PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
SCHOOL OF ENGINEERING

ECONOMIC IMPACTS OF INSTALLING SOLAR POWER PLANTS IN THE NORTH OF CHILE

FELIPE DEL SOL FERNÁNDEZ

Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Advisor:
ENZO SAUMA

Santiago de Chile, October 2010

PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
SCHOOL OF ENGINEERING

ECONOMIC IMPACTS OF INSTALLING SOLAR POWER PLANTS IN THE NORTH OF CHILE

FELIPE DEL SOL FERNÁNDEZ

Members of the Committee:
ENZO SAUMA
RICARDO PAREDES
ANDRÉS GUZMÁN
JUAN DIXON

Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Santiago de Chile, October 2010

To my parents for supporting every
peculiar idea I had in the past.

ACKNOWLEDGEMENTS

Foremost, I would like to thank my supervisor, Prof. Enzo Sauma, who shared with me a lot of his expertise and research insight. A great mentor and professor, whose thoughtful advise and time served to give direction during my M.Sc. studies. I also like to express my gratitude to Andrés Guzmán, a great professional, whose knowledge and directions for the correct simulation helped to obtain one of the most important results of this research. And I am grateful to Prof. Ricardo Paredes, whose knowledge of statistics were fundamental for the understanding and interpretation of the regression results.

It is difficult to overstate my appreciation to my uncle Fernando del Sol, who first brought me into the world of Solar Power. To him I owe all my expertise on the subject.

I am tempted to individually thank all of my friends which, from my childhood until university, have joined me in the discovery of what is life about and how to make the best of it. However, because the list might be too long and by fear of leaving someone out, I will simply say thank you very much to you all. Some of you are, anyway, quite lucky: thank you Agustín, Alberto, Andrés, Cristián, Fernando, Gonzalo, Hans, Ignacio, José Tomás, Nicolás, Rodolfo and Rodrigo for being some of my very best friends.

I cannot finish without saying how grateful I am with my family: grandparents, uncles, aunts and cousins, all have given me a loving environment where to develop. Particular thanks, of course, to Patricio my brother and best mate, and Alicia my lovely sister. Lastly, and most importantly, I wish to thank my parents, Patricio and María del Carmen. They have always supported and encouraged me with all my peculiar ideas and to do my best in all matters of life. To them I dedicate this thesis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

This document has the objective of studying the economic impacts of installing solar power plants in the north of Chile, which has one of the best conditions of the world for the generation of electrical energy from solar resources.

The specific objectives of this thesis is to identify a limited number of variables which explain the variation on the investment and generation costs of solar power plants and to use them to evaluate the social and private benefits of the installation of these plants in the north of Chile.

Solar energy is measured as radiation in W/m^2 and can be transformed to electric energy using different technologies. Thermal technologies use radiation to heat a fluid that produces a mechanical movement to finally produce electrical energy. Photovoltaic technologies are made of different semiconductor materials that captures solar radiation and transforms it to electrical energy.

Along the document the different technologies are explain with its process of transforming solar energy to electrical energy together with their cost. Energy storage technologies were also included as a chapter to this study.

Multiple linear regressions were formulated with information of 45 thermal and 37 photovoltaic solar plants and projects, to explain the variation on the investment and generation costs. Also, 11 technologies were simulated in 4 locations using OSE2000 software to determine the change in the total system cost and the social and private net present value of some projects.

The results show that it was possible to determine a limited number of variables which correctly explain the variation on the investment and generation costs of solar energy power plants and that the installation of a solar power plant in the north of Chile will not bring net social or private benefits to the country and companies unless certain conditions, such as carbon bonds prices, labor growth rate, solar plants parts prices, etc., change.

Keywords: Solar Radiation, Solar Energy, Chile Solar Power, Econometric Analysis, Solar Technologies, Solar Thermal, Solar Photovoltaic, Energy Storage, Chile Solar Simulation.

RESUMEN

Este documento tiene el objetivo de estudiar los impactos económicos de la instalación de plantas de energía solar en el norte de Chile, en donde existen una de las mejores condiciones del mundo para la generación de energía eléctrica a partir de recursos solares.

Los objetivos específicos de esta tesis son identificar un número limitado de variables que expliquen la variación de los costos de inversión y generación de plantas de energía solar y usar esa información para evaluar los beneficios sociales y privados de la instalación de una planta de energía solar en el norte de Chile.

La energía solar se mide como radiación en W/m^2 y se puede transformar en energía eléctrica utilizando diferentes tecnologías. Las tecnologías termales usan la radiación para calentar un fluido que produce un movimiento mecánico para finalmente producir energía eléctrica. Las tecnologías fotovoltaicas están hechas de diferentes materiales semiconductores que captan la radiación solar y la transforma en energía eléctrica.

A lo largo del documento, se explican las diferentes tecnologías con su proceso de transformación de energía solar en eléctrica junto con su costo. Las tecnologías de almacenamiento de energía también se incluyeron en este estudio.

Regresiones lineales múltiples fueron formuladas con información de 45 plantas solares térmicas y 37 fotovoltaicas para explicar la variación de los costos de inversión y generación. Luego, 11 tecnologías se simularon en 4 lugares utilizando el software OSE2000. Así se determinó el cambio en el costo total del sistema y el valor presente neto,social y privado, del proyecto.

Los resultados muestran que fue posible determinar un número limitado de variables que explican correctamente la variación de los costos de inversión y generación de plantas solares de energía y se demostró que la instalación de una planta de energía solar en el norte de Chile no traerá beneficios netos sociales o privados a los diferentes agentes involucrados,

a menos que las condiciones, como los precios de los bonos de carbono, crecimiento en la tarifa del trabajo, precio de partes de la planta solar, etc., cambien.

Palabras Claves: Radiación Solar, Energía Solar, Solar Chile, Análisis Econométrico, Tecnologías Solares, Solar Termal, Solar Fotovoltaica, Almacenamiento de Energía, Simulación Solar en Chile.

1. INTRODUCTION

1.1. Problem Description and research motivation

The north of Chile has one of the best conditions of the world for the production of electrical energy from solar resources (SWERA, 2010).

Many important astronomical observatories have been installed on the north of Chile because of the low number of cloudy days and the better sky clearness index, which can be represented on our matter as a high amount of radiation received and more generation of electric energy than other locations.

In the north of Chile there are many mining companies who demand big loads of energy for their operation. They currently use electricity provided from fossil fuels thermoelectric plants that are subject to fuel prices. Moreover, because about the 99% of the electrical generation of the Northern Interconnected Power System is thermoelectric, a diversification of the matrix is needed to protect the price of energy from changes on the fuel prices. On the other hand, environmental regulations are getting stricter and customers are demanding companies to make a reduction on the greenhouse gas (*GHG*) emissions or mitigating their carbon footprints.

The current literature has very limited applicability for Chilean energy generation companies, since it doesn't describe the variables that explain the investment and generation cost of a solar power plant. On the other hand, it is interesting to analyze the economical impacts, such as private income from the generated energy and change on the marginal and total cost of the system.

1.2. Hypothesis

There are two hypotheses in this investigation:

(i) It is possible to identify a limited number of explanatory variables which explain the variation on the investment and generation costs of solar energy power plants.

(ii) It is possible to quantify the social and private net benefits of the installation of a solar power plant in the north of Chile and determine the conditions in which they are positive.

1.3. Objectives

The first objective is to identify the variables, such as technology, installed capacity, area, generation, construction year, among others, that explain the variation on the investment and generation costs of solar energy power plants.

The second objective is to study the economic impact that will cause the installation of a solar power plant in the northern interconnected power system of Chile (SING).

1.4. Methodology

This research will include a review of the literature that will introduce the reader to the subject of solar energy. At first defining and explaining what is solar radiation and the different ways to capture it for energy production. Secondly, an explanation of the process of converting solar radiation into electrical energy associated with the used technology. A separate chapter will explain the state of art of the different energy storage technologies with their costs, which can be included in a project to ensure the continuous energy generation over time of the day.

For the cost analysis, a multiple linear regression is formulated with data gathered from studies and project information from different real world projects. The result of the regression model will show the most statistically significant variables and their effect on the investment and generation cost.

Finally, to obtain the economic impact of installing a solar power plant, social and private net benefits are calculated from the OSE2000 simulation. This information will be projected for a period of 30 years and all the economical benefits will be quantified.

1.5. Expected Results

The expected results of this research are that, because of the higher solar radiation and other factors, the investment and generation costs of a solar power plant located in the north of Chile are lower than the plants located in Spain or United States.

With a more accurate determination of the different costs of a solar power plant, it is expected that the benefits from the installation of a solar power plant will not be economically feasible for private companies.

In the other hand, this research will quantify the social net benefits as the delta between the total system price with and without the solar plant to compare it with the private results. It is expected that the social benefits would be lower than the private ones.

2. SOLAR ENERGY BACKGROUND: CHILE IRRADIATION COMPARED WITH THE WORLD

2.1. General Features

Solar energy is obtained from radiant light and heat from the Sun. Through different processes, which will be explain along the document, this energy is transformed into electricity. For the correct understanding of these processes we first need to understand solar radiation and the different ways it is collected.

Solar radiation is the energy, originated from the sun, that impacts a surface during a specific period of time. The typical unit for instant radiation is $\frac{Watt}{m^2}$.

2.2. Types of Radiation

There are different types of radiation depending on the orientation of the surface that measures the energy from the sun.

(i) **Direct Horizontal Irradiation** is measured on a fixed flat horizontal plane. It depends on the angle of incidence of the direct beam originated from the rays the sun.

(ii) **Diffuse Horizontal Radiation or Diffuse Irradiation (DI)** is originated from bodies that absorb, reflect or emit the radiation from the sun. It includes all radiation that doesn't come directly from the sun.

(iii) **Global Horizontal Irradiation (GHI)** is the sum of the direct and diffuse components of the horizontal irradiation.

(iv) **Direct Normal Irradiation (DNI)** is measured on a perpendicular or normal plane to the sun rays beam. To collect this radiation, the surface has to follow or track in two axis the movement of the sun.

(v) **Latitude Tilt Irradiation (LTI)** is measured on a fixed flat plane oriented with a certain angle given by the latitude that the plane is installed.

The solar energy generation technologies could utilize one or more of different types of radiation described above. This will be described in detail on the next chapter.

Besides $\frac{Watt}{m^2}$, solar radiation is also measured in $\frac{kWh}{m^2 day}$. This unit represents the weighted average of the instant radiation collected by its period of time in hours with the total hours of a day.

2.3. Determining Solar Radiation in Chile

There are mainly two ways or methods of obtaining solar radiation data, the first one is by land measurements using instruments like pyrheliometers, pyranometers or solar colorimeters which are basically sensors that use a photo-sensitive material. And the second way is by satellite estimation, on which, organizations such as NASA and NREL have developed algorithms to obtain the solar radiation in different parts of the world.

To obtain the radiation in Chile, there are several sources of information, this sources will be exposed and contrasted to find and use the most accurate data available.

The Chilean National Commission of Energy (*CNE*) has installed three land stations on different parts of the north of Chile. The location of these stations, together with the simplified diagram of the North Interconnected Power System (*SING*), are shown in Figure 2.1.

These stations measure GHI, DNI, DI, temperature, humidity and wind speed at a sample rate of 10 minutes for every day. The stations were installed in different period of time. For Pozo Almonte the CNE provides 15 months of information, for San Pedro 6 months and for Cruzero only 4 months (CNE, 2010a).

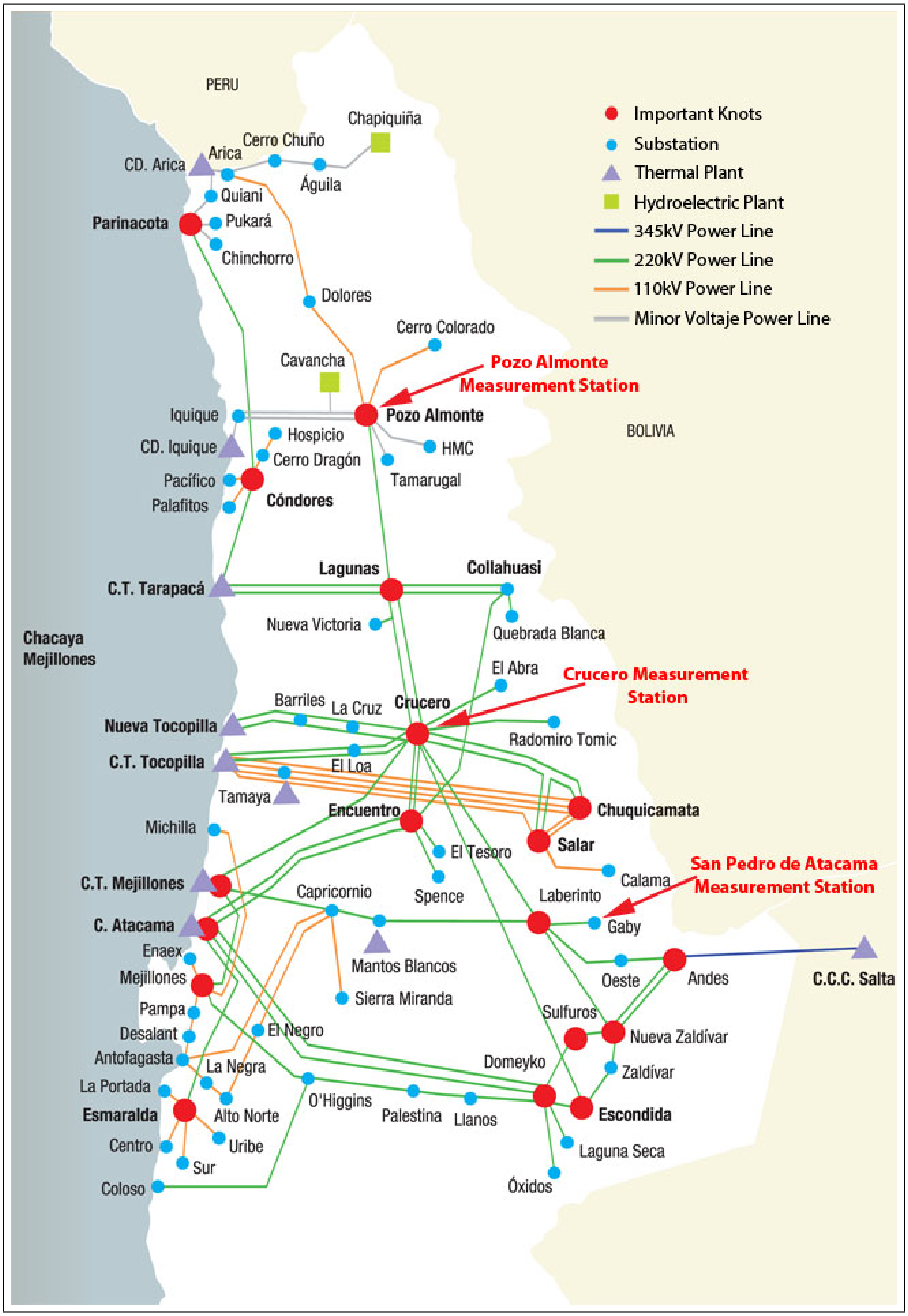


FIGURE 2.1. Northern Interconnected Power System Map with CNE's Land Measurement Stations

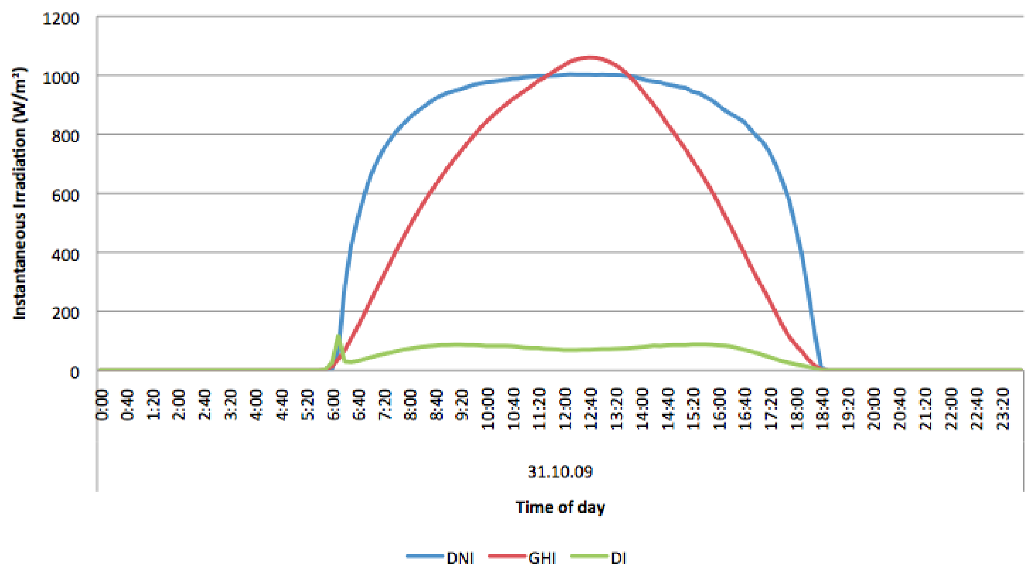


FIGURE 2.2. Hourly Radiation for Pozo Almonte Station

Hourly radiation (Figure 2.2) is needed for the correct simulation of a solar energy power plant. Unfortunately these in-situ stations don't follow the international measurement regulations, and the numbers are overvalued[1].

The National Renewable Energy Laboratory (*NREL*) use satellite and surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone information for all the South American continent to estimate annual and monthly averages of GHI, DNI, LTI and DI for a spatial resolution of $40km \times 40km$. A map of de DNI of the north of Chile is shown in Figure 2.3.

NASA together with the Atmospheric Science Data Center use 23 years of historical data to estimate daily average of GHI, DI, DNI, Temperatures and humidity for a spatial resolution of $1^\circ \times 1^\circ$, which is approximately $111km \times 111km$, of the whole world (Figure 2.4).

Contrasting the three sources of information (Figure 2.5 and Figure 2.6), there are big similarities on the shape of the curve in GHI, having the CNE measurements always on the top.

[1]Information provided by Rodrigo Escobar

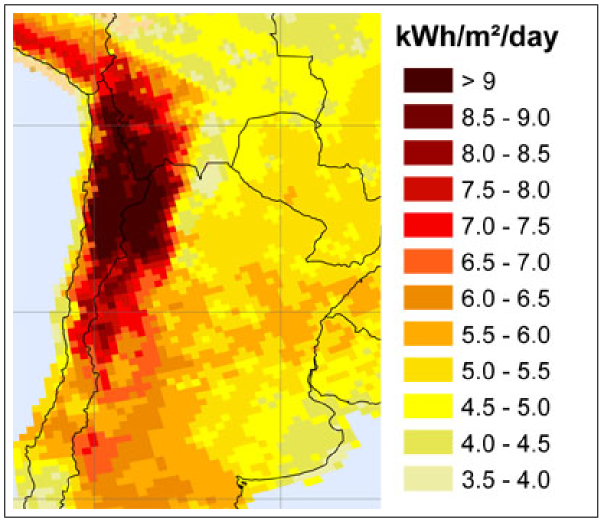


FIGURE 2.3. SWERA Annual Direct Normal Solar Radiation for the North of Chile (SWERA, 2010)

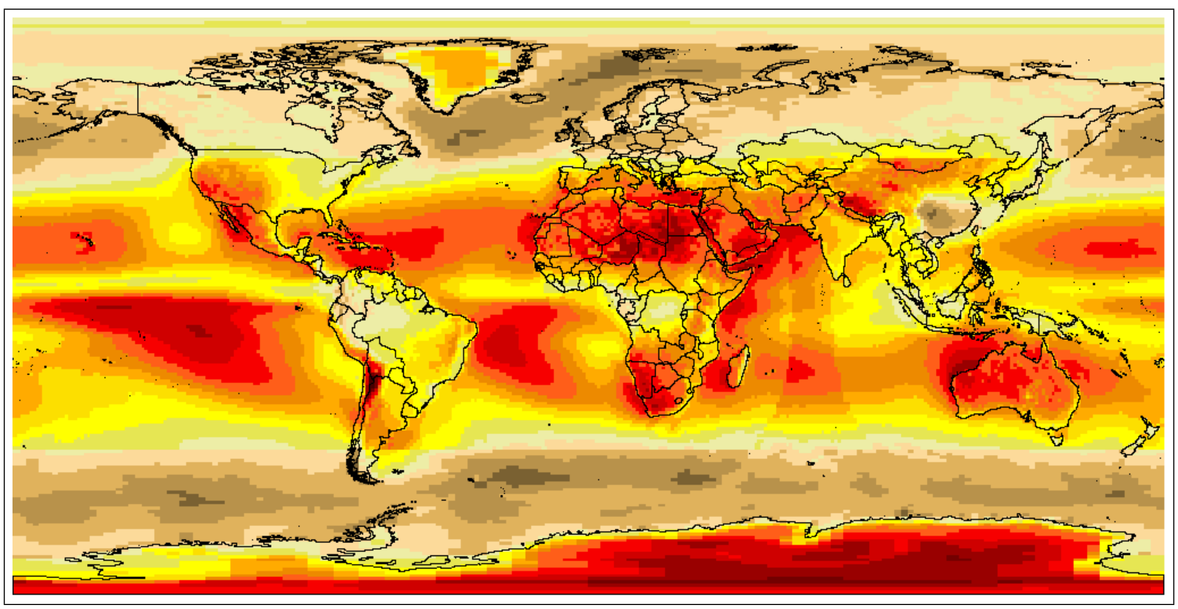


FIGURE 2.4. NASA World DNI (NASA, 2010)

Meteonorm software uses information from NREL and gives hourly information for different locations. This software will be used for obtaining the required information (DNI, GHI, DI, temperature, humidity, wind speed, etc.) that will be the input for the simulation

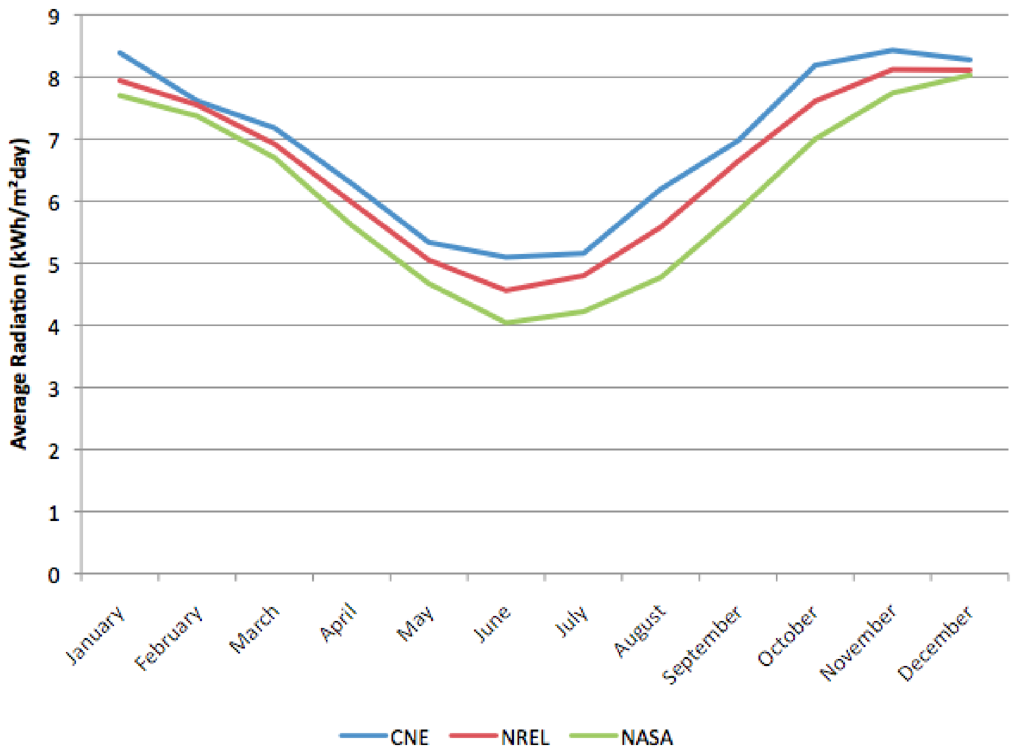


FIGURE 2.5. Average GHI in Pozo Almonte using the different sources

that will give us the hourly electric energy production of the different solar energy technologies, used for simulating the Chilean northern interconnected power system (SING) in Chapter 7.

