MSc Program
Renewable Energy in Central and Eastern Europe

On the technical and economic feasibility of PV systems with storage to support electricity supply for mining utilities in Chile

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Affidavit

I, JOAQUÍN HERNÁNDEZ HERRERA, hereby declare:

1. that I am the sole author of the present Master Thesis, "***On the technical and economic feasibility of PV systems with storage to support electricity supply for mining utilities in Chile*** ", 141 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and

2. that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

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*To Gabi, who made this possible and
is always there… always.*

Abstract

Chile's economy, as one of the main mining countries in the world, is quickly growing. However this growth finds the handicap of the already high and increasing cost of electricity due to the convergence of different political, geographical and meteorological factors. This quick increase of electricity cost is affecting the competitiveness of their raw material and compromising the economic growth. This work intends to present hybrid systems as a feasible alternative to the traditional thermal generation of electricity in the mining sector, mainly based on diesel generators in certain areas. As a result, it is shown that a proper and optimized integration of photovoltaic with storage and diesel generators represents an improvement in the system from the economic, technical and environmental point of view to both, bringing additional value to investors and mining companies. To support the analysis it will be presented a general case study, describing a hypothetical copper mine where photovoltaic and storage is combined with existing diesel generators. Sensitivity analysis involving the main parameters and variables are presented to discuss the results.

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List of acronyms

AC	Alternate Current
a-Si	Amorphous Silicon
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
CNE	Comision Nacional de la Energia *(National Commission of Energy)*
Codelco	Corporación del Cobre de Chile *(Cooper Corporate of Chile)*
DC	Direct Current
DoD	Depth of discharge
Enami	Empresa Nacional de Minería *(National Mining Company)*
ESA	Energy Storage Association
EPC	Engineering, Procurement and Construction
IPP	Independent Power Producer
IRR	Internal Rate of Return
JRC	Joint Research Centre
kMT	Kilo-Metric Tons (thousands of Metric Tons)
LCOE	Levelized Cost of Energy
Mono-Si	Mono-crystalline Silicon
MT	Metric Ton
NCRE	Non-conventional Renewable Energies
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
Poly-Si	Poly-crystalline Silicon
PPA	Power Purchase Agreement
PV	Photovoltaic
RES	Renewable Energies
SCADA	Supervisory Control and Data Acquisition
STC	Standard Conditions
UPS	Uninterruptible power supply
WACC	Weighted Average Cost of Capital

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1 Introduction

In the near future energy storage will play a key role in all countries to enable them to develop low-carbon policies. It will enable to increase the capacity of the already collapsed electricity grid system. Energy storage can supply more flexibility by balancing the grid and providing a back-up to intermittent renewable energies. It improves the management of distribution networks as well as reducing costs and improving efficiency of the grid.

It can also improve the efficiency of traditional systems of generation such as diesel generators. Working as a buffer to absorb instant unbalances of micro-grids, it allows diesel generators to work in a nominal charge, avoiding the start-stop process.

The most interesting application though, is to produce the energy when available and consuming it when necessary. This load shifting concept represents the core principle of the growing interest to use storage in combination with intermittent renewable energies like photovoltaic or wind.

In the past and for many years, the use of storage for electricity was almost exclusively consisting on pumped hydro and to small battery systems, mainly for the mobility sector (lead-acid batteries) and electronic devices (Li-ion batteries). However nowadays, due to the development of other technologies, the decrease in their costs, the increasing cost of fossil fuels, the increasing share of intermittent renewable energies to be integrated in the system and the necessity to better match the available energy and demand in a short term, other solutions become more and more attractive for all parties: investors, utilities and final users.

One of the applications with potential where this win-win situation can be achieved is the mining sector in Chile. A combination of high prices of the energy, high sunlight resources and the presence of remote areas with high energy consumption, where a weak and saturated electricity grid system arrives only after covering many kilometers and collecting many losses, represents the perfect combination to deploy and develop this kind of symbiosis between renewable energy and storage.

This work intends to give an overview on the energy situation of the energy market in Chile and its repercussion in a key sector for the economy, the mining sector, and to present the inclusion of photovoltaic energy integrated with storage not only as a potential improvement in terms of reliability, dispatchability but also from an economic point of view by decreasing the global levelized cost of energy and by bringing additional value to a project. With that purpose, it will be defined as a case study to examine the technical and economic feasibility of combining photovoltaic and storage in the Northern region of Chile to support the energy intensive activity of extracting and refining copper.

1.1 Motivation

In the 1920s, Thomas Edison, in conversation with Henry Ford and Harvey Firestone mentioned:

> "*When we learn how to store electricity, we will cease being apes ourselves. Until then, we are tailless orangutans.*
>
> *You see, we should utilize natural forces and thus get all of our power. Sunshine is a form of energy and the winds and the tides are manifestations of energy.*
> *Do we use them? Oh, no! We burn up wood and coal as renters burn up the front fence for fuel. We live like squatters, not as if we owned the property.*
> *I hope we don´t have to wait until oil and coal run out before we tackle that"…*

(Strategen - Strategy for Clean Energy, 2013)

Nowadays we have the technology and the know-how to fulfill Mr. Edison´s visions, but even more important is that we have the necessity to do it. With a big increase of the intermittent renewable energies, a rising price of conventional fossil fuels and an electricity system almost collapsed in some areas with long distances for energy transportations and a huge carbon footprint, it is mandatory to approach the concept of hybrid systems. The concept of hybrid system involves a combination of different technologies working together in a symbiosis to achieve a final target, generally to cover the electricity demand in a more efficient way. This symbiosis between technologies includes renewable energies, such as photovoltaic and energy storage systems.

1.2 Objectives

The core objective of this work is to answer the following question: Is it feasible from a technical and economical point of view to substitute conventional fossil systems with RES in a steady and reliable way for a specific application? In particular, is it feasible to substitute diesel generators, totally or partially, with PV supported by storage for the mining activity in Chile? If yes, in which proportion can it be substituted in a feasible and cost-efficient way?

From the economical point of view, the concept of “cost-effectiveness” in this work is related to the combination of diesel generation, photovoltaic and energy storage that represents the lowest levelized cost of energy for the system.

An eventual substitute to conventional generation must comply with the following requirements:

- ***Necessary:*** there must be a reason or driver to carry on the project. The new solution must present an added value to existing solutions

- ***Reliability:*** is the ability of a system to perform and maintain its functions in routine circumstances as well as in hostile or unexpected circumstances

- ***Dispatchability*** refers to sources of electricity that can be instantly dispatched at the request of power grid operators. That is, generating plants that can be turned on or off, or can adjust their power output on demand

- ***Feasibility:*** the potential that the system presents must be technically possible and economically convenient

- ***Quick reaction:*** in case of necessity, the system must react in seconds or even milliseconds to fulfill the demand and absorb instant unbalances of the system.

The intention of this work is to cover all these points and show that a combination of PV and storage in the mentioned application can achieve the fulfillment of all of these requirements and present it as a feasible alternative to conventional generation systems based on fossil fuels, bringing additional value to a project.

1.3 Methodology, main literature and tools

As any thesis, this is the result of an extensive research in different books, articles and websites, but also my own experience from working seven years in the PV sector is incorporated here. As main references the following can be cited:

- Huggis, Robert A.: Energy Storage. Springer, 2010: description and analysis of the main energy storage systems

- Luque, A. and Hegedus, S.: Handbook of Photovoltaic Science and Engineering. Wiley, 2008: extensive work about photovoltaic, including deep analysis of most topics relating that science

To support the study and calculations, three main tools have been used, all of them commercially available:

- SOLARGIS radiation database

- PVSYST 5.62 from the University of Geneva to simulate PV installations

- Microsoft Office EXCEL 2010

The idea is not to present a real case study and develop a solution for that specific case, but rather to present a general problem statement and define a possible line of action against that problem. To support the analysis, the solution will be applied to a general case study, where certain assumptions will be taken and duly explained. This general case study tries to be representative of the situation of the mining activity in the North of Chile.

1.4 Structure of work

This work is divided in three different parts. A first part, including chapters 2 and 3 presents a general description of the Chilean framework with detail descriptions of the electrical market in that country and the situation of the main mining activities.
In sections 4 and 5 there is a breakdown of the technical approach to the topic of hybrid systems as a specific combination of photovoltaic and energy storage, and

the possibility to support the mining activities with this system, giving a global overview of the technologies and solutions available. This approach is widely developed in section 6, where the main study is carried out and final results for the case study are presented, including the sensitivity analysis of the main variables.
At the end, a conclusions' section summarizes the outcomes of the work.

2 Background: The electricity market in Chile

The electrical market in Chile includes the activities of generation, transmission and distribution of electricity throughout the country. Those activities are performed by companies controlled with 100% private capital. In fact, Chile was a worldwide pioneer to liberalize the electrical market in 1982 (Roman, 1999). The State only performs activities of regularization, inspection and planning. In the electric sector around 40 generation companies are participating, 10 of transmission and 31 of distribution, which cover the total electricity demand. In 2007 for instance this total demand was of 52.961,8 GWh (CNE, Market description).

2.1 Description of the electrical system

The electrical system in Chile is divided into four sub-systems: Sistema interconectado del Norte Grange *(Northern Interconnected System, SING),* Sistema interconectado Central *(Center Interconnected System, SIC),* Sistema de Aysén *(Aysén System)* and Sistema de Magallanes *(Magallanes System*). The figure below (CNE, 2009) describes the four systems by regions and capacity

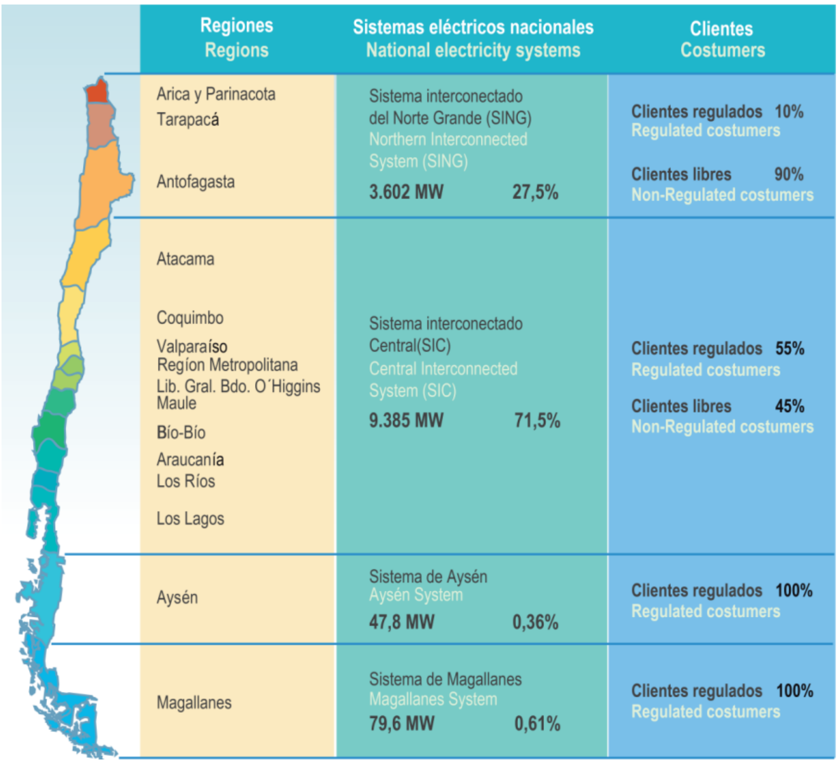


Figure 2.1: Electrical system in Chile and production capacity in 2008

Source: (CNE, 2009)

In terms of electricity generation, around 99% of the facilities are located in the SING and SIC regions where 93% of the population and industrial areas are located (CNE, 2005). Table 2.1shows their historic of generation in the period 1996-2012.

Table 2.1: Historic of Generation (in GWh) in the SING and SIC in the period 1996-2012

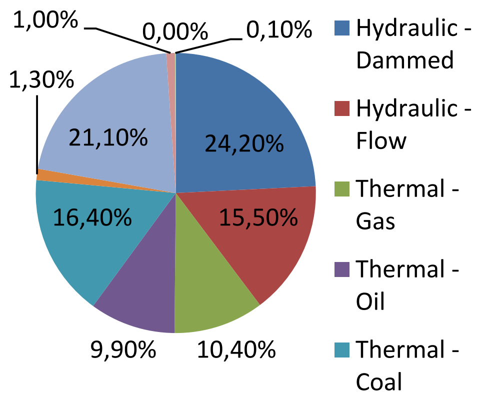
TOTAL SIC-SING	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
HYDRO - DAMMED	11.735	13.194	10.253	7.938	12.221	13.975	14.682	14.225	13.727	17.941	20.072	14.542	15.312	16.038	13.208	12.886	12.054
HYDRO - FLOW	4.278	4.798	4.885	4.879	6.285	7.083	7.842	7.641	7.161	7.495	7.995	7.685	8.258	8.518	8.047	7.697	8.069
GAS	0	42	3.775	6.476	9.949	12.729	12.440	15.956	17.508	14.651	12.230	5.822	2.938	3.958	5.122	4.218	2.356
GNL	-	-	-	-	-	-	-	-	-	-	-	-	-	980	6.233	9.935	10.101
COAL-PETCOKE	1.515	1.830	2.450	7.711	6.080	4.651	5.527	5.474	4.092	5.438	5.668	5.551	5.521	6.153	5.966	5.043	5.029
COAL	4.313	2.563	2.893	5.322	3.346	1.621	1.375	1.309	5.312	3.378	6.428	9.165	9.765	9.583	11.606	16.441	21.828
WASTE	238	653	813	914	616	387	374	432	646	474	570	744	884	966	841	928	1.828
DIESEL	89	582	357	2.156	213	48	17	8	60	1.130	443	11.805	13.076	9.953	6.514	4.080	3.609
FUEL	0	0	0	298	76	43	12	12	24	57	52	561	491	332	280	274	216
DIESEL-FUEL	191	124	164	163	12	1	1	1	57	8	44	43	31	92	115	70	48
WIND	-	-	-	-	-	-	-	-	-	-	-	3	31	71	325	324	383
SOLAR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
COGENER	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	25
TOTAL	22.359	23.787	25.590	35.858	38.798	40.538	42.269	45.055	48.589	50.572	53.502	55.920	56.307	56.644	58.257	61.934	65.547

Source: Own elaboration with data from CNE (CNE, 2013)

For the particular case of 2007, table 2.2 shows the generation distribution in each region of Chile, chosen as an example of the situation in a period of energy crisis. This year was the most critical after the crisis of 2006, when Argentina decided to cut radically the natural gas exports to Chile. This fact will be further discussed in the next chapter.

