof with an angle of 20° and the orientation is 75° towards the east, implying it receives more sunlight in the morning than a north facing one. The usable are of the rooftop is 250 square meters since the HVAC systems are located on the back of the roof.

The total rooftop area on the site is approximately 4,940 square meters, which is equal to 1.2 acres. The maximum usable area for a solar system purpose is 2,800 square meters, 0.7 acres.

It is worthwhile to notice that there are no major objects or buildings with shading potential close to the complex, and since it is an industrial area with majorly warehouse's type of buildings the risks of having more than 4 stores constructions is low.

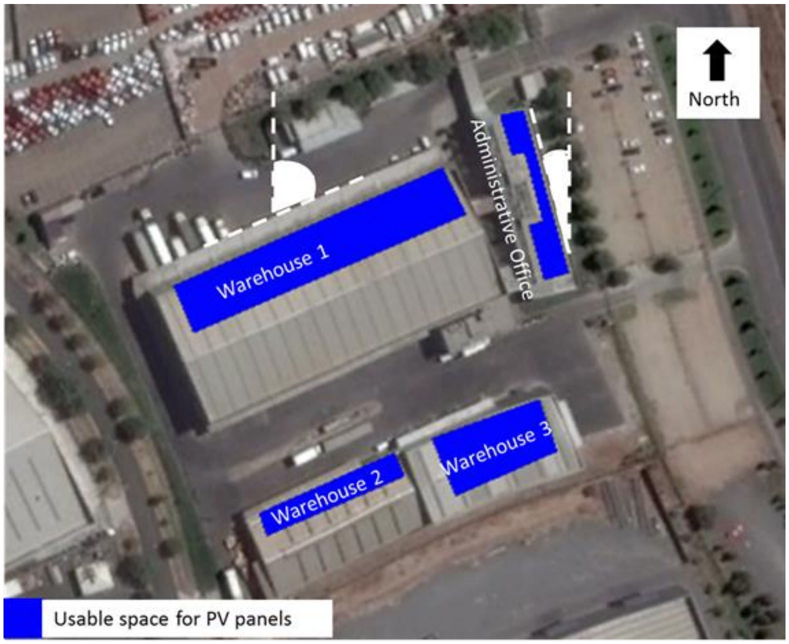

Figure 3: Aerial photograph of the facility

Table 1: Site's roof characteristics

-	Area (sqm)	Usable Area (sqm)	Azimuth (°)	Roof tilt (°)
Administrative Office	450	300	75	20
Warehouse 1	2800	1400	325	20
Warehouse 2	700	700	325	20
Warehouse 3	790	400	325	20

Solar resource

The solar resource or solar energy available at a particular location and instant of the day, is one of the most relevant inputs to determine the electricity that Photovoltaic systems can convert. By general convention, the solar resource is determined by solar irradiance, which according to the National Aeronautics and Space Administration (NASA) is the amount of electromagnetic energy incident on a surface per unit time per unit area and is quantified in Watts per square meter[6]. The solar irradiance, also known as radiation flux, refers to the combination of the hours of sunlight and the strength of it in a particular site[7] . The total solar irradiance depends on the direct normal irradiance, the diffuse irradiance and the reflected irradiance[8] that contact a surface, which could be tilted or horizontal to the ground. Since the earth is tilted on its axis at 23.45° and has an ellipse orbit around the sun[9], the

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[6] (NASA, 2015)
[7] (Boxwell, 2016)
[8] (Holbert, 2007)
[9] (Holbert, 2007)

solar irradiance varies depending on the day of the year, the latitude, the longitude, the sun position during the day, and the angle in which the horizontal plane is fixed. Therefore, the solar resource for a specific site and tilt varies not only daily, but also on an hourly basis, and even minute by minute. Each solar panel has a specific generating capacity or expected number of watts of power they can generate based on a solar irradiance of 1,000 Watts per square meter, known as Watts's peak or power that can be achieved in ideal conditions. These ideal conditions are based on the solar irradiance you expect to receive at noon in the middle of the summer at the equator, 1,000 Watts[10]

For this particular case study sited in Santiago, Chile, different data sources were consulted, including the Chilean Energy Secretary (Ministerio de Energía de Chile), and the National Renewable Energy Laboratory (NREL). In the two cases, data corresponds to the solar irradiance in Watts per square meter, however, given that the Chilean Energy Secretary records had 15 years of observations and the highest time resolution (1 hour) these were the ones used to build the solar resource model. The NREL data was used to compare and validate the model built with the data from the Chilean Energy Secretary, and also to get broad view of the solar resource in that region. For instance, the NREL solar assessment map, shown below (Figure 4), presents the central region of Chile among the mid-highest areas in the solar resource compared to the globe. Specifically, on the site where the case study is located, the average annual solar irradiance ranges between 4,500 and 6,500 (Watts/m²/day), which is a range in which most areas of California are represented. This is a general indicative that the site to be analyzed presents a useful and worthy solar resource.

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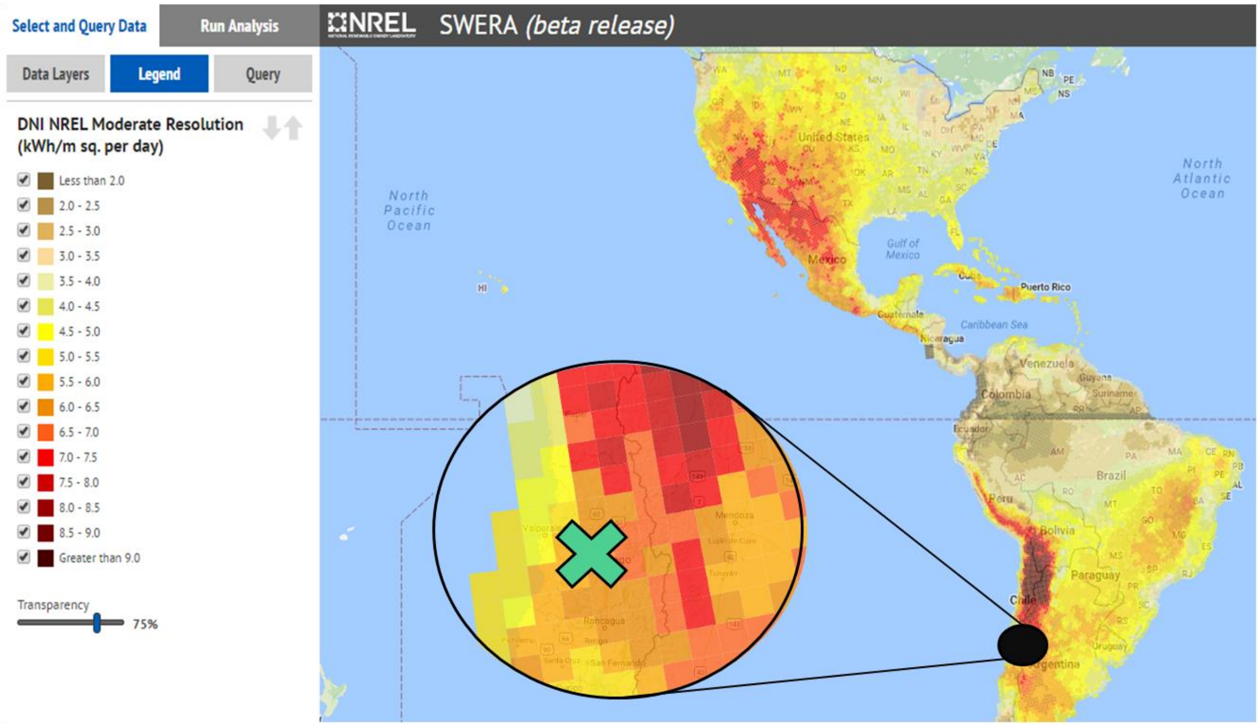
[10] (Boxwell, 2016)



[11]

Figure 4: Average Irradiance map

Estimating the Solar Resource

To estimate the solar irradiance at the site location on an hourly basis, the Chilean Energy Secretary data was used to build a model to calculate the direct, diffuse, and reflected irradiance on a tilt surface. This data set was chosen because it has hourly data points, including the three irradiances (direct, diffuse, and reflected) and temperature for 15 years, all after considering the effects of the shadows and cloudiness of the day. Meanwhile the NREL data includes most of the values mentioned before, but just for a one year period named “typical year”. Having more data to analyze was the main decision driver. Then, a model was built to calculate the hourly solar irradiance for the site and to

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[11] (National Renewable Energy Laboratory, 2016)

develop analysis of the resource. Through a series of equations which include inputs, such as the panel tilt, azimuth, angle of incidence in the panel, latitude, longitude, day of the year, solar time, etc, the total solar irradiance that hits the tilted surface can be calculated. The formulas and variables can be found in Appendix 1. Also, to develop the model for the site, some physical specifications were considered as fixed parameters, such as the latitude, longitude, the panel tilt, and azimuth (resumed in Table 1).

Solar Resource Analysis and Model

Using the data and formulas discussed above, the solar energy model was developed. The 15 years of hourly solar irradiance data and the formulas from Appendix 1 the Global Irradiance Normal to Tilt Surface (GI) was calculated. The GI is one of the major inputs on the calculation of the electricity generated in the solar panel. To begin the analysis, a base case, flat surface horizontal to the ground, was considered. Under these conditions the Global Irradiance averages 4,670 Watts per square meter per day, or 1,704,649 Watts per square meter per year (see Table 2). These figures range from 4,556 to 4,833 Watts per square meter per day, or 1,662,912 to 1,764,124 Watts per square meter per year, depending if the best or worst year was used.