The main reasons for choosing this software for determining the solar resource in the north of Chile are: the data available from CNE don't follow the international measurement regulations, it is available to any site on the north of Chile and it provides hourly information.

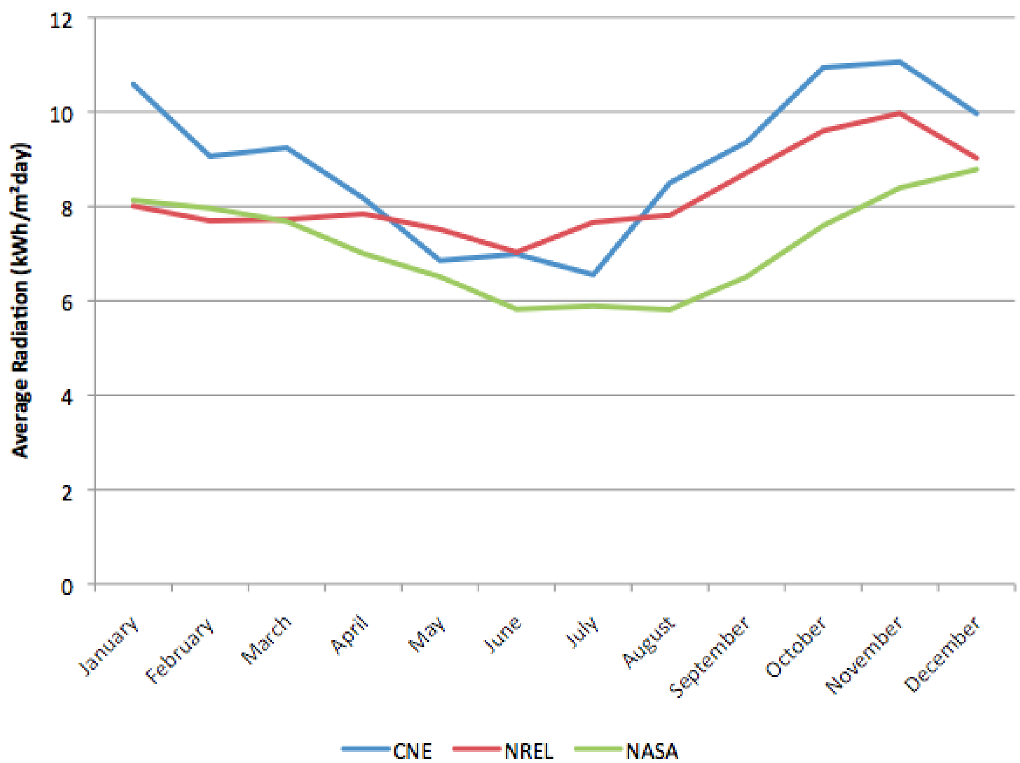


FIGURE 2.6. Average DNI in Pozo Almonte using the Different Sources

3. SOLAR ENERGY GENERATION TECHNOLOGIES

Solar technologies transform the solar radiation in electric energy and can be grouped in two families: Thermal and Photovoltaics. Solar thermal technologies use irradiation as a source of heat to raise the temperature of a fluid. To minimize the land usage and maximize the efficiency, the sunlight is concentrated onto receivers. Via a Steam Turbine or a heat engine connected to a generator, electric energy can be generated. Solar Photovoltaics convert solar radiation into direct current due the photovoltaic effect.

Both technology families will be explain in detail, together with the different technologies and their electric energy generation process.

3.1. Parabolic Trough

The parabolic trough use linear concentrating solar power collectors to obtain the energy irradiated from the sun. This concentrated energy is used to heat a fluid that is part of the cycle shown in Figure 3.1.

Linear parabolic mirrors reflect the radiation onto a linear receiver that consists of a tube positioned along the focal line of the parabola. The mirrors and the tube track in one

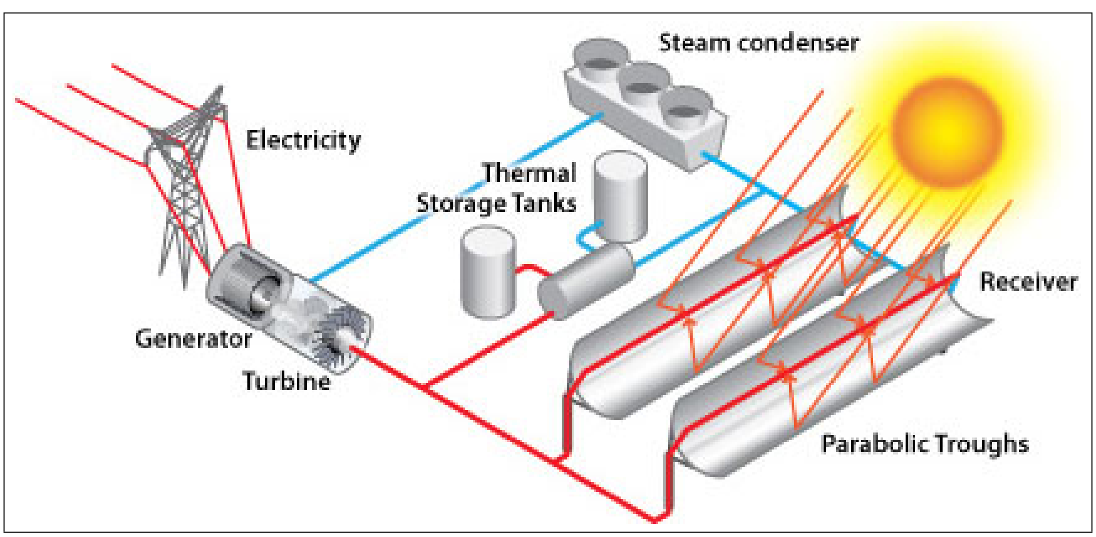


FIGURE 3.1. Parabolic Trough Energy Conversion Process(US DOE, 2010)

axis the position of the sun during the day to maximize the amount of radiation collected (Philibert, 2005).

There are two type of systems: The ones that use a heat-transfer fluid (*HTF*) and using a heat exchanger it evaporates water to drive a steam turbine, and the ones that use water/steam directly onto the tube receiver.

The combined cycle together with the heat collector system, makes possible the generation of electric energy.

As the most commercially developed thermal technology, there are several parabolic trough plants currently on operation. As shown on Table 3.1, some of them use fossil fuel backup to produce electric energy during low and non-solar hours. Nevada Solar One and Andasol I use thermal energy storage tanks for 0.5 and 7.5 hours respectively, to produce their peak energy.

TABLE 3.1. Parabolic Trough Operational Power Plants (NREL, 2010)

Plant Name	Location	First Year of Operation	Net Output MW_e	Fossil Fuel
Andasol I	Granada, Spain	2009	50	None
Nevada Solar One	Boulder City, NV	2007	75	None
APS Saguaro	Tucson, AZ	2006	1	None
SEGS IX	Harper Lake, CA	1991	80	Natural Gas
SEGS VIII	Harper Lake, CA	1990	80	Natural Gas
SEGS III→VII	Kramer Junction, CA	1987→1989	30	Natural Gas

This technology requires water for mirror cleaning and cooling the steam circuit. Andasol I needs about 870,000 m^3 of water per year. This could be a very important issue for choosing the technology in the north of Chile, where water availability is very limited.

3.2. Linear Fresnel Reflector

Linear Fresnel Reflector Systems use flat or slightly curved mirrors to simulate a parabola that track the sun focusing the radiation on a fixed tube receiver.

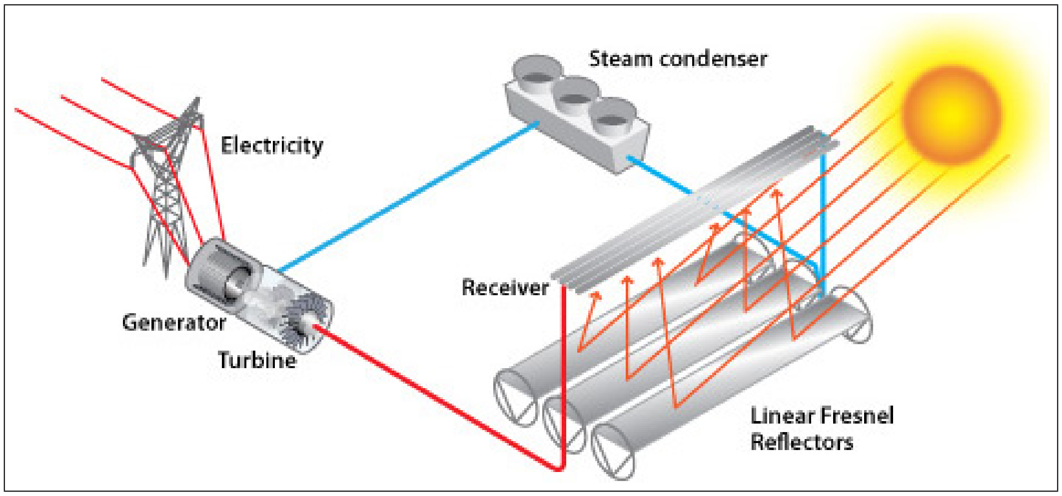


FIGURE 3.2. Lineal Fresnel Energy Conversion Process (US DOE, 2010)

This technology is an evolution of parabolic trough where the main difference is that the flat mirrors are significantly cheaper than parabolic-shaped mirrors and that the central receiver stays in a fixed position.

As shown in Figure 3.2 the steam production is made directly, and the current plants heat water in a closed cycle without using *HTF* and a heat exchanger.

3.3. Solar Power Tower

Power tower systems concentrate solar radiation onto a high punctual receiver located at the top of a tower. A big number of flat mirrors, known as heliostats, track the sun in 2 axis to focus sunlight and increase the temperature of a *HTF* or water/steam used for the generation cycle.

The cycle for electrical energy generation is identical of the one described for parabolic trough and is shown on detail in Figure 3.3.

Planta Solar 10 and Planta Solar 20 are currently operating tower systems located in Spain with capacities of 11 and 20 MW, respectively. These plants use water/steam directly to drive the steam turbine in the combined cycle.

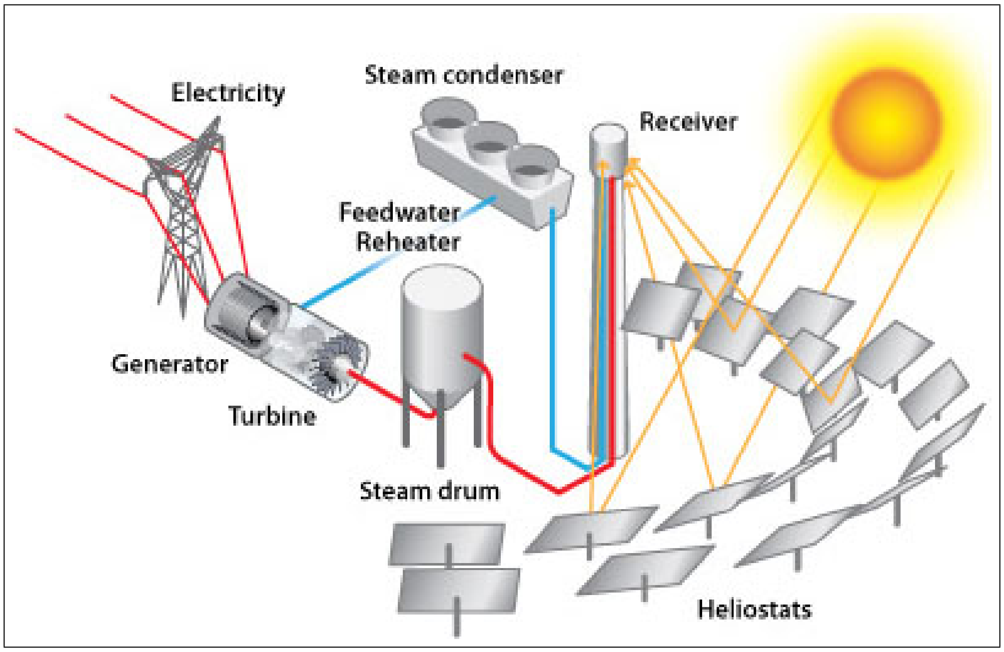


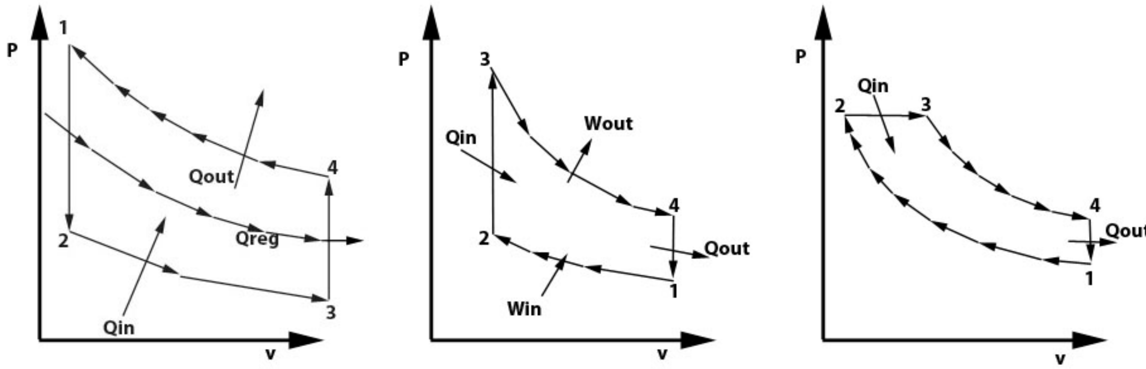
FIGURE 3.3. Solar Power Tower Energy Conversion Process (US DOE, 2010)

3.4. Stirling Solar Dish

Stirling systems use a parabolic mirror dish to concentrate solar radiation onto a central point or focus heating a gas that produces the operation of a stirling engine. As the gas spans, pistons move and create a mechanical rotation of the engine's crankshaft that drives a generator to produce electrical power.

Robert Stirling designed the stirling engine in 1816 and is the most efficient thermal engine being close to the efficiency of a Carnot cycle. The key of its efficiency is that the heat flow is continuous in its four stages, different from Otto (gasoline) and Diesel Engines where the heat flow happens in only two of the cycle stages. The three thermodynamic cycles are shown on Figure 3.4.

Figure 3.5 shows the operation of a stirling engine. The red section is where the solar collector is placed and the blue section where a dissipater is placed to extract the heat. The upper piston is called the power piston and the lower is called the displacer piston. In phase 1 the power piston compresses the gas and the displacer piston moves so most of the gas is adjacent to the hot heat exchanger. In phase 2 the pressure of the heated gas increases and



(A) Stirling Cycle (B) Otto Cycle (C) Diesel Cycle

FIGURE 3.4. Comparison Between Different Engine Cycles

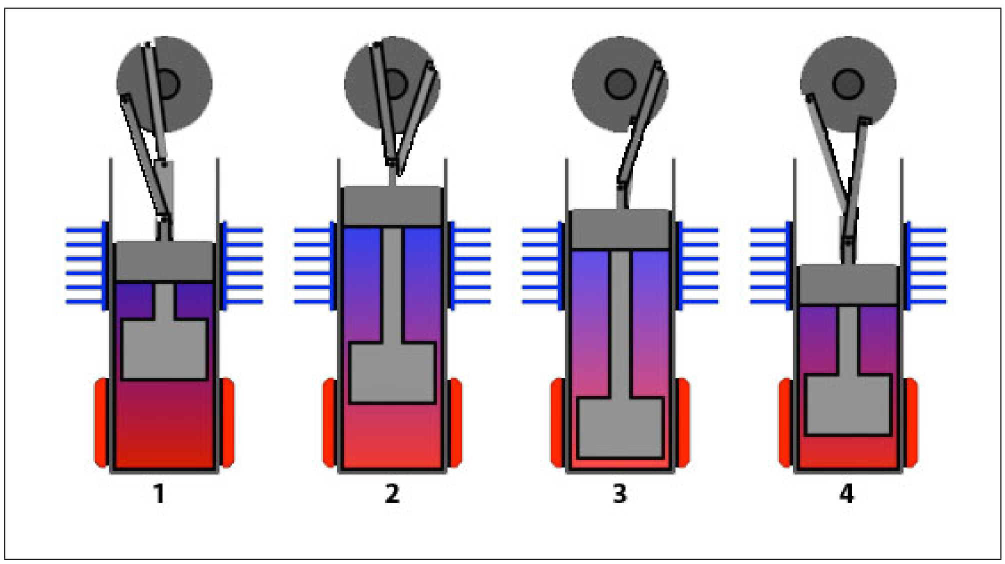


FIGURE 3.5. Stirling Engine Workflow Diagram (Wheeler, 2007)

pushed the power piston to the top limit. That makes that the displacer piston push the gas to the cold end of the cylinder and begin phase 3. The gas lowers its temperature and its pressure so the power piston gets to the position shown in phase 4.

Every stirling dish produces a small amount of energy that is in the range of 3 to 25 KW of electrical power.

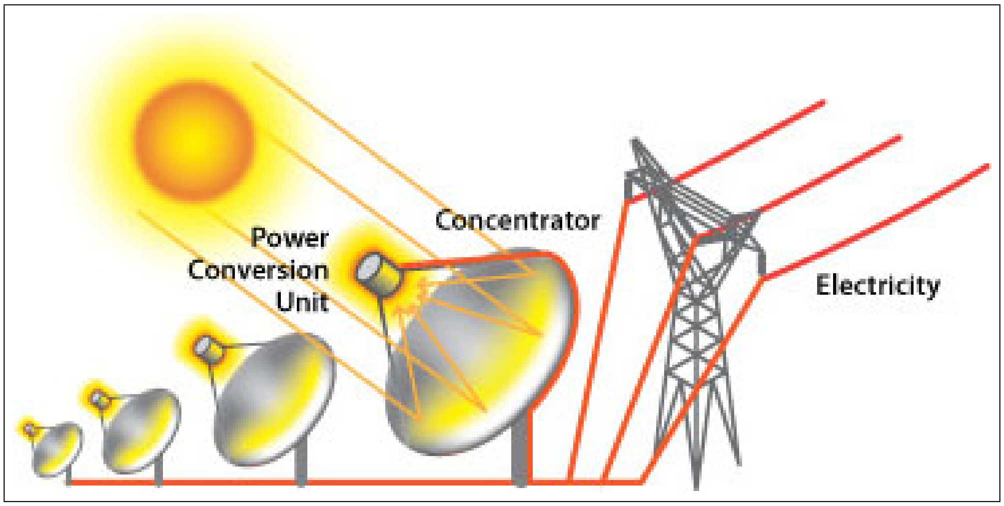


FIGURE 3.6. Stirling Solar Dish Energy Conversion Process (US DOE, 2010)

3.5. Photovoltaics

Photovoltaics *(PV)* cells have a semiconductor material that works similarly to a diode, electrical current flows in only one direction. This material captures the energy irradiated from the sun and causes emission of electrons called photoelectrons. For the photoelectric effect to take place, the energy of the photoelectrons has to be higher than the band gap of the semiconductor material. The band gap is the range of energy of a solid material, measured in electron-Volts *(eV)*, where no electrons exist. The result of a higher band gap is a more efficient absorption of the solar spectrum.

Photovoltaic modules or panels are made from an arrangement of solar cells. There are several kinds of photovoltaics modules depending on the material and the production process. They can be divided on first, second and third generation PV.

(i) **First Generation PV** are made from crystalline silicon and there are two types depending of the manufacturing process. The thickness of a cell varies from 400 to 200 μm.

(a) **Mono-crystalline Silicon** modules are manufactured by first purifying the silicon, melting it and crystallizing in ingots. These ingots are cut in thin wafers to produce a cell. This is the most common type of PV solar module in the market.

(b) **Polycrystalline Silicon** ***(Poly-Si)*** manufacturing process is very similar to the mono-crystalline silicon. The main difference is that it uses low cost silicon making the module less efficient, but at the same time, manufacturers pursue a lower price per kW.

(ii) **Second Generation PV** are commercially known as thin-film PV panels and differ from the first generation on their lower cost and the decrease of their efficiency. The lower cost is achieved because less material is needed in the manufacturing process of the module. The thickness of the cell is around 5μm.

(a) **Amorphous Silicon** ***(a-Si)*** manufacturing process is simpler and cheaper than all the other types, but its 8% efficiency is also the lowest.

(b) **Cooper Indium Gallium Selenide** ***(CIGS)*** thin-film modules have a big potential for its high efficiency and low cost. The manufacturing of CIGS cells, changing the composition of Indium-Gallium, allow to have a variable band gap so the spectrum absorption is maximized. On the other hand, the complicated manufacturing process, the low availability of the materials and the toxicity of Selenide are some of the cost of this technology.

(c) **Cadmium Telluride** ***(CdTe)***, as CIGS technology, has a superior spectrum absorption and has better performance at high temperatures. First Solar, the world leader in all thin-film PV technology development and global sales, manufactures and sells CdTe PV modules.

FIGURE 3.7. Thin-Film PV Panel (NREL, 2008)

(iii) **Third Generation PV** are known as multi-junction PV cells and were developed to achieve a higher efficiency. They consist on multiples thin-film layers with different band gap so different range of the spectrum is absorbed in each layer and take advantage of the radiation available. This higher efficiency translates to higher output energy using the same surface or identical output energy using a smaller collector surface.

The main primary materials used to manufacture the different types of multi-junction PV cells are Gallium Arsenide*(GaAs)*, gallium Indium Phosphide*(GaInP)* and Germanium*(Ge)*.

3.6. Concentrating Photovoltaics *(CPV)*

CPV systems are mainly used on high radiation zones. Unlike PV systems that can produce output energy on cloudy days, CPV technology produces energy only when the sunrays come directly, reason for including a 2 axis tracking in the system.