Table 2.2: Installed capacity (MW) and energy generation (GWh) in 2007

Type of generation	GWh	%
Hydraulic - Dammed	14.541,85	24,20%
Hydraulic - Flow	7.684,95	15,50%
Thermal - Gas	5.821,60	10,40%
Thermal - Oil	5.551,30	9,90%
Thermal - Coal	9.162,40	16,40%
Waste	744,2	1,30%
Thermal Diesel	11.805,10	21,10%
Thermal Fuel	561	1,00%
Thermal Diesel-Fuel	42,6	0,10%
Wind	2,8	0,00%
Total	**55.920,00**	**100,00%**



Source: Own elaboration with data from (CNE, 2009)

As conclusion of those numbers the following can be pointed out:

- The SING system is completely based on fossil fuel. Around 90% of the customers are non-regulated and get their contracts via PPAs with the electricity generators. Prices are highly attached to the cost of fossil fuels like coal, natural gas and oil and to the political situations in the exporting countries.

- The SIN system presents a higher diversification with a significant presence of hydro generation. This has a big impact in the electricity price, since it is extremely subjected to the rain seasons. In periods of drought the prices can rise drastically.

- Magallanes and Ayrés systems are both very small and do not represent a significant impact in the global situation of the country.

Figure 2.3 shows the distribution of the main generation centers in the country, including all the technologies presently used. As it can be observed, the north of the SIC is integrated exclusively by thermoelectric diesel facilities. This is one of the reasons why it will be chosen as the location for the case study later on in section 6.

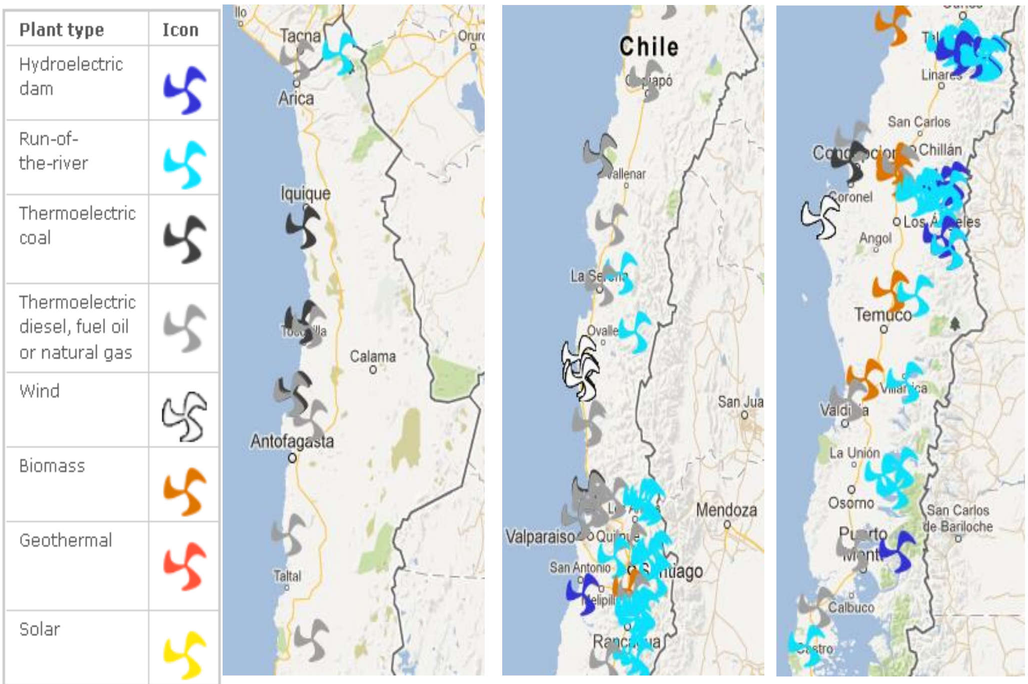


Figure 2.2: Distribution of main generation centers in Chile

Source: (Centralenergia.cl)

2.2 The problem of the electrical market

Due to its geographical condition, thin but long shape and extremely intensive industry (mainly mining), Chile must face certain problems in its energy sector. Some of these have been already anticipated in previous points (reference where did you mention them):

2.2.1 Centralized production with long-distance transmission lines

With about 4.500 Km of longitude, it covers from parallels 17º 30´ to 55º 59´. It has around 360 Km width at the thickest point and a total surface of 756.096.30 km^2 (Wikipedia), Chile is by far the slenderest and slimmest country on earth. This presents a handicap for the generation strategy in the different areas and for the interconnection between them, making it extremely challenging to set up a steady and reliable transmission grid. Figure 2.4 below shows in a schematic way the configuration of the current transmission grid.

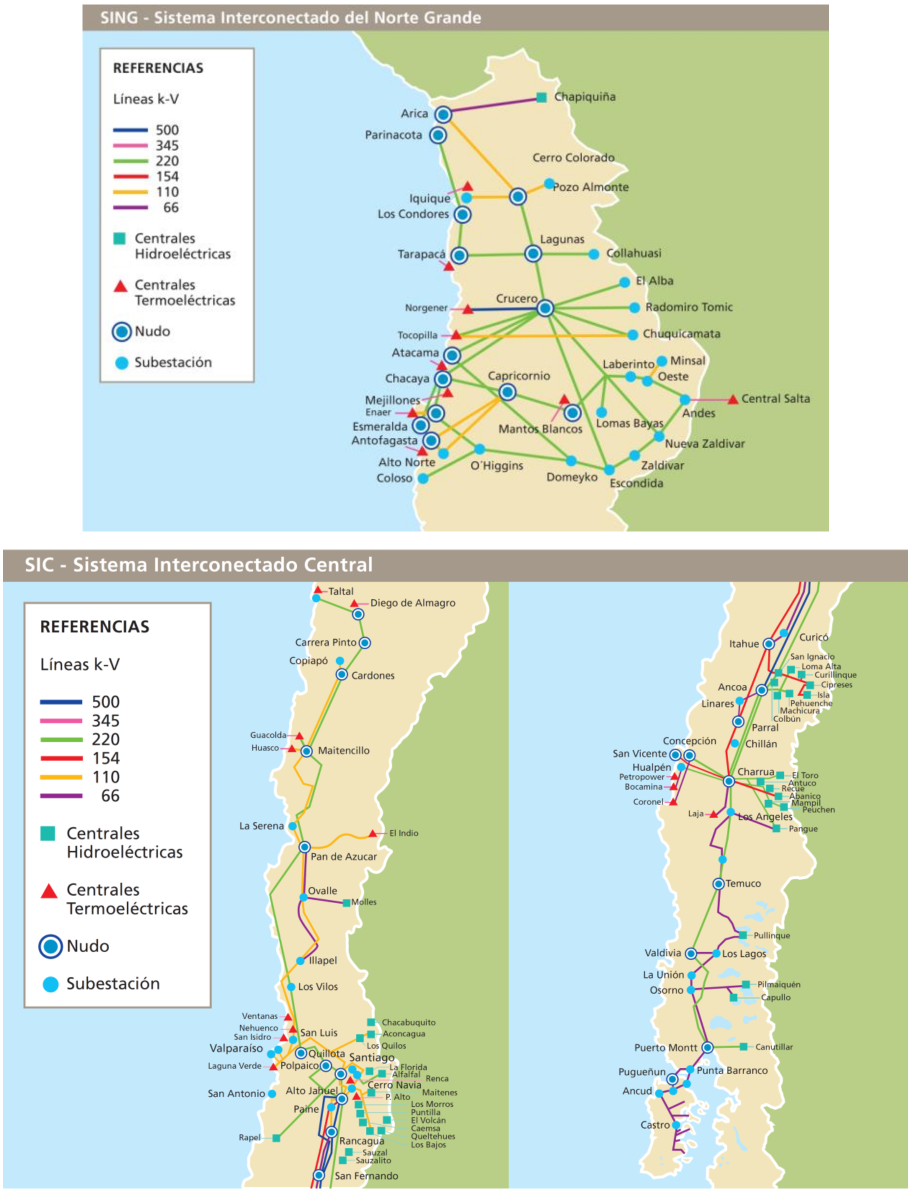


Figure 2.3: Simplified scheme for the SING and SIC transmission line

Source: (CNE, 2005)

The transmission system consists mainly of a 220kV core line and several branches that connect the generation centers, mainly on the coast, with the main cities and mines in the interior. This configuration presents two main issues: weak reliability and high losses. Especially in the SING system it can be seen that a failure in the core 220 kV line would affect the supply service of the complete system in the North. An example of how necessary it is to reinforce the grid system and how long it takes and how hard it is to get it, is the region of Chuquicamata, where the biggest open cast mine in the world is located. Due to the importance for the economy of the activity in this region an additional 110kV line was built from the Tocopilla central to Chuquicamata to reinforce the grid and prevent blackouts. The first studies to build this line were carried out in 1980, and the project was finally executed and commissioned on November 1987, almost 8 years later (CDEC - SING, 2005)

Of relevant importance is also the fact that up to this day, there is no interconnection between the SIC and the SING systems, and they are still operating as completely independent systems. This gives an additional idea of the rigidness of the transmission system and the necessity to integrate flexible and decentralized solutions close to the main consumption centers.

2.2.2 Strong dependency of external factors

As already mentioned, the Chilean electricity sector was pioneer in establishing in 1982 competitive conditions in the generation and sale of electricity. Additionally, private investments in generation, transmission and distribution led to significant expansions in the capacity of each of the electricity systems. However, the regulatory framework of the sector has shown significant weaknesses which became clear when particular situations and handicaps happened:

- A severe drought in the late 1990s resulted in electricity rationing

- The unexpected restrictions in the supply of natural gas from Argentina from 2006 onwards

- Low rainfall period of recent years: around 40% of the electricity generated and consumed in Chile comes from hydro systems. A drought period has a strong impact in the price of the electricity, especially in the SIC region, where the main populated areas are located

To face them Chile has undergone a transition to generation by power plants mainly based on coal and diesel. Thus, the strategy has come to increasingly relying on fossil fuels. This was the sector's response to the complex energy situation that Chile had to face over the last decades, but it was not the result of a long-term strategy or plan. In addition, the temporary dependence of the market on certain sources of fuel, (Argentine gas for instance) resulted in the lack of consideration of long-term guidelines or the expansion of other sources of generation when planning and developing the transmission infrastructure. Figure 2.5 shows the significant impact on the share of energy production of these factors in the generation map of the last years: after the crisis of 2006, a significant decrease in natural gas and increase in oil and derivatives can be observed.

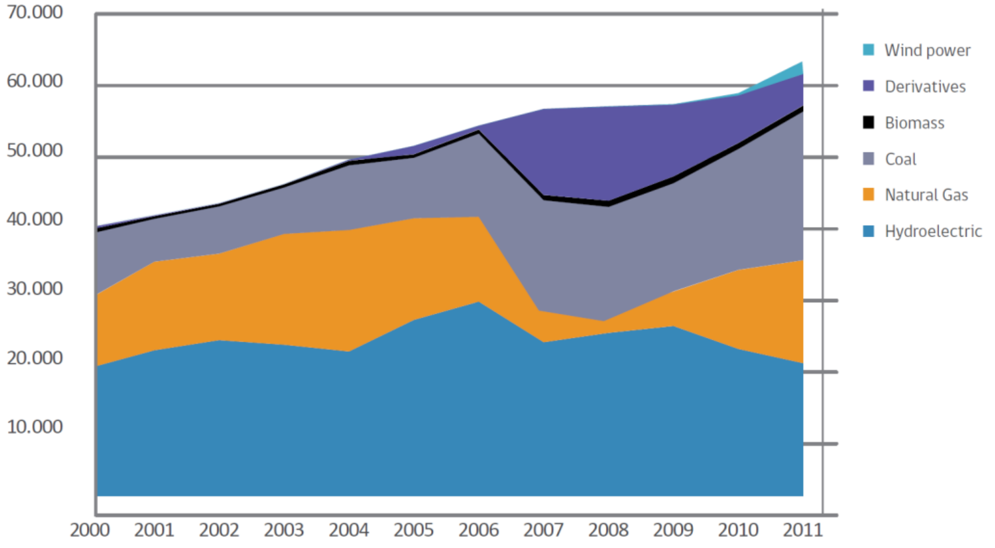


Figure 2.4: Gross generation distribution (GWh) for SIN and SING in the period 2000 - 2011

Source: (Ministery of Energy, 2012)

The combination of those events resulted in a dramatic increase of electricity prices and a loss of general competitiveness in the country, due to the restrictions and necessity to utilize more expensive (and more contaminating) sources of energy and to increase the imports to cover the rising electricity demand. Figure 2.6 shows the high values (in $/MWh) that the energy prices have reached during the last years after the crisis.