Table 2: Base Case Global Irradiance per day – yearly and season averages (Watts per square meter)

	Year Average	Fall	Winter	Spring	Summer	
2004	4,616	3,398	2,113	5,501	7,503	
2005	4,571	3,393	1,857	5,704	7,379	
2006	4,585	3,661	1,884	5,500	7,344	
2007	4,706	3,480	2,081	5,888	7,425	
2008	4,690	3,538	2,079	5,689	7,507	
2009	4,556	3,659	2,037	5,041	7,537	**worst year*
2010	4,833	3,702	2,305	5,879	7,501	**best year*
2011	4,825	3,615	2,258	6,005	7,473	
2012	4,716	3,587	2,084	5,890	7,357	
2013	4,710	3,657	2,135	5,733	7,366	
2014	4,665	3,708	2,019	5,518	7,467	
2015	4,571	3,676	2,035	5,332	7,385	
Average	4,670	3,589	2,074	5,640	7,437	

In addition, observations of the GI on an hourly basis (Figure 5) indicate that the time of the day with major solar resource is systemically 1pm, or hour 13. In the summer months, this GI gets produces an average of 1,140 Watts per square meter and in the winter, 340 Watts per square meter.

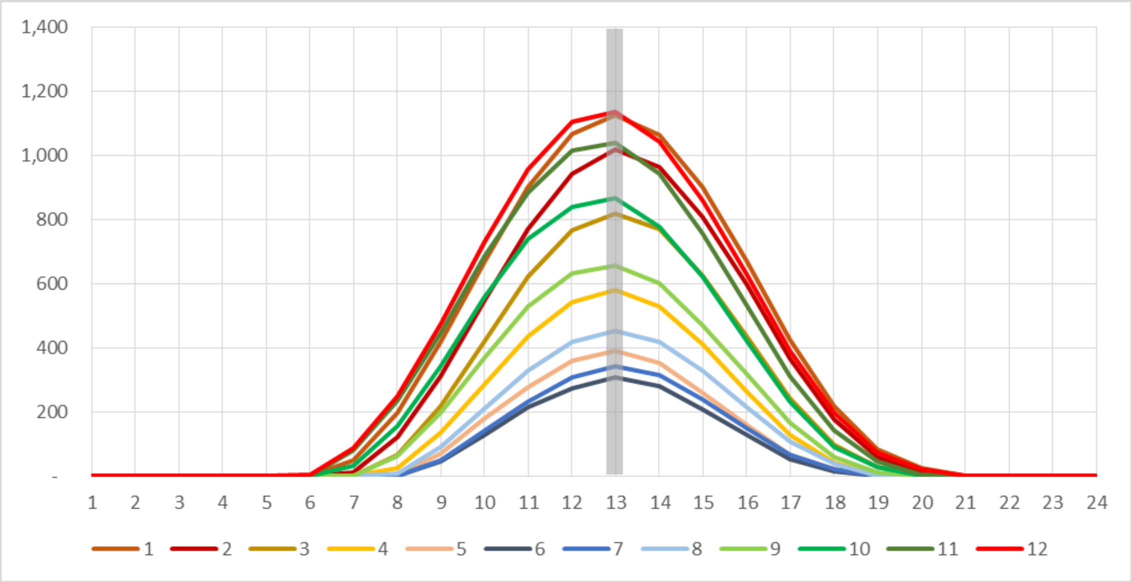


Figure 5: Base Case Average Monthly Irradiance by hour of the day (Watts per square meter)

Now, it is imperative to include into the solar resource analysis the angle and the orientation of the panel. By tilting the solar panels towards the sun, the intensity of the sunlight is stronger and therefore it is possible to capture more of sun's energy, thus changes in these factors have strong impact on the Global Irradiance. Since the site specific physical characteristic, angle of the roof and orientation, are fixed the GI differs from a surface horizontal to the ground (0° tilted). As analyzed previously, the site has two buildings, with different roof characteristics and orientations, consequently each building will present different Global Irradiance results.

- Administrative Office:

According to the data the administrative office, which has a 20° tilted roof oriented 75° to the east, gets in average 4,269 Watts per square meter per day (1,568,136 per year), 374 less than the base case (Table 3). The strong orientation to the east (75°) has a negative effect on the total GI that receives the panel, but also shift the hour of the day in which the maximum energy is received. In the base case the maximum energy was received at 1 pm, but adding the specified orientation and tilt the peak is at noon, thus, more energy is captured in the morning hours (see Figure 6).

Table 3: Administrative Office Global Irradiance per day – yearly and season averages (Watts per square meter)

	Year Average	Fall	Winter	Spring	Summer	
2004	4,246	3,181	2,026	5,025	6,800	
2005	4,193	3,192	1,786	5,183	6,659	
2006	4,211	3,418	1,808	5,018	6,645	
2007	4,326	3,258	2,001	5,381	6,712	
2008	4,306	3,313	1,991	5,187	6,778	
2009	4,201	3,426	1,960	4,628	6,836	**worst year*
2010	4,448	3,465	2,214	5,372	6,791	**best year*
2011	4,436	3,375	2,171	5,481	6,767	
2012	4,346	3,366	2,010	5,370	6,685	
2013	4,332	3,431	2,055	5,238	6,654	
2014	4,299	3,477	1,942	5,057	6,769	
2015	4,210	3,447	1,959	4,874	6,685	
Average	4,296	3,362	1,993	5,151	6,732	

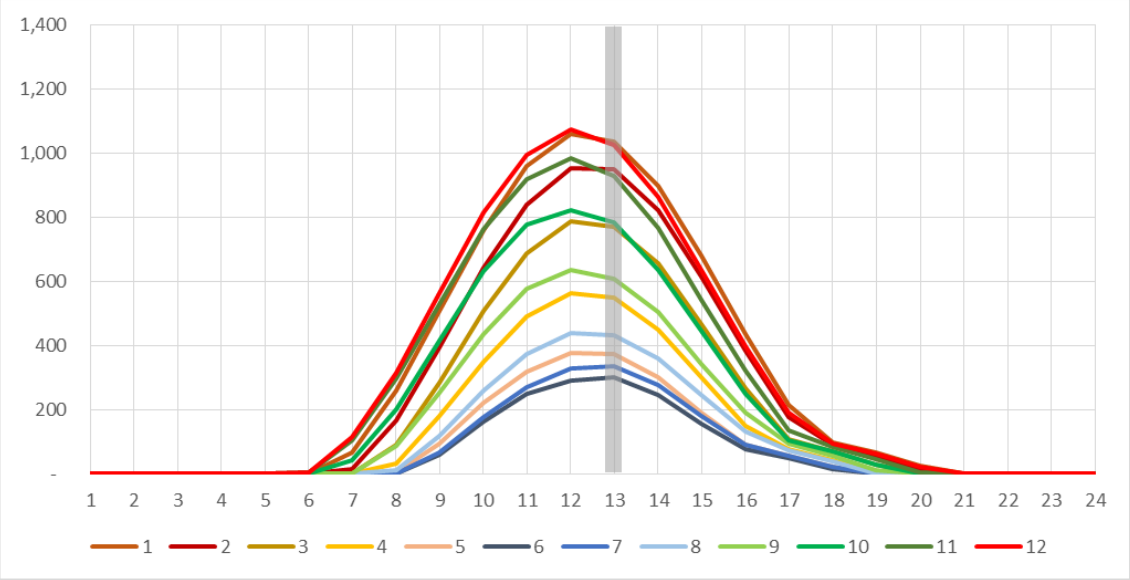


Figure 6: Administrative Office Average Monthly Irradiance by hour of the day (Watts per square meter)

- Warehouse 1:

In contrast, the Warehouse 1 which has a 20° tilted roof oriented 25° to the west, receives in average 5,119 Watts per square meter per day (1,868,366 per year), 449 more than the base case and 823 more than the administrative office (Table 4). Since the roof is slightly oriented (25°) towards the west the peak energy received is marginally past 1pm (see Figure 7)

Table 4: Warehouse 1 Global Irradiance per day – yearly and season averages (Watts per square meter)

	Year Average	Fall	Winter	Spring	Summer	
2004	5,055	4,031	2,688	5,897	7,661	
2005	4,987	3,992	2,333	6,136	7,544	
2006	5,012	4,341	2,370	5,890	7,503	
2007	5,148	4,103	2,639	6,321	7,588	
2008	5,136	4,198	2,641	6,084	7,678	
2009	4,990	4,333	2,595	5,396	7,690	**worst year*
2010	5,327	4,400	2,976	6,331	7,662	**best year*
2011	5,314	4,312	2,902	6,469	7,630	
2012	5,165	4,237	2,645	6,332	7,504	
2013	5,171	4,337	2,723	6,146	7,536	
2014	5,107	4,397	2,564	5,898	7,627	
2015	5,011	4,358	2,574	5,700	7,552	
Average	5,119	4,253	2,637	6,050	7,598	