A CPV system uses optical elements to concentrate solar radiation on the PV panel, reducing the area of the module, which is the most expensive component. In this mater,

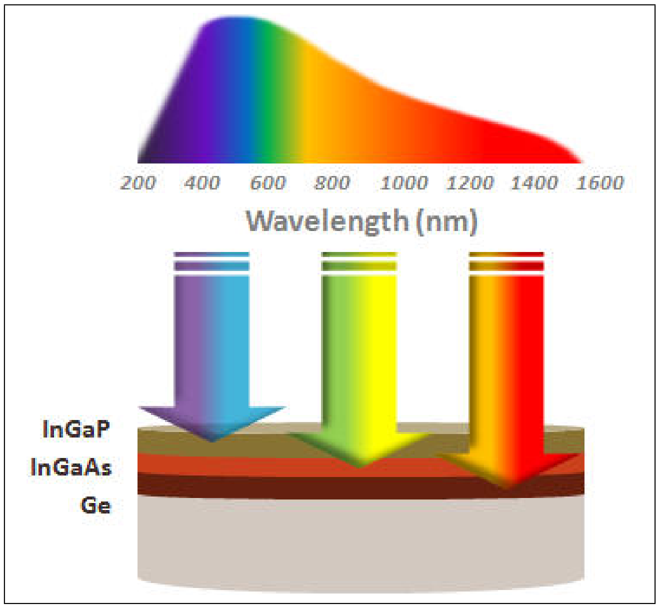


FIGURE 3.8. Multi-junction Cell Spectrum Absorption (US DOE, 2010)

there are three types of CPV systems defined by the capacity of multiplying intensity of sunrays (suns).

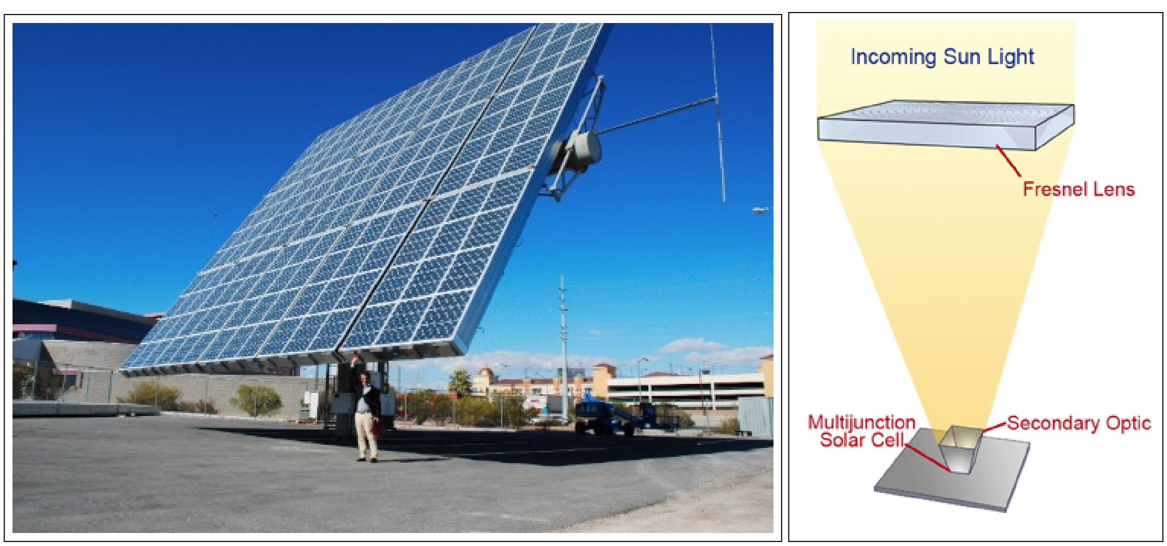
(i) **Low Concentration CPV** have a 2-100 suns concentration and a crystalline silicon cell mainly is used. Cooling and tracking are not necessary, but it would increase the output energy of the system.

(ii) **Medium Concentration CPV** have 100 to 300 suns concentration and require solar tracking and cooling.

(iii) **High Concentration CPV** ***(HCPV)*** have 300 or more suns concentration and a multi-junction PV cell is used.
The concentration can be perform principally by two methods: one based on lenses and another based on curved mirrors. An advantage of using lenses to concentrate is that the cell is located at the back of the panel, and if technology changes, it could be replaced easily. On the other hand, using curved mirrors the cell is located at the focus point of the parabola (similar to the stirling system),

where changing the technology could be a tedious process.

FIGURE 3.9. SolFocus HCPV Curved Mirror System (Solfocus, 2007)



(A) Amonix HCPV System (B) Lens System

FIGURE 3.10. Amonix HCPV Lens System (Amonix, 2008)

4. TECHNOLOGIES COST INFORMATION

4.1. Source of Information

In this study, six main sources of information will be used for the estimation of the cost of different technologies.

(i) The first source is the National Renewable Energy Laboratory (NREL), which has the information of the operational, under construction and under development concentrating solar power projects for thermal technologies.

(ii) The second source is the Ranking Solar website, which has the information of operational photovoltaics projects.

(iii) The third source is the *U.S. Department of Energy's (DOE) Office of Solar Energy Technologies Multi-Year Program Plan, 2007-2011 & 2008-2012 and Price, Margolis, 2010*, which data is used on Solar Advisor Model (SAM) software for the financial results of the solar energy power plant simulation.

(iv) The fourth source is the *California Energy Commission*, where power plant owners have to fill in an Application for Certification (AFC). Currently there are several applications under review, including solar trough, solar tower, stirling engine and fresnel projects.

(v) The fifth source is different project proposals made by companies that sell or operate solar power plants of photovoltaic manufactures. For the confidentiality agreement with those companies, their name will not be included.

(vi) The sixth source is the *International Energy Agency Technology Roadmap for Concentrating Solar Power and Solar Photovoltaic Energy, 2010*, which information is shown in ranges of values depending on different factors.

4.2. Investment Cost And Variable Energy Production Cost

In this research, a linear multiple regression was run to determine the most significant variables that affect the investment and variable cost. The information used for the regressions is shown in Appendix A on Tables A.1, A.2, A.3 and A.4.

The information in this chapter is representative for showing how the investment cost is divided and presenting cost information from different literature not included in the regression data because not all the studied variables were available.

4.2.1. Parabolic Trough

Investment Cost together with technical information of the installed SEGS plants in California are displayed on Table 4.1.

TABLE 4.1. Technical Data for Parabolic Trough SEGS Plants in California (German Solar Energy Society, 2005)

Plan	I	II	III	IV	V	VI	VII	VIII	IX
Yeah of commissioning	1984	1985	1986	1986	1986	1988	1988	1989	1990
Net capacity (MW)	13.8	30	30	30	30	30	30	80	80
Land use (1000m^2)	290	660	800	800	860	660	680	1620	1690
Aperture (1000m^2)	83	165	233	233	251	188	194	464	484
HTF outlet temp. ($^{\circ}C$)	306	321	349	349	349	391	391	391	391
Efficiency									
- Steam turbine (solar)	31.5	29.4	30.6	30.6	30.6	36.6	36.6	36.6	36.6
- Steam turbine (gas)	-	36.3	36.3	36.3	36.3	39.5	39.5	36.6	36.6
- Solar field (thermal)	35	43	43	43	43	43	43	53	50
- Solar-to-electric (net)	9.3	10.6	10.2	10.2	10.2	12.4	12.3	14.0	13.6
Investment Cost (US$/W)	4.49	3.2	3.6	3.63	4.13	3.86	3.86	2.89	3.44

Cost information for installing a 200MW parabolic trough system with 7 hours of storage is shown on Tables 4.2, 4.3, 4.4 and 4.5. It was obtained from SAM simulation software, which uses data from DOE Office of Solar Energy Technologies Multi-Year Program Plan, 2007-2011. The software calculates the cost of the systems using different variables specified by the user. This simulations uses a maximum direct normal radiation of 1100 W/m^2, maximum temperature of 27$^\circ C$ to calculate the size of the solar field.

TABLE 4.2. Direct Capital Cost: 200MW Parabolic Trough

Item	Value	Unit	Cost per Unit	Total Cost
Site Improvements	1,424,730	m^2	20.00 \$/m^2	\$28,494,536
Solar Field	1,424,730	m^2	350.00 \$/m^2	\$498,654,387
HTF System	1,424,730	m^2	50.00 \$/m^2	\$71,236,341
Storage	3710	MWht	70.00 \$/kWht	\$259,671,436
Fossil Backup	200	MW_e	0 $\$/kW_e$	\$0
Power Plant	200	MW_e	880 $\$/kW_e$	\$176,000,000
Contingency	10%			\$103,405,670
Total Direct Capital Cost				\$1,137,462,371

TABLE 4.3. Indirect Capital Cost: 200MW Parabolic Trough

Item	Direct Cost %	Non-fixed Cost	Fixed Cost	Total Cost
Engineer, Procure, Construct	15%	\$170,619,356	\$0.00	\$170,619,356
Project, Land, Management	3.5%	\$39,811,183	\$0.00	\$39,811,183
Sales Tax of	7.75%	Applies to 80%	of Direct Cost	\$70,522,667
Total Indirect Cost				\$280,953,206

TABLE 4.4. Total Capital Cost: 200MW Parabolic Trough

Total Installed Cost	\$1,418,418,576
Total Installed Cost per Capacity	7.8 \$/W

TABLE 4.5. Operation and Maintenance Costs: 200MW Parabolic Trough

Fixed Cost by Capacity	80.00 $/kW-yr
Variable Cost by Generation	3.00 $/MWh

There are several parabolic trough projects submitted to the California Energy Commission[1] and all of them agree with the same installed capital cost of 4 $/W. The main difference is that Solar Millennium power plants use air-cooled cycle using approximately 5.86 liters per second of water on a 250MW power plant.

The big difference in cost can be explained because all the projects submitted to the California Energy Commission don't include energy storage.

The International Energy Agency (IEA, 2010a) establishes an investment cost range of USD 4.2/W to USD 8.4/W depending on storage capacity, size of solar field, labor and land costs, technologies and the DNI. Investment cost per watt are expected to decrease by 12% if we move from a plant of 50MW to a 100MW parabolic trough plant (IEA, 2010a). Figure 4.1 shows the percentages of the investment cost for a parabolic trough solar power plant.

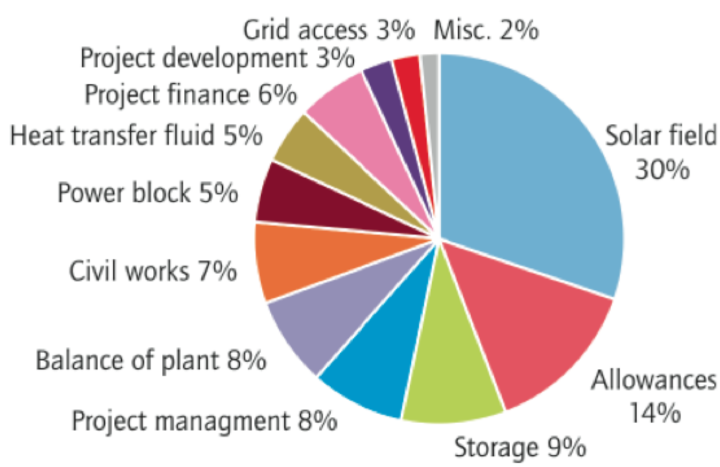


FIGURE 4.1. Percentages of investment cost of a 50MW trough plant with 7-hour storage (IEA, 2010a)

[1]Beacon Solar Energy Project, Abengoa Mojave Solar Project, Solar Millennium Blythe, Solar Millennium Ridecrest and Next Era Energy Resources Genesis Solar

Also, an operation and maintenance cost of 13 USD/MWh to 30 USD/MWh is estimated, where the highest value is including fuel cost for backup (IEA, 2010a).

4.2.2. Linear Fresnel Reflector

Ausra CA II, LLC proposed to build the Carrizo Energy Solar Farm, a 177 MW plant, using 195 compact linear fresnel reflectors, solar concentrating lines, steam turbine generators and air-cooled condensers. Its AFC stated a total capital cost of $500 MM USD, but the application was withdrawn and the committee cancelled the proceedings.

No other source was found for obtaining information for a detailed estimation of the cost of this solar technology.

4.2.3. Solar Power Tower

Capital cost information for installing a 200MW Solar Power Tower system with 7 hours of energy storage in USA, shown on Tables 4.6, 4.7, 4.8 and 4.9 was obtained from SAM simulation software, which uses data from DOE Office of Solar Energy Technologies Multi-Year Program Plan, 2007-2011.

TABLE 4.6. Direct Capital Cost: 200MW Solar Tower

Item	Value	Unit	Cost per Unit	Total Cost
Site Improvements	1,867,921	m^2	20 $\$/m^2$	$37,358,423
Heliostat Field	1,867,921	m^2	201 $\$/m^2$	$375,452,154
Storage System	3,294	MWht	30 $/kWht	$98,823,529
Balance of Plant	200	MW_e	345 $\$/kW_e$	$69,000,000
Power Block	200	MW_e	575 $\$/kW_e$	$115,000,000
Total Tower Cost				$21,803,076
Total Receiver Cost				$57,730,202
Contingency	10%			$77,513,738
Total Direct Capital Cost				$852,684,123

Ivanpah Solar, a 400 MW of capacity solar tower project, was submitted to the California Energy Commission on August of 2007 and the application for certification (AFC)

TABLE 4.7. Indirect Capital Cost: 200MW Solar Tower

Item	Direct Cost %	Non-fixed Cost	Fixed Cost	Total Cost
Engineer, Procure, Construct	15%	$127,902,618	$0.00	$127,902,618
Project, Land, Management	3.5%	$29,843,944	$0.00	$29,843,944
Sales Tax of	7.75%	Applies to 80%	of Direct Cost	$52,866,416
Total Indirect Cost				$210,612,978

TABLE 4.8. Total Capital Cost: 200MW Solar Tower

Total Installed Cost	$1,063,297,102
Total Installed Cost per Capacity	5.848 $/W

TABLE 4.9. Operation and Maintenance Costs: 200MW Solar Tower

Fixed Cost by Capacity	80.00 $/kW-yr
Variable Cost by Generation	3.00 $/MWh

stated a capital cost of $1,100 MM USD (2.75 $/W) and a O&M Cost of 4.16 $/MWh. It is important to note that this project doesn't include energy storage.

Rice Solar, a 150 MW energy project, was submitted to the California Energy Commission on October of 2009 and the AFC stated a capital cost of 5.3 $/W and a O&M Cost of 9.1 $/MWh which includes 7 hours of energy storage.

The International Energy Agency (IEA, 2010a) estimate a higher cost than parabolic trough but they could fall by 40% to 75% as the solar industry matures compared to 30% to 40% in parabolic trough in the next decade.

4.2.4. Stirling Solar Dish

Capital cost information for installing a 200MW stirling solar dish system in USA, shown on Tables 4.10, 4.11, 4.12 and 4.13 was obtained from SAM simulation software, which uses data from DOE Office of Solar Energy Technologies Multi-Year Program Plan, 2007-2011.

TABLE 4.10. Direct Capital Cost: 200MW Stirling Dish

Item	Value	Unit	Cost per Unit	Total Cost
Site Improvements	1,800,000	m^2	3 $/m^2	$5,400,000
Collector Cost (Projected Area)	87.7	$m^2/unit$	400.00 $/m^2	$280,640,000
Receiver Cost	25	kW/unit	250 $/kW	$50,000,000
Engine Cost	25	kW/unit	500 $/kW	$100,000,000
Contingency	10%			$479,644,000
Total Direct Capital Cost				$479,644,000

TABLE 4.11. Indirect Capital Cost: 200MW Stirling Dish

Item	Direct Cost %	Non-fixed Cost	Fixed Cost	Total Cost
Engineer, Procure, Construct	16%	$76,743,040	$0.00	$76,743,040
Project, Land, Management	3.5%	$16,787,540	$0.00	$16,787,540
Sales Tax of	7.75%	Applies to 80%	of Direct Cost	$29,737,928
Total Indirect Cost				$123,268,508

TABLE 4.12. Total Capital Cost: 200MW Stirling Dish

Total Installed Cost	$602,912,508
Total Installed Cost per Capacity	3.015 $/W

TABLE 4.13. Operation and Maintenance Costs: 200MW Stirling Dish

Fixed Cost by Capacity	50.00 $/kW-yr
Variable Cost by Generation	0.70 $/MWh

SES Solar TWO, a 750 MW of capacity stirling dish project, was submitted to the California Energy Commission on June of 2008 and the application for certification (AFC) stated a capital cost of $1,150 MM USD and a O&M Cost of 8.95 $/MWh.

4.2.5. Photovoltaics

The International Energy Agency (IEA) established a investment cost of 4 USD/W for a utility scale and 6 USD/W for a small-scale in 2008. For 2009, the best system price reported in IEA countries was 3 USD/W (IEA, 2010b).

Cost information for PV technology are project proposals for 1MW solar plant made from different manufacturing and supplying companies.

TABLE 4.14. Capital Cost:1 MW_{ac} *Mono-Si* PV 1 Axis Tracking

Item	Total Value
System	
PV Panel	$2,509,000
Inverter	$242,000
1 Axis Tracker	$368,000
Combiner Boxes	$14,000
Monitoring	$18,000
Installation	
Posts	$251,000
Concrete	$2,000
Cables, Conductors	$201,000
Labor Hours	$950,000
Site Work	$40,000
International Engineer	$50,000
Supervision	$150,000
Contingencies	$200.000
Total Cost	$4,995,000

Table 4.16 shows the total capital cost for a Thin Film a-Si photovoltaic plant in Chile. This values include shipping, local labor, local materials, site work and all the other costs.

4.2.6. Concentrating Photovoltaics

For estimating the cost of installing Concentrating Photovoltaics technology, two sources where used: a proposal from a supplying company and the document DOE Office of Solar Energy Technologies Multi-Year Program Plan, 2008-2012. Both agree that the capital cost of a HCCPV system with 2 axis tracking is in the range of 7.5→8 $/W.

TABLE 4.15. Capital Cost:1 MW_{dc} *Mono-Si* PV

Item	Total Value
Solar Module	$2,152,000
Solar Array Bracket	$335,000
Wire Boxes	$44,000
Inverter	$320,000
Monitoring	$8,000
Cables	$254,000
Accessory equipment	$294,000
Investment Cost	$603,000
Contingencies	$200,000
Total Cost	$4,210,000

TABLE 4.16. Capital Cost:1 MW_{ac} *a-Si* Thin Film PV in Chile

Item	Total Value
Solar Module	$1,656,000
Inverter	$229,000
Monitoring	$60,000
Electric Components	$30,000
Shipping	$89,000
Installation	$1,267,000
Other	$95,000
Contingencies	$63,000
Terrain	$55,000
Total Cost	$3,544,000

4.3. Future Costs: Dynamic Analysis

All the literature agrees that the cost of solar power will go down on time. In this section, *IEA Technology Roadmap 2010* and *DOE Solar Energy Technologies Program Multi-Year Program Plan: 2008-2012* will be used for explaining the different costs of the solar energy technologies.

Figure 4.2 shows the projected evolution of the levelized electricity cost from CSP plants, in USD/MWh, under two different DNI levels in kWh/m2/y. The levelized cost for high DNI zones, such as the north of Chile, would be 100 USD/MWh in 2020 and 55 USD/MWh in 2030 (IEA, 2010a).

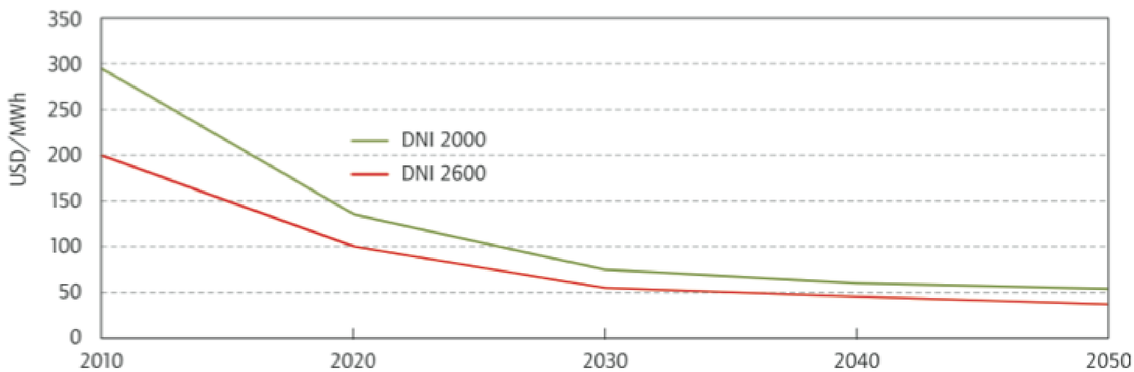


FIGURE 4.2. Future Levelized Cost for CSP Technology (IEA, 2010a)

Figure 4.3 shows the projected evolution of the levelized electricity cost from PV utility plants and from PV residential installations. The levelized cost for high radiation zones, such as the north of Chile, would be around 130 USD/MWh in 2015, 100 USD/MWh in 2020 and 70 USD/MWh in 2030 (IEA, 2010b).

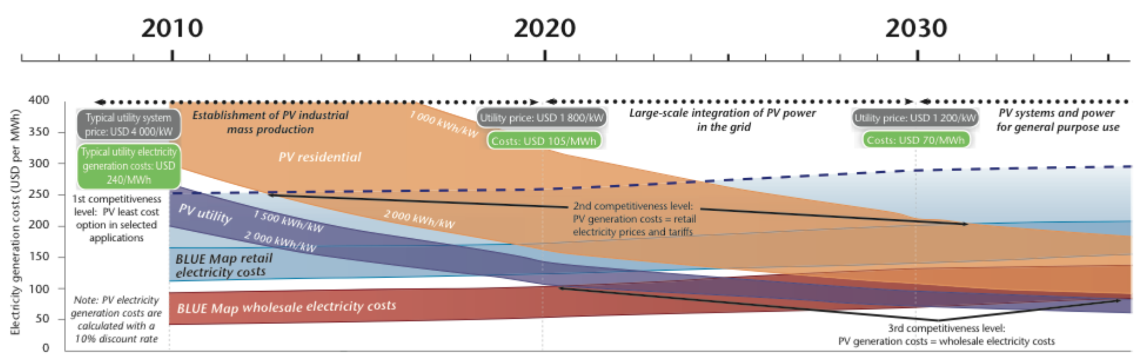


FIGURE 4.3. Future Levelized Cost for PV Technology (IEA, 2010b)

Figure 4.4 shows the projected evolution of the investment cost for different solar technologies, although it doesn’t include all the solar technologies, it agrees that the cost will go down and includes CPV technology which was not studied by the IEA.