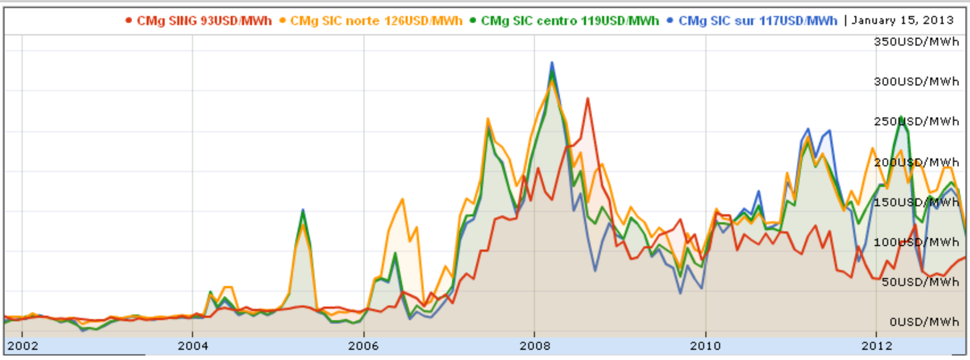


Figure 2.5: Price evolution in the SIN and SING systems

Source: (Centralenergia.cl)

Therefore, Chilean society began to show increased concern about the configuration of the electricity system forcing the government to react and develop a long term strategy that is more cost efficient and environment-friendly. The reply of the government to this request was the National Energy Strategy 2012 - 2030 (Ministery of Energy, 2012)

2.3 Energy strategy

To face the problem of the energy sector, Chile has developed a national strategy with strong investments, education of the population and a new orientation. This strategy has five main pillars (Ministery of Energy, 2012)

1. Growth of the energy efficiency: An extensive campaign is being carried out to make aware and educate people of the necessity to save energy and to use it more efficiently. This campaign includes efficiency labeling for electrical devices and houses, improvements on the public lighting, environmental certifications for companies (ISO 5001) and the creation of an Energy Efficiency Committee inside the ministry.

2. Promotion of conventional and non-conventional RES: In the National Energy Strategy 2012 – 2030 report the government has clearly declared their affinity for RES. Their intention is to promote clean energies in order to decrease the CO_2 footprint and the environmental effect of conventional fossil fuel systems. The Law 20.257 to promote Non-Conventional

Renewable Energy sources sets a target of 10% for NCRE by 2024 (Ministery of Energy, 2012)

3. Traditional energy generation: Despite this commitment towards the RES, it is assumed that they cannot supply the total of energy needed and cannot cover the expected increase of the demand in the next years, which is expected to be very intense (figure 2.7)

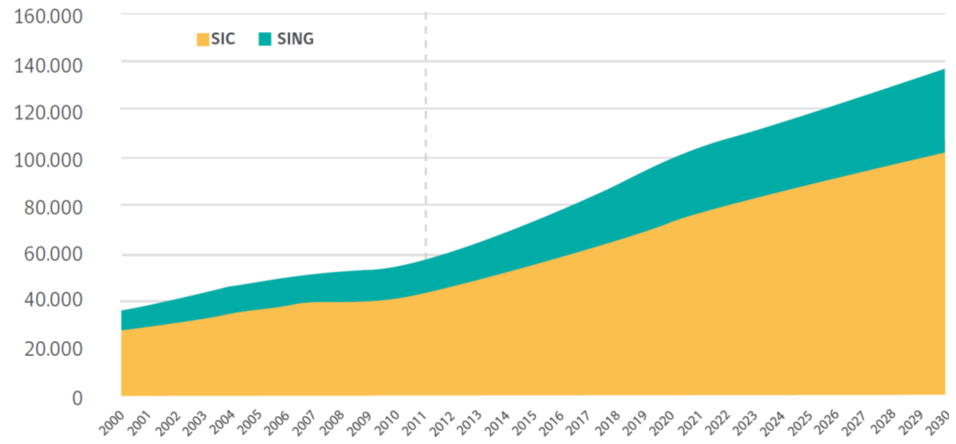


Figure 2.6: Electricity demand (GWh) growth expected until 2030 by the CNE in Chile

Source: (Ministery of Energy, 2012)

Therefore traditional systems are also supported and new conventional systems, especially for coal, will be built in the next years. In fact new generation facilities based on coal fuel have been already announced with a total of 1.225 MW: Punta Alcalde (740 MW), Central Pacífico (350MW) and Central Patache (135MW) (Ministery of Energy, 2012)

4. New focus for transmission: big investments are being carried out in order to renew and upgrade the transmission line between the SIC and SIGN system. On 30th of August 2012 the president announced an investment of US$ 700 million to build a new line that will connect the nodes of Encuentro (SIGN) and Cardones (SIC) to reinforce the week transmission grid between North and South, where the main hydro generation systems are

5. Increase competitiveness: The government wants to make the market more competitive by controlling the different players.

3 General description of the mining sector in Chile

As one of the main mining countries in the world, Chile comes in the top of several worldwide rankings of production of crucial raw materials for the worldwide economy. Table 3.1 shows the ranking of Chile in the production of several minerals, metallic and non-metallic together with its worldwide share.

Table 3.1: Participation of Chile for some elements in the worldwide production

Mineral	Production (2007)	Worldwide production share	Worldwide reserves share	Ranking
		METALLIC		
Copper (MT)	5.557.000,0	35,8%	38,0%	1º
Molybdenum (MT)	44.912,0	20,8%	13,0%	3º
Silber (MT)	1.936,5	9,8%	NA	4º
Gold (MT)	41,5	1,9%	NA	15º
		NON-METALLIC		
Nitrates	1.160.384,0	1,0	1,0	1º
Iodine	15.473,0	0,6	0,7	1º
Lithium	55.452,0	0,4	0,4	1º

Source: http://www.cochilco.cl/atencion_usuario/chile_mineria.asp

It has also been ranked in the third position as one of the main mining destinations in the world for investors based on the following criteria (Behre Dolbear, 2012):

- the country's economic system
- the country's political system
- the degree of social issues affecting mining in the country
- delays in receiving permits due to bureaucratic and other issues
- the degree of corruption prevalent in the country
- the stability of the country's currency
- the competitiveness of the country's tax policy

The mining sector is mainly based on the production of copper, gold and silver, with the parallel production of other sub-products such as Molybdenum, nitrates, Lithium, etc. The global mining activity represents a 38,5% of the PIB (table 3.2), what is by far the most important source of incomes and growth of the country. On 5th of March 2013, the Central Bank of Chile announced on their monthly IMACEC report a growth of 6,7% of the PIB, which places Chile among the faster growing countries worldwide.

Table 3.2: Sector share of GDP at constant price of 2010 (%)

SECTOR ECONÓMICO / Sector of Economy	2003	2004	2005	2006	2007	2008	2009	2010
AGROPECUARIO-SILVÍCOLA / Agriculture, Livestock and Forestry	3,6	3,3	3,2	2,8	2,8	2,7	2,7	2,5
PESCA / Fisheries	1,2	1,0	1,0	1,0	0,8	0,6	0,7	0,6
MINERÍA / Mining	8,4	12,9	15,7	22,3	22,8	17,6	15,6	19,2
MINERÍA DEL COBRE / Copper Mining	7,0	11,6	14,1	20,6	21,1	15,5	13,5	17,4
OTRAS ACTIVIDADES MINERAS / Other Mining Activities	1,4	1,3	1,6	1,7	1,7	2,0	2,1	1,9
INDUSTRIA MANUFACTURERA / Manufacturing	16,4	15,9	14,9	13,5	13,1	12,4	12,5	11,1
ELECTRICIDAD, GAS Y AGUA / Electricity, Gas and Water	2,9	2,7	2,9	2,8	2,6	3,5	4,0	3,2
CONSTRUCCIÓN / Construction	6,9	6,3	6,1	6,2	6,4	8,0	7,5	7,9
COMERCIO, HOTELES Y RESTAURANTES / Commerce, Hotels and Restaurants	9,7	9,3	9,0	8,2	8,1	9,0	9,0	9,1
TRANSPORTE / Transport	6,9	6,9	6,3	5,5	5,2	5,2	5,5	5,7
COMUNICACIONES / Communications	2,3	2,1	2,0	1,9	1,9	2,0	1,8	1,6
SERVICIOS FINANCIEROS(2) / Financial Services	15,0	14,3	14,2	13,3	13,8	14,7	15,4	15,7
PROPIEDAD DE VIVIENDA / Home Ownership	5,8	5,3	4,9	4,5	4,4	4,7	4,8	4,2
SERVICIOS PERSONALES(3) / Personal Services	11,6	10,8	10,1	9,3	9,4	10,2	11,6	11,2
ADMINISTRACIÓN PÚBLICA / Public Administration	4,3	4,1	4,0	3,7	3,7	4,1	4,7	4,5
Subtotal	**95,0**	**94,7**	**94,3**	**94,9**	**95,0**	**94,6**	**95,9**	**96,6**
MENOS: IMPUTACIONES BANCARIAS / Less: Bank Charges	3,4	3,1	2,9	2,9	3,1	3,4	4,2	4,6
MÁS: IVA NETO RECAUDADO / Plus: Net VAT Revenues	7,4	7,5	7,8	7,3	7,3	8,1	7,8	7,4
MÁS: DERECHOS DE IMPORTACIÓN / Plus: Import Duties	1,0	0,8	0,8	0,7	0,8	0,7	0,5	0,6
PRODUCTO INTERNO BRUTO / Gross Domestic Product	**100,0**	**100,0**	**100,0**	**100,0**	**100,0**	**100,0**	**100,0**	**100,0**

Source: (Cochilco, 2011)

This fast growth is in a good way due to the fast growth of the mining sector and increase of production of the mines, which rises their production between 5 and 25% every year as presented in the next point

This involves also a strong increase of the general demand of energy, and electricity in particular, which worsens even more the already serious problem in the electricity sector.

3.1 Description of the most common activities

The main activities in the mining sector are the production of copper, silver and gold, which also generate other sub-products such as molybdenum, lead, zinc, iron, manganese and other non-metal components (iodine, lithium, nitrates, etc.). The largest mining areas are in the North of the country where the main copper mines are located.

Table 3.3: Mining production in kMT(thousands of Metric Tons) for metal elements 1991 – 2010

YEAR	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Copper (MT Fine Content)	1.814,3	1.932,7	2.055,4	2.219,9	2.488,6	3.115,8	3.392,0	3.686,9	4.391,2	4.602,0
Silver (Kg Fine Content)	676.339,1	1.024.822,7	970.067,9	983.004,7	1.041.097,5	1.147.002,4	1.091.311,4	1.340.199,1	1.380.711,4	1.242.193,5
Gold (Kg Fine Content)	28.879,4	34.472,7	33.637,5	38.785,9	44.585,4	53.174,1	49.459,0	44.979,7	48.068,8	54.142,6
Molybdenum (MT Fine Content)	14.434,0	14.840,0	14.899,0	16.027,7	17.888,5	17.415,0	21.339,4	25.296,9	27.308,6	33.186,8
Lead (MT Fine Content)	1.050,0	298,0	344,0	1.008,0	944,0	1.374,0	1.264,0	337,0	608,0	785,0
Zinc (MT Fine Content)	30.998,0	29.730,0	29.435,0	31.038,0	35.403,0	36.004,0	33.934,0	15.943,0	32.263,0	31.403,0
Iron (MT Ore)	8.414,4	7.224,0	7.379,0	8.340,5	8.431,6	9.081,7	8.738,2	9.112,1	8.345,0	8.728,9
Manganese (MT Ore)	43.767,0	49.857,0	62.989,0	62.870,0	70.449,0	62.887,0	63.673,0	48.931,0	40.505,0	41.716,0

YEAR	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Copper (MT Fine Content)	4.739,0	4.580,6	4.904,2	5.412,5	5.320,5	5.360,8	5.557,0	5.327,6	5.394,4	5.418,9
Silver (Kg Fine Content)	1.348.666,8	1.210.473,1	1.312.789,0	1.360.139,6	1.399.539,0	1.607.164,0	1.936.467,0	1.405.020,0	1.301.018,0	1.286.688,0
Gold (Kg Fine Content)	42.672,6	38.687,9	38.953,6	39.985,7	40.447,0	42.100,0	41.527,0	39.162,0	40.834,0	39.494,0
Molybdenum (MT Fine Content)	33.491,9	29.466,4	33.373,8	41.883,2	48.040,7	43.277,6	44.912,1	33.686,5	34.924,9	37.185,5
Lead (MT Fine Content)	1.193,0	2.895,0	1.697,0	2.286,0	878,0	672,0	1.305,0	3.985,0	1.511,0	695,0
Zinc (MT Fine Content)	32.762,0	36.161,0	33.051,0	27.635,0	28.841,0	36.238,0	36.453,0	40.519,0	27.801,0	27.662,0
Iron (MT Ore)	8.834,2	7.268,8	8.011,0	8.003,5	7.862,1	8.628,2	8.817,7	9.315,6	8.242,3	9.129,5
Manganese (MT Ore)	31.320,0	12.195,0	19.641,0	25.801,0	39.786,0	37.169,0	26.808,0	18.273,0	5.722,0	-

Source: Own production with data from (Cochilco, 2011)

They can be divided into three different sectors: grand mining, medium mining and small mining. The main companies, Codelco and Enami are 100% state-owned and together represented in 2012 around 32% of the total activities. The private sector is also present in all levels and it is linked to Enami by public-private agreements and supply contracts. In appendix 1 can be found a map with the location of the main mining centers in the country.

3.2 Electrical consumption of the mining sector

This intense mining activity and growth are only possible with intensive energy consumption. All processes involved in the material production, from the ore material until the fine raw material is dispatched require a vast amount of energy. In particular, the average electrical consumption is reflected in the table 3.4.