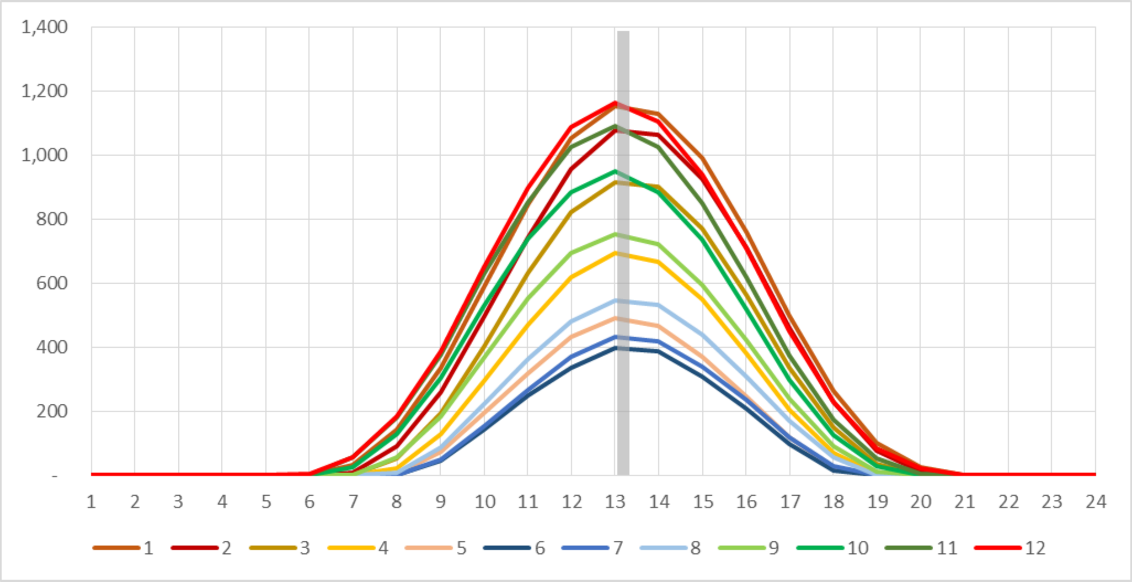


Figure 7: Warehouse 1 Average monthly Irradiance by hour of the day (Watts per square meter)

Data sets to be used

To do the PV calculations and then feed the economic model, three scenarios were considered: a) average or typical solar resource year, b) best solar resource year, and c) worst solar resource year. To analyze the project future benefits under average, best or worst conditions, it is assumed that the typical, best or worst year repeats annually. The best year in terms of total irradiance was 2010, and the worst one, 2009, so these are the years assumed to repeat for the best and worst case scenarios, and estimate a range of profits of the project.

As can be seen in Figure 8 and Figure 9, there are important differences between the best and the worst years. For instance, the best year average irradiance per day was 4,448 and 5,327 Watts per square meter on the administrative office and warehouse 1 respectively, while the worst year ones were 4,201 and 4,990 Watts per square meter.

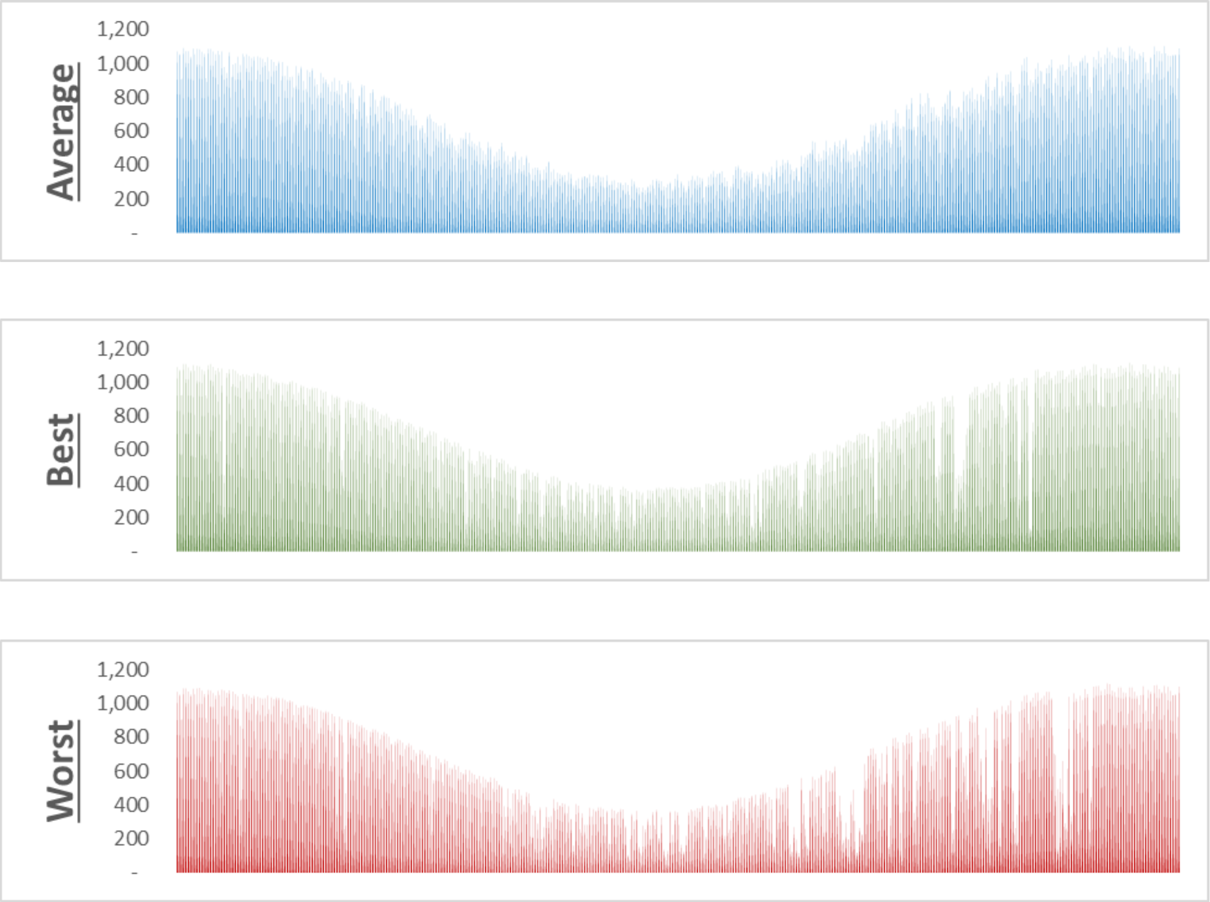
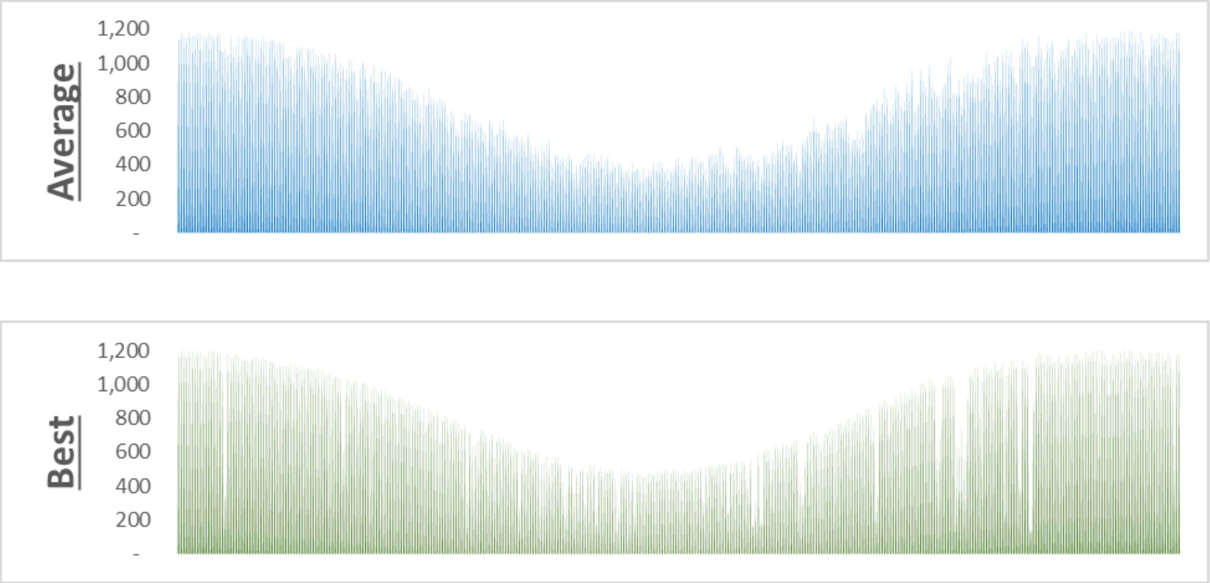


Figure 8: Administrative office 1 daily Irradiance (W/sqm)



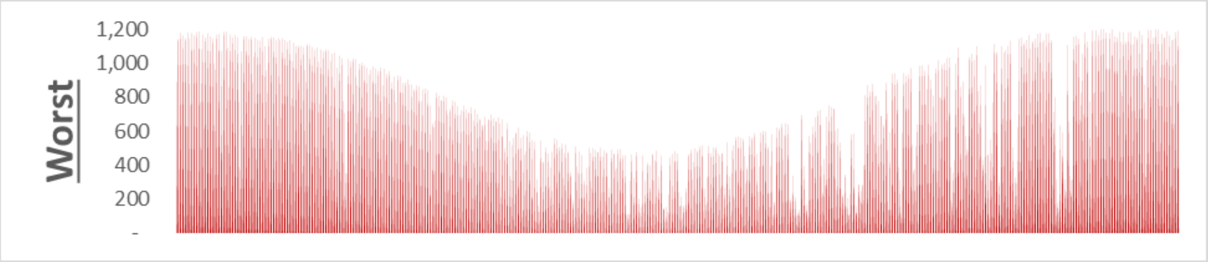


Figure 9: Warehouse 1 daily Irradiance (W/sqm)