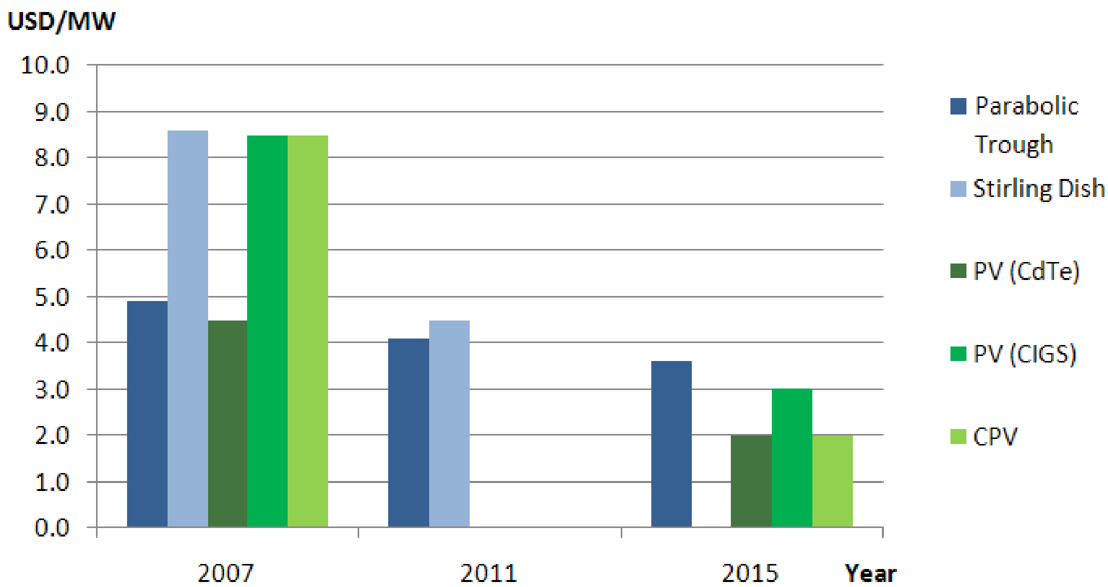


FIGURE 4.4. Future Investment Cost for Solar Technologies (DOE, 2008)

5. ENERGY STORAGE TECHNOLOGIES AND COST ANALYSIS

5.1. Energy Storage Technologies

Since the sun is an unpredictable source of energy and fluctuates independently from demand of electric energy, storage systems are be needed to assure power capacity and network load stability.

The main idea behind energy storage is to utilize the energy that was produced at a very reduced cost, in a period of low demand, and utilized at peak demand when the energy has a higher price.

Several techniques are used for energy storage: mechanical, chemical and thermal on which they can be divided into two categories (Ibrahim, Ilinca, Perron, 2008):

(i) **Small-scale systems** can store as kinetic energy (flywheel), chemical energy, compressed air, hydrogen (fuel cells), or in supercapacitors or superconductors.

(ii) **Large-scale systems** can store as gravitational energy (hydraulic systems), thermal energy (sensible, latent), chemical energy (accumulators, flow batteries), or compressed air.

5.1.1. Pumped Hydro

Pumped hydro storage is a fully matured technology. It uses electricity from the grid when the demand is low and pump the water from a lower reservoir to a upper one. When the demand is high, the water flow to activate the turbines generating electricity when the selling price is higher and store the water in the lower reservoir (Figure 5.1).

This cycle has a efficiency of 75% average and about 65-80%, depending on the system used (Multon Rouer, Stocker 2003).

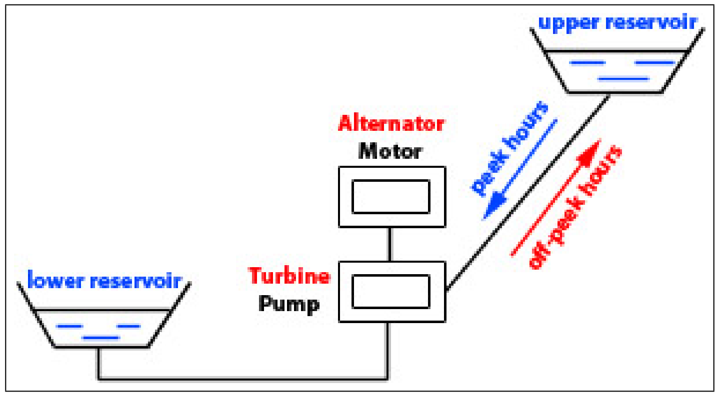


FIGURE 5.1. Pumped Hydro Storage System

5.1.2. Thermal

There are two types of thermal energy storage systems, one uses sensible heat and the other latent heat (Gil, Medrano, Martorell, et al., 2010).

(i) **Latent-fusion-heat thermal storage** uses the transition of the liquid-solid state of a material at a constant temperature. The system uses a heat-transfer fluid that makes the thermal connection between the accumulator and the exterior environment.

(ii) **Sensible heat thermal storage** heats a bulk material such as sodium, molten salt and pressurized water maintaining its state. Heat produces water vapor that drives a turbo-alternator system.

Most of the operating thermal solar plants that include storage use sensible heat (Figure 3.1) and they can produce energy up to 7 hours after the sunset.

Figure 5.2 shows a technology called high-temperature sensible heat storage with turbine. It is estimated that investment cost of this technology are among the lowest, but it has not been fully developed.

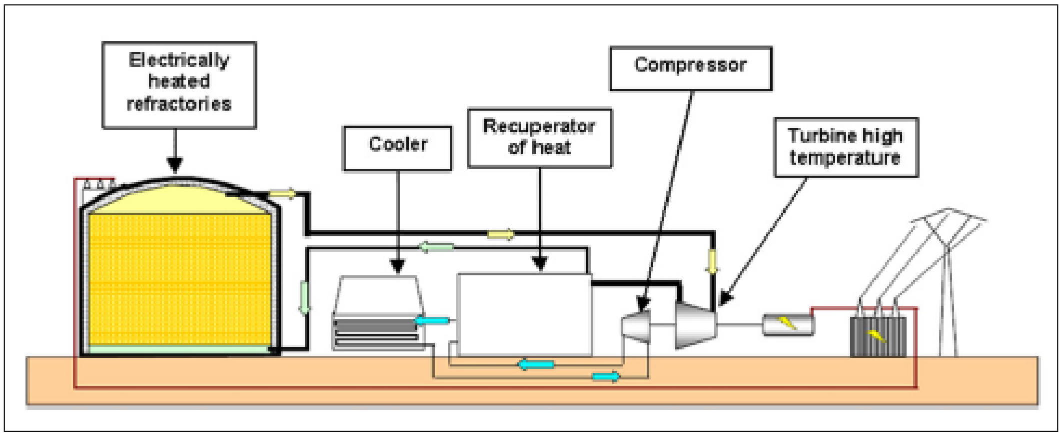


FIGURE 5.2. High-temperature heat storage with turbine (Ibrahim et al., 2008)

5.1.3. Compressed Air (CAES)

Similar to pumped hydro, compressed air energy storage technology uses electrical power during off-peak hours to compress the air, and during peak hours the air expands in a combustion chamber before feeding it into the turbines (Figure 5.3). This technology has an estimated efficiency of around 70% (Robyns, 2005).

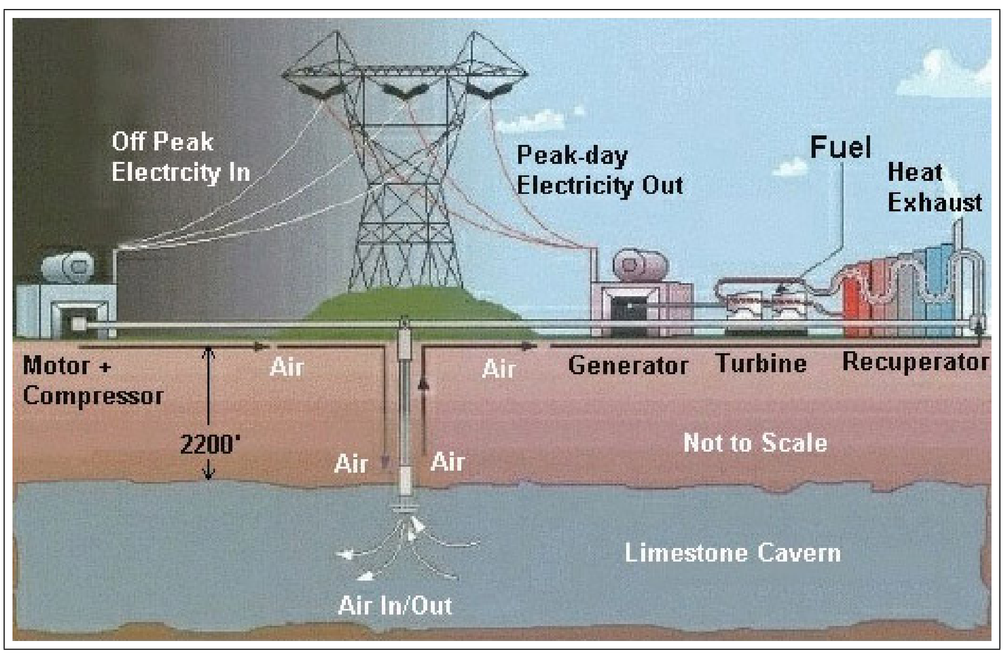


FIGURE 5.3. Compressed Air Energy Storage (Ibrahim et al., 2008)

It is important to know that two-thirds of power used from fuel to drive a standard gas turbine, is used to compress the combustion air. Therefore, with the air already compressed, the power produced would be three times more with the same fuel consumption (Ibrahim et al., 2008).

Compressed air storage in a high pressure cylinders is used for small and medium scale application. This technology uses an electric compressor that can be turned into a generator during retrieval of the air, and the overall process has an overall efficiency of 50% (Ibrahim et al., 2008).

5.1.4. Flow Batteries

Flow batteries energy storage technology is a two-electrolyte system that each electrolyte flows through the same chemical compound (Figure 5.4).

In England there is an operating flow battery system of a storage capacity of 15MW-120MWh and has a overall efficiency of 75%(Ibrahim et al., 2008).

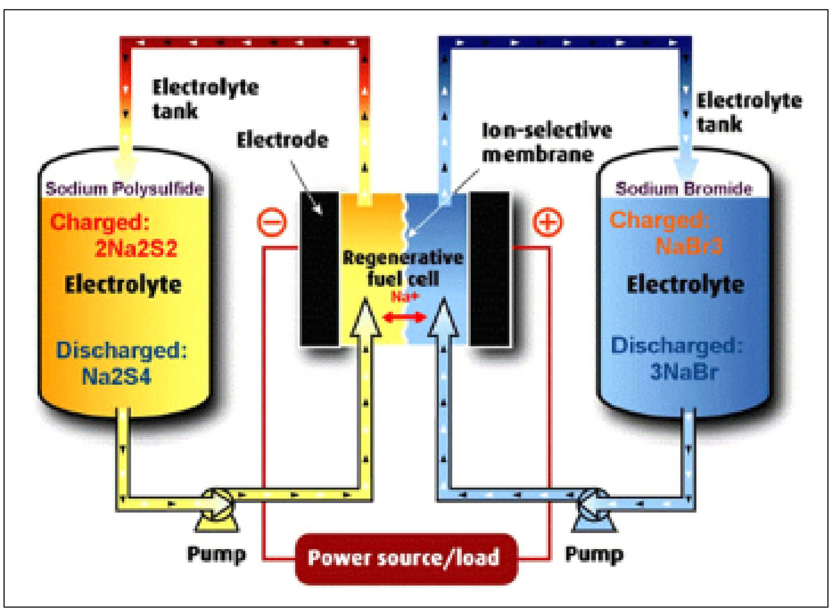


FIGURE 5.4. Flowbattery type FSB (Polysulfide Bromide Battery) (Ibrahim et al., 2008)

5.1.5. Fuel Cells-Hydrogen

Fuel cells-Hydrogen energy storage uses electrical power during off-peak hours to produce water electrolysis. Separating hydrogen and oxygen, the system has a buffer tank of hydrogen that goes to the fuel cell and mixes it with oxygen from air to generate peak-hour electricity (Figure 5.5).

Alkaline Fuel Cell (AFC), Polymer Exchange Membrane Fuel Cell (PEMFC), Direct Methanol Fuel Cell (DMFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC) are some of the many types of fuel cells.

This technology is used for low-power stations with a storage capacity of around 100kW and a low efficiency of 35%(Ibrahim et al., 2008).

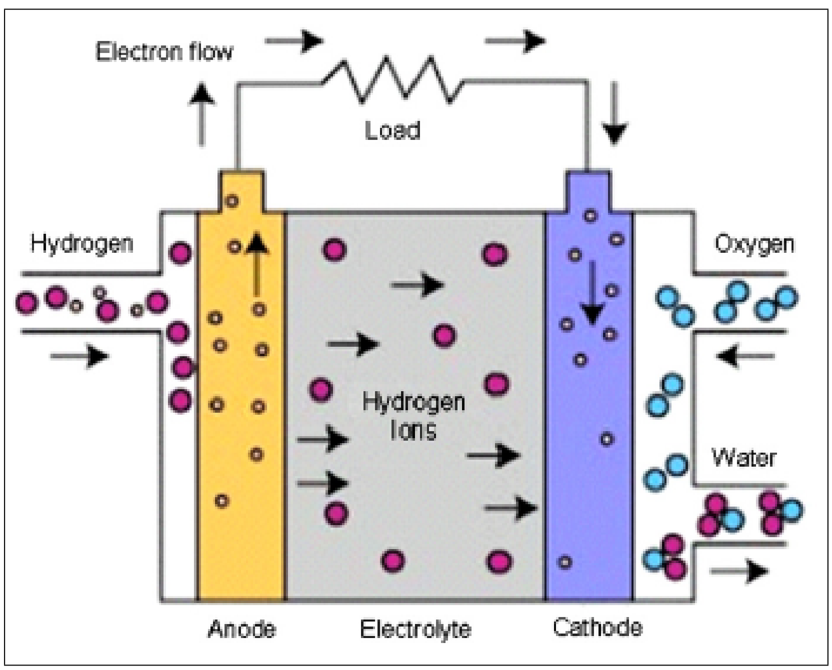


FIGURE 5.5. Fuel Cells-Hydrogen Energy Storage (Ibrahim et al., 2008)

5.1.6. Chemical

Chemical storage is achieved through a wide range of accumulator materials. Figure 5.6 shows the energy and power densities of the different materials used for energy storage.

The main advantages of these systems is that they have the possibility of alternating the charge-discharge phases requiring little maintenance, noise free and have a efficiency of 90 to 95%. The main inconvenient is that they have low durability for large-scale applications, regularly 100 to 1000 charging-discharging cycles (Ibrahim et al., 2008).

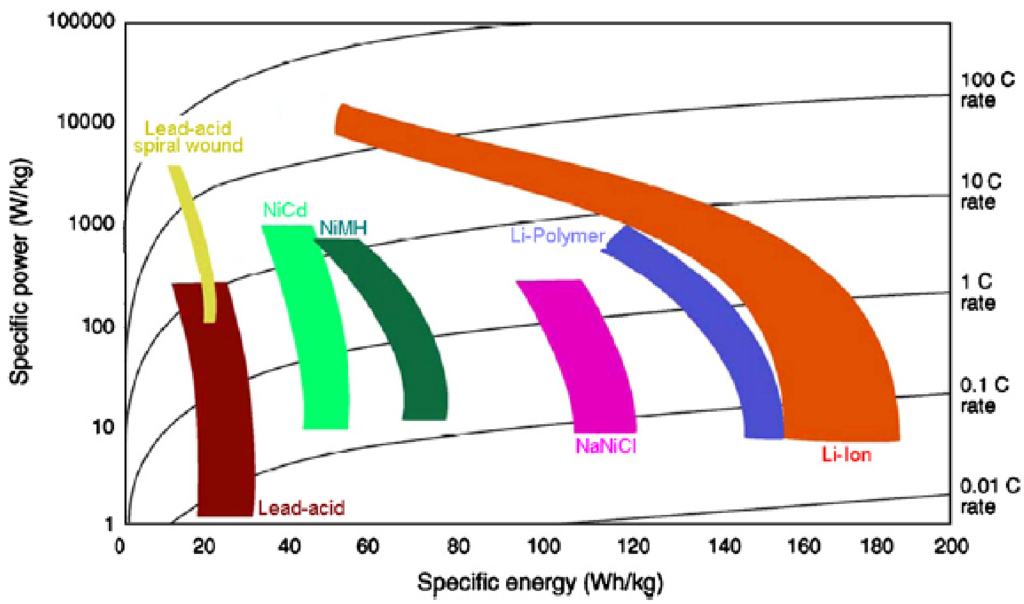


FIGURE 5.6. Different Electrochemical accumulators according to their energy densities and power (Ibrahim et al., 2008)

5.1.7. Flywheel

Flywheel systems consist of a motor-alternator that uses electric energy during off-peek hours to accelerate a heavy rotating disk. The rotating disk stores the kinetic energy that would produce energy on peek hours (Figure 5.7). For a higher efficiency and longer storage time, friction must be kept to a minimum level.

These systems have a efficiency that starts from 85%, dropping to 78% after 5 hours and to 45% after a day of using continuously the stored energy. They are capable of storing up to 1MW that can be released within 1 hour.

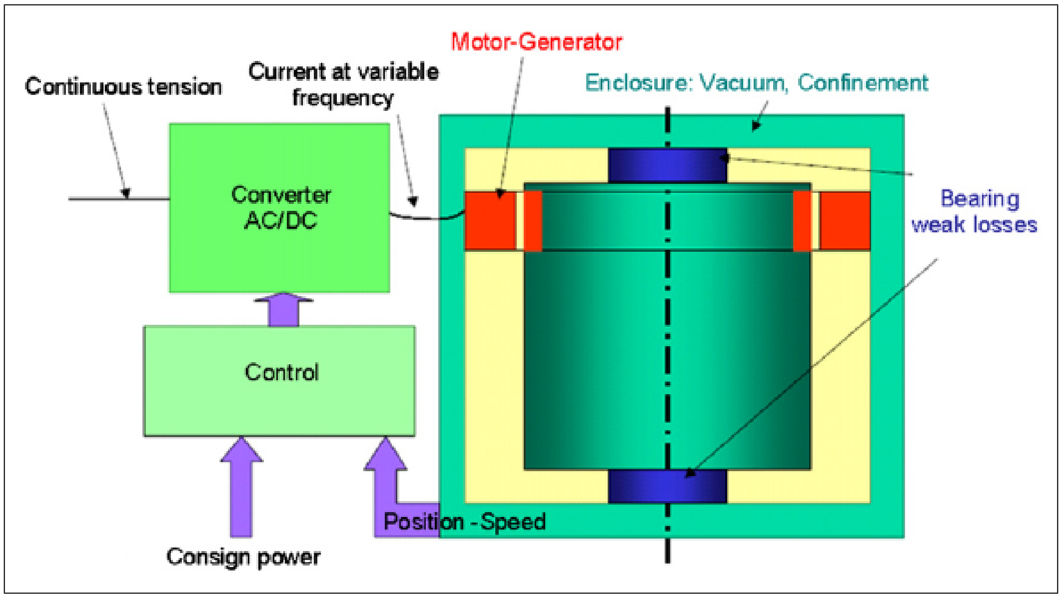


FIGURE 5.7. Flywheel Energy Storage System (Ibrahim et al., 2008)

5.1.8. Superconducting magnetic (SMES)

Superconducting Magnetic Energy Storage systems, use magnetic fields originated by inducing a direct current flow into a coil that has been cooled to achieve its superconducting critical temperature.

While charging the current increases until it is fully charged and the magnetic energy can be stored indefinitely. As well, these systems are highly efficient (greater then 95% (Cheung et al., 2003)), capable of discharging the near totality of the stored energy and have a fast response time.

The main disadvantages are that they are very costly and large coils are needed for large project applications (100m diameter for 10,000 MWh of energy (Ibrahim et al., 2008)).

5.1.9. Supercapacitors

Energy is stored in supercapacitors in form of an electric field between two electrodes. Energy obtained can be up to 15Wh/kg and a power of up to 2000W/kg. The main disadvantages are that they are very costly and the operational voltage is very low (from 2.5 to

3V). Supercapacitors are serial connected to reach voltages for power applications with a regular capacity of 100kW (Figure 5.8).

They main advantage of supercapacitors is that they have a life time of 8 to 10 years and an efficiency of 95%. On the other hand, the stored energy must be used quickly because it has a 5% self-discharge per day.

FIGURE 5.8. Supercapacitors assembled in series (Ibrahim et al., 2008)

5.2. Technical and Cost Comparison of the Different Energy Storage Technologies

It is important that the technology chosen for energy storage is adapted for the type of use that is needed. Depending on the power output capacity, energy stored, discharge time, efficiency and cost, a certain technology will be chosen.

Figure 5.9 doesn't include thermal technology, mostly used in solar applications, but it shows an idea of the technologies that might be suitable for our application.

For large-scale application, technologies can be classified into three main operational categories (Figure 5.10)(Ibrahim et al., 2008):

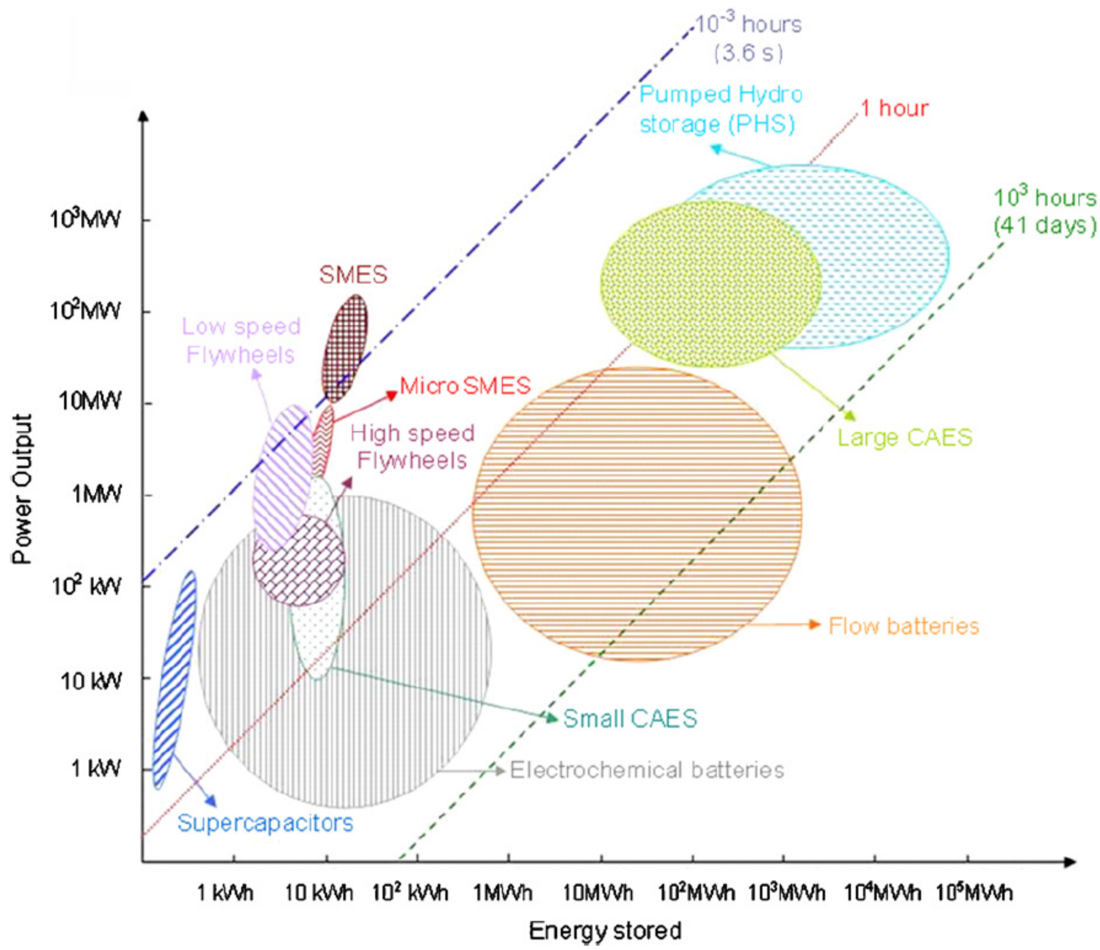


FIGURE 5.9. Energy Storage and Power Output for the Different Technologies (Ibrahim et al., 2008)

(i) **Power quality required:** Where the stored energy is used for a few seconds to ensure the quality of power delivered.