Table 3.4: Electricity use per ton of copper content (fine raw material) by process in MWh

PROCESS	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Extraction Open Pit Mine	0,124	0,135	0,151	0,163	0,178	0,171	0,172	0,182	0,203	0,174
Extraction Underground Mine	0,347	0,371	0,387	0,349	0,433	0,470	0,470	0,583	0,548	0,559
Weight average for extraction (open pit & underground)	0,158	0,172	0,187	0,191	0,214	0,211	0,210	0,225	0,244	0,215
Concentration Plant	1,698	1,912	1,982	1,929	2,011	2,062	2,184	2,280	2,515	2,485
Melting	0,971	1,026	1,053	1,066	1,048	1,050	1,080	1,101	0,981	1,039
Electrolitic Refining	0,346	0,345	0,344	0,355	0,353	0,343	0,339	0,357	0,349	0,364
LX / SX / EW	2,651	2,771	2,839	2,897	2,801	2,814	2,911	2,973	2,860	2,954
Services	0,146	0,154	0,139	0,143	0,160	0,140	0,123	0,155	0,171	0,189
TOTAL	**5,969**	**6,380**	**6,545**	**6,580**	**6,586**	**6,618**	**6,848**	**7,090**	**7,120**	**7,245**

Source: Own elaboration with data from Chilean Copper Commission, based on annual company survey ((Cochilco, 2011)

Thus, **7,245 MWh** of electricity were needed in average to produce refined copper in 2010 (this calculation takes into consideration the weighted average cost between pit and underground mining). Considering that the production that year was **5.418,9 kMT** (Cochilco, 2011), the total electricity consumption only for the production of copper (not considering production of other secondary sub-products) was **39.259,9 GWh.** Just to get an idea of the amount of energy that this represents, it can be considered that the total final energy consumed in the region of Vienna in 2011 (including agriculture, private households, industry, transport and service sector) was 37.763,9 GWh. Considering only electricity, the consumption in this region was 8.228,3 GWh, around five times lower (Statistics Austria).

It is clear that this consumption requires a huge infrastructure to support the complete system. In the next chapters a possible alternative to conventional generation systems to support this extensive energy need will be presented. This eventual alternative is based on the combination of NCRE, solar in particular, and a storage system with the idea to supply a clean, steady, reliable and dispatchable source of energy. It is important to consider at this point that by no means the intention of this work is to promote the complete and total substitution of conventional generation based on fossil fuels, but rather to present a mechanism to optimize the system, improve the global efficiency, bring the total LCOE down and to reduce the carbon footprint of this energy intensive activity. Further the different possible configurations, feasibility, technical aspects and economics of a general case study will be examined.

3.3 CO_2 emissions and carbon footprint of the copper mining sector

In their report “Consumo de Energía y Emisiones de efecto Invernadero en al Minería del Cobre, 2001 – 2011” *(Energy Consumption and Greenhouse Gases in the mining sector in Chile),* the “Comision Nacional del Cobre” of Chile *(National Commission of Copper)* issues the information summarized in figure 3.1 and table 3.3.

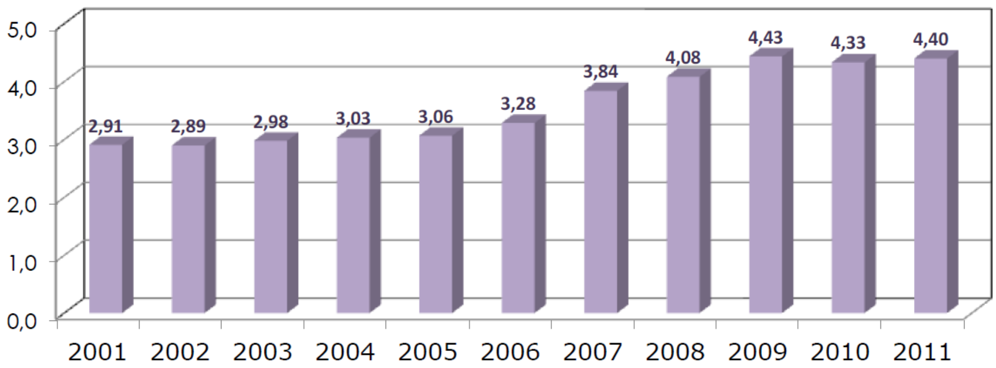


Figure 3.1: Evolution of the direct emissions of GEI (millions of MT CO2eq.) from the copper mining activity between 2001 and 2011

Source: (Betancour, 2012)

Figure 3.2: Annual energy consumption per type (Petajoules) and copper production (kMT)

Energy	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	% (2011)
Fuel	39,0	38,3	40,8	42,5	42,0	44,3	52,9	57,0	64,4	60,6	65,7	47,75
Electrical Energy	47,2	49,5	53,9	58,1	58,8	59,7	63,9	64,7	68,3	68,9	71,9	52,25
Total	**86,2**	**87,8**	**94,7**	**100,6**	**100,8**	**104,0**	**116,8**	**121,7**	**132,7**	**129,5**	**137,6**	**100,0**
Cu Production (kMT ref mat)	4.739	4.581	4.904	5.413	5.321	5.361	5.557	5.330	5.390	5.419	5.263	

Source: (Betancour, 2012)

Taking 2011 as a reference, we get the following conclusions:

- For a total production of 5.263 kMT of copper, a total of 4,40 millions of MT of CO_2 eq. split into 47,75% from fuels and 52,7% from the electricity generation was generated and emitted.

- This represents **0,836 MT CO_2 eq./ MT of copper**

- Considering only the 52,25% part from the generation of electricity, means 0,437 MT CO_2 eq./ MT of copper

- Considering the 7,245 MWh/MT energy required per MT of refined material, that is an average of **60,29 kg CO_2 eq/ MWh** of electricity generated from the mining activity.

4 Hybrid systems

When talking about electricity generation, a hybrid system is a combination of different sub-systems that interact together to cover the energy demand. Each of these sub-systems is usually integrated by different technologies. Although the design, installation and operation of hybrid systems can be extremely complex and a real challenge from the engineering point of view (especially on regard of the control and monitoring of the activity), the idea behind is quite simple: use the cheapest energy available in each moment to cover the load of demand in that moment.

The proposed hybrid system in this paper is a combination of diesel generation in their different modalities (continuous, prime and standby versions), photovoltaics and storage systems. During the day, when sunlight as a resource is available, the energy coming from the PV system with the support of storage as a buffer to absorb fluctuations and mismatches between generation and demand (some disperse clouds, peaks of demand, etc) can be used, having the expensive diesel generation only as a backup. During the night, the load of demand can be covered with the energy from the storage while available, and eventually with the diesel generators when none of the other sources, PV or storage are available anymore.

The design, optimization, feasibility, economics and penetration of renewable energies, solar combined with storage in this case, will be further discussed in section 6.

Figure 4.1 shows a general configuration with different technologies integrated into a global system. Wind, PV, batteries and a diesel generator are integrated, interconnected and monitored together with the purpose to dispatch electricity to the grid.

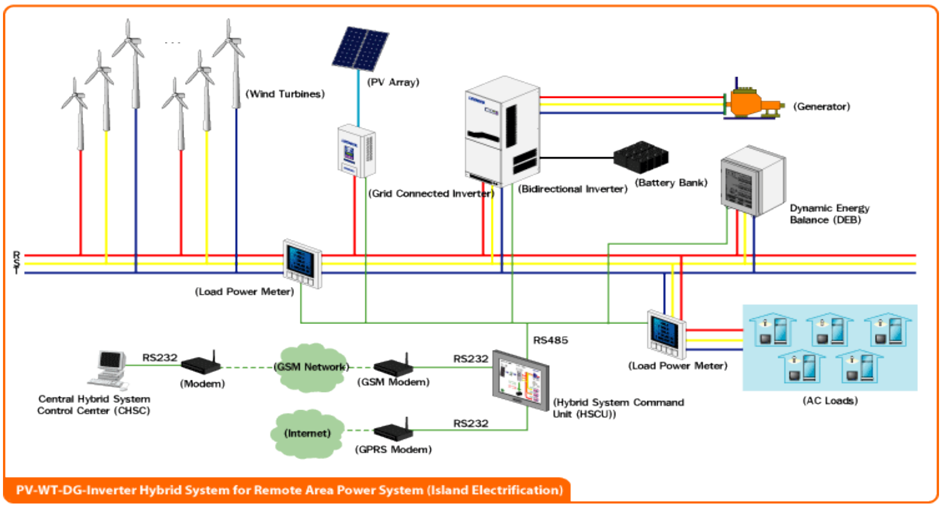


Figure 4.1: Example of configuration for a Hybrid System with Wind, Solar PV, Diesel generation and storage

Source: www.Leonics.com

In this chapter it will be presented a brief description of the different types of diesel generators and the most important and relevant PV technologies available. It will also be introduced the different technologies for the balance of system (BOS) to support the electricity production, to know, mounting systems, converters, monitoring and control units. The issue to solve is what would be the best combination of components and design that optimizes the system for a specific application?

There are several types of **diesel generators** depending on what kind of service they have to provide: stationary and steady, or rather following changing loads. The diesel engine operates in different regimes while activating the coils of an electric generator to supply the needed electricity.

The photovoltaic concept is also rather simple: the energy content in photons of the sunlight is transformed into electricity by means of the photovoltaic effect. **Photovoltaics** is the technology that generates direct current (DC) electrical power measured in Watts (W) from semiconductors when they are illuminated with light. As long as it is available, electrical power is generated (Luque & Hegedus, 2008). This transformation occurs in the solar cells that are grouped and connected in solar modules.

On the other hand, choosing the right technology for each application is not so simple, since many variables and parameters must be considered: economics, technical feasibility, environmental, dust, corrosion, degradation, layout design, land available, etc.

4.1 Modules technologies

In photovoltaics, when discussing about the different module technologies and comparing them, there are certain parameters to be taken into consideration:

- ***Nominal power*** of the modules is measured and given by the manufacturer in so-called standard conditions (STC): a temperature of 25ºC, an irradiance of 1000W/m^2 and an air mass (spectrum) of 1,5. Usually this power is referred as "peak power" of a PV module or PV installation, and it is expressed in Wp, kWp, etc. Although the International System of Units does not permit to use additional suffixes or symbols, this is a colloquial way to identify the nominal DC power of a module.

- ***Efficiency:*** It is the ratio between the electrical energy generated by the solar modules and the solar energy radiating on the total of the surface of the module. It is expressed in % and is calculated as

$$\eta = \frac{Pstc}{Am * Gs}$$

Being $\boldsymbol{P_{stc}}$ the power delivered by the module in STC in W, $\boldsymbol{A_m}$ the area of the module in m^{2}and $\boldsymbol{G_{std}}$ the solar irradiance in standard conditions and equal to 1000 W/m^2. As shown in figure 5.1, the efficiency of the solar cells that integrate the solar modules depend on the technology, and have been suffering a strong evolution from the origins of the photovoltaics, achieving current values approx. 44,1% for experimental concentration cells.

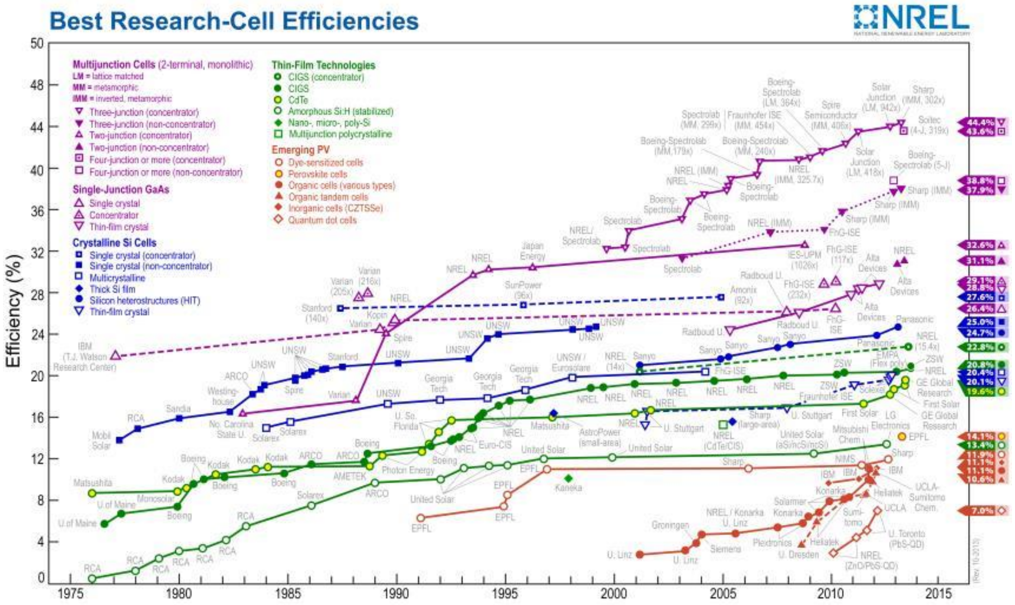


Figure 4.2: Evolution of the efficiency of solar cells of different technologies

Source: (NREL: Efficiency Chart) http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

- ***Coefficient of temperature***: solar cells, and therefore modules, suffer a negative effect of the power delivered with the temperature, meaning that they lose a percentage of the nominal power when the temperature of the cells increases from the STC (25ºC) and increases for temperatures below that value. The percentage of loss/gain with the temperature is the temperature coefficient. It is given in %/K, it is different for each technology and it is always negative. Anticipating discussion on following points, it can be stated that the coefficient of temperature depends inversely on the grade of uniformity of the internal structure of the solar cells.