PV Generation formulas

It is important to notice that the data that has been analyzed before, specifically the solar global irradiance, is equivalent to the maximum amount of solar energy that could be harvested. In other words, if the system to be used has a 100% efficiency, the energy generated will be equal to the Global Irradiance. Unfortunately, after more than 20 years of technology improvements on solar panels, the maximum efficiency recorded by a concentrated solar panel is around 46%[12] (see Appendix 2). Yet, this 46% maximum efficiency has been harvested only in laboratory conditions and the economically practical solar panels (Crystalline Silicon and Thin Film cells) have efficiencies ranging from 12% to 22%, thus the GI has to be adjusted by the solar cells efficiency. Moreover, solar panels are designed to operate at a certain range of temperatures, so depending on the quality of the solar cells, if the temperature at which the solar panel is exposed increases, the solar panel efficiency decreases. Similarly, the aging of the solar cells affects negatively its efficiency. In addition to the solar cells inefficiencies, there are other elements in the system that contributes to increase the energy losses. For instance, the inverter to convert current from Direct (DC) to Alternate (AC) has typically an efficiency of 96%[13]. Therefore, to calculate the electricity available that can be either injected to the grid or used for

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[12] (National Renewable Energy Laboratory, 2016)

[13] (National Renewable Energy Laboratory, 2016)

auto-consumption, the formula below was used to include the losses due to converting Direct Current (DC) to Alternate Current (AC), inverter efficiency losses, panel de-rating over time, losses due to temperature, and other system losses (Soiling, manufacturing mismatch, wiring, resistivity in connections, etc). The efficiency losses depend on the solar panel quality and inverter quality, the age of the panel, and the ambient temperature affecting the panel at a particular time.

$$E = \sum_{0}^{w,a} [I \times \mu \times (1 - \alpha) \times (1 - \beta) \times (1 - \gamma) \div \theta]$$

Where,

E: Total Available Electricity at a certain moment (Watts AC)

I: Total Global Irradiance on the Administrative Office and Warehouse 1 (Watts per square meter)

w: Warehouse 1

a: Administrative Office

μ: Panel rated efficiency (%)

α: Inverter losses (%)

β: Accumulated panel degradation rate (%)

γ: Efficiency loss due to temperature (%)

Ɵ: DC to AC ratio

CHAPTER 4: DEMAND ANALYSIS

Operations and electricity demand

With a clear idea of the solar resource that the site disposes on an hourly basis, the analysis continues with the electricity consumption on the site. Using the data obtained from an energy efficiency research dated from 2016 and developed by the company Efizyt, and using the electric utility bill of the company from the last 3 years, the site energy consumption analysis and conclusions were built.

In general terms, considering 3 years' data, the site annual electricity consumption averages 982,500 Kilowatt hours[14], equivalent to 506 houses (a typical house in Chile consumes 1,940 Kilowatt hours per year [15] [16]) in Chile. As Figure 10 shows, the energy consumption monthly records range between 70,000 and 94,000 Kilowatt hours, averaging 81,800 Kilowatt hours. The company spends on average 120,000 dollars per year in electricity, which suggests an average price of $12.2 cents per Kilowatt hour. Even though it is hard to stablish a clear seasonal trend on the site's energy consumption, there are peaks on the winter months (July and August), due to increased heating and lighting needs. The months with higher and lower consumption were August 2015 and September 2014 respectively.

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[14] Information provided by the company.
[15] (International Energy Agency, 2016)
[16] (Instituto Nacional de Estadísticas de Chile, 2016)

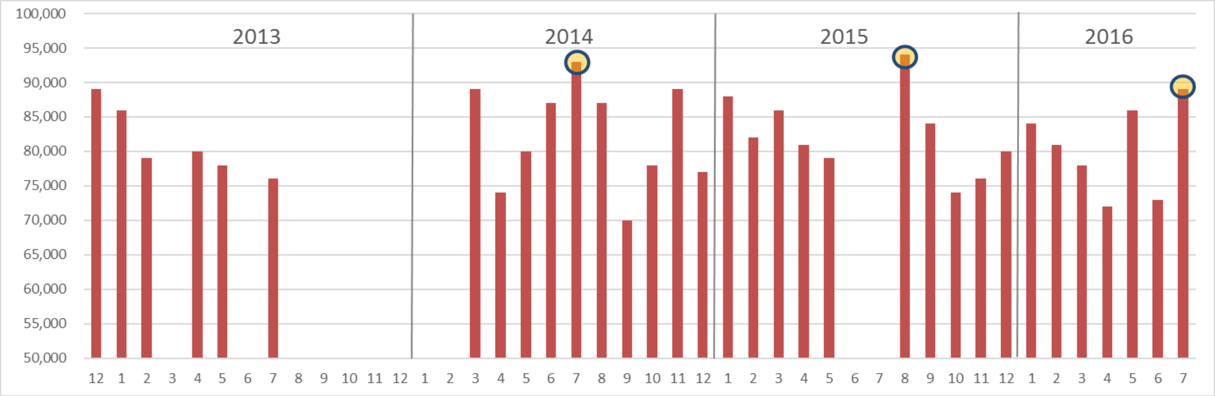

Figure 10: Electricity Consumed per month (KWh)

The end uses of energy consumed can be classified into 5 categories (HVAC, Sorter, Warehouse 1, Administrative office, and Servers). The two end uses directly associated with the distribution and warehousing activities are Sorter and Warehouse 1 and account for more than 42% of the consumption (see Figure 11).

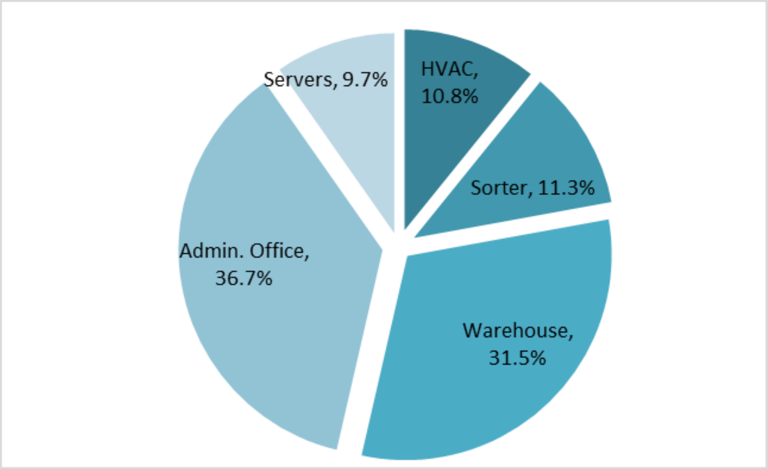

Figure 11: Electricity consumption breakdown (based on KWh)

Electricity tariff

The company electricity tariff was evaluated in deep to understand the potential saving in electricity costs. The company is subject to a regulated tariff with the utility Enel Distribucion which operates in the city of Santiago. The tariff in use is “AT-4.3”, which accounts for Alta Tension (High voltage in Spanish) and has a maximum power connection of 650 Kilowatts. This tariff is divided into 4 different charges; one fixed charge and 3 variables charges. The fixed charge considers the fee for the supporting services of being connected to the grid (meter reading, billing, and collection), accounting for 2% of the monthly bill (see Figure 12). Then, the variable charges are related to the electricity consumed during the month, to the maximum power needed during the month, and the maximum power used at peak hours, between 7:00 pm and 11:00 pm. The electricity charge accounts for 79% of the monthly bill, and the power charges for the 18% of it. The low hanging fruit is the electricity charge since it can be reduced significantly by installing a solar system, and they can get to zero when the solar energy generation surpasses the internal electricity consumption (electricity injection to the grid). Also, there are significant potential savings on the power charges if the solar system generates electricity at the same time when the power maximums take place.

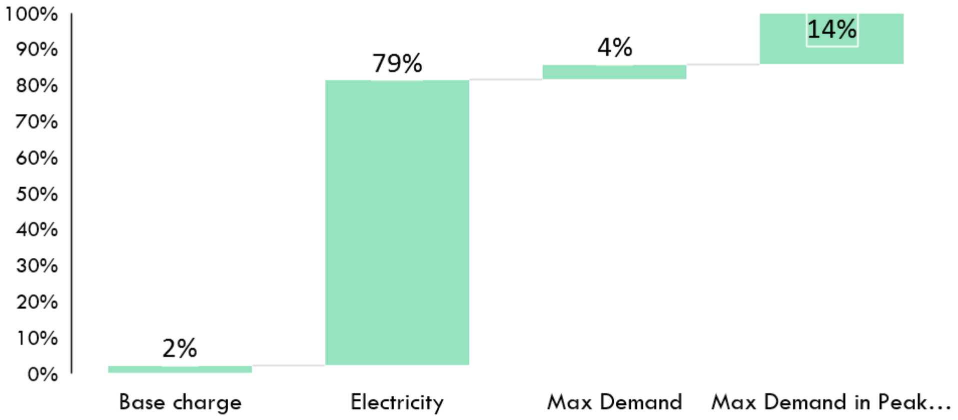

Figure 12: Electricity Bill Breakdown (% of total)

Now, to help build the economic model later, it is important to have a sense of the monetary value of the different charges, and thus have the most accurate projections. To do that, Figure 13[17] summarizes the data taken from the company monthly electricity bills and the utility tariff disclosures. As can be seen in Figure 13, the Price for electricity fluctuates around c$10 per Kilowatt hour, averaging c$9.5 per Kilowatt hour in the last 24 months, while the Power Charges fluctuates around $2 per Kilowatt for the monthly maximum (Max demand rate) and $9 per Kilowatt for the peak-time maximum (Peak hours), and averages $1.72 and $8.85 respectively.