(ii) **Buffer and emergency storage:** Where the stored energy is used for a seconds to minutes to ensure service continuity when sources of electricity change.

(iii) **Network management:** Where the stored energy is used to decouple synchronization between generation and consumption.

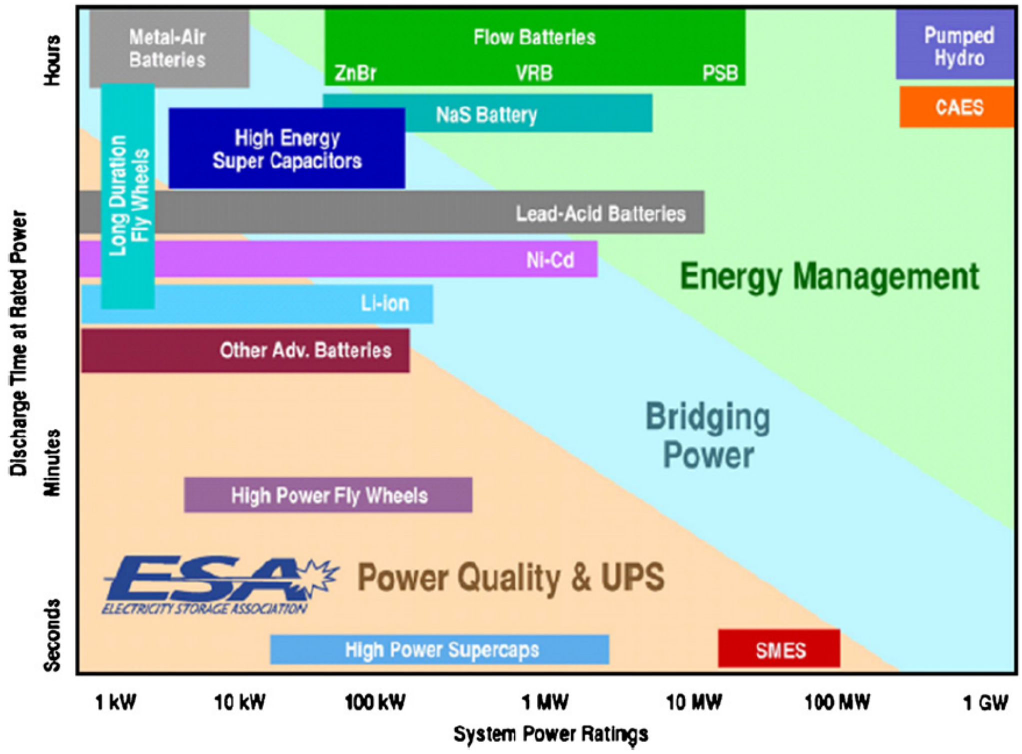


FIGURE 5.10. Distribution of Storage Technologies as a Function of Their Field of Application (Ibrahim et al., 2008)

Capital cost per installed capacity and capital cost per energy is shown on Figure 5.11. These cost change depending the type and size of the storage. The information shown should only be used as a guide, detailed data is shown on Figure 5.12.

The cost for battery storage is adjusted to exclude the cost of power electronics conversion. The capital cost per energy is divided by the storage efficiency so the cost of useful energy is shown.

The round trip efficiency (electric-storage-electric) of the different technologies together with their capital cost, is summarized on Figure 5.13.

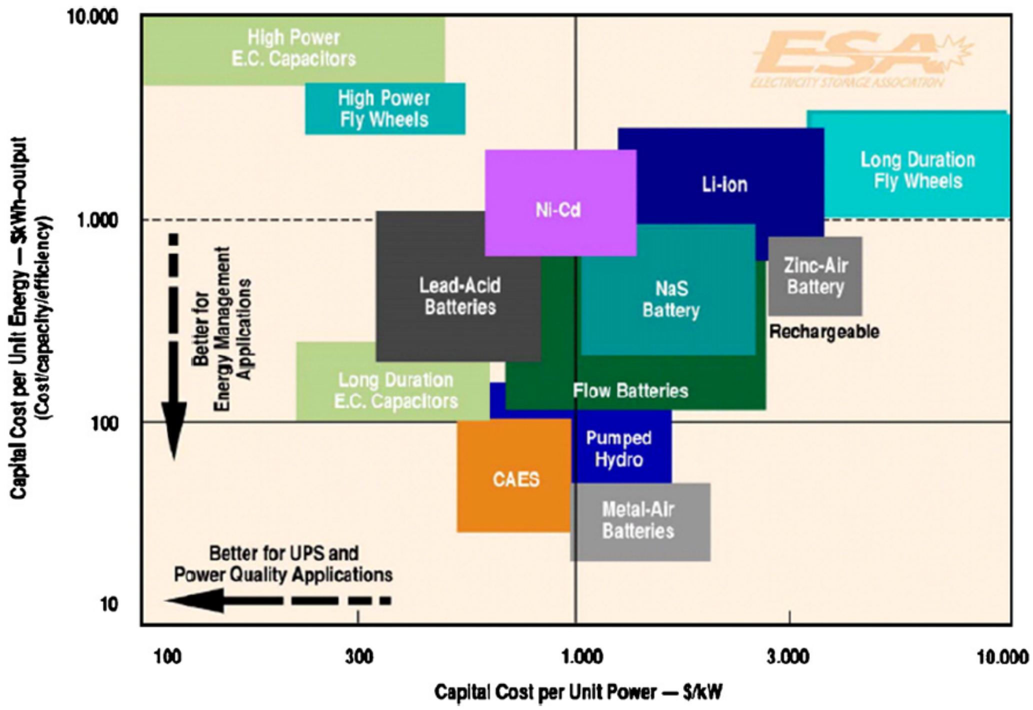


FIGURE 5.11. Investment Costs per Unit and Power or Unit of Energy for Different Storage Technologies (Ibrahim et al., 2008)

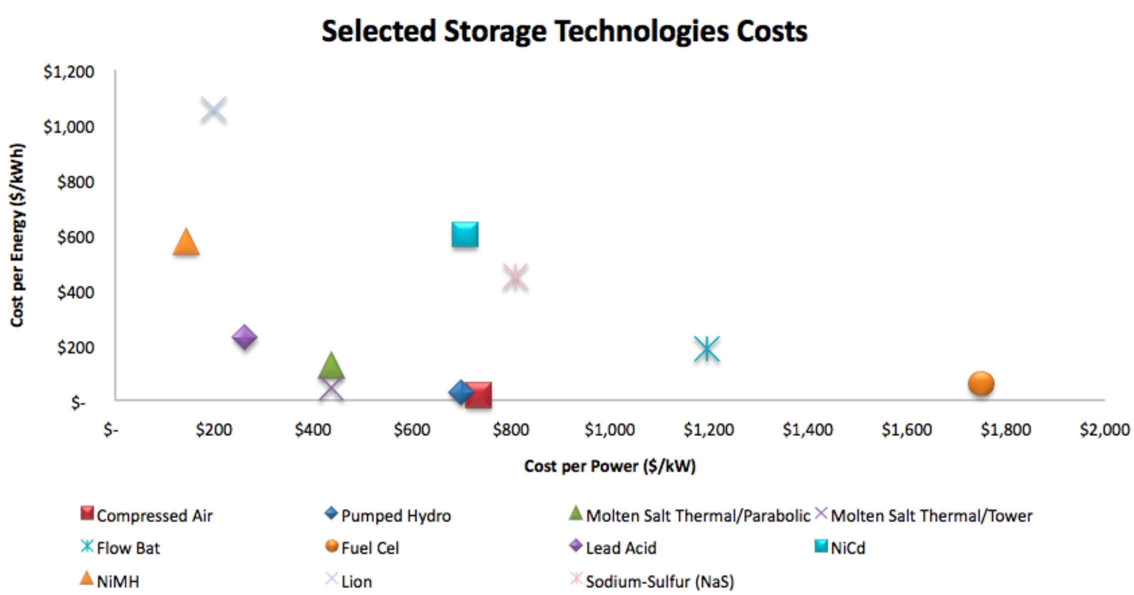


FIGURE 5.12. Investment Costs per Unit of Power or Unit of Energy for Different Storage Technologies (Tom Konrad, Alt Energy Stocks, 2009)

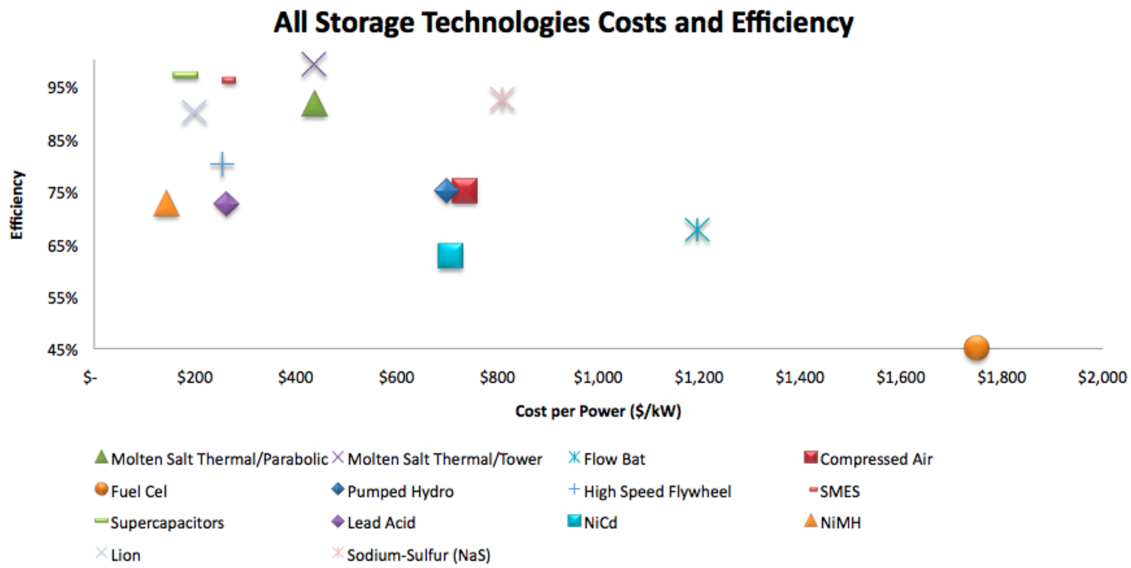


FIGURE 5.13. Investment Costs per Unit of Power and Efficiency for Different Storage Technologies (Tom Konrad, Alt Energy Stocks, 2009)

5.3. Benefits and effects of Energy Storage

All the technologies mentioned above store energy during off-peak periods and use or discharge it during on-peak time. The benefits of energy storage rely on smoothing the load pattern by lowering on-peak and increasing off-peak generation loads. This will produce a similar smoothing of on- and off-peak prices (Sioshansi, 2010).

Sioshansi (2010) verifies that the use of the storage energy depends on the agent that owns the facility. It studies three different possible owners: a merchant storage operator, electricity consumers and generators, and finds that the merchant operators and generators will underuse and consumers will overuse storage compared to the social optimum.

Sioshansi (2010) concludes that “for most reasonable storage device efficiencies merchant ownership of storage is welfare-maximizing compared to the alternatives of consumer or generator ownership. When storage assets can be divided amongst agent types the socially optimal allocation of storage favors merchants, although some consumer ownership of storage can be beneficial since their overuse of storage can compensate for underuse by merchants. In another case, if storage is owned by a municipality, cooperative, or integrated utility, which owns generation assets and serves native loads, may result in more socially optimal storage use since these entities would be concerned with both producer and consumer surplus changes”.

6. ECONOMETRIC ANALYSIS

6.1. Determining an investment cost function

A total of 45 thermal solar plants and 37 photovoltaics solar parks were studied for determining an investment cost function for the different technologies of solar power generation. Different variables were chosen and studied to determine the significance of them on the investment cost of the plants. Because the variables that mostly explain the investment cost of thermal and photovoltaics are different, the analysis was separated in two regression models: thermal and photovoltaics.

Of the total of 45 thermal solar plants, 15 are currently on operation, 14 are on construction and 16 are proposed projects. All the photovoltaics solar parks studied are currently on operation with the exception of *Calama Solar One* that is a proposed project in Chile.

6.1.1. Studied variables

The studied variables (the ones for which data were recopilated) of the thermal solar parks are: total installed cost, technology, power capacity, storage capacity, installed country, year of commissioning, mirror solar field, electricity generation, capacity factor, total plant area and radiation. On the other hand, for photovoltaics solar parks the studied variables are total installed cost, technology, power capacity, installed country, year of commissioning, total plant area, electricity generation, capacity factor and radiation.

With these variables, a linear multiple regression was run, for thermal and photovoltaics separately, to determine the main explanatory variables and coefficients that determine the total investment or installed cost of a solar power plant.

6.1.2. Thermal solar power plants regression model

Several regressions were formulated with different combinations of the variables mentioned in *6.1.1*. The model described in this section is the one that mostly explained the data and had the highest statistical significance levels.

It was found that the main explanatory variables for thermal solar plants are: Capacity, technology, total area, storage capacity and installed country. These were used to formulate a multivariable linear regression, which results are shown on Tables 6.2, 6.3 and 6.4.

Table 6.2 shows the variance of the model and the residual. **SS** are the Sum of Squares associated with the three sources of variance, Total, Model and Residual; **DF** is the degrees of freedom associated with the sources of variance and **MS** is the Mean Squares, the Sum of Squares divided by their respective DF.

Table 6.3 shows overall information about the model estimation; **F(x,y)** is the F-statistic corresponding to the Mean Square Model divided by the Mean Square Residual, and the numbers in parentheses are the Model and Residual degrees of freedom taken from the ANOVA table; **Prob** $>$ **F** is the p-value associated with the above F-statistic. It is used in testing the null hypothesis that all of the model coefficients are 0; **R-Squared** is the proportion of variance in the dependent variable (Installed Cost) which can be explained by the independent variables chosen in the model, this is an overall measure of the strength of association; **Adjusted R-squared** penalizes the addition of extraneous predictors to the model; and **Root MSE** is the standard deviation of the error term.

Table 6.4 shows the estimated parameters of the multiple regression model, the first column are the chosen independent variables for predicting the installed cost of the solar plant; **Coefficient**, are the values for the regression equation of those variables; **Std. Err.** are the standard errors associated with the coefficients; **t** are the t-statistics used in testing whether a given coefficient is significantly different from zero; **P**$>|$**t**$|$ shows the 2-tailed p-values used in testing the null hypothesis that the coefficient (parameter) is 0, using an alpha of 0.05; and **Beta** or standardized coefficients measure the change on the dependent variables (in standard deviation) produced by a unitary change in the independent variable (in standard deviation), maintaining the rest of the variables constant. These Beta coefficients will allow us to know which independent variables have a bigger impact or more significance on explaining the model.

In our model we find that all the coefficients of the model are different from 0 and an R-Squared of 98%. In a first approach it is important to review the sign of the coefficients; in capacity, area and storage capacity we find positive coefficients, which implies that the investment cost would be higher with an increase on these variables.

The Beta column tells us that capacity of the plant is the variable that has the highest impact on explaining the model; then we have total area; then the Storage Capacity; then the installed country; and finally technology.

Equation (6.1) shows the investment cost function for thermal solar power plants in millions of US dollars depending on the capacity (in MW), area (in hectares), Storage Capacity (in hours of storage per capacity in MW), technology (parabolic trough, stirling and solar tower) and country to install (Chile, Spain, USA). It is important to consider that each coefficient has its significance level shown on Table 6.4.

Studying categorical variables, the installed country has an important correlation with the radiation and construction expenses; then this two variables are mostly explained by the country, which was included in the model.

$$InvestmentCost = \beta_0 + \beta_1 \cdot Capacity + \beta_2 \cdot Area + \beta_3 \cdot StorageCapacity + \\ + D_{Technology} + D_{Country} \tag{6.1}$$

where:

TABLE 6.1. Coefficients for Investment Cost regression

β_0	-54.75032
β_1	2.948655
β_2	0.2770259
β_3	0.2660928

$$D_{Technology} = \begin{cases} 0 & \text{if Parabolic Trough} \\ -430.7149 & \text{if Stirling Dish} \\ -198.2559 & \text{if Solar Tower} \end{cases}$$

$$D_{Country} = \begin{cases} 0 & \text{if Chile} \\ 168.0975 & \text{if Spain} \\ 57.89077 & \text{if USA} \end{cases}$$

TABLE 6.2. Anova Table for Thermal Investment Cost Regression Model

Source	SS	df	MS
Model	19,373,967.7	7	2,767,709.67
Residual	358,475.493	37	9,688.527
Total	19,732,443.2	44	448,464.618

TABLE 6.3. Overall Model Fit for Thermal Investment Cost Regression Model

Number of Observations	45
F(10,32)	285.67
Prob > F	0
R-squared	0.9818
Adjusted R-squared	0.9784
Root MSE	98.43

6.1.2.1. Correlation factors

Table 6.5 show the correlation factor for the most explanatory numerical variables. It shows the high correlation between investment cost, area and capacity. For storage capacity the results show what it is expected, that has a positive correlation with investment cost and area and very low correlation with capacity.

A partial correlation factor tells the existing degree of relationship between 2 variables after removing ,of both of them, the effects of other related variables in the regression. Table 6.6 show the partial correlation factors for the thermal cost regression model and

TABLE 6.4. Parameter Estimates for Thermal Investment Cost Regression Model

Variables	Coefficient	Std.Err	t	P>|t|	Beta
Capacity	2.948655	0.6396223	4.61	0.000	0.7634482
Storage Capacity	0.2660928	0.0652536	4.08	0.000	0.1344595
Area	0.2770259	0.1853443	1.49	0.143	0.2851702
Dummy Stirling	-430.7149	158.1715	-2.72	0.010	-0.0958781
Dummy Tower	-198.2559	45.96038	-4.31	0.000	-0.1085101
Dummy Spain	168.0975	124.9699	1.35	0.187	0.1266426
Dummy USA	57.89077	127.7035	0.45	0.653	0.0431794
Constant	-54.75032	120.0461	-0.46	0.651	.

their significance level in parenthesis. Comparing these tables with Table 6.5 we find that a big amount of the correlation between installed cost and area, was explained with other variables in the model. Because storage capacity is the multiplication between storage hours and capacity, the partial correlation with cost is higher than its normal correlation.

TABLE 6.5. Correlation Factors for Thermal Cost Regression Model

	Cost	Capacity	Area	Storage Capacity
Capacity	0.9694	1		
Area	0.9089	0.9104	1	
Storage Capacity	0.1569	-0.0053	0.2176	1

TABLE 6.6. Partial Correlation Factors for Thermal Cost Regression Model with its level of significance

	Cost	Capacity	Area	Storage Capacity
Capacity	0.9(0)	1		
Area	-0.15(0.34)	0.54(0)	1	
Storage Capacity	0.64(0)	-0.78(0)	0.5(0)	1

6.1.2.2. Discussion of the results

From all the information shown about the investment cost for a solar thermal power plant, it was found that the most important variables are capacity, area, technology, storage capacity and installed country. Chile is the less expensive country for the installation of a solar power plant. On the other hand, stirling dish systems have the lowest investment cost of all technologies, followed by Solar tower and then parabolic trough. It is important to consider that the regression had 37 parabolic trough, 7 tower and only one stirling dish plant.

It is important to emphasize that the radiation was not included in the model because installed country explains it with an R-squared of 96%, and country also explains labor work and other variables that are difficult to quantify.

6.1.3. Photovoltaics solar power plants regression model accuracy and statistical significance

It was found that the main explanatory variables for photovoltaics solar power plants are: capacity, technology, year of commissioning and installed country. These were used to formulate a multivariable linear regression which results are shown on Tables 6.8, 6.9 and 6.10.

In our model we find that all the coefficients of the model are different from zero and an R-Squared of 96.4%.

It is important to notice that the installation year has a negative coefficient that is consistent with all the cost studies, and First Solar Cadmium Telluride Thin Film is the technology that has the lowest investment cost (with a coefficient of -173 and statistically significant).

The Beta column tells us that capacity of the plant is the variable that has the highest impact on explaining the model; then we have the technology and country (if we look at the factor from Thin Film and USA; and finally we have the installation year.

Equation (6.2) shows the investment cost function for photovoltaic solar power plants in millions of US dollars depending on the capacity (in MW), year of installation, technology (Polycrystalline and Monocrystalline Silicon with different tracking and first solar cadmium telluride thin film) and country to install (Germany, Italy, Korea, Spain, USA and Chile). It is important to consider that each coefficient has its significance level shown on Table 6.10.

$$InvestmentCost = \beta_0 + \beta_1 \cdot Capacity + \beta_2 \cdot Year + D_{Technology} + D_{Country} \quad (6.2)$$

where:

TABLE 6.7. Coefficients for photovoltaics investment cost regression

β_0	29,594
β_1	8.59
β_2	-14.74

$$D_{Technology} = \begin{cases} 0 & \text{if 1-Axis Mono-crystalline Silicon} \\ -30.9 & \text{if 1-Axis Polycrystalline Silicon} \\ -21.1 & \text{if 2-Axis Polycrystalline Silicon} \\ -173.4 & \text{if First Solar Cadmium Telluride} \\ 26.8 & \text{if Mono-crystalline Silicon} \\ -38.3 & \text{if Polycrystalline Silicon} \end{cases}$$

$$D_{Country} = \begin{cases} 0 & \text{if Germany} \\ -16.2 & \text{if Italy} \\ 17.8 & \text{if Korea} \\ -21.8 & \text{if Spain} \\ 5.85 & \text{if USA} \\ -34.7 & \text{if Chile} \end{cases}$$

TABLE 6.8. Anova Table for Photovoltaic Cost Regression Model

Source	SS	df	MS
Model	452,258	13	34,789
Residual	17,082	23	742,7
Total	469,340	36	13,037

TABLE 6.9. Overall Model Fit for Photovoltaic Cost Regression Model

Number of Observations	37
F(10,32)	46.84
Prob > F	0
R-squared	0.9636
Adjusted R-squared	0.943
Root MSE	27.25

6.1.3.1. Correlation factors

Table 6.11 shows the correlation factor for the most explanatory numerical variables.