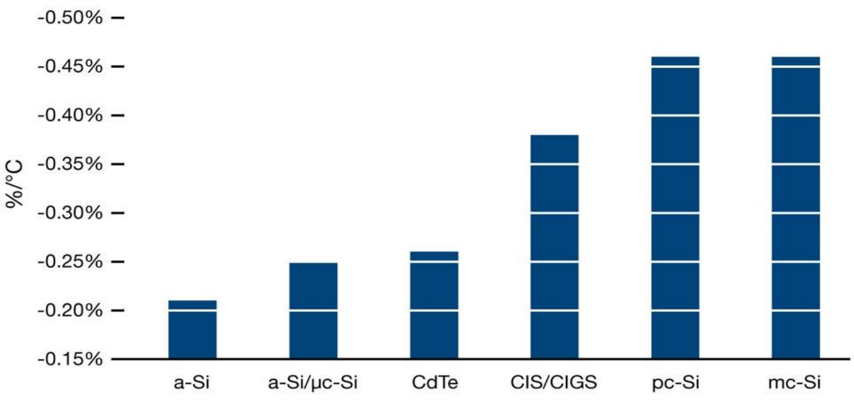


Figure 4.3: Representative coefficient of temperature for the main technologies

Source: (Holz, 2011)

Thus, mono-Si usually presents higher values than poly-Si, this higher than CIS and so on. The minimum value normally belongs to a-Si technology modules.

- ***Degradation:*** each year the performance of the modules suffers a decrease that is given in a percentage reduction of the nominal power. The value is different for each technology and also evolves differently with the time depending on the technology. Table 4.1 summarizes the result of different studies about degradation carried out in the USA for different technologies, different systems and numbers, considering installation of the modules from different suppliers previous and post the year 2000. From this table, it can be concluded that the degradation is a complex process that depends on many factors and is not linear, evolving with the time and the development of the technologies. (Jordan & Kurtz, 2012)

Table 4.1: Median of the degradation rate, number of data points reported and number of publications partitioned by date of installation, technology and configuration. Pre and post installation in 2000

		Nº References		Nº Modules Tested		Median Exposure Time		Yearly degradation %	
Technology	**Configuration**	**Pre 2000**	**Post 2000**	**Pre 2000**	**Post 2000**	**Pre 2000**	**Post 2000**	**Pre 2000**	**Post 2000**
Mono-Si	Modules	31,000	11,000	1.133,000	55,000	21,000	3,000	0,47	0,36
	System	19,000	13,000	42,000	37,000	7,000	5,000	0,90	0,23
Poly-Si	Modules	15,000	9,000	409,000	36,000	10,000	3,000	0,61	0,64
	System	6,000	8,000	5,000	21,000	9,000	5,000	0,60	0,59
Am-Si	Modules	10,000	12,000	45,000	31,000	7,000	2,000	0,96	0,87
	System	14,000	9,000	21,000	14,000	5,000	4,000	1,30	0,95
CIGS	Modules	2,000	6,000	2,000	10,000	8,000	3,000	1,44	0,96
	System	1,000	5,000	1,000	5,000	4,000	6,000	3,50	0,02
CdTe	Modules	3,000	4,000	7,000	6,000	3,000	2,000	3,33	0,40
	System	3,000	2,000	3,000	6,000	10,000	3,000	0,69	0,30

Source: (Jordan & Kurtz, 2012)

Another important parameter to consider, still talking about the same topic, is the initial degradation that the modules suffer after the first hours of exposition to the sunlight. In the sometimes so-called “curing” or “light soaking” process, modules suffer deviation from the initial nominal power out of the factory. They usually suffer some losses that go from one to three percent for mono-Si and poly-Si, and up to 20% for a-Si. Other technologies like CIS can even suffer an improvement of performance after the light soaking process. In general, the degradation processes are very complex, involving quantum mechanics effects, and will be described separately for each technology a bit more in detail in the next points.

In order to define the advantages and disadvantages of each technology, the brief comparison that follows will focus on the differences in values of these parameters mentioned above.

Both crystalline and thin-film modules receive their names directly from the process to manufacture them: crystalline modules are integrated from cells that come from a bulk crystal, so-called ingot, made of pure Silicon that are right after cut into wafers and turn into cells, and thin-film cells are directly primed on a substrate, usually a glass, and then framed in modules (Luque & Hegedus, 2008).

Numbers and data mentioned in points 4.2.1 and 4.2.2 are based on information from the Handbook of Photovoltaic by Antonio Luque (Luque & Hegedus, 2008), but also on market research and datasheets from the most important and representative modules manufacturers for each technology such as Suntech (mono), Yingly (poly), Sharp (amorphous), First Solar (CdTe) or Solar Frontier (CIS).

4.1.1 Crystalline modules. Mono & Poly-crystalline

Crystalline Silicon modules are constructed by first putting a single slice of Silicon through a series of processing steps, to finally create a solar cell. These cells are later on assembled together in multiples to make a solar panel. This process is the most mature, well-known and most widely used in commercial solar panels.

a. ***Mono-crystalline:*** modules are integrated by cells coming from wafers cut from a piece of Silicon grown from a single, uniform crystal ingot. Efficiency of these modules is the highest among all technologies, with values for commercial applications between 15 and 17% for most of the manufacturers. Some of them like Sunpower or the “Pluto” line of Suntech present special modules with efficiencies close to 21% though. They require the highest purity in Silicon and have the most involved manufacturing process. This combination generally makes them the most costly modules in the market. Beyond the price, the main disadvantage of this technology is the highest coefficient of temperature with values around -0,45 and-0,47%/ºC, which is a handicap in hot regions with average temperatures far higher than the STC. The degradation is quite linear with the time and currently with values around 0,36%/year (table 5.1)

b. ***Poly-crystalline (also called multi-crystalline)*** modules use solar cells from wafers made out of multifaceted Silicon crystal ingots. They are less uniform in appearance than mono-Si cells, resembling pieces of shattered glass. Efficiency of these modules is lower than mono-crystalline cells with values around 14 to 16%. Poly-Si modules present a minor improvement in the coefficient of temperature with values slightly lower than Mono-Si: 0,43-0,45%/ºC. Degradation is also quite linear and constant with the time and around 0,6%/year (table 5.1). These are the most common solar panels on the market, being less expensive than mono-crystalline.

In comparison with mono-Si, they need more space for the same nominal power, they behave better in high temperature regions but they degrade faster, so the compared global yield for both technologies, and which would eventually perform better during the lifetime period will depend on the working conditions.

4.1.2 Thin-Film. Amorphous, CdTe and CIGS

Thin-film solar modules are made by placing thin layers of semiconductor material onto various surfaces called substrate (usually glass). Contrary to popular belief, most thin-film panels are not flexible. Overall, thin-film solar panels offer the lowest manufacturing cost, and are becoming more prevalent in the industry, especially in growing markets with extreme hot climate conditions due to the better behavior they present in these environments. They are also less efficient and present complex processes of degradation, sometimes even unpredictable.

a. ***Amorphous and micro-amorphous:*** a-Si is the non-crystalline form of Silicon and was the first thin-film material to become commercially available, first used in consumer items such as calculators or small toys. It can be deposited in thin layers onto a variety of surfaces and offers lower cost than traditional crystalline Silicon. It is less efficient though, with values around 8-9%. Micro-amorphous is a similar technology, but achieves performances slightly better with efficiencies approx. 9-10%.

   The main advantage of a-Si/µ-Si, beyond relative low price of production, is the excellent coefficient of temperature: with values around -0,22%/ºC, they present the best performance of all technologies in high temperature conditions. However there is a significant disadvantage in the degradation behavior. This technology suffers the so called Staebler-Wronski effect, which consists of an increase in the micro-cracks in the amorphous structure which increases the percentage of losses due to imperfections in the material. The degradation occurs mainly in the first months or year, and depends on the average ambient temperature and on the differences between minimum and maximum temperature. It can be up to 20% during the first months. To avoid the impact on the system, manufactures tend to overpower the modules 10-13% which cause additional electrical inconvenience when designing and commissioning a PV installation with these modules. Once initial degradation is stabilized, modules still suffer a stationary variation with a constant yearly average decrease of performance of around 0,8 – 0,9%/year. The complex processes of degradation for Silicon modules are described by Donald E. Osborn (Osborn, 2003) and Muirhead & Hawkins (Muirhead & Hawkins, 1996) .

Figure 4.4 presents the typical curve of degradation though time for mono-Si, poly-Si and a-Si, showing the different behaviors inherent to each of the technologies.

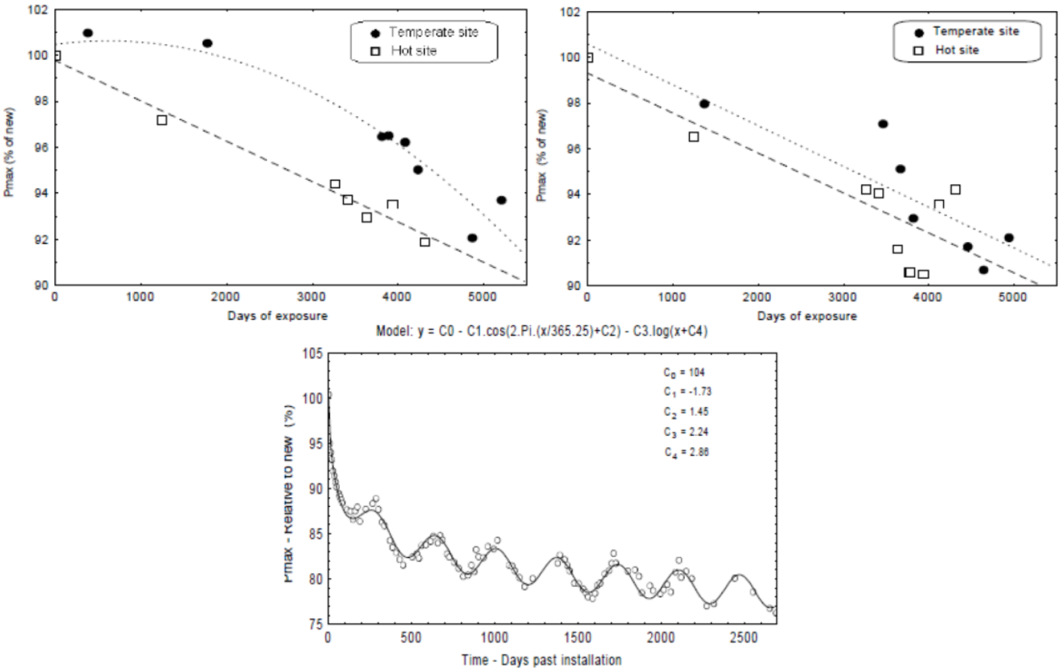


Figure 4.4: Influence of time and temperature on degradation of Silicon modules: Mono-Si (up left), Poly-Si (up right) and A-Si

Source: (Muirhead & Hawkins, 1996)

All in all, a-Si modules present good performance in hot climates, but need even more space than poly-Si for the same nominal power and present a complex and sometimes unpredictable degradation process. To assess the final yield during the lifetime all these parameters must be carefully studied.

b. ***Cadmium Telluride (CdTe):*** CdTe is a semiconductor compound formed from Cadmium and Telluride. CdTe solar panels are manufactured on a substrate of glass. These are the most commonly installed type of thin-film solar panel on the market and the most cost-effective to manufacture. With efficiencies around 10-11,5%, CdTe panels perform significantly better in high temperatures (coefficient of temperature around -0,27%/ºC) and in low-light conditions than crystalline modules. Main disadvantages for them is the extreme toxicity of the Cadmium that cannot be found directly in the nature as a raw material an must be produced in high-risk processes, and the tellurium which is not found abundantly and can suffer shortages or brakes of stock. The degradation process is also quite complex, presenting an initial period of improvement of performance and later degradations with a low but constant value of around -0,3%/year.

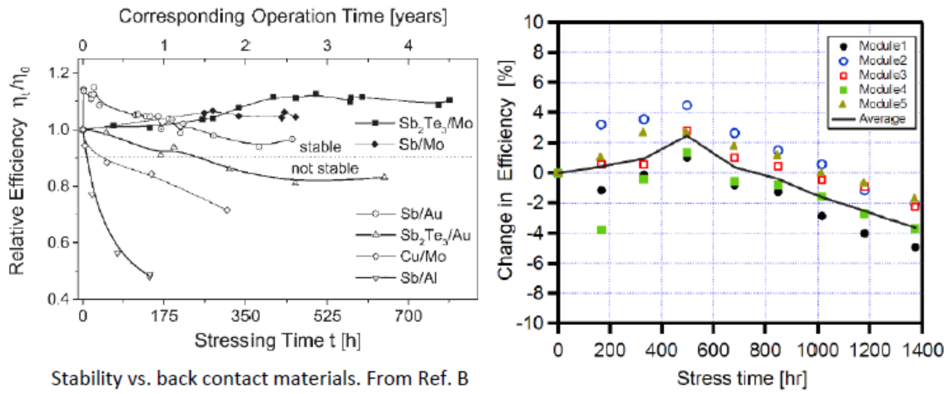


Figure 4.5: Stabilization and degradation process in CdTe modules

Source: (Gostein & Dunn, 2011)

As a curiosity, it is interesting to mention that the main CdTe modules manufacturer, First Solar, decided to stop selling their modules to the market due to an unexpected accelerated degradation of their modules produced and sold in the period June 2008 – June 2009, which obliged them to recall, retire and replace the complete production of that period, around 30MW. After that event First Solar main strategy is to use their modules almost exclusively for its own projects. (Enkhardt, 2011).

c. ***Copper Indium Gallium Selenite (CIGS):*** CIGS is a compound semiconductor than can be deposited onto many different materials. CIGS has only recently become available for small commercial applications and is considered a developing PV technology. Some manufacturers such as the Japanese Solar Frontier (CIS in this case) are achieving a significant penetration in the market. In particular in 2011 Solar Frontier launched a 1GWp capacity facility, the largest in the world of its kind, which was entirely installed in Japan. (Schneider, 2013). This technology presents values of efficiency between 11,4-13% and a coefficient of temperature around -0,31%/ºC which positions them between amorphous and CdTe on one side and crystalline on the other. Particularly interesting is the stabilization and degradation process strongly affected for the "Light Soaking" effect, which consists for this case of an improvement in the performance after some hours of exposure to the sunlight (Gostein & Dunn, 2011).