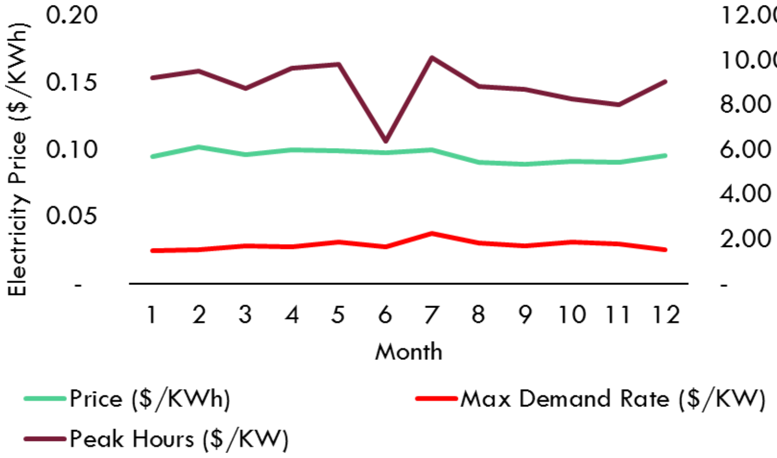

Figure 13: Variable charges values ($ per KWh and $ per KW)

Hourly consumption analysis

To develop an hourly consumption model to assess yearly electricity needs for the next 25 years, it was necessary to have hourly consumption data for at least one week. These data was taken on a typical week on the month of September using a digital meter. The observations are shown in Figure 14[18].

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[17] Company electricity Bills, and Enel Distribution tariff disclosures.

[18] (Client company, 2015).

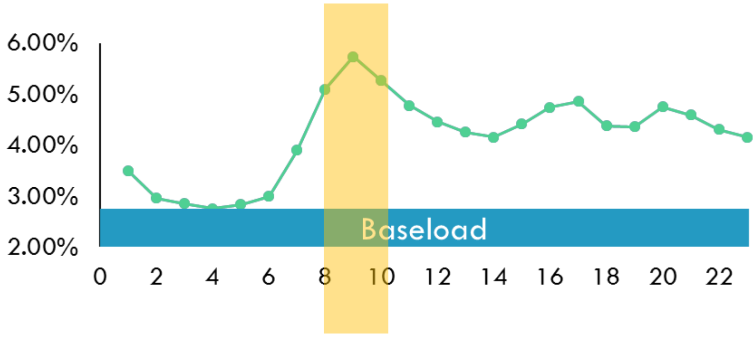

Figure 14: Typical day across in the company facilities (% of daily electricity consumption)

As Figure 14 shows, a typical week-day at the company site has an electricity consumption peak between 8:00 am and 9:00 am, with a maximum consumption of 184 KW (6% of the day consumption) on average at those hours. Also, it is possible to realize that there is a baseload, or minimum consumption of 54 KW (3% of the day consumption). These results coincide with the hour of the morning in which most packages are sorted and prepared to distribution, and when most of the employees start arriving to work (between 8:00 am and 9:00 am).

The operational and administrative peaks are specially stablished at the hours mentioned above for strategic operational purposes for the shipping company. Therefore, it is reasonable to assume that the electricity consumption behavior at the site during that week in September could be replicable to the rest of the year, and hence, the average week-day load for the years projected in to the future are assumed to exhibit the same pattern as the one showed on Figure 14.

CHAPTER 5: REVENUE MODELS

Potential Revenue Models

Based on the design of the Chilean electricity markets and the main energy policies and legislation[19] (Comision Nacional de Energía), it is found that the most appropriate revenue models for a facility trying to develop a commercial and industrial (C&I) PV solar project are two: a) Net Metering and b) Grid Interconnection at mid voltage. An alternative revenue model that was not considered in this study would include the installation of energy storage devices (i.e., batteries). This is omitted due to the high costs of the technology and previous research that indicates that without a time of use tariff or payment for ancillary services[20], this option will not be economic.

Net Metering

Under a Net Metering approach, the solar system is connected to a smart meter, which drives electricity in and out depending on the need or excess of electricity resulting from the demand and the generation of the PV panels (see Figure 15). The revenues from installing the panels under this approach come from two sources: a) savings in the monthly electricity bill because of lower consumptions from the grid due to self-supply of with the solar system, and b) payments from injecting electricity into the grid when the solar system generates more than what is consumed in the facility.

The economic gains from lower use of grid electricity are dependent on the price for electricity charged by the utility company. However, the electricity injection into the grid is valued at the utility price but also includes a charge for the use of the utility infrastructure. After the charge, the injection cost rate is equal to 60% of the utility price. This revenue model has the disadvantage of being

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[19] (Comisión Nacional de Energía de Chile, 2016), (Comisión Nacional de Energía de Chile, 2016)
[20] (Bradbury, Pratson, & Patiño-Echeverri, 2014)

constrained in size: the maximum system allowed for Net Metering is 100 Kilowatts. The advantage of the Net Metering approach is that the permitting process is simple and can take between 2 to 4 months.

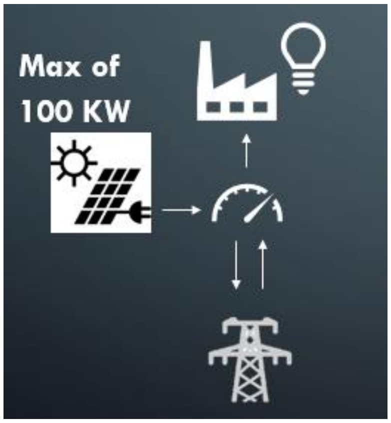

Figure 15: Net Metering Model

Grid interconnection at medium voltage

On the other hand, the Grid interconnection at mid-voltage revenue model works as an interconnection to the grid in which the solar system operates independently of the facility meter (see Figure 16). In this case, the electricity needs of the company are provided fully by the utility and the solar system is connected directly to the grid with a medium voltage power transmission line, and therefore the company is payed for electricity injected to the grid at the nodal price at that location. To be able to connect at medium voltage the system size cannot exceed 9 Megawatts, and it requires going through the interconnection and environmental procurement processes, which could take around 1 year. To remove the exposure of C&I customers to nodal electricity price volatility, the PMGD legislation[21] allows the nodal price to be made stable by making it equal to the average price for a 12-month period on a location.

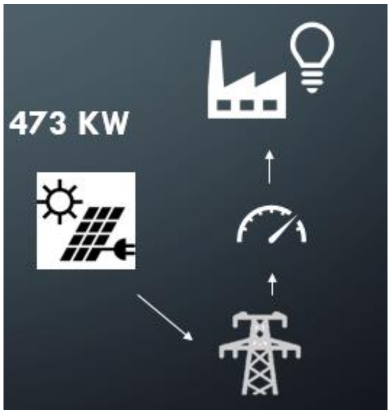

Figure 16: Grid interconnection at mid-voltage Model

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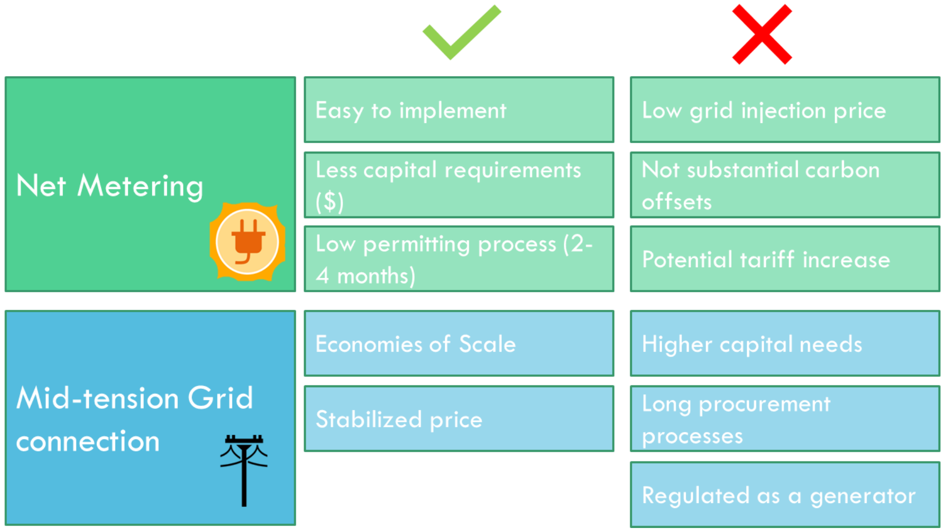
[21] (Comisión Nacional de Energía de Chile, 2016)

A summary and comparison of the two revenue models or approaches that the company can choose when deciding what type of system to install is presented on Table 5.