Table 6.12 shows the partial correlation factors for the thermal cost regression model and their significance level in parenthesis. Comparing these tables, we find that a big amount of the correlation between investment cost and installed year is affected by other variables, and if that affect is removed, we get a partial correlation factor of -37% with a high significance level.

TABLE 6.10. Parameter Estimates for Photovoltaic Cost Regression Model

Variables	Coefficient	Std.Err	t	P>|t|	Beta
Capacity	8.591094	0.3966235	21.66	0	1.090921
Year	-14.74198	11.12181	-1.33	0.198	-.0770194
Dummy Poly-Si-1a	-30.96369	23.63689	-1.31	0.203	-0.085368
Dummy Poly-Si-2a	21.09363	20.83619	1.01	0.322	0.069034
Dummy FS-CdTe	-173.3545	33.7273	-5.14	0	-0.3480482
Dummy Mono-Si	26.82862	23.79392	1.13	0.271	0.0538645
Dummy Poly-Si	-38.30032	19.23369	-1.99	0.058	-0.1669608
Dummy Italy	-16.18226	42.0044	-0.39	0.704	-0.0446151
Dummy Korea	17.84908	40.52226	0.44	0.664	0.0256994
Dummy Portugal	-21.81824	36.11095	-0.60	0.552	-0.052878
Dummy Spain	-5.854757	52.51334	-0.11	0.912	-0.0084298
Dummy USA	39.51574	40.02543	0.99	0.334	0.1642426
Dummy Chile	-34.69045	40.28342	-0.86	0.398	-0.0696489
Constant	29,594.06	22354.92	1.32	0.199	.

TABLE 6.11. Correlation Factors for Photovoltaic Cost Regression Model

	Cost	Capacity
Capacity	0.8664	1
Year	-0.1646	0.0246

TABLE 6.12. Partial Correlation Factors for Photovoltaic Cost Regression Model with its level of significance

	Cost	Capacity
Capacity	0.88(0)	1
Year	-0.37(0.025)	0.33(0.043)

6.2. Determining a levelized cost of energy function

A convenient metric for comparing energy costs from different sources is using levelized cost of energy (LCOE). Besides investment and operation and maintenance costs, the levelized cost, measured in USD/KWh, represents the minimum price at which the energy can be sold for obtaining a positive net present value.

LCOE is the monetary value of the solar energy-generating plant that includes the investment, operational costs and energy generation over its lifetime using a determinated discount rate. Equation (6.3) shows how the LCOE is calculated, where: I_t is the investment cost of year t in US dollars, $O\&M_t$ are the operational, maintenance and salaries cost of year t in US dollars (variable cost), E_t is the generated energy of year t in MWh, and r is the discount rate of the project.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{6.3}$$

Because information about variable cost of the solar plants is very limited, the database consists of 11 thermal solar plants projects located in California.

6.2.1. Studied Variables

The recopilated and studied variables of the thermal solar parks are: total installed cost, technology, power capacity, storage capacity, installed country, year of commissioning, mirror solar field, average water use, variable cost of energy, annual variable cost, electricity generation, capacity factor and radiation.

With these variables and a discount rate of 8%, a linear multiple regression was run to determine the main explanatory variables and coefficients that determine the levelized cost of energy of a thermal solar power plant.

6.2.2. Regression model accuracy and statistical significance

The model consists on 13 variables to explain 11 solar plants projects. Having more variables than data in the model can explain it completely with a standard deviation of the error term of 0. The objective was to find the less amount of variables that explain the most of the projects with high significance level.

It was found that the main explanatory variables are: technology, storage capacity and capacity factor. These were used to formulate a multivariable linear regression which results are shown on Tables 6.14, 6.15 and 6.16.

In our model we find that all the coefficients of the model are different from zero and an R-Squared of 99.53%.

We find that all the chosen variables have a high significance level and that the technology with the lowest LCOE is Stirling Dish. Also, with one plant in the model that has storage technology, we find that storage has a low, but positive effect on the LCOE. This means that including storage the generated energy would have a higher cost, and this could be explained because now storage is too expensive, cost that should be driven down throughout the years.

The results show that the average water use was not a determinant variable to the model. On the other hand, water availability is a very important variable that determines the operational and maintenance cost of the solar plant in extreme situation. In this case, the studied plants are located in California, and the results might change if the plants were installed in the Sahara or Atacama desert.

The Beta column tells us that technology is the variable that has a bigger impact on explaining the model; then we have storage capacity and finally the capacity factor of the plant.

Equation (6.4) shows the levelized cost of energy for thermal solar plants in millions of US dollars depending on technology (parabolic trough, fresnell, stirling and solar tower), storage capacity in MWh and capacity factor.

$$LCOE = \beta_0 + \beta_1 \cdot StorageCapacity + \beta_2 \cdot CapacityFactor + D_{Technology} \quad (6.4)$$

where:

$$D_{Technology} = \begin{cases} 0 & \text{if Parabolic Trough} \\ -50.03798 & \text{if Fresnell} \\ -106.4286 & \text{if Stirling Dish} \\ -68.29733 & \text{if Solar Tower} \end{cases}$$

TABLE 6.13. Coefficients for LCOE regression

β_0	306.0381
β_1	0.1101922
β_2	-519.2542

TABLE 6.14. Anova Table for LCOE Regression Model

Source	SS	df	MS
Model	19,958.726	5	3,991.745
Residual	94.7316	5	189463
Total	20,053.458	10	2,005.3458

TABLE 6.15. Overall Model Fit for LCOE Regression Model

Number of Observations	11
F(10,32)	210.69
Prob > F	0
R-squared	0.9953
Adjusted R-squared	0.9906
Root MSE	4.3527

TABLE 6.16. Parameter Estimates for LCOE Regression Model

Variables	Coefficient	Std.Err	t	P>|t|	Beta
${}_{I}TechN_2$	-50.03798	4.710324	-10.62	0.000	-0.3369061
${}_{I}TechN_3$	-106.4286	3.565667	-29.85	0.000	-0.9613989
${}_{I}TechN_4$	-68.29733	4.710324	-14.50	0.000	-0.6169486
Storage Capacity	0.1101922	0.0094507	11.66	0.000	0.7790214
Capacity Factor	-519.2542	86.48013	-6.00	0.002	-0.35927
Constant	306.0381	21.98025	13.92	0.000	.

7. CHILEAN NORTHERN INTERCONNECTED POWER SYSTEM (SING) SIMULATION

7.1. Simulation General Aspects

This chapter focuses on obtaining the economic impact of installing a solar power plant on the northern interconnected power system (SING) of Chile. The social and private net benefits are calculated from the OSE2000 simulation. This information will be projected for a period of 30 years and all the economical benefits will be quantified.

OSE2000 software was used for the simulation of 11 different technologies on 4 sites of the northern interconnected power system of Chile. This software is used by the Comisión Nacional de Energía (CNE), generators, transmission agents and consulters for planning the future generation and establishing the future prices of electricity. In summary, 44 different scenarios were simulated, where each scenario corresponded to only one solar plant added to the system. Finally each scenario was compared with the actual operation of the system.

The sites chosen for the simulation are Calama, Dolores, Pozo Almonte and Tamarugal, because of their higher price of energy, obtained from the simulation of the system without solar plants, and solar radiation, obtained from Meteonorm software.

It was chosen to simulate plants of 200MW of capacity for thermal technologies and 100MW for photovoltaic technology. It was found that the investment cost is lowest for thermal plants with over 200MW of capacity (IEA, 2010a). Photovoltaics is a modular technology, where 100 MW was used for creating an impact in the total system cost.

The radiation and weather information for the chosen sites was obtained from Meteonorm 6.0 software, which uses satellite information from NREL and NASA together with statistical and mathematical models to predict hourly information.

The generated energy from the different solar technologies was obtained from SAM version 2010.4.12. Using this software, hourly energy generation for a complete year was simulated for parabolic trough, solar tower, stirling dish, First Solar CdTe, Poly-crystalline and Mono-crystalline Silicon for a fixed position, 1 axis and 2 axis tracking.

The hourly generation information, together with the consumed electricity for the plants operation, was transformed into blocks of energy, according to the different periods of demand of the system, so it could be included in the OSE2000 model. This model has all the information of the Chilean northern interconnected power system (SING) actual operation. The results of the simulation include the total cost and operational cost of the system, total income from the installed solar plant and more information that wouldn't be used in this investigation.

With this information, the net present value (NPV) is calculated for social and private players. For social NPV the benefits will be the difference between the actual system cost of operation and failure and the cost of the system including the solar power plant. For private players, the benefits would be monetary income of the solar plant from energy and power.

7.2. Total System Cost

The output of the OSE2000 simulation gives us the total cost of the system in millions of USD and the marginal cost of the system for a period of 11 years, on which different power plants are incorporated during these years. The OSE2000 model assumes that the electricity market is perfectly competitive and the demand is perfectly inelastic.

Figure 7.1 shows the variation of the average marginal cost of the system, throughout the years, with the incorporation of the different solar power plants. Parabolic through with 7 hours of storage is the technology that reduces the most the marginal cost of the system, followed by solar tower and stirling dish. It is important to notice that the change of the marginal cost because the location of the plant is not significant.

If we install a 200MW solar parabolic trough plant with 7 hours of storage in Dolores, there will be an average decrease of 3.3 USD/MWh on the marginal cost of the system on

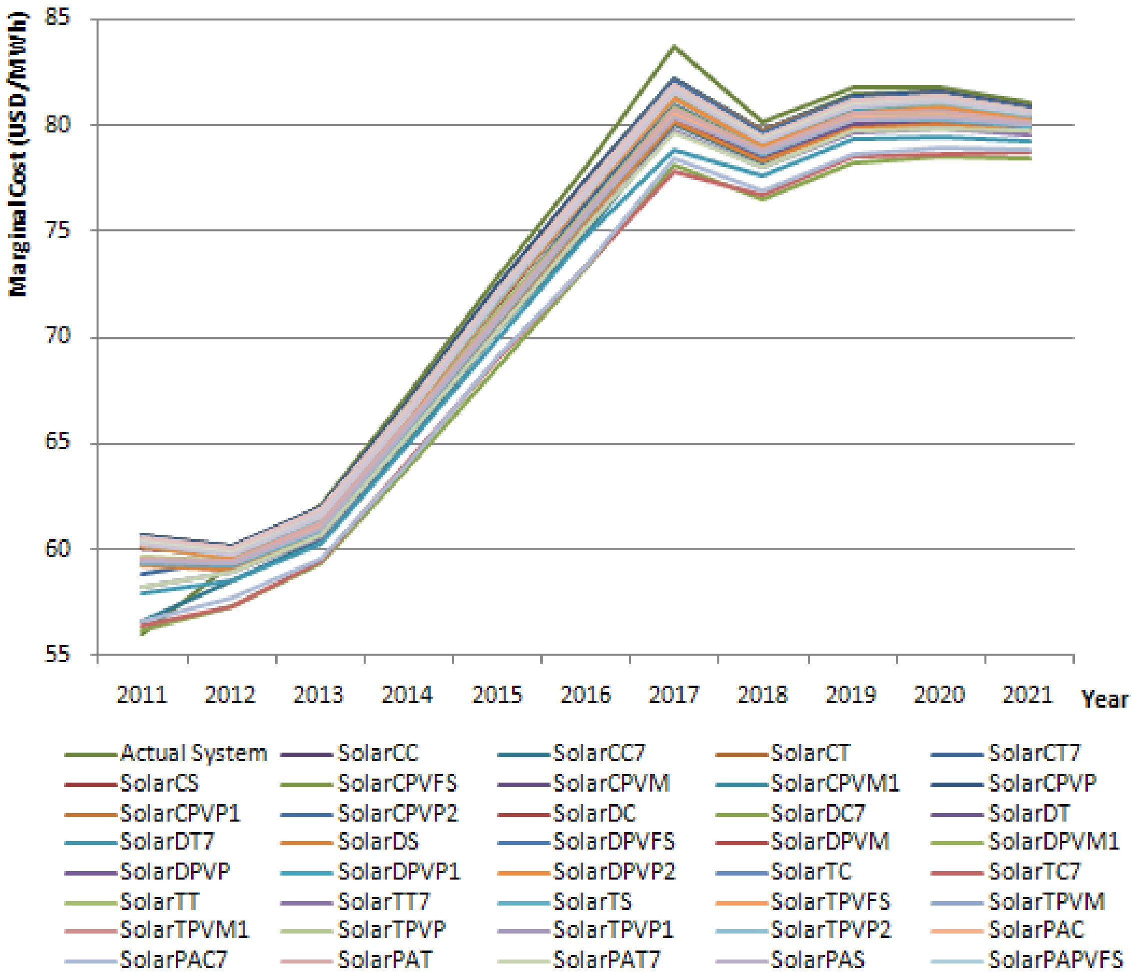


FIGURE 7.1. Marginal system cost for actual and new solar scenarios

the 11 years shown in Figure 7.1. The biggest difference in the marginal cost happens in year 2017, where the difference if we install the same plant would be 5.6 USD/MWh.

Because of the scale of Figure 7.1 it might seem that the marginal cost will increase drastically, but the real change is less than 30 USD/MWh from 2011 to 2017.

Figure 7.2 shows the total system cost, throughout the years, with the incorporation of the different solar power plants. Again, parabolic through with 7 hours of storage is the technology that reduces the most the total cost of the system. If we install a 200MW solar parabolic trough plant with 7 hours of storage in Calama, there will be an average decrease throughout the years of 26 million dollars on the total system cost.

The nomenclature used in the references of both figure are the following format: Solar[Place][Technology], where:

$$Place = \begin{cases} C & \text{is Calama} \\ D & \text{is Dolores} \\ T & \text{is Tamarugal} \\ PA & \text{is Pozo Almonte} \end{cases}$$

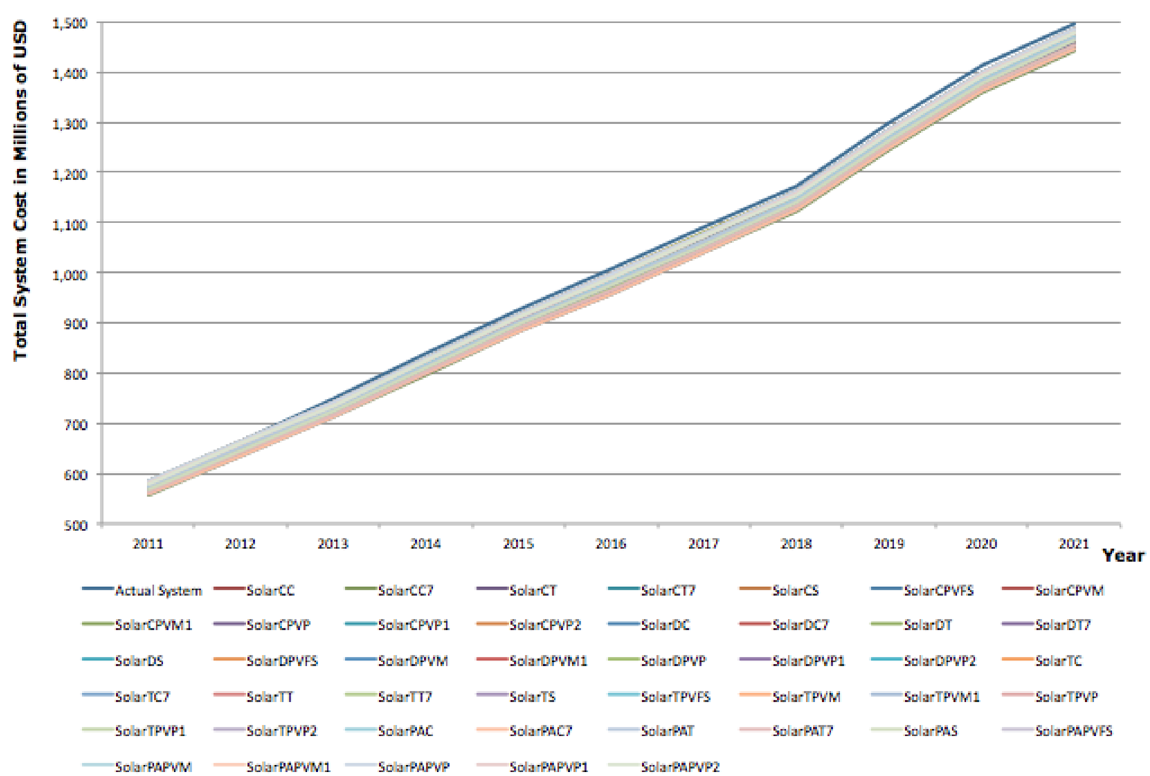


FIGURE 7.2. Total system cost for actual and new solar scenarios

$$Technology = \begin{cases} C & \text{is Parabolic Through} \\ C7 & \text{is Parabolic Through with 7 hours of Storage} \\ T & \text{is Solar Tower} \\ T7 & \text{is Solar Tower with 7 hours of Storage} \\ S & \text{is Stirling Dish} \\ PVFS & \text{is First Solar CdTe PV} \\ PVM & \text{is Monocrystalline silicon PV} \\ PVM1 & \text{is Monocrystalline silicon PV with 1 axis tracking} \\ PVP & \text{is Polycrystalline silicon PV} \\ PVP1 & \text{is Polycrystalline silicon PV with 1 axis tracking} \\ PVP2 & \text{is Polycrystalline silicon PV with 2 axis tracking} \end{cases}$$

7.3. Economical evaluation considerations

For obtaining an evaluation on the lifetime of the solar plant, a period of 30 years was chosen at an interest rate of 6% for the social and 8% for the private evaluation.

OSE2000's 11 year output was projected to 30 years using a linear fit curve for all the cases. Figure 7.3 shows the nominal projected system cost for all the plants. Although the figure is not clear enough to see which curve belongs to each plant, it shows how was the projection made and how the total system cost increases along the years the same as the growth obtained from OSE2000 simulation.

The income from sold energy of each plant for 11 years was given from OSE2000 simulation, this values were projected to 30 years using a linear fit curve for all cases. Figure 7.4 shows the projected private income from energy generation for the new solar plants.

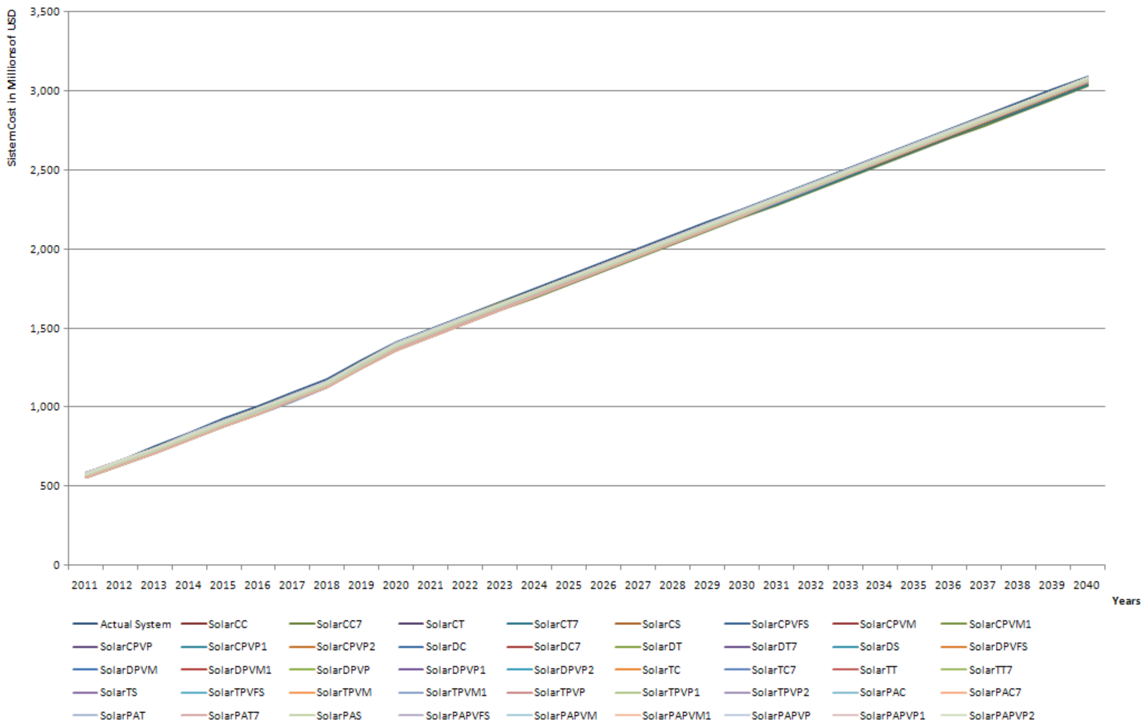


FIGURE 7.3. Projected system cost for actual and new solar scenarios

7.3.1. Carbon Credits

For all the solar projects, carbon credits were included as benefits along the years of operation. An emission factor of 0.57 Ton/MWh that was approved by the UNFCC for Canela Windfarm project in Chile was used in this study (Endesa Eco, 2008). With a price of 18.8 USD/Ton (European Market Exchange, 2010) the benefits from carbon credits were added to the social and the private project evaluation of every solar plant.

Figure 7.5 shows the annual benefits in millions of USD that the different solar technologies would obtain from carbon credits. The difference is because each technology has a different capacity factor so they generate a different amount of electric energy throughout the year.