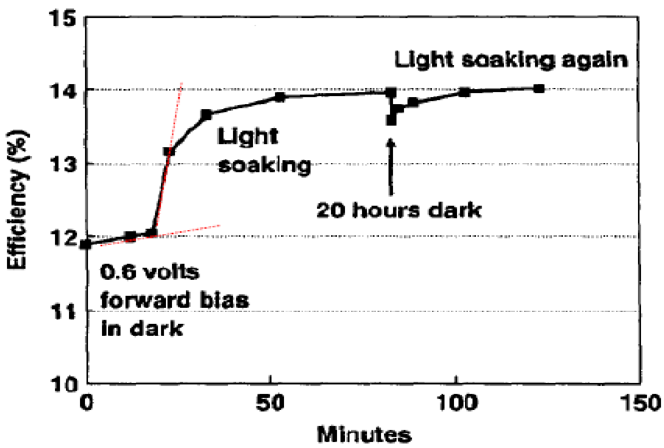


Figure 4.6: Light Soaking Effect in CIGS modules

Source: (Gostein & Dunn, 2011)

Generally speaking and to give a view on the current market situation, it can be stated that crystalline modules present the highest share in market. This big gap might be balanced in the next years though, due to the evolution of markets like MENA region, Australia, Chile or Japan where thin-film technologies are very interesting, and to the deep penetration of companies like First Solar that develops and builds PV installation with thin-film.

Table 4.2: MWp of PV modules produced worldwide in the last years

PV Modules Production (MWp)								
	2006	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2012%**
Crystalline Silicon Modules	1.550	2.253	5.839	8.456	16.122	26.100	28.000	91
Thin-Film Modules	210	434	887	1.665	2.346	2.958	2.701	9
Total PV Modules Produced	**1.760**	**2.687**	**6.726**	**10.121**	**18.468**	**29.058**	**30.701**	**100**

Source: Own elaboration from (Navigant Consulting, 2012) and (Simbolotti, 2013)

4.2 Mounting systems for PV

The mounting system has two main purposes: support the modules, to fix against external agents like wind, rain or snow, and to position and orientate them toward the sun in order to optimize, or at least improve the yearly performance of the installation. The optimal orientation depends on the latitude of the installation and on the application. There are mainly two different types of mounting systems: fix and tracking ones

4.2.1 Fix mounting systems

These systems are the simplest and most economical solution. Modules are placed on a fixed structure tilt with a certain angle and orientated toward a direction, ideally North for the South Hemisphere and South for the North Hemisphere. They are robust and reliable solution, with simple or even no O&M, and can be extremely flexible to follow complex and irregular terrains. Separation between them to avoid shadowing depends on the tilt and the latitude.

4.2.2 Tracking mounting systems

The idea of the tracking systems is to keep the surface of the modules as perpendicular as possible to the solar beams, by tracking the modules to follow the movement of the sun. There are several types and categories of tracking systems, but basically they can be divided into one and two single trackers. Differentiation comes from the number of free liberty movements that they have in order to track daily movement or also correct the azimuth and follow stationary variations. In general, the big advantage of these systems is a significant improvement on the yield vs. fix systems. Depending on the latitude, application and configuration this improvement can be 20 to 50% more yield vs. horizontal plane and 15% to 35% vs. optimum fix tilt for the region (PVSYST, University of Geneva, 1999 - 2013). As disadvantages the following can be mentioned: higher capital costs, more complex and expensive O&M, less flexibility to adapt irregular terrains and more space needed to install the same nominal power.

Final decision on which of the systems is more appropriate for each application is usually driven mainly by the economics of the project, studying whether the increase of CAPEX and OPEX are paid off by the increase in yield and revenue. However additional technical requirements need to be considered to assess the feasibility of using trackers: regions with extreme irregular terrain, where space is tightly limited and/or areas with strong winds might not be economically and technically feasible for tracking systems for example.

In point 6.6 will follow an analysis to evaluate: 1) Whether tracking systems are technically feasible in the Arica Desert region, considering that it presents extreme conditions (wind, dust, corrosion, etc.) and 2) Which of the two options, fix or tracking systems, presents a lower LCOE and economically more convenient.

4.3 Additional electrical components

When talking about converters in the electronic of power area, it refers to devices able to change the DC or AC character of the electricity.

4.3.1 Inverters

Inverters are the devices in charge of switching DC into AC current. This is usually the “heart” of a PV installation, since it undertakes also the tasks of controlling the quality and stability of the service. The inverters sector is currently very well developed with excellent companies and products. The “big boom” in the last years of RES such as wind or solar that require this technology has grant the perfect opportunity to deeply develop the concept of inverter. Nowadays they do not only convert DC into AC, but also undertake the control of the system and guarantee the accurate levels of voltage and frequency to fulfill with the requirements of the grid operator. They are also able to control the reactive power and power factor, delivering a high quality signal to the grid and modulate in a dynamic way the energy output in a way that can be “tuned” to the necessities of the load.
There are two main types: string and central inverters:

a. ***String inverters:*** are smaller in size and capacity, generally placed outdoors and connected directly to the module strings. They are robust and reliable, easy to operate and maintain and allow a very simple connection on the DC side. In case of failure the losses are relative small, and usually solved by quickly replacing the complete defect inverter. They are also more flexible to adapt to installations with differentiate generation profile (different orientations for example) as each unit presents one or two MPP tracker. As disadvantages, they present a complex AC connection and a worse performance since they usually have lower efficiencies than central inverters. They generally cover the range of power between one to 30-40KWac

b. ***Central inverters:*** bigger in size and capacity, they cover the range between 50 kW and 1-2MWac. Certain models can be installed outdoor, but usually they are installed indoor in the interior of inverters stations together with the transformer and medium voltage switchgear. They present a better efficiency and performance, allowing higher yields and a very simple AC side connection. On the negative side, DC connectivity is more complex and usually need of combiner boxes to group all the cables coming from the different strings. O&M is more complex and expensive and in case of failure the losses of yield are quite significant. They are also generally not suitable for installations with differentiated generation profiles since they usually only have one MPP tracker.

Both categories work well and present pros and cons. The most suitable one depends on the application, but also on the preferences of the designer. In general, there is a tendency to use string inverters in small/medium installations in residential and commercial scale, especially on rooftops or installations with different orientations, and central inverters for utility scale projects.

4.3.2 Rectifiers and bidirectional converters

Rectifier devices on the other hand are in charge of switching AC current into DC. In “standard” PV installations, where energy is generated in DC and poured into the AC grid, rectifiers are not necessary. Hybrid systems though are much more complex and, under certain configurations, require rectifiers to charge the batteries from the AC bus channel. In these cases bidirectional converters are usually used, allowing DC→AC and AC→DC transformations.

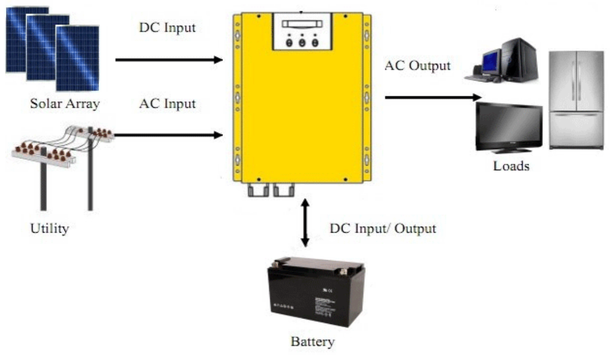


Figure 4.7: General diagram of a system with bidirectional inverters

Source: http://www.energycontrolsystems.net/solarpower.html

4.3.3 Batteries charge controllers

Batteries have the task to store the energy and dispatch it in a quick and reliable way. They should be considered as "deposits", so they need some kind of regulation. This is the function of the charge controllers, which will control the processes of charge and discharge of the batteries. This control has three main scopes (Huggis, 2010):

- ***Security:*** some batteries achieve a high density of energy which can be concentrated in small areas. An overcharge of the batteries is extremely dangerous, and they can even explode causing serious damages.

- ***Optimize the charge/discharge cycle and limit the depth of discharge (DoD):*** certain technologies like Lead-acid batteries or Li-ion see their life cycle drastically reduced when they are discharged beyond to a limit. Charge controllers limit the discharge to avoid over passing this limit and guarantee a long duty and life of the batteries.

- ***Control power/energy ratio:*** a too quick charge or discharge process of a battery can also damage their electrochemical components.

4.3.4 Control and monitoring units

Large scale installations are usually monitored in detail in all the levels: arrays, combiner boxes, meteorological sensors, inverters and transformers. For the most advanced applications this is usually done by integrating all the components into a

SCADA system *(Supervisory Control and Data Acquisition)* which connects all the components, typically via fiber optic, allowing a communication among them. The integration of the different protocols of communication is usually done in an industrial PC and the information acquired is stored in a server connected to the internet, allowing remote access and control. Via the SCADA web portal all required parameters in the installation like current, voltage, power, alarms, switchers, temperature, radiation, wind speed, etc. can be monitored and controlled.

In hybrid installations where different systems are interconnected (PV, diesel generator, battery system, etc.) all the subsystems are connected to a CAN Bus (Control Area Network) divided into a DC Bus and an AC Bus allowing a reliable communication among the different parts of the system, granting an efficient and quick control tool. Figure 5.8 shows the general schemes for SCADA and CAN Bus interconnection (Gantner Instruments, 2013)

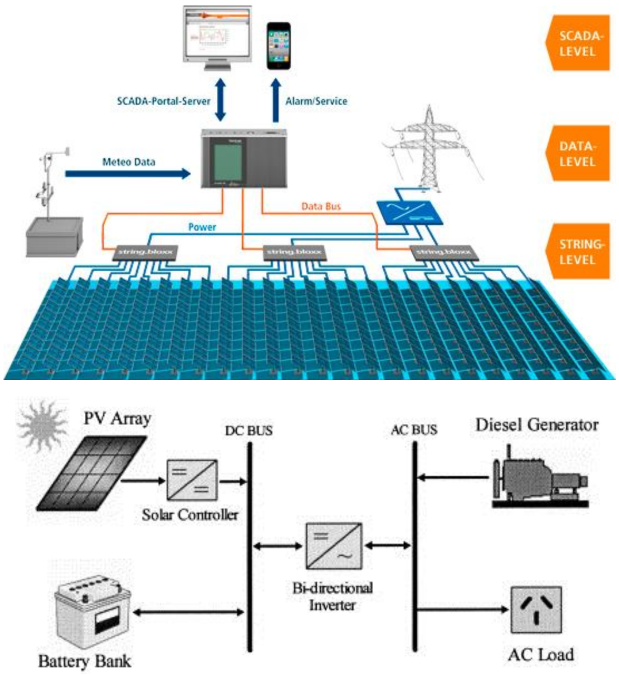


Figure 4.8: General schemes of connection for a SCADA (up) and CAN Bus (down) communication systems

Source: (Gantner Instruments, 2013)

4.4 Diesel generators

Diesel generator sets are sorted by their intended application. The following descriptions and specifications are taken from the website of CAT, one of the main manufacturers worldwide for this kind of equipment (CAT, 2013) and who are representative for this kind of generators.

4.4.1 Diesel Emergency Standby Power (ESP)

This type of generators is only used as an auxiliary UPS to cover emergency situations (hospitals for example). Output is available with varying load for the duration of an emergency outage. Average power output is 70% of the emergency standby power rating. Typical operation is 50 hours per year with maximum expected usage of 200 hours per year. Standby power should be in accordance with ISO8528 and fuel stop power with ISO3046.

4.4.2 Diesel Standby Power

For this type of generators, output is available with varying load for the duration of the interruption of the normal source power. Average power output is 70% of the standby power rating. Typical operation is 200 hours per year, with maximum expected usage of 500 hours per year. Standby power should be in accordance with ISO8528. Fuel stop power is in accordance with ISO3046.

4.4.3 Diesel Prime Power

Output is available with varying load for an unlimited time. Average power output is 70% of the prime power rating. Typical peak demand is 100% of prime rated ekW with 10% overload capability for emergency use for a maximum of 1 hour in 12. Overload operation cannot exceed 25 hours per year. Prime power should be in accordance with ISO3046.

4.4.4 Diesel Continuous Power

Output is available with non-varying load for an unlimited time. Average power output is 70-100% of the continuous power rating. Typical peak demand is 100% of continuous rated ekW for 100% of operating hours. Continuous power should be in accordance with ISO3046.

5 Electricity storage technologies

The system becomes more complex when adding storage. There are several interesting technologies with a great potential to support the generation of intermittent sources of energy like PV or wind, although some of them are still in an early stage of development. The Energy Storage Association, ESA, presents an interesting comparison of them and a useful orientation of the range where each of them should be used. Each of them has advantages and disadvantages, and is especially suitable for certain applications. The below points briefly describe the main storage technologies for electricity generation and figure 5.1 summarizes some of the features of them, rating their capacities for power and energy applications. (ESA - Energy Storage Association, 2009). This chapter refers to several sources and information, but the main source was the Energy Storage book by Robert A. Huggis (Huggis, 2010).

Storage Technologies	Main Advantages (relative)	Disadvantages (Relative)	Power Application	Energy Application
Pumped Storage	High Capacity, Low Cost	Special Site Requirement		●
CAES	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries: PSB VRB ZnBr	High Capacity, Independent Power and Energy Ratings	Low Energy Density	◑	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	●	●
Li-ion	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy Densities, Efficiency		●	◑
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when Deeply Discharged	●	○
Flywheels	High Power	Low Energy density	●	○
SMES, DSMES	High Power	Low Energy Density, High Production Cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy Density	●	◑

● Fully capable and reasonable
◑ Reasonable for this application
○ Feasable but not quite practical or economical
None Not feasable or economical

Figure 5.1: Summary of energy storage technologies with pros & cons and feasibility

Source: (ESA - Energy Storage Association, 2009)

5.1 Pumped hydro

This is the oldest and most developed storage system. It uses the gravity potential energy in the water stored in a dam and turns it into electrical energy using a water turbine and an electrical generator. The general configuration involves several water reservoirs in different levels, natural or artificial, covering a wide range of power. Water in higher level is released toward a lower level and passes through the turbine, which actions the electrical generator. Then, with the surplus of energy, water can be pumped back to a higher level to store it. The average efficiency of the process is around 80%, although for the largest facilities can achieve up to 95% (Huggis, 2010).