Table 5: Revenue model pros and cons



	✓	✗
Net Metering	Easy to implement	Low grid injection price
	Less capital requirements ($)	Not substantial carbon offsets
	Low permitting process (2-4 months)	Potential tariff increase
Mid-tension Grid connection	Economies of Scale	Higher capital needs
	Stabilized price	Long procurement processes
		Regulated as a generator

CHAPTER 6: ECONOMIC ASSESSMENT MODEL

Model assumptions

The Economic Assessment Model integrates the Solar Generation Model and the Electricity Demand Estimation Model with the different approaches to generate revenue reflected in the Revenue Calculation Model, to estimate the Cash Flow of the PV investment and determine its profitability, NPV, return. This model also estimates the greenhouse gas emissions reductions associated to the PV electricity production, assuming the average emissions rates of the grid. The model is based on estimates of revenues and costs for 25 years using the information and hourly data of the solar energy generation and electricity consumption. Then the non-cash or operational components are taken away to reflect in the future estimations what the project can really produce in monetary value. The future cash flow benefits are then discounted at a hurdle rate to reflect the time value of money. A sensitization analysis was developed to be able to identify areas where there is value to capture, areas of risk, which ultimately help draw the conclusions.

The same model was used for each revenue approach in which they share the same inputs and assumptions with some minor adjustments. The main inputs and assumptions are presented in Table 6, where it is worth to mention and highlight that the solar panels considered for the analysis have an efficiency of 17.03%, a size of 1.6 square meters per panel, and a rated capacity of 270 Watts. After doing a market research, considering PV Watts from NREL and after asking for price quotes for solar panels manufacturers, the panel costs are estimates to be $0.63 per Watt. Same exercise was extended to the other components of the solar system (Inverter and Balance of system), totaling $0.49 per Watt. Then, the installation cost, which mainly refers to the labor cost needed to install the system, was estimated based on the monthly salary of an electrical technician and a solar installer in Chile. The cost of the installed solar system ascends to $1.62 per Watt. Just for depreciation matters the useful life of the PV system was set to 10 years, however, the system continues operating until year 25. However, an annual degradation on the panel and system efficiency was considered, same as a rate for efficiency loss due to high temperatures (system start losing efficiency with temperatures over 25 °C). Also, the model considers a price per carbon offset, which in the base case scenario is $0 per ton of CO_2e (Carbon Dioxide equivalent). Finally, the model includes adjustments due to the yearly inflation, which estimation is based on the Chilean FED (Banco Central de Chile) long term inflation targets. The main assumptions and inputs are listed in the table below.

Table 6: Economic Assessment Model Assumptions and Inputs

Solar System Inputs		Source
Solar panel efficiency (%)	17.03%	Market research, PVWatts
Solar panel rated capacity (W)	270	Market research, PVWatts
Solar panel area (sqm/panel)	1.6	Market research, PVWatts
Inverter efficiency (%)	96%	PVWatts
DC to AC ratio	1.1	PVWatts
Total system cost ($/Wp)	1.62	
Panel Cost ($/Wp)	0.63	Renvu, SAM NREL
Inverter ($/W)	0.13	SAM NREL
Balance of System ($/W)	0.36	SAM NREL
Installation Cost ($/W)	0.5	
Degradation rate (%/year)	0.50%	PVWatts
Efficiency reduction over 25°C (% loss per additional °)	0.30%	PVWatts
Other losses of efficiency	2%	
System useful life (years)	10	
O&M year expense ($/W installed)	0.01	SAM NREL

Carbon Credits Inputs		Source
Price per carbon Offset ($/ton CO2e)	$0	EPA
US Electricity CO2 Intensity (tons CO2e/MWh)	0.56	eGrid EPA
Carbon to CO2 conversion (ton CO2)	3.67	

Other assumptions		Source
Energy Consumption growth (%)	0%	Company
Inflation	3%	Chilean Economy secretary
monthly inflation	0.247%	
Corporate Taxes	24%	Chilean Economy secretary
WACC	10%	

Net Metering - Economic Assessment Model

In the Net Metering Revenue model, the maximum size of the solar installation must be less than 100 Kilowatts. With this constraint, the lar-roof area to be used equals 590 square meters since 270 rated capacity panels of 1.6 square meter each are considered. The system will have 280 square meters on the Administrative Office roof and 310 square meters on the Warehouse 1 roof. This requires the installation of 369 panels with a total installed system cost of $161,838. In this model, there are two sources of revenue, the electricity savings valued at a utility price of c$9.5 per Kilowatt hour, and the electricity injections to the grid valued at a net metering price of c$5.7 per Kilowatt hour (approximately 60% of the utility price). The energy production per year is about 145,000 Kilowatt hours, and the yearly cash flow ranges between $11,000 and $15,000 (see Figure 17). The difference of the later values is explained due to the panel degradation, the depreciation tax benefits during the first 10 years, and the 2% annual price increase.

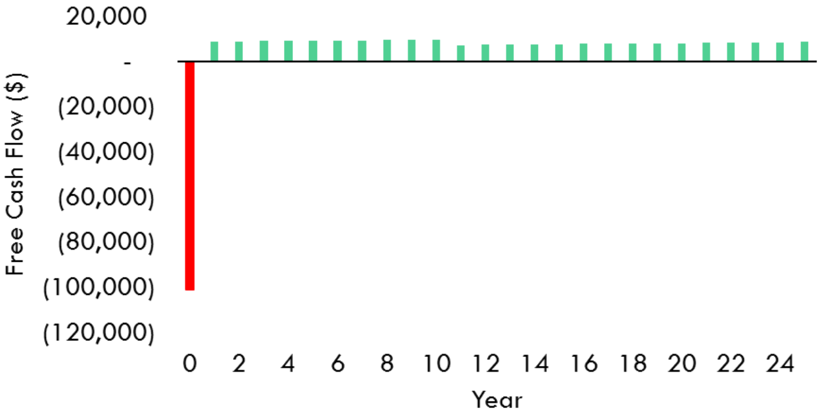


Figure 17: Project Free Cash Flow

As Table 7 shows, the base case results indicate that under a Net Metering model the project has a negative NPV of -$33,600 an IRR of 6% and a payback period of 12 years. The Levelized Cost of

Electricity (LCOE)[22] or the cost of producing electricity considering capital and operating costs increases to c$13 per Kilowatt hour. The capacity factor of the solar system is 17.5% and assuming the average Green House Gas (GHG) intensity of the Chilean grid is equal to that of all the U.S., the amount of GHG emissions avoided (i.e., equivalent offsets) would be 77.2 tons of CO_2e.

Table 7: Base Case results

BASE CASE RESULTS	
NPV (25 years)	**$ (33,600)**
IRR	6%
Payback period (years)	12
Revenue at y1	*$ 14,152*
Energy prod at y1 (KWh)	*146,285*
Cash Flow at y1	*$13,870*
CF	**17.5%**
LCOE ($/KWh)	**0.13**
Emision reduction (tons CO2e/y)	**77.2**

Grid interconnection at mid-voltage - Economic Assessment Model

Alternatively, under the Grid interconnection at mid-voltage model the system can have a size up to 9 Megawatts, but due to rooftop space limitations, the installed solar system size adds up to 473 Kilowatts. The rooftop area used from all the facility buildings is 2,800 square meters, consisting of 300 square meters on the Administrative Office and 2,800 on the Warehouses. The total system cost ascends to $764,450 and the revenue comes from the sale of electricity to the grid at the node price of c$7.3 per Kilowatt hour. Since the availability of the resource is less than 90%, it does not have revenues for capacity or capability to provide power at any time. Each year the project electricity generation

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[22] The LCOE is calculated by dividing the total yearly costs (includes capital and operating costs) by the total generation.

approximates to 724,000 Kilowatt hours, and Cash Flow of ranges from $42,000 to $59,000 (See Figure 18).

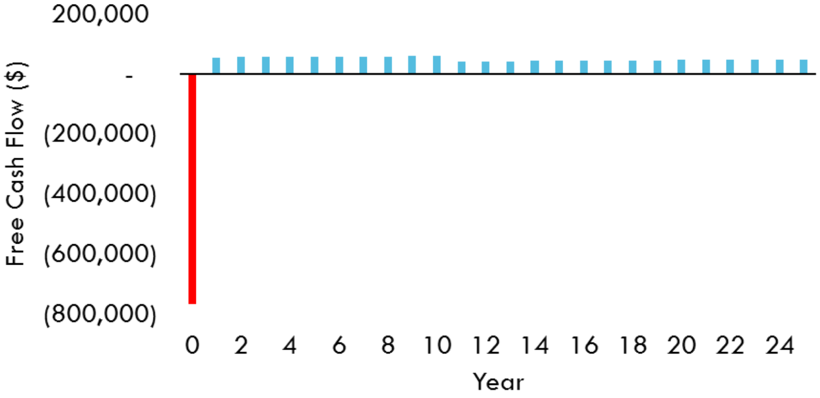

Figure 18: Project Free Cash Flow

As Table 8 presents, the base case results indicate that under a Grid interconnection model the project has a negative NPV of -$258,426 an IRR of 3% and a payback period of 15 years. The LCOE increases to c$12 per Kilowatt hour. The capacity factor of the solar system is 18.2% and the yearly CO_2 equivalent abated reaches the level of 387 tons of CO_2e.