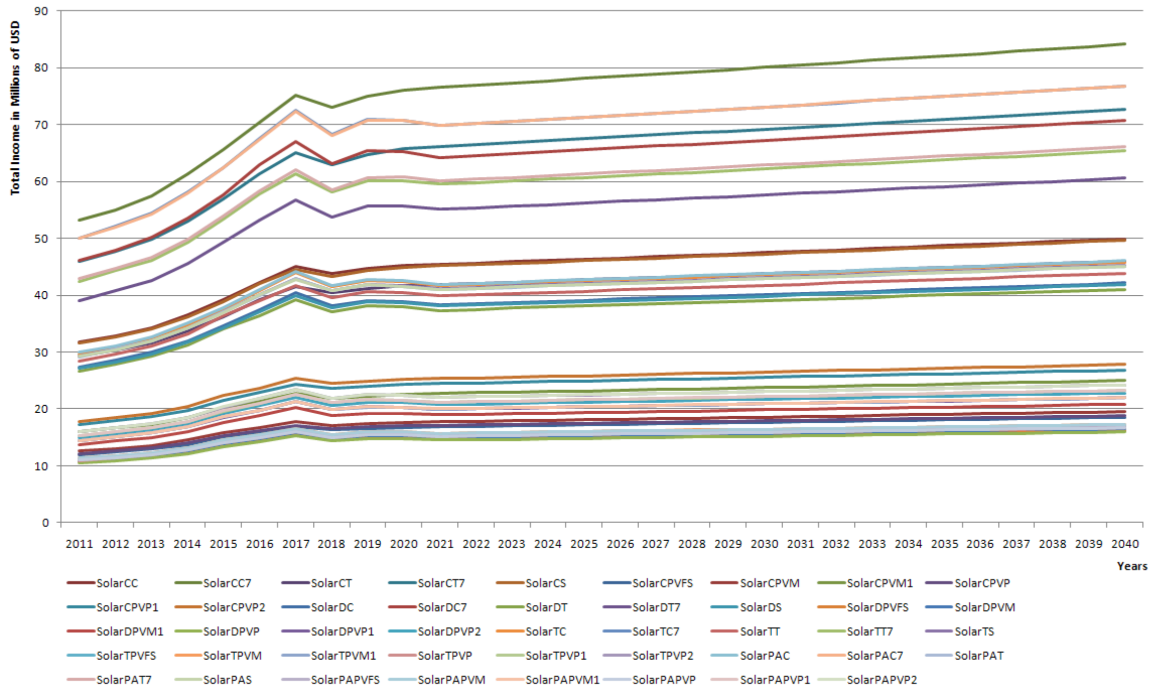


FIGURE 7.4. Projected private income from energy generation for new solar plants

7.3.2. Private evaluation considerations

7.3.2.1. Income from energy generation

Annual private income from energy generation in million of USD is shown in Figure 7.6 for the different solar technologies located in Calama.

7.3.2.2. Income from installed power

In Chile the energy generation agents have income from their installed power. The last report from CNE stated a price of 8.7142 USD/KW/months equivalent to 0.105 USD/MW/year for firm power (CNE, 2010b). To obtain the income, the firm power preliminary factor (FPPF)[1] of 0.606 from wind farms in Chile was used (CDEC-SIC, 2010).

Equation 7.1 shows how the income from installed power is calculated (CDEC-SING, 2010).

[1]This factor establishes the percentage of firm power that a certain power plant can provide.

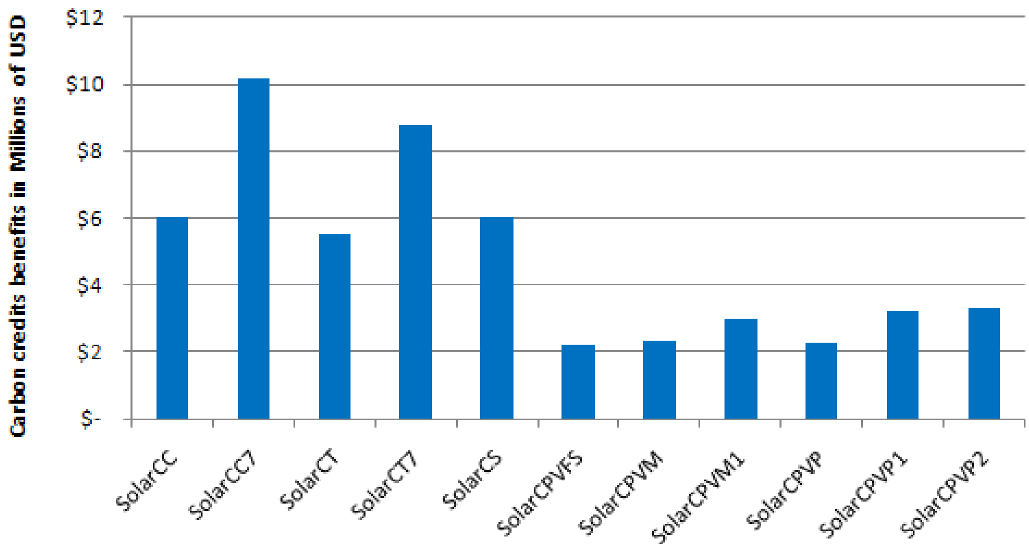


FIGURE 7.5. Annual income from carbon credits for solar plants in Calama, Chile

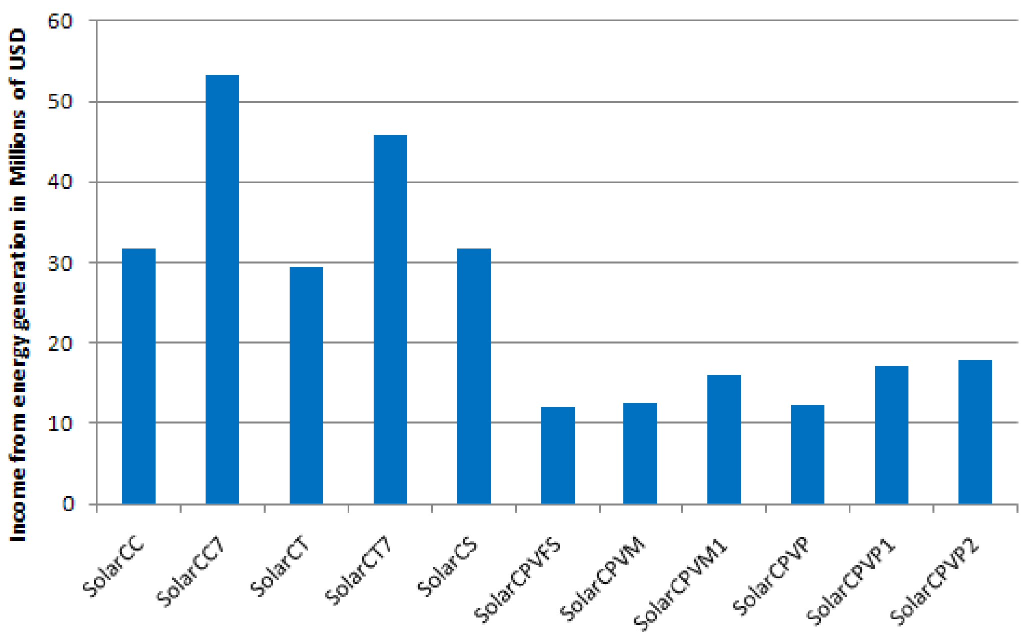


FIGURE 7.6. Annual income from energy generation for solar plants in Calama, Chile

$$Income = Capacity * CapacityFactor * FirmPowerPrice * FPPF \tag{7.1}$$

Figure 7.7 shows the annual income, in millions of USD, for the different solar technologies located in Calama.

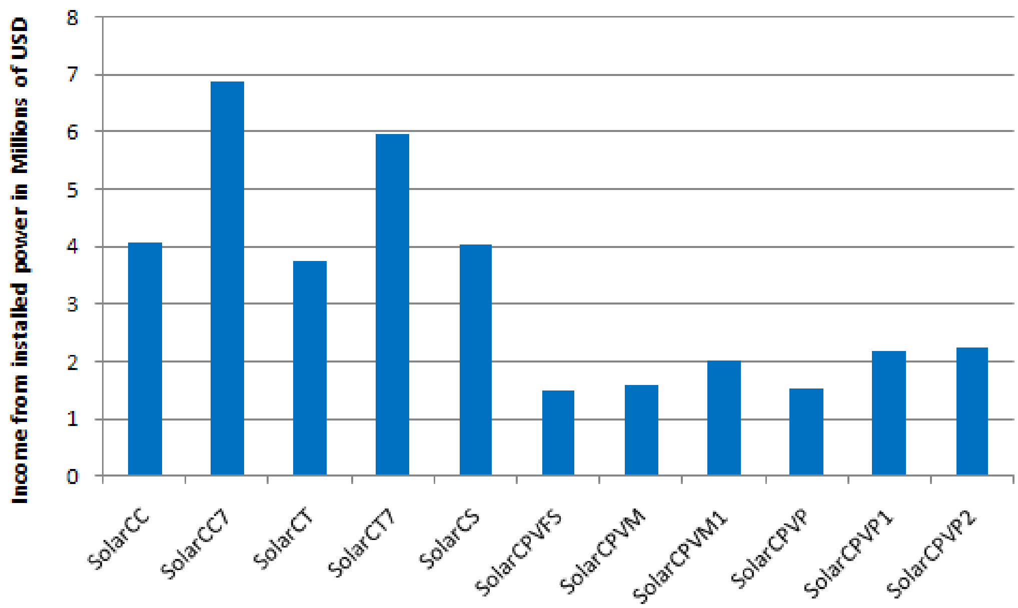


FIGURE 7.7. Annual income from installed power for solar plants in Calama, Chile

The best estimation for the projection of the income from installed capacity is the value shown in Figure 7.7 due to the lack of capacity market information.

7.3.3. Investment costs

Applying the multivariable regression results of chapter 6, we got the investment cost of the considered solar power plant installed in Chile. Figure 7.8 shows the investment cost, in millions of dollars, of the different solar generation technologies. It can be seen that the cost of mono-crystalline photovoltaic is higher than the same technology with 1 axis tracking. This is explained because most of the power plants that use 1 axis tracking belong to SunPower Corp., which is one of the market leaders of this technology and they have and offer lower costs.

It is important to remember that these costs are for thermal plants with a capacity of 200MW and PV plants with a capacity of 100 MW. However, the information used for the multivariate regression consisted of plants of different capacities and calculating the investment cost for PV plants with 100 MW is not in the range of any of the included plants.

For resolving this issue and because PV technology is modular, the range of the capacities of every PV technology was used and the average of this was calculated to for obtaining the investment cost per MW[2]. Two blocks of 50 MW was used for First Solar thin-film PV, five blocks of 20MW for mono-crystalline silicon and polycrystalline with 2 axis tracking and four blocks of 25 MW for the rest.

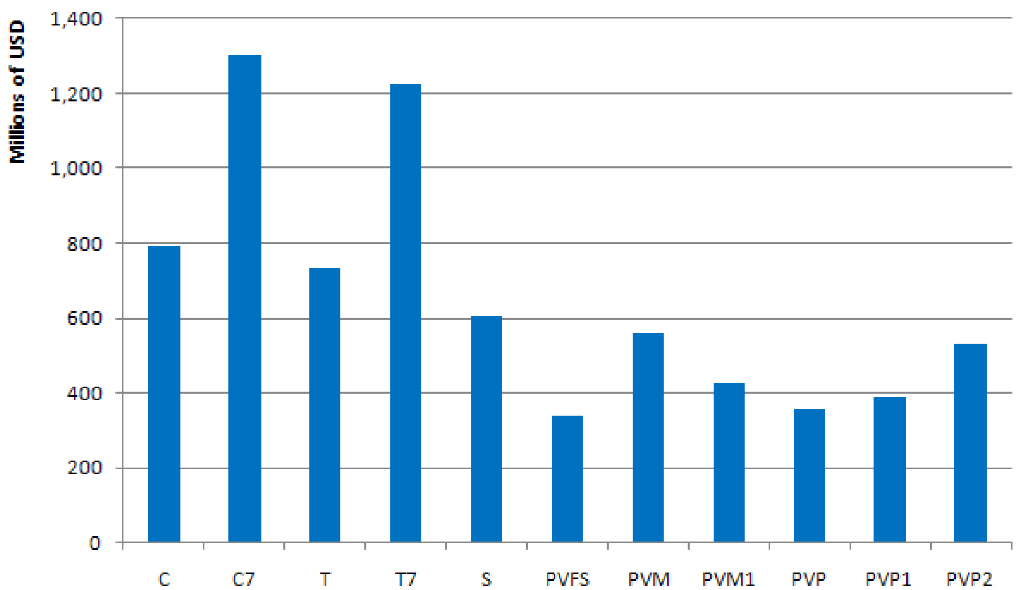


FIGURE 7.8. Investment cost for a solar plant in Chile

7.3.4. Operational and maintenance costs

Operational and maintenance cost for thermal technologies were taken from projects of the California Energy Commission (a multiple linear regression was not successful on providing this information), using an average cost per each technology. For photovoltaics, information from the US Department of Energy's 2008 solar technologies market report was used.

[2]For example, polycrystalline technology has 15 different plants, with capacity from 6 to 60 MW. It was chosen a block of 20 MW because the average of the capacities of the 15 plants is approximately 20 MW.

Figure 7.9 shows the operational and maintenance cost, in USD/MWh, of the different solar generation technologies.

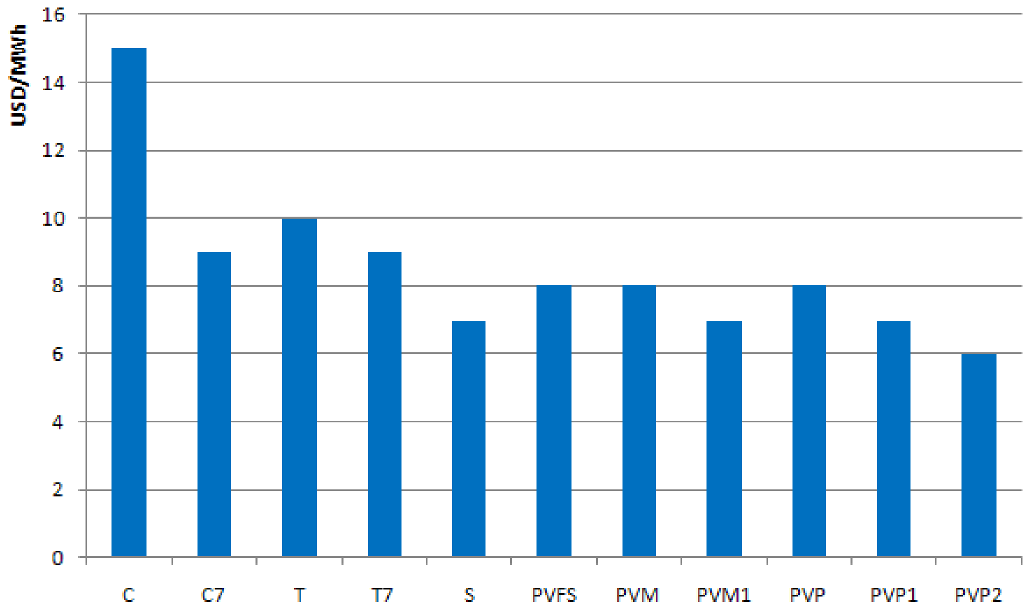


FIGURE 7.9. Operation and maintenance cost for a solar plant in Chile

7.3.5. Investment depreciation

The investment depreciation is made on 15 years so it reduces taxes to the company on these years of operation. The reduced tax to the company will be considered as a benefit in the project evaluation.

7.4. Economical Results

The results of every solar power plant evaluated are shown on Figures 7.10 and 7.11. They show that installing solar power in the north of Chile is not economically feasible for all solar technologies and locations studied.

The social benefits were calculated as the difference of all the system cost without and with the solar power plant. It doesn't include all the positive externalities that these projects could bring to the country.

To compare the private and the social net present value (NPV), an interest rate of 6% was used in the private case. Tables 7.1 and 7.2 show the information for a plant located in Calama in millions of US dollars. It shows that the private NPV is always higher than the social one. This can be explained because when installing a solar plant, the other plants of the system are economically disadvantaged because of the lower marginal costs.

TABLE 7.1. Social and private NPV differences (rate=6%) for a thermal plant located in Calama, Chile

Technology	C	C7	T	T7	S
Social NPV	-367.98	-513.36	-314.73	-545.15	-74.91
Private NPV	-199.5	-242.63	-157.47	-298.83	18
Difference	168.49	270.72	157.26	246.32	92.91

For the private evaluation an interest rate of 8% was used, the NPV, in millions of US dollars is shown in Tables 7.3 and 7.4

We found that the best locality for installing solar power plants is Calama. It was found that a plant installed in this location gives more electrical generation and more monetary income than other location studied.

From technology, it was found that stirling dish is the technology that gives the lowest NPV. From Table 7.1 Stirling Dish has a NPV of 18 Million of USD for an interest rate of 6%. Recall that cost data from this technology was taken from US Department of Energy Solar Energy Technologies Multi-year Program Plan.

From storage, it was found that is not economically beneficial to include it with parabolic trough or solar tower. For the case of a parabolic trough plant located in Calama, to add 7 hours of thermal storage it represents a decrease of 129 millions of dollars to the private NPV and 145 millions of dollars to the social NPV.

TABLE 7.2. Social and private NPV differences (rate=6%) for a PV plant located in Calama, Chile

Technology	PVFS	PVM	PVM1	PVP	PVP1	PVP2
Social NPV	-159.44	-369.37	-172.73	-176.11	-114.45	-242.3
Private NPV	-95.92	-281.42	-98.68	-110.33	-44.79	-157.07
Difference	63.53	87.95	74.05	65.78	69.66	85.23

TABLE 7.3. Private NPV (rate=8%) for a thermal plant located in Calama, Chile

Technology	C	C7	T	T7	S
Private NPV	-308.92	-438.24	-263.74	-469.31	-97.68

TABLE 7.4. Private NPV (rate=8%) for a PV plant located in Calama, Chile

Technology	PVFS	PVM	PVM1	PVP	PVP1	PVP2
Private NPV	-140.21	-330.69	-158.5	-155.54	-108.19	-225.13

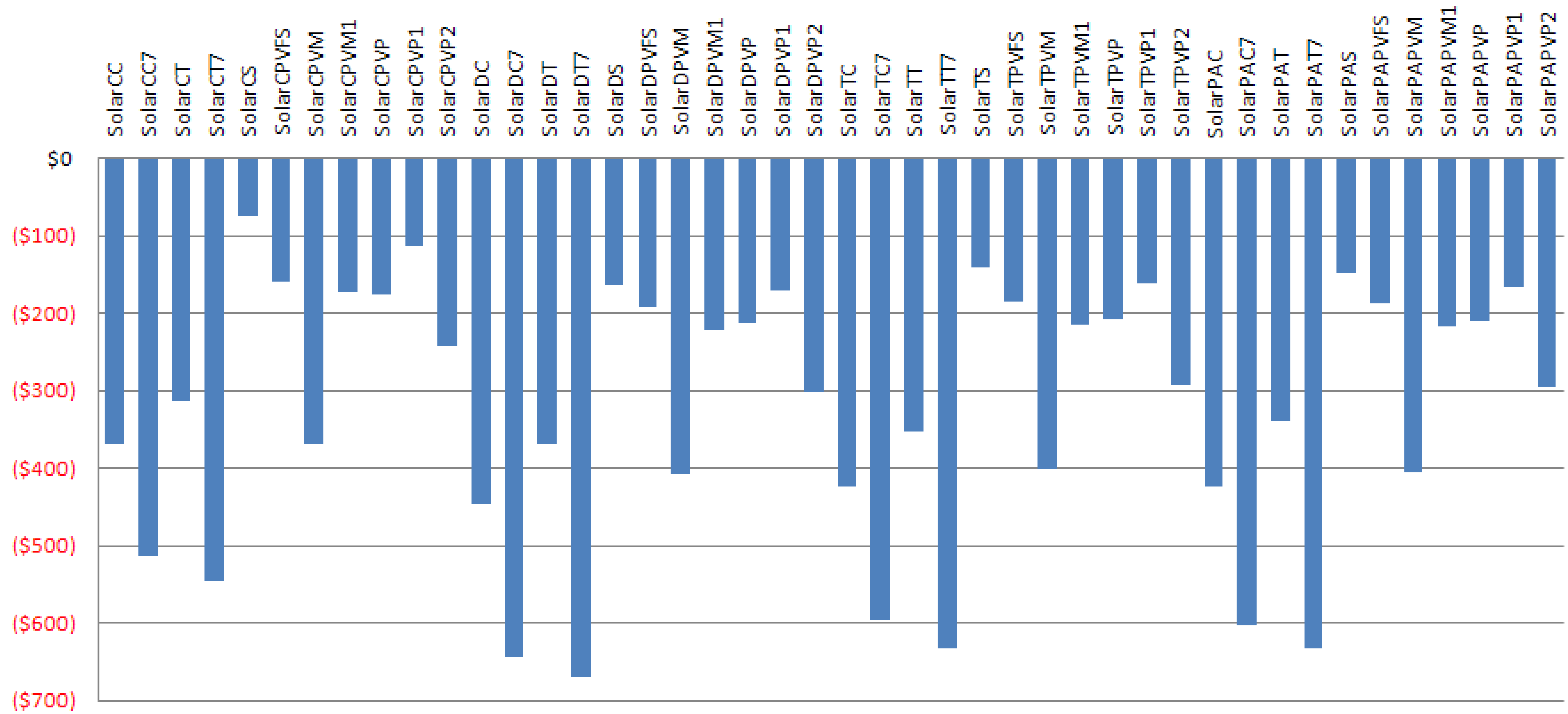


FIGURE 7.10. Social NPV of the different solar power plants

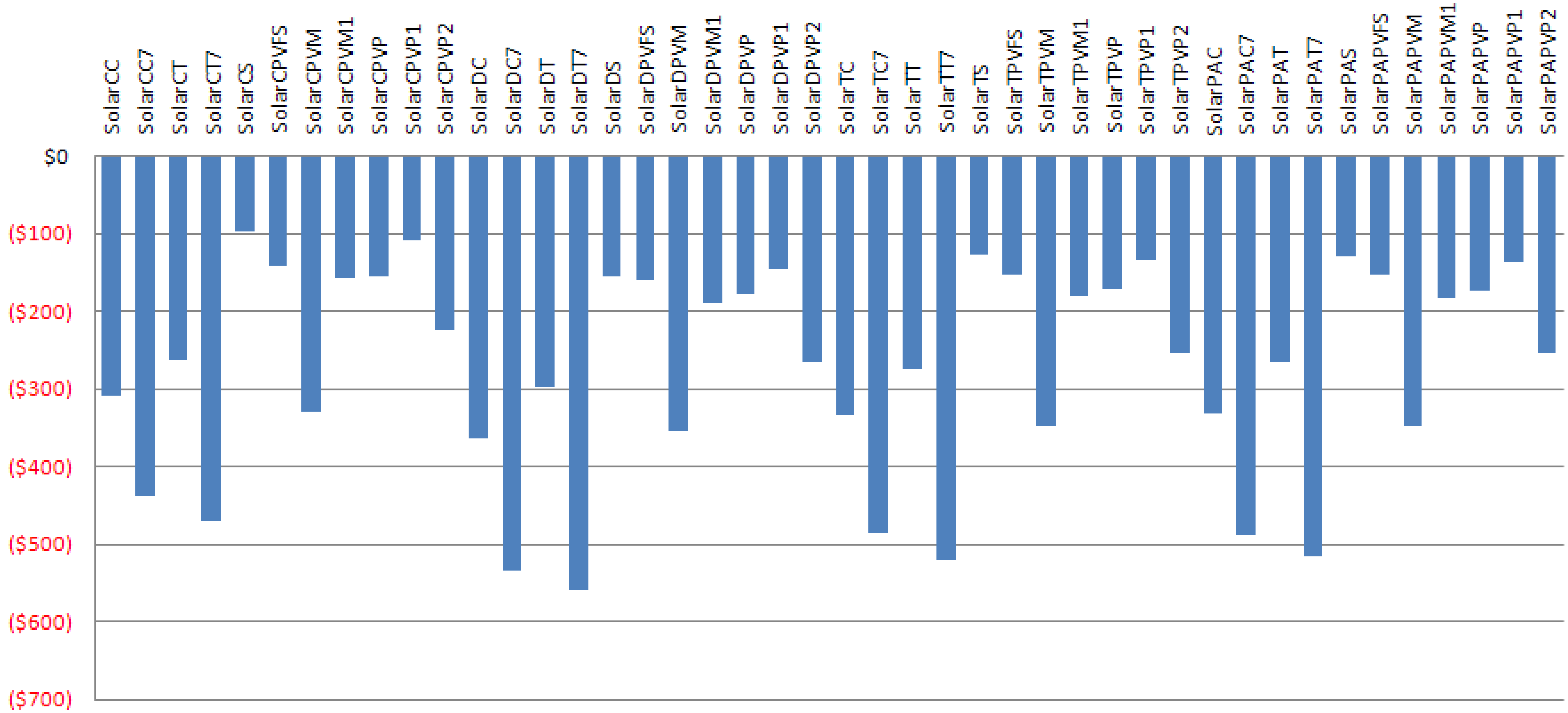


FIGURE 7.11. Private NPV of the different solar power plants

With these results we might think why is there a PV plant being constructed in Calama. We have to consider that these results are obtained from the methodology used. And using this, the PV plant in Calama is not economically feasible. On the other hand, there are different projects, such as a Stirling Dish solar plant located in Calama, that have a NPV very close to zero, which indicates that a higher carbon bonds prices, a small decrease in cost or an increase in the cost of fuel (traduced in a higher marginal cost of energy) could make the private NPV positive. Also, considering all the positive externalities that this project brings, political, strategic and communicational considerations, which are not quantified in this research, the social NPV should increase and could become positive.