This technology is reliable and delivers high capacities in a wide range of scales to relatively low costs. However it is also strongly ruled by a large economy of scale, which makes it not feasible for small applications. The biggest disadvantage is that it requires reservoirs at different levels, which is not possible everywhere. Only mountain regions such as Austria are suitable for them. In countries like Germany or the Northern region of Chile this application is not feasible since they are quite flat areas and/or are quite deserted.

5.2 Compressed air

This technology is not used to generate electricity directly but rather to improve the efficiency of a standard generation process of a gas turbine based on a Brayton Cycle (figure 5.2). CAES systems use the excess of energy to compress air which is stored in special deposits or in underground cavities. This high-pressure air is afterwards used together with the fossil fuel (usually kerosene) to feed the combustion chamber of the Brayton process. The combustion gases then go through the gas turbine, which connected to an electrical generator produces the electricity. Considering that around two thirds of the energy generated in the turbine is needed to compress the air in a standard cycle, this process represents a significant improvement for the global efficiency of the system: CAES can produce the same energy that a standard gas turbine installation but using less than 40% of the fuel. (ESA - Energy Storage Association, 2010)

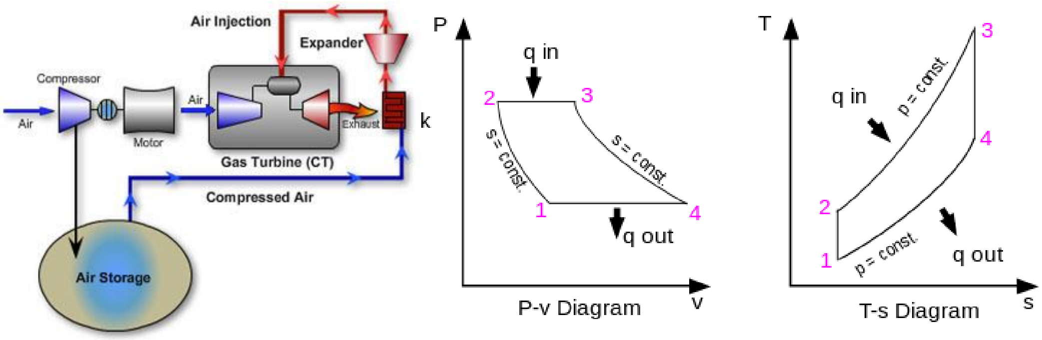


Figure 5.2: Adapted Brayton cycle of a gas turbine for electricity generation with a CAES system

Source: (University of Texas of the Permian Basin, 2012)

Same as pumped hydro, CAES has a wide range of applications and a high capacity in relatively low costs. However it also has special site requirements and needs a source of gas. Considering that gas is only available in small quantities in Chile, CAES is not feasible for the application under discussion.

5.3 Flywheel

Additionally to the gravity potential, it is possible to store also kinetic energy. This is usually done in a spinning wheel called the "Flywheel". This name comes from the fact that the wheel is levitating in a magnetic field with minimum direct contacts with the chassis. Flywheels store up to 125Wh/kg, which is a rather low energy density, with capacities from 2kWh and up to some MWh (Huggis, 2010). They are able to deliver quickly big power, making them more suitable for power applications rather than energy-focused ones. This technology can bridge the gap between short-term ride-through power and long-term energy storage with excellent cyclic and load following characteristics. They have low maintenance and long life periods (up to 20 years).

It should be pointed though that flywheels can be very dangerous. When they are unbalanced their parts can be like projectiles with high levels of energies. That is the reason why they need to be built in small units to avoid eventual massive destructions. Recent failures (2011) in an US installation of fly wheels for frequency regulation raised some doubts about this technology: Beacon Power's Stephentown, NY, frequency regulation plant (20 MW), which was only commissioned in July 2011 lost one of its 100-kW-Flywheels on 27th of July and another one on 13th of October. Another failure in a German lab (an engineer was killed in August 2011) added further safety issues. Their technical maturity is well advanced. Fly wheels will always stay in niche applications, as they suffer from high self-discharge (20% to 100% per day) and from extremely high costs for high capacity storage (€/kWh). The market for flywheels will be focused more on selling ancillary services to distribution grids (voltage stabilization, frequency stabilization, etc.) (Directorate-Generale for Energy, 2013).

5.4 Hydrogen

Hydrogen is used as an energy vector or energy carrier. It is clean, reliable and with a high energy density: with 34.400 Kcal/kg, it presents one of the highest calorific power values among all the existing fuels. Beyond that, one of the biggest advantages is that the exhaust gas of combustion is only steam of water.

Hydrogen can be used in traditional internal combustion engines with only minor modifications, in turbines, and in heating processes, making available a wide range of applications. However, probably the greatest potential for the future is to use it in fuel cells to directly produce electricity with a global efficiency of up to 60%, while traditional engines present efficiencies in the range 30 – 40%. When used in cogeneration processes, combined generation of heat and electricity, high temperature fuel cells can achieve up to 80% (Huggis, 2010).

Hydrogen cannot be found in the nature as an independent element. There are different ways to obtain it, but mainly are:

- Electrolysis of the water: in a “Power to Gas” process, energy coming from green sources of energy like wind or photovoltaic can be used for the electrolysis of water and hydrogen can be storage, being used later on in a standard Rankine or Brayton process, or even in a fuel cell to generate electricity.

  $$\boldsymbol{H_2O + Energy \rightarrow H_2 + \tfrac{1}{2}\,O_2}$$

  Although this process presents a big potential, it is not yet of application in the desert region of the North of Chile where the main mining activity is located.

- From natural gas: Pure H_2 can be obtained from methane in a two-step process to decarbonize it.

$$CH_4 + H_2O + Energy \rightarrow CO + 3H_2$$
$$CO + H_2O + Energy \rightarrow CO_2 + H_2$$

  Again the handicap of resources of natural gas and water, which are very limited in the area, is found here.

Thus, in spite of being very interesting and being considered in other applications as a storage driver, hydrogen is not a feasible solution in the case under study. Additionally, hydrogen presents other disadvantages such as the requirements to development its own gas facilities (already existing for natural gas cannot be shared), high risks of inflammation and extremely high CAPEX investments.

5.5 Electrochemical storage

Electromechanical storage involves the conversion of chemical energy into electricity and vice versa. This process takes in the batteries. Batteries enjoy a special attention in this work since they represent the technology that best fits into the described framework. They are a flexible and scalable technology, so they can be used in a wide range of sizes and application.

To better understand them in the different forms and types, with all the advantages and disadvantages they represent, it is necessary to initially introduce some concepts and parameters:

a. ***Chemical reaction and electrolyte:*** a chemical reaction usually involves a transformation where one or more components interact and evolve to generate new and different components. Electrochemical processes imply reactions that usually follow the following schemes:

$$\textbf{Formation reaction}: A + B \rightarrow AB.$$
$$\textbf{Displacement reaction}: AX + B \rightarrow A + XB$$
$$\textbf{Insertion reactions}: Ax + BX \rightarrow AxBX$$

These reactions typically occur inside the batteries and are favored and take place in a substrate call the electrolyte.

b. ***Energy density and capacity:*** energy density is defined as the Wh/kg that a component or solution can store. It is closely related with the capacity of a battery, which is the total amount of energy (in Wh) that the system can store.

c. ***Energy quality****:* The same that the quality of the thermal energy depends on the temperature (concept of exergy), the quality of the electrochemical energy depends on the voltage. A high voltage cell will be able to deliver more and better performance in the different applications.

d. **Depth of discharge *(DoD):*** it is the percentage of the capacity of the battery that is consumed. A DoD of 30% for example means 30% of the energy stored in the battery has been used. The DoD is an important parameter that will drastically affect the lifespan of the batteries.

e. ***Cycling behavior and capacity degradation through the lifespan:*** some chemical batteries present the particularity that the charge & discharge cycle and capacity varies through the lifespan, presenting a progressive degradation that depends on the technology, the temperature and the depth of discharge.

f. ***Self-discharge process:*** chemical storage, like most of the storage technologies, presents a loss factor when energy is stored for a long period. In the context of batteries it is because of the self-discharge processes due to different factors depending on the technology such as recombination, reaction of the components, degradation of the electrolyte, etc. Each type of battery presents a characteristic discharge process and rate.

5.5.1 Lead-acid batteries

This is by far the most extended used technology since they are installed in vehicles and machinery worldwide. As main advantages and limitations the following points can be listed:

Advantages:

- Production relatively cheap. Talking about CAPEX, they can be up to 50-60% cheaper than other technologies. Standardization and big volumes of production guarantee a cost-effective solution.

- Reliable and well tested. Chemistry is well understood and manufacturing can be optimized in many ways like with gel electrolytes and other solutions that make the technology very reliable (within the technological limits).

- New generation of gel electrolyte batteries allows a maintenance-free system. This will decrease the cost in a sensible way.

- No special hardware and/or software required to control charge and discharging processes. A standard and simple charge controller would work perfectly.

Limitations:

- Lifetime of the battery for this technology is extremely sensible to the DoD, presenting a drastic reduction of the lifetime of the battery when the ratio of discharge increases. This means, in practical only 30-50% of the battery should be used to guarantee a reasonable lifespan. Otherwise the battery would degrade quickly.

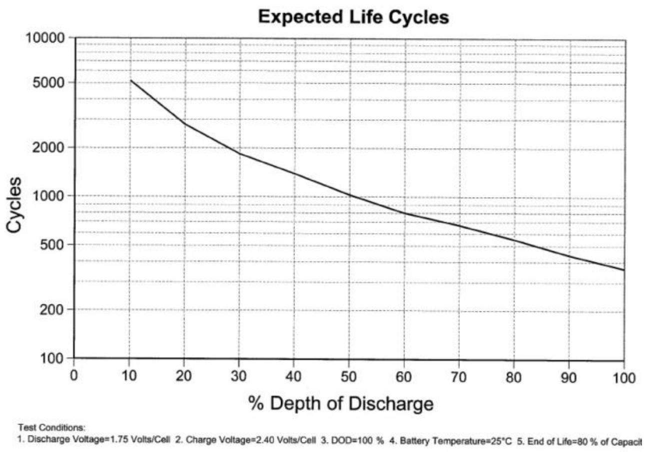


Figure 5.3: Typical curve DoD vs. Cycles for a Lead-acid battery for heavy duty applications

Source: Lifeline manufacturer http://www.lifelinebatteries.com/battery-lifespan.php

- With a proper use, the number of cycles is still very limited and far below from other technologies like Li-ion or flow batteries.

  Temperature is another parameter that drastically affects the performance of these batteries. High temperatures allow higher capacities, but increases also the self-discharge ratio as shown in figure 5.4. These two opposed effects mean that the real capacity expected from a lead-acid battery is quite unpredictable and estimations inaccurate.

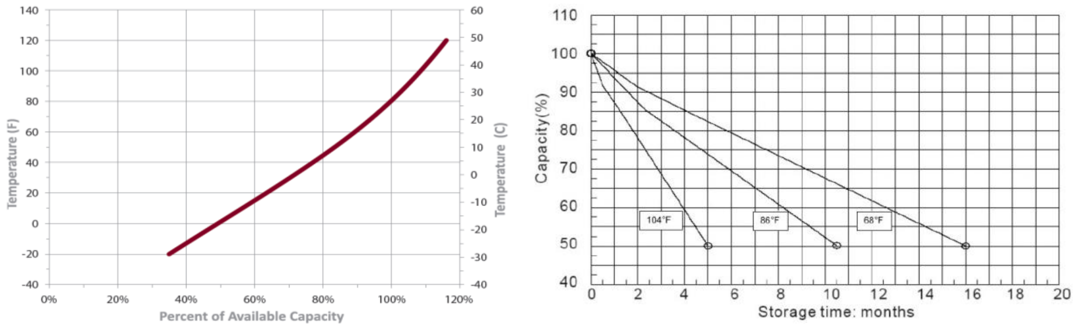


Figure 5.4: Typical influence of the temperature on the capacity and self-discharge parameters for commercial Lead-acid batteries

Source: Lifeline and Trojan manufacturers:
http://www.trojanbatteryre.com/PDF/datasheets/T605_TrojanRE_Data_Sheets.pdf

http://www.lifelinebatteries.com/battery-lifespan.php

- In case of maintenance, it is necessary to handle dangerous product such as sulfuric acid for example

5.5.2 Lithium-ion batteries (Li-ion)

Also worldwide spread are the Lithium –ion batteries, which nowadays can be found in electrical devices like mobile phones, watches, calculators, etc. Within the Li-ion field there are several technologies available. The main technologies are: Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), Lithium Iron Phosphate (LFP), Lithium Nickel Manganese Cobalt (NMC), Lithium Nickel Cobalt Aluminum Oxide (NCA) and Lithium Titanate (LTO). Each of them has different features, advantages and disadvantages. Additional information can be found in (Huggis, 2010), but for the purpose of this study, it is enough to know that LMO and LFP are the most commonly used for utility scale and to be combined with renewable energies. This technology is usually associated with "power driven" application, where the ratio energy/power or Wh/W is close to the unit.