Table 8: Base Case results

BASE CASE RESULTS	
NPV (25 years)	**$ (258,426)**
IRR	3%
Payback period (years)	15
Revenue at y1	*$ 52,947*
Energy prod at y1 (KWh)	*724,510*
Cash Flow at y1	*$ 55,020*
CF	**18.2%**
LCOE	**0.12**
Emision reduction (tons CO2e/y)	**387.02**

CHAPTER 7: RESULTS

Analysis of results - Net Metering Model

Under the base case assumptions, the project exhibits a negative Net Present Value of -$33,600 after investing $161,838 in the solar system. This result is not very encouraging, but as it will be shown, sensibility analysis indicates that project value can significantly increase if conditions change.

Figure 19 shows how sensitive are the NPV estimates to changes on assumptions. As it can be observed, the System Cost and the Price of Electricity are extremely important factors affecting the value of the project. Regarding the first one, a reduction of $0.5 per Watt of system costs (i.e., 31% reduction from baseline costs) can increase the project value in $38,500 ($4,981 minus $-33,600), implying a $7,700 increase in NPV (23% increase) for every c$10 reduction (6% reduction) on the system costs. Similarly, if electricity prices were to increase 1% over the inflation rate, (i.e., 4% annually), the NPV of the project would increases by $17,500. But, if the price decreases, the NPV of the project could be hit negatively and decrease by $13,700. If carbon emissions reductions were compensated at a price of $40 per ton of CO_2 equivalent, the project NPV would increase by $25,000, implying a gain in NPV of $625 for every additional dollar on the carbon credit price. It is worth to notice that the orientation and inclination of the panel can have an important effect on the project value. In this case, if panels were oriented to maximize solar production, facing north and with an inclination of 30°, the NPV would increase by $7,123. Finally, the variation of the solar resource quality can have an impact of $4,600 in the NPV.

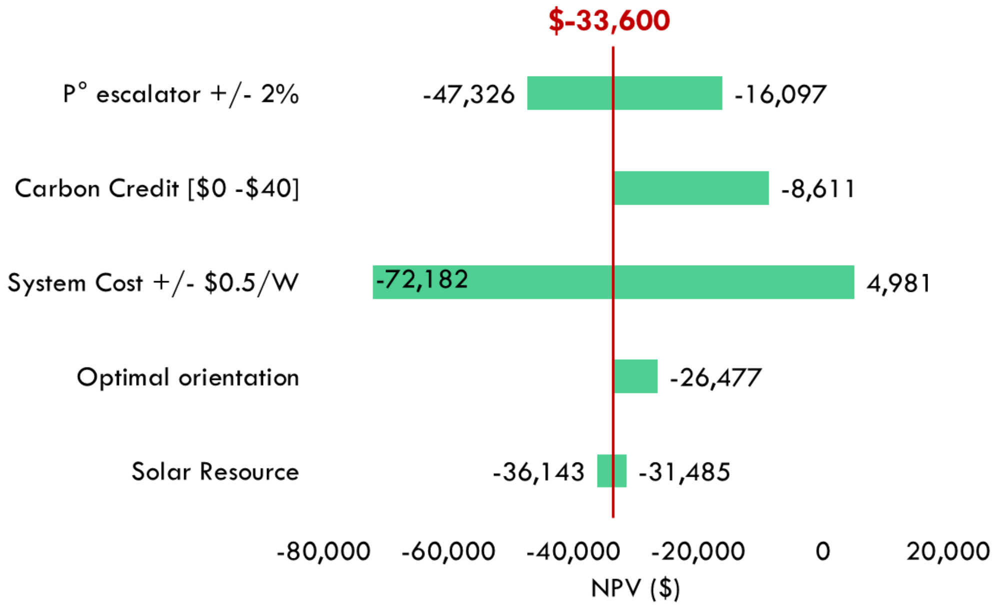

Figure 19: Net Metering Scenario Analysis of NPV ($)

Considering again the base case scenario resulting in an NPV of $-33,600, to break-even (i.e., to reach a point where NPV is equal to zero) the system cost needs to decrease to $1.2 per Watt (Table 9). In the best possible scenario, in which all the upside value of the sensitivity analysis above is captured, the project reaches an NPV of $58,116, requiring a system cost of only $1.87 per Watt to break-even. On the other hand, in the worst-case scenario, the value of the project drops to $-88,036, requiring a system cost of $0.97 to break even.

Table 9: Extreme Scenarios

	Base Case	**Best Case**	**Worst case**
NPV	$ -33,600	$ 58,116	$ -88,036
System Cost Break-even	$1.2 per watt	$1.87 per watt	$0.97 per watt

Analysis of results - Grid interconnection

Same as with a Net Metering revenue approach, assuming a Grid Interconnection, the base case NPV is negative $-258,426 with an initial investment of $764,450. The sensitivity analysis (Figure 20) reinforces the argument that the system cost plays an important role in the profitability of the project. A $0.5 per Watt reduction on the cost of installation (i.e., 31% reduction from baseline costs), would increase the NPV of the project to $183,000 (70% increase), which is equivalent to $3,660 per each cent of system cost reduction. The effect of the electricity price is also important: a 2% annual increase in electricity prices can rise the project value by $67,000. Moreover, if a $40 per ton of CO_2e credit on carbon is considered, the NPV rises by $124,000, or $3,100 per each dollar of carbon credit. Finally, by maximizing the orientation and by contemplating the solar resource quality variations, the project NPV can vary by $14,000 and $10,000 respectively.

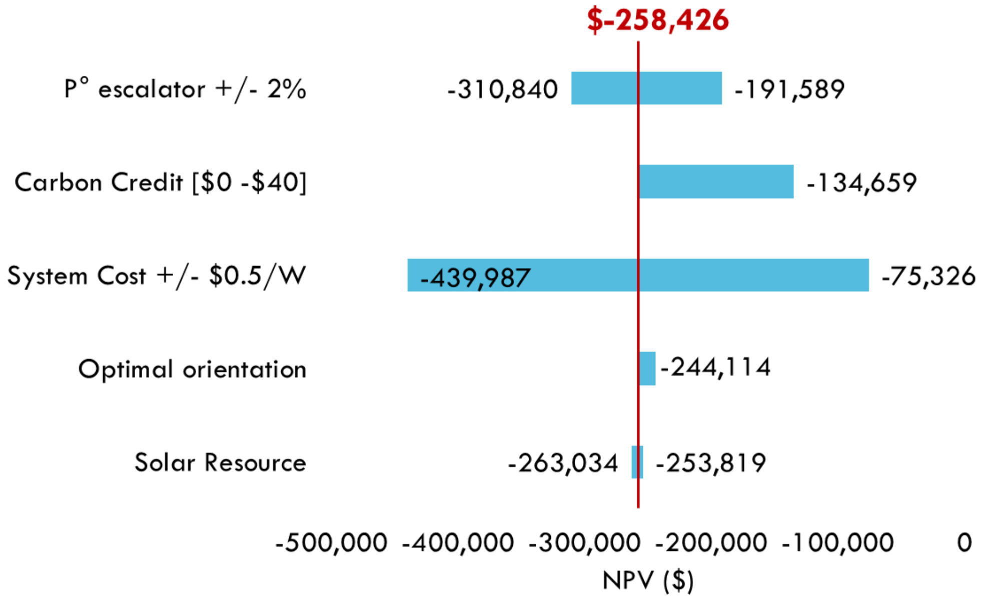

Figure 20: Grid interconnection Sensitivity Analysis of NPV ($)

In the grid interconnection base case scenario, in which the project is worth $-258,426, the system cost needs to reach a $0.91 per Watt level to break-even. As Table 10: Extreme Scenarios shows, if the best possible scenario is considered, the project NPV raises to $136,916, with a break-even point in system cost of $1.49 per Watt. Conversely, the project value can fall to $-497,900 if the worst-case scenario assumptions are applied. In this case, the system cost needs to be $0.76 per Watt to have a project with value of 0.

Table 10: Extreme Scenarios

	Base Case	**Best Case**	**Worst case**
NPV	$ -258,426	$ 136,916	$ -497,900
System Cost Break-even	$0.91 per watt	$1.49 per watt	$0.76 per watt

CHAPTER 8: CONCLUSIONS

Conclusions

After analyzing the model results it can be concluded that under current market conditions a C&I PV solar installation in Santiago, Chile is not economically viable. For the two revenue models tested, Net Metering and Grid Connection at Mid Voltage, the profitability (measured by Net Present Value) was negative: $-33,600 for the Net Metering case and $-258,426 for the grid connection case, with payback periods of over 10 years. This assumes average solar resources throughout a 25-year period (i.e., for each hour of the year, it is assumed the solar irradiance and temperature will be equal to the average of the values observed for that hour during the last 15 years), a PV installation price of $1.6/watt with an efficiency 17%, current electricity prices increasing at 2% annually (see tariff), and discount rate 10%.