8. CONCLUSION AND FUTURE RESEARCH

8.1. Review of the Results and General Remarks

For the first hypothesis of this investigation: It is possible to identify a limited number of explanatory variables which explain the variation on the investment and generation cost of solar energy power plants, the results show that it is possible excluding for the generation cost of PV which operation and maintenance data for the studied plants was not found in the literature.

The investment cost of solar thermal power plants is explained by its technology, capacity, area, storage capacity and installed country. The results show that capacity is the variable that is most significant to the investment cost, Chile is the less expensive country for the installation of a solar thermal power plant and Stirling Dish is the technology with the lowest investment cost. The model has an R-Squared of 98% for 45 different solar thermal power plants.

The investment cost of solar photovoltaic power plants is explained by its technology, capacity, installation year and country. The results show that capacity is the variable that is most significant to the investment cost, Chile is the less expensive country for the installation of a solar photovoltaic plant (considering that it was not statistical significant in the model) and that First Solar CdTe Thin Film is the technology with the lowest investment cost. The model has an R-Squared of 96% for 37 different solar photovoltaics power plants.

The generation or levelized cost of energy(LCOE) of solar thermal power plants is explained by its technology, storage capacity and capacity factor. The results show that technology is the variable that is most significant to the generation cost and Stirling Dish is the technology with the lowest LCOE.

The results show that for the second hypothesis of this investigation: It is possible to quantify the social and private net benefits of the installation of a solar power plant in the north of Chile and determine the conditions in which they are positive, is true.

The net present value (NPV) of 11 different technologies was calculated for 4 different locations in the north of Chile and the results show that the best place for installing solar is Calama, where more electrical generation and more monetary income is obtained than in other locations studied. Considering the cost data from Stirling Dish(US Department of Energy, 2008), this technology has the lowest NPV. Thermal energy storage is not economically beneficial for parabolic trough or solar tower plants.

The plant that most reduces the total system cost is a parabolic through with 7 hours of storage located in Calama. This is explained because this is the technology and location that generates more electrical energy and the operational cost is the lowest. It was found an average decrease of 26 millions of USD on the total system cost by introducing this solar plant.

As expected, using the same interest rate of 6% for comparing, the social are lower than the private benefits. This confirms that the benefits as the change in the total cost of the system of the north of Chile are lower than the private benefits of selling the energy at a marginal cost and having income from installed power by a private actor.

Recall that the results show a NPV very close to zero, which indicates that a higher carbon bonds prices, a small decrease in cost or an increase in the cost of fuel (traduced in a higher marginal cost of energy) could make the private NPV positive. On the other hand, considering all the positive externalities that this project brings, political, strategic and communicational considerations, which are not quantified in this research, the social NPV should increase and could become positive.

8.2. Future Research

As every investigation, there are future research that has to be made in order to have more information on this subject.

Since investment cost is one of the main variable that would define if the project is economically feasible, adding projects, to the database would give a better estimation of the final value of the investment cost. As for statistical results, the more data we have, the more sense it gives to the results and the variables that explain the investment cost of a solar power plant.

Also, we have to consider that the investment cost of Stirling Dish technology is taken from only one project, and currently there are not any installed plant of this technology. To make the cost study more precise we need information of installed stirling dish plants that are not currently available because they don't exist.

Radiation in the simulation of the different solar plants in the Chilean northern interconnected system was taken from satellite information provided by the NASA. In this subject it would be more precise to use radiation information measured in the different sites of Chile, information that is not available today, but should be available in the future.

In the future, Solar Advisor Model Software could be updated. It is important to use the last version of this software, since it will provide more accurate information about the energy generated by the different solar power technologies.

Since economical and operational information about the chilean northern interconnected system is always changing, using the updated OSE2000 model is very important for the future research that could be made.

From a public-policy viewpoint, it would be very useful to include the economic impact on labor rate and other externalities, like environmental local co-benefits of solar power plants installation, into the evaluation model.

In Appendix B, an attempt to calculate an annual operation and maintenances cost function for thermal plants was made but was not successful, future research could include this calculation for thermal and photovoltaic plants.

References

Amonix. (2008). *Lens cpv technology*. Accessed on August 9 of 2010 of http://www.amonix.com.

Cameron, C., Hanley, C., Hulstrom, R., Hurwitch, J., Mancini, T., Mehos, M., et al. (2006). *Solar energy technologies multi-year program plan 2007-2011* (Tech. Rep.). US Department of Energy. Accessed on March 23 of 2010 of http://www1.eere.energy.gov/solar/pdfs/set_myp_2007-2011_proof_1.pdf.

CDEC-SIC. (2010). Cálculo Definitivo Potencia Firme. Accessed on August 9 of 2010 of http://www.cdec-sic.cl/est_opera_publica.php#C6.

CDEC-SING. (2010). *Balance preliminar de potencia firme de 2010.* Informe de Cálculo. Accessed on August 9 of 2010 of http://www.cdec-sing.cl.

Cheung, K., Cheung, S., Silvia, R. N. D., Juvonen, M., Singh, R., & Woo, J. (2003). Large-scale energy storage systems. Imperial College London: ISE2.

Comisión Nacional de Energía Chile (CNE). (2010a). Solar Radiation in Pozo Almonte. Accessed on May 3 of 2010, of http://www.cne.cl/cnewww/opencms/03_Energias/Otros_Niveles/renovables_noconvencionales/Tipos_Energia/otros_renovables_noconvencionales/pozo_almonte/pozo_almonte.html.

Comisión Nacional de Energía Chile (CNE). (2010b). *Fijación de precios de nudo abril de 2010 sistema interconectado del norte grande (sing)*. Accesed on August 9 of 2010 of http://www.cne.cl.

Endesa Eco. (2008). *Canela wind farm project, validation of the project activity*.

European Market Excange. (2010). Accessed on August 9 of 2010 of http://www.ecx.eu/ECX-EUA-Indices.

German Solar Energy Society. (2005). *Planning and installing solar thermal systems*. James & James / Earthscan.

Gil, A., Medrano, M., Martorell, I., Lázaro, A., Dolado, P., Zalba, B., et al. (2010). State of the art on high temperature thermal energy storage for power generation. part 1: Concepts, materials and modellization. *Renewable and Sustainable Energy Reviews*, *v. 14*, 31–55.

Gilman, P., Blair, N., Mehos, M., Christensen, C., Janzou, S., & Cameron, C. (2008). *Solar advisor model user guide for version 2.0.*

Ibrahim, H., Ilinca, A., & Perron, J. (2008). Energy storage systems—characteristics and comparisons. *Renewable and Sustainable Energy Reviews*, *v. 12*, 1221–1250.

International Energy Agency. (2003). *Renewables for power generation: Status & prospects* (Tech. Rep.). IEA. Accessed on August 9 of 2010 of http://www.iea.org/textbase/nppdf/free/2000/renewpower_2003.pdf.

International Energy Agency. (2010a). *Technology roadmap: Concentrating solar power* (Tech. Rep.). IEA. Accessed on August 9 of 2010 of http://www.iea.org/papers/2010/csp_roadmap.pdf.

International Energy Agency. (2010b). *Technology roadmap: Solar photovoltaic energy* (Tech. Rep.). IEA. Accessed on August 9 of 2010 of http://www.iea.org/papers/2010/pv_roadmap.pdf.

Mills, D. (2004). Advances in solar thermal electricity technology. *Solar Energy*, *v. 76*, 19–31.

Montes, M., Abánades, A., Martínez-Val, J., & Valdés, M. (2009). Solar multiple optimization for a solar-only thermal power plant, using oil as heat transfer fluid in the parabolic trough collectors. *Solar Energy*, *v. 83*, 2165–2176.

NASA. (2010). (RREX) Renewable Resource Energy Explorer. Accessed on May 27 of 2010, of http://na.unep.net/swera_ims/map2/.

National Renewable Energy Laboratory (NREL). (2008). *New film solar panels*. Accessed on August 9 of 2010 of http://www.greenpacks.org/2008/05/07/new-film-solar-panels-holds-efficiency-record-of-199/.

National Renewable Energy Laboratory (NREL). (2010). *Concentrating solar power projects home page*. Accessed on May 3 of 2010 of http://www.nrel.gov/csp/solarpaces/.

National Renewable Energy Laboratory, Sandia National Laboratory, U.S. Department of Energy. (2010). Solar Advisor Model (SAM) (Version 2010. 4.12) [Software]. Available at National Renewable Energy Laboratory: https://www.nrel.gov/analysis/sam/download.html.

Philibert, C. (2005). *The present and future use of solar thermal energy as a primary source of energy* (Tech. Rep.). IEA.

Price, S., & Margolis, R. (2010). *2008 solar technologies market report* (Tech. Rep.). US Department of Energy.

Quaschning, V. (2004). Technical and economical system comparison of photovoltaic and concentrating solar thermal power systems depending on annual global irradiation. *Solar Energy*, *v. 77*, 171–178.

Quaschning, V., & Blanco, M. (2001). Solar power- photovoltaics or solar thermal power plants. *Solar Energy*, Presented at VGB Congress Power Plants 2001. Brussels, Belgium.

Ranking Solar. (2010). *Parques solares*. Accessed on May 3 of 2010, of http://www.rankingsolar.com.

Solar Pack S.A. (2009). *Declaración de impacto ambiental planta solar fotovoltaica calama solar 1, ii región*. Accessed on August 9 of 2010 of http://www.e-seia.cl/.

SolFocus. (2007). *Curved mirror cpv technology*. Accessed on August 9 of 2010 of http://www.solfocus.com.

SWERA. (2010). Solar Resource Information. Accessed on May 27 of 2010, of http://swera.unep.net/index.php?id=solar.

The California Energy Commission. (2010). *Large solar energy projects*. Accessed on July 22 of 2010 of http://www.energy.ca.gov/siting/solar/index.html.

Thirugnanasambandam, M., Iniyan, S., & Goic, R. (2010). A review of solar thermal technologies. *Renewable and Sustainable Energy Reviews*, *v. 14*, 312–322.

US Department of Energy (DOE). (2008). *Solar energy technologies multi-year program plan 2008-2012* (Tech. Rep.). Energy Efficiency and Renewable Energy.

US Department of Energy (DOE). (2010). *Solar energy technologies program: Technologies*. Accessed on May 3 of 2010 of http://www1.eere.energy.gov/solar/technologies.html.

Wheeler, R. (2007). Accessed on August 9 of 2010 of http://en.wikipedia.org/wiki/Stirling_engine.

APPENDIX A. ECONOMETRIC ANALYSIS DATA

Tables A.1, A.2, A.3, A.4 show the data used for the econometric analysis used in Chapter 6.

TABLE A.1. Recopilated information of solar thermal plants

Name	Tech	Capacity *MW*	Country	Year	Solar Field *ha*	Cost *MM$*	Generation *MWh*	CF *%*	Area *ha*	Storage *MWh*	Radiation $KWh/m^2 year$
SEGS I	PT	13.8	USA	1984	8.3	61.962	16500	14	29	41.4	2725
SEGS II	PT	30	USA	1985	16.5	96	32500	12	66	0	2725
SEGS III	PT	30	USA	1986	23.3	108	68555	26	80	0	2725
SEGS IV	PT	30	USA	1986	23.3	111.9	68278	26	80	0	2725
SEGS V	PT	30	USA	1986	25.1	123.9	72879	27	86	0	2725
SEGS VI	PT	30	USA	1988	18.8	116.1	67758	26	66	0	2725
SEGS VII	PT	30	USA	1988	19.8	116.1	65048	25	68	0	2725
SEGS VIII	PT	80	USA	1989	46.4	231.2	137990	20	162	0	2725
SEGS IX	PT	80	USA	1990	48.4	275.2	125036	18	169	0	2725
Andasol I	PT	49.9	ESP	2008	51	349.19296	158000	36	200	374.25	2136
Nevada Solar One	PT	64	USA	2007	35.72	266	134000	24	161.874	32	2606
PS10	T	11	ESP	2007	7.5	47.006744	23400	24	55	11	2012
PS20	T	20	ESP	2009	15	107.44399	48000	27	80	20	2012
Saguaro	PT	1	USA	2006	1.03	6	2000	23	6.47	0	2636
SAM PT	PT	200	Chile	2011		789.95048	562255	32	933	0	3253.2
SAM T	T	200	Chile	2011		785.05141	517542	30	1437	0	3253.2
SAM St	St	200	Chile	2011		602.91251	560341	32	1800	0	3253.2
SAM PT-s	PT	200	Chile	2011		1418.4156	949595	54	1424	1400	3253.2
SAM T-s	T	200	Chile	2011		1063.2971	822445	47	1867	1400	3253.2
Alvarado I	PT	50	ESP	2009	36	316.95976	105200	23	135	0	2174
Andasol II	PT	49.9	ESP	2010	51	402.91495	158000	36	200	374.25	2136
El Reboso II	PT	50	ESP	2011	31.9	389.55234	110006	25	160	0	2200
Extersol-1	PT	49.9	ESP	2010	51	402.91495	158000	36	200	374.25	2168

TABLE A.2. Recopilated information of solar thermal plants 2

Name	Tech	Capacity *MW*	Country	Year	Solar Field *ha*	Cost *MM$*	Generation *MWh*	CF *%*	Area *ha*	Storage *MWh*	Radiation $KWh/m^2 year$
Gemasolar	T	17	ESP	2010	31.8	229.66152	100000	67	190	255	2062
Ibersol	PT	50	ESP	2010	28.77	268.60997	103000	24	150	0	2061
Lebrija 1	PT	49.9	ESP	2010	41.2	402.91495	120000	27	188	0	1993
Majadas I	PT	50	ESP	2010	35.72	323.67501	104500	24	135	0	2142
Manchasol-1	PT	49.9	ESP	2010	51	402.91495	158000	36	200	374.25	2208
Solnova	PT	50	ESP	2010	30	282.04046	113520	26	115	0	2012
Puertollano	PT	50	ESP	2009	29	268.60997	114000	26	150	0	2061
Palma del rio	PT	50	ESP	2010	35.72	268.60997	122000	28	130	0	2291
La Dehesa	PT	49.9	ESP	2010	55.275	335.76246	175000	40	200	374.25	2291
Helioenergy 1	PT	49.9	ESP	2010	30	335.76246	97000	22	115	0	2217
Astexol 2	PT	50	ESP	2011	54.28	402.91495	141400	32	160	410	2291
Solaben 2	PT	50	ESP	2011	45.78	197.42833	135890	31	209	200	2217
Serrezuela Solar 2	PT	50	ESP	2011	51.012	265.52095	174000	40	180	345	2217
Valle I	PT	50	ESP	2011	51.012	443.20644	175000	40	230	375	2097
Abengoa-Mojave Solar	PT	250	USA	2012	575	1000	615000	28	850	0	2636
Abengoa-Beacon Solar	PT	250	USA	2012	502	1000	600000	27	814	0	2636
SM-Genesis	PT	250	USA	2014	550	1000	600000	27	850	0	2636
BS Ivampah Solar	T	440	USA	2012	229.6	1100	960000	25	1376	0	2636
Rice Solar	T	150	USA	2012	554	850	450000	34	571	1050	2636
SM-Blyth	PT	1000	USA	2016	2266	4000	2100000	24	3400	0	2636
SM-Ridgecrest	PT	250	USA	2013	567	1000	500000	23	850	0	2636
SM-Palem	PT	500	USA	2013	1117	2000	1000000	23	1700	0	2636

TABLE A.3. Recopilated information of solar photovoltaic plants

Name	Technology	Capacity *MW*	Country	Year	Cost *MM$*	Generation *MWh*	CF %	Area *ha*	Radiation $KWh/m^2 year$
Olmedilla de Alarcón	Poly-Si	60	Spain	2008	515.7	87,500	17	180	1,685
Puertollano	Poly-Si	47.6	Spain	2008	402.9	65,000	16	97	1,693
Arnedo	Poly-Si	34	Spain	2008	243.1	44,020	15	70	1,458
La Magoscona	1-Poly-Si	20	Spain	2008	201.5	40,000	23	100	1,704
Merida SPEX	2-Poly-Si	30	Spain	2008	335.8	63,000	24	195	1,722
Fuente Alamo	Mono-Si	26	Spain	2008	268.6	44,000	19	62	1,739
Almaraz	2-Poly-Si	20	Spain	2008	243	43,034	25	60	1,699
Moura	1-Poly-Si	46	Portugal	2008	350.5	93,000	23	250	1,766
Strakirchen	Poly-Si	54	Germany	2009	402.9	57,000	12	135	1,104
Lieberose	FS-CdTe	53	Germany	2009	214.9	53,000	11	162	1,014
Waldpolenz	FS-CdTe	40	Germany	2008	174.6	40,000	11	220	1,032
DeSoto	1-Mono-Si	25	USA	2009	150	42,000	19	70	1,885
SinAn	1-Mono-Si	24	Korea	2009	147.7	33,000	16	72	1,402
Monalto di Castro	1-Mono-Si	24	Italy	2009	201.5	40,000	19	80	1,536
Lucainena Torres	Poly-Si	23.2	Spain	2008	188	35,566	18	30	1,779
Abertura	2-Poly-Si	23.1	Spain	2008	302.2	47,400	23	178	1,710
Hoya Vicentes	1-Poly-Si	23	Spain	2008	201.5	41,600	21	100	1,716
Mengkofen	Poly-Si	21.7	Germany	2009	93.31	22,811	12	79	1,109
El Coronil 1	1-Poly-Si	21.4	Spain	2008	152.5	40,000	21	90	1,761
Beneixama	Poly-Si	20	Spain	2007	167.9	30,000	17	50	1,694
Olivenza	1-Mono-Si	15	Spain	2008	201.5	32,000	24	70	1,751
Gochang	1-Mono-Si	15	Korea	2008	100	23,500	18	39	1,382
Nellis	1-Mono-Si	14	USA	2007	100	30,000	24	56.6	2,051
Taean	Mono-Si	1.59	Korea	2009	9.4	2,256	16	3.8	1,196

TABLE A.4. Recopilated information of solar photovoltaic plants 2

Name	Technology	Capacity *MW*	Country	Year	Cost *MM$*	Generation *MWh*	CF %	Area *ha*	Radiation $KWh/m^2 year$
Guadarranque	1-Mono-Si	13.6	Spain	2008	120.9	24,000	20	37	1,792
Las Gabias	2-Poly-Si	18	Spain	2008	193.4	34,000	22	111	1,825
Sierresita	Poly-Si	10	Spain	2009	80.6	17,571	20	36.4	1,779
Cortijo Viejo	Poly-Si	10	Spain	2009	80.6	16,430	19	41.9	1,779
El Realengo	Poly-Si	6.1	Spain	2008	48.3	9,000	17	11.2	1,730
Alconchel	Poly-Si	10	Spain	2008	87.3	15,350	18	40	1,758
Figueruelas	Poly-Si	10	Spain	2008	67.2	15,100	17	18.3	1,525
Arroyo San Serván	Poly-Si	10	Spain	2008	80.6	17,900	20	35	1,728
Belmez	Poly-Si	10.856	Spain	2008	99.4	16,167	17	30	1,760
Corella	2-Poly-Si	10.81	Spain	2008	103.7	16,500	17	50	1,465
Benahadux	Poly-Si	10.6	Spain	2008	91.5	16,400	18	36	1,777
Brdenas	2-Poly-Si	10.11	Spain	2008	101	15,410	17	50	1,477
Calama Solar I	1-Mono-Si	9	Chile	2010	40	27,500	31	65	2,416

APPENDIX B. ANNUAL OPERATION AND MAINTENANCE COST ECONOMETRIC ANALYSIS RESULTS

$$O\&\text{M Cost} = \beta_0 + \beta_1 \cdot Generation + \beta_2 \cdot CapacityFactor + \beta_3 \cdot Year + \\ + D_{Technology} \tag{B.1}$$

where:

TABLE B.1. Coefficients for O&M Cost regression

β_0	5913.195
β_1	0.0000135
β_2	61.96676
β_3	-2.945363

$$D_{Technology} = \begin{cases} 0 & \text{if Parabolic Trough} \\ -6.282042 & \text{if Fresnell} \\ -8.946752 & \text{if Stirling Dish} \\ -9.899304 & \text{if Solar Tower} \end{cases}$$

TABLE B.2. Anova Table for Annual Thermal O&M Cost Regression Model

Source	SS	df	MS
Model	218.72583	6	36.454305
Residual	9.49598714	4	2.37399678
Total	228.221817	10	22.8221817

TABLE B.3. Overall Model Fit for Annual Thermal O&M Cost Regression Model

Number of Observations	11
F(6,4)	15.36
Prob > F	0.0098
R-squared	0.9584
Adjusted R-squared	0.896
Root MSE	1.5408

TABLE B.4. Parameter Estimates for Annual Thermal O&M Cost Regression Model

Variables	Coefficient	Std.Err	t	P>|t|	Beta
Tech.Fresnell	-6.282042	2.033416	-3.09	0.037	-0.3964842
Tech.Stirling	-8.946752	2.008919	-4.45	0.011	-0.7575769
Tech.Tower	-9.899304	1.750641	-5.65	0.005	-0.8382354
Year	-2.945363	.7909251	-3.72	0.020	-0.8478043
Capacity Factor	61.96676	21.51171	2.88	0.045	0.401898
Generation	0.0000135	2.06e-06	6.55	0.003	1.711879
Constant	5913.195	1589.746	3.72	0.020	.