However, an exploration of the sensitivity of NPV to assumptions regarding solar resource, installation costs, electricity prices, and a carbon price, indicate that it is likely that in the future a project like this will be economically attractive. The sensitivity analysis shows, that if the discount rate was reduced to 6% then NPV would be positive for the Net Metering approach (with an installed capacity of 100kW). The discount rate would have to be reduced to 3% for a system connected to the Grid at mid voltage (with a capacity of 473 kW) to reach a positive NPV. Similarly, it shows that for each cent of reduction on the per watt system cost, the NPV of the project can increase between $800 and $3,600 depending on the revenue model, and that the cost required to break even is 1.2-0.9 $/watt (depending on the revenue/size model). Also, if the future 25 years had a solar resource as that observed during the best year during the 2002-2016 period, an installation operating under the Net Metering model would have an NPV of $2,100, while one operating connected to the grid would be have and NPV of $4,600. Indeed, variations on the solar resource due to the yearly changes in radiation can have an impact between $5,000 and $10,000 on the NPV. The potential value of the project under best case conditions assuming the best year of solar resource, electricity price increases of 4%/year, system cost of $1.12/watt, and a greenhouse gas emission credit of $40/ton CO2e, are $58,000 for Net Metering and $157,000 for Grid Interconnection.

It is worth to mention that under the scenarios that make the NPV positive, the net metering revenue models seems the most appropriate solution for the company. As analyzed in chapter 5, the net metering revenue model is easier and simpler to implement than the grid interconnection, entails a lower investment and shorter procurement period, and avoids being regulated as Independent Power Producer by the Chilean Electricity Commission. Although, the payment received for injecting electricity though the meter is heavily penalized by the utility (60% of the price), the effect on the project value is none since the system size is capped at 100 Kilowatts and the facility consumption at the solar hours exceeds the system capacity.

Finally, the hypothesis that the solar system may reduce the power charges, which accounts for 20% of the electricity bill, did not apply for the case study since the facility peak electricity consumption takes place between 8:00 am and 10:00 am, when the solar energy is still low.

Potential further analyses

By looking at the economics of a roof-top PV installation in a large industrial facility in Chile, this analysis has shed some light on the broad trends for C&I PV solar development in this country. However, in order to get a better understanding of the potential and economics of developing PV in the entire industrial sector in Chile this analysis could be expanded in different directions. First, it would be useful to look at the northern region of Chile how the profitability of Commercial and Industrial solar business models will change with a better solar resource. In the facility analyzed, the capacity factor of the PV installation observed for the average year was 17.5%. In the Atacama Desert this value could increase to 25-30%[23].

It would also be useful to explore the economics of a revenue model that allows installing a system larger than the 100kW allowed by net metering, but smaller than the baseload consumption of the company, (and possibly paired with an energy storage system); with the goal of minimizing the amount of electricity injected into the grid. This would allow the facility to get most of its electricity at a cost equal to the Levelized Cost of Electricity (LCOE) of the PV system and not at the higher price set by the electric utility company (including nodal prices plus distribution charges), and it would also allow it to reduce the Power Charges (associated to peak monthly energy consumption, and peak consumption during peak hours). Finally, these models could be used to explore the most promising policy mechanisms that the Chilean government could pursue to incentivize the adoption of distributed PV solar in the C&I sector.

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[23] (Mearns, 2016)

APPENDIX

Appendix 1: Solar calculations[24]

“The direct irradiance normal to the tilted module surface can be estimated from the GHI as follows:

$Im{=}GHIcos\theta z\ cos\theta$ (2)

where θz , the solar zenith angle, and θ, the angle of incidence, are defined by equation 3 and 4 respectively.

$\theta{=}\ cos{-}1(cos\theta zcos\beta\ {+}sin\theta zsin\beta\mathrm{cos}\ (\gamma s-\gamma))$ (3)

$\mathrm{cos}\theta z{=}cosL\ cos\delta\ cosHA{+}sinL\ sin\delta$ (4)

L is the latitude of the gridded cell, β is the module tilt angle, γ is the module azimuth angle. For our study the module tilt angle β was set to 25 degrees to represent a module located on a tilted roof surface. The module azimuth angle γ is assumed to be 180 degrees or facing directly south which is the optimal orientation for solar exposure in the northern hemisphere. The solar azimuth angle γs , declination angle δ, and hour angle HA are calculated using the equations 5-10. The declination angle is determined by the Day of the year DOY.

$\delta{=}23.45^{\circ}\ sin[DOY{+}284365\times 360^{\circ}]$ (5)

The solar azimuth angle, γs , is calculated from the following equation:

$cos\ \gamma s\ {=}sin(90{-}\theta z)\mathrm{sin}\ L{-}sin\delta\mathrm{cos}(90{-}\theta z)cosL$ (6)

The hour angle is determined by equation 7, where solar time is a function of longitude, time zone, hour of the day and the Equation of Time (EoT), and a constant x determined by equations 8-10.

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[24] (Moore Holt, 2014)

$\mathrm{HA}=(Solar\ Time\ \times 60-720)4$ (7)

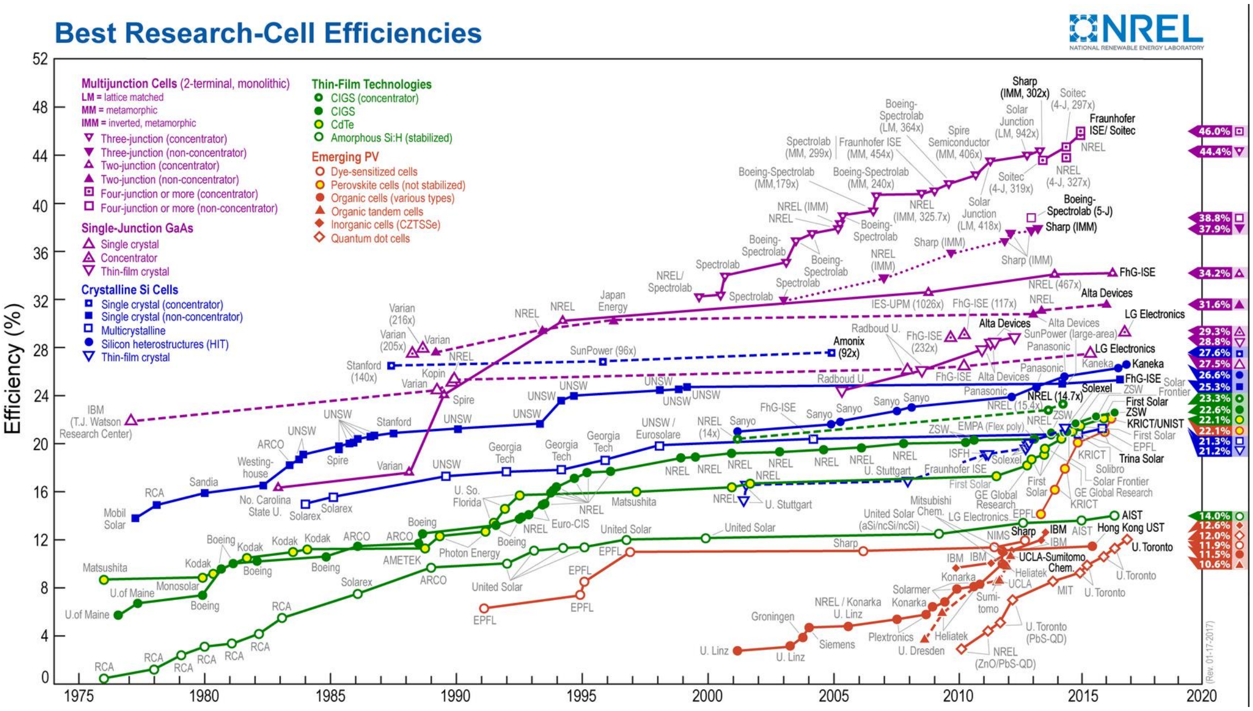
$\mathrm{Solar\ Time}=hour\ of\ day+(4\ \times(75-Longitude)+EoT60)$ (8)

$\mathrm{EoT}=9.87\sin(2x)-7.53\cos(x)-1.5\ \sin\ (x)$ (9)

$\mathrm{x}=360(DOY-81)365$ (10) ”

Symbol	Description	Definition	Unit
GenPV	PV Generation	The amount of electricity produced from a PV system with rated capacity of pvc at an irradiance level of Im	W
Im	Irradiance on tilted module surface	The portion of the GHI that is normal to the tilted module	W/m2
pvc	Name Plate PV Capacity [W]	The name plate capacity of the PV system at test conditions of 1000 W/m2	W
GHI	Global Horizontal Irradiance	The total irradiance reaching a surface horizontal to the surface of the earth	W/m2
θz	Solar Zenith Angle	The position of the sun’s elevation relative to being directly overhead which is the compliment of the solar elevation angle	Degrees
θ	Angle of Incidence	The angle between the sunlight rays incident to module and normal to the tilted module	Degrees
β	Module Tilt Angle	The angle in which the module is tilted	Degrees
γ	Module Azimuth Angle	The module orientation relative to 180 degree south.	Degrees
γs	Solar Azimuth Angle	The sun’s orientation relative to 180 south	Degrees
δ	Solar Declination Angle	The angle, which varies seasonally due to the earth’s tilted axis, between the rays of the sun and the equatorial plane.	Degrees
L	Latitude		Degrees
DOY	Day of Year	The day of the year from 1 to 365	Days
HA	Hour Angle	Angular measurement of time	Degrees
x	Constant	A constant used in the equation of time	None
EoT	Equation of Time	A formula used to account for the earth’s orbit and earth’s tilt	None
Solar Time	Solar Time	The local time in terms of the position of the sun in terms of a 24 hour day (1440 mins) corrected for time zones	Hours

Appendix 2: NREL Solar efficiency chart[25]



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[25] (National Renewable Energy Laboratory, 2016)

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