Figure 5.5 shows two spider web diagrams with the main features of both Li-ion technologies (Buchmann, 2013)

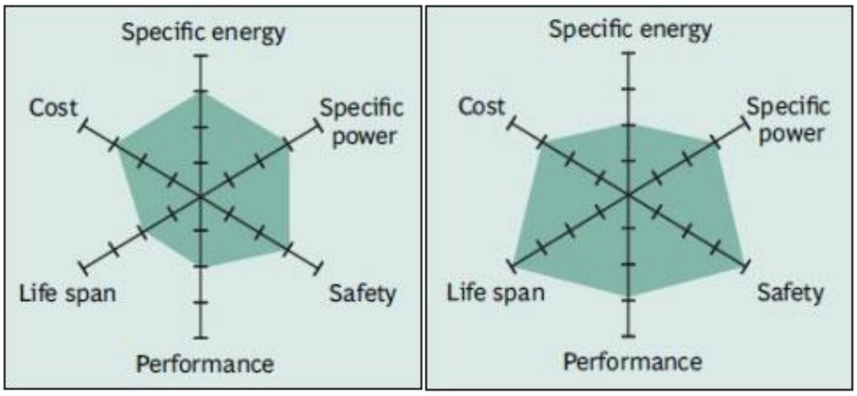


Figure 5.5: Typical features of a Li-manganese (left) and Li-iron phosphate (right) battery

Source: http://batteryuniversity.com/learn/article/types_of_lithium_ion

In general terms, and in comparison with other battery technologies, main advantages and limitation are:

Advantages

- High energy density potential for yet higher capacities. This makes them ideal for mobility applications such as cars, aircraft, and for small electronic devices where size and weight plays an important role.

- They admit higher DoD ratios and degradation is less sensible to this parameter than in lead-acid.

- Long lifespan. Due to lower degradation through the charge and discharge processes, they can achieve 5 to 10 times more cycles than lead-acid batteries

- Less sensible to temperature effects

- Does not need prolonged priming when new. Only one regular charge is needed.

- Relatively low self-discharge (less than half compared to a nickel-based battery for instance). Low sensitivity to variations in temperature.

- Low Maintenance - no periodic discharge is needed; and no “memory effect” is detected.

- Specialty cells can provide very high current, making them suitable for applications where both, energy and power services are required.

Limitations

- Extremely flammable electrolyte with risk of explosion in case of overcharge. Requires protection circuit to maintain voltage and current within safe limits. Protection circuitry involves both hardware and software. Monitoring and alarms will be required for safe operation.

- Subject to aging and degradation effects, even if not in use. Figure 5.6 shows the typical degradation process through 20 years of a Li-ion battery

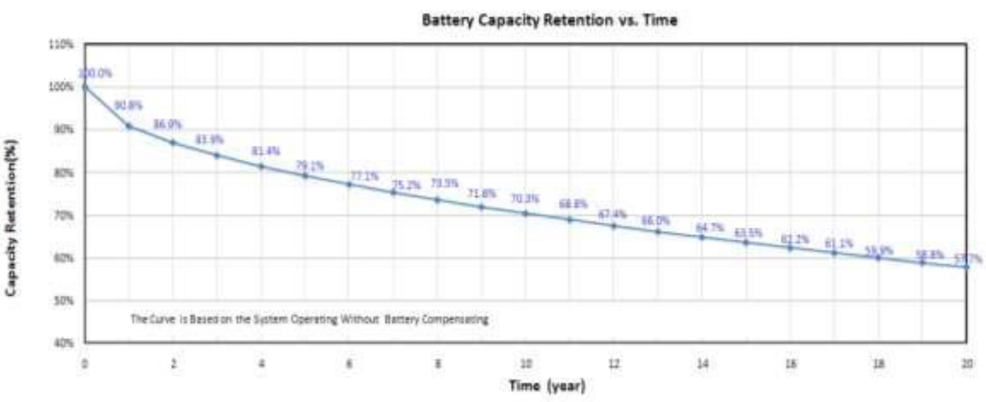


Figure 5.6: Degradation process of a LFP Li-ion battery

Source: (BYD Energy Storage System Warranty Letter)

In the figure a degradation of up to 40% of the initial capacity during through 20 years can be observed.

- Very sensitive to heat and hot temperatures. Placing the batteries in a cool place at 40% charge reduces the aging effect.

- Transportation restrictions. Shipment of larger batteries may be subject to regulatory control.

- Expensive to produce. 5 to 10 times more expensive than lead-acid batteries. However when comparing the cost per kWh delivered though the lifetime, Li-ion can achieve more competitive prices than Lead-acid due to lower degradation, longer lifespan and higher DoD (see figure 6.5 in next section).

- Not a fully mature chemistry - metals and chemicals are changing on a continuing basis. Many variants of Li-Ion batteries are available. There are negative and positive electrodes in lithium systems, including carbon and metallic alloys, but is not yet clear which the optimum combination is. All of them have pros and cons, but the lack of standardization is a handicap for the mass production and therefore, the decrease of prices.

5.5.3 Flow batteries. REDOX reactions

Opposite to Lead-acid and Li-ion batteries where a chemical reaction and conversion takes place, in the flow battery technology there is no conversion, and only a transfer of electrons between the anode and the cathode happens. That is, how only REDOX (deduction and oxidation) processes take place as schematically shown in figure 5.7.

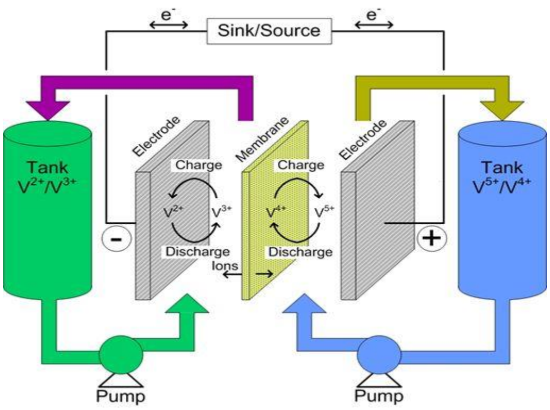


Figure 5.7: Diagram of functionality of a vanadium flow battery

Source: http://www.messib.eu/about_project/MESSIB_results/redox_flow_batteries

Two different tanks with solutions of different ions of the same component (vanadium in this case) are pumped through a power stack where the transfer of electrons takes place.

Advantages:

- In this type of batteries there is a clear separation of the production and storage units (separated into tanks and stack unit).

- High electrical efficiency for the charge and discharge cycle (around 80%)

- Good cycling stability and thus, long lifetime. They present a very low degradation and low self-discharge level. Electrolyte suffers no degradation, so O&M only consists in revising and changing the pumps every certain period.

- Since there is no chemical conversion, only transfer of electrons, these batteries can achieve a DoD of 100% without affecting the lifetime.

- Easily scalable in capacity by adding additional electrolyte. Ideal for applications which are “energy driven” and where it is interesting to supply energy for a long period of time for a given power.

Limitations:

- Very high initial investment required. That is why this technology is only economically feasible for medium-scale applications. For small-scale the fix costs of the system (stack, pumps, etc.) make it too expensive to be considered. For medium and larger applications the cost per kWh asymptotes the cost of the electrolyte (see figure 6.6 below). Cost of the stacks are relatively high but the addition of additional electrolyte is relatively cheap, so ratios one to two, one to four of even one to eight make the cost per MWh decrease for a given power.

- Due to its physiognomy, where the stack determines the power of the batteries and the quantity of electrolyte in the tasks determine the capacity, this solution is only interesting in “energy driven” solutions, where a low ration power/energy is seek.

- Very low energy density, which makes them unsuitable for mobility application.

- Although the process is well known from the 1960s, the technology has been developed only during the past few years and so, it is not yet mature enough. Only few companies are developing and investing in R&D for this technology (Gildemeister in Austria, Sumitomo in Japan and Schmid in Germany are the most significant) so the potential reduction of price and standardizations is quite limited for the time being.

5.5.4 Molten salt batteries. Sodium sulfur (NaS)

The family of the molten salt batteries has several different compositions (sodium sulfur, lithium sulfur, etc.) but all of them show similar characteristics.

These batteries have the particularity that they operate at high temperature, around 300 to 400ºC. They typically have a high charge and discharge efficiency (89-92%) and a long cycle life. (Wikipedia, 2013). However, due to the high temperature of operation the highly corrosive nature of the components is only suitable for large scale installations, with typical sizes of 2MW and 12MWh. NGK Insulators is among the main suppliers for this kind of batteries. The most advanced technology among them is the sodium sulfur (NaS). The NaS battery consists of sulfur at positive electrode, sodium at negative electrode as active materials and Beta alumina of sodium ion conductive ceramic which separates both electrodes. If a load is connected to terminals, electric power is discharged through the load. (NGK Insulators , 2013)

This hermetically sealed battery is operated under the condition that the active materials at both electrodes are liquid and its electrolyte is solid.

A special mention to the ZEBRA battery *(Zeolite Battery Research Africa Project)* is worth. It is being developed in South Africa, and attempts to solve some of the limitations of this type of batteries. Once in operation, it will be able to operate at temperatures below 245º and solve the problems of corrosion (Wikipedia, 2013).

In general, this type of batteries is still in an early stage of development and their attempt to become commercial only reaches some companies like Fiamm or NKG.

In table 5.1 some of the most significant and representative values of the different parameters above discussed are collected. Also appendix 2 presents a compilation of the most significant technologies and features of each of them (Directorate-Generale for Energy, 2013).

Table 5.1: Summary of the main parameters for the main battery technologies

Storage technology	Storage Mechanism	Power	Capacity	Storage Period	Density		Efficiency	Lifetime	Cost		
		MW	MWh	time	kWh/ton	kWh/m³	%	# cycles	$/kW	$/kWh	¢/kWh-delivered
Lithium Ion (Li Ion)	Electro-chemical	< 1,7	< 22	day - month	84 - 160	190 - 375	0,89 - 0,98	2960 - 5440	1230 - 3770	620 - 2760	17 - 102
Sodium Sulfur (NAS) battery	Electro-chemical	1 - 60	7 - 450	day	99 - 150	156 - 255	0,75 - 0,86	1620 - 4500	260 - 2560	210 - 920	9 - 55
Lead Acid battery	Electro-chemical	0.1 - 30	< 30	day - month	22 - 34	25 - 65	0,65 - 0,85	160 - 1060	350 - 850	130 - 1100	21 - 102
Redox/Flow battery	Electro-chemical	< 7	< 10	day - month	18 - 28	21 - 34	0,72 - 0,85	1510 - 2780	650 - 2730	120 - 1600	5 - 88

Source: (Hauer, 2013)

A more detailed discussion about the current price level of the batteries will follow in the next section.

Every technology described in section 5 presents a great potential in different applications and all of them have presented promising and encouraging researches and results in the last months/years. (Huggis, 2010). However, considering the type, scale and size of the application under study, this work will focus only in electrochemical batteries since they are in the understanding of the author, the most suitable technology for the case study. They have the fastest time reaction and are by far, apart from pumped storage, the most developed storage technology at the moment. In addition, they are technically speaking the best fits in the range of power and capacity for the application under discussion, and best fulfills the condition of instant reaction and dispatchability that the application requires.

Figure 5.8 presents a chart made by the German institute Frauenhofer with the suggested range of application for the different technologies in base to the power and capacity requirements of the application. This chart will be useful later when analyzing the case study to double check whether the assumption made and technologies selected for storage are appropriate and accurate or not.

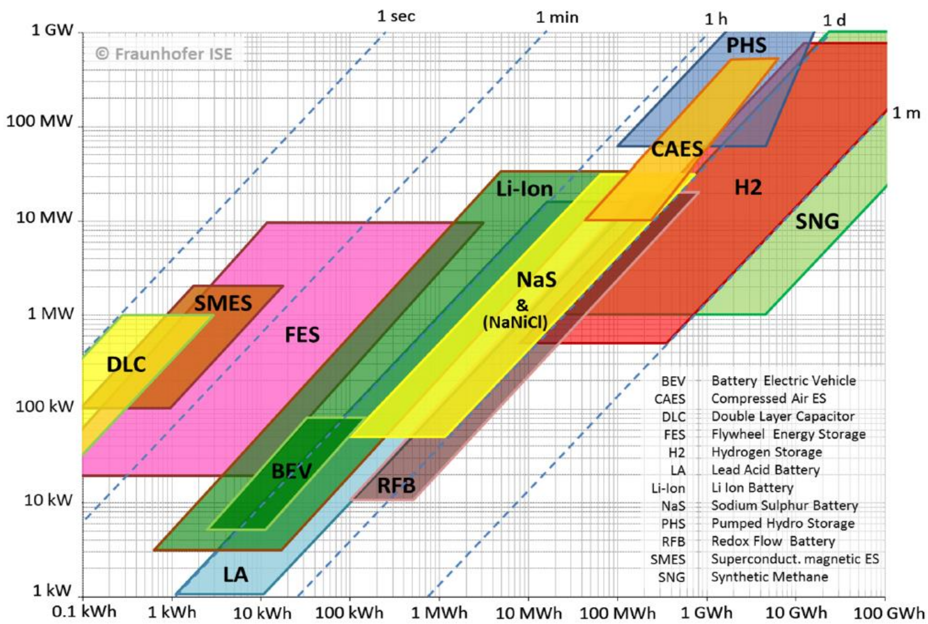


Figure.5.8: Feasible range of operation for the different technologies

Source:Fraunhofer ISE, 2012

To conclude this section, it is to mention that several leading-edge technologies are also being developed additionally to those discussed above. However they are still on a development stage or in a very early maturity, so they were not further considered for this analysis. Thus for the sake of completeness the following should be named:

- Metal-air batteries.
- Na-ion batteries including Na-halide chemistries.
- New types of Na/S cells (e.g. flat, bipolar, low-temperature, high-power).
- New Li-ion chemistries that improve performance and safety characteristics.
- Advanced lead-carbon batteries.
- Ultra-batteries (a hybrid energy storage device that combines a VRLA battery with an electrochemical capacitor) and ultracapacitors.
- New flow battery couples including iron-chrome and zinc/chlorine (Zn/Cl).

6 Technical & economic feasibility of a hybrid system combining PV, storage and diesel generation

6.1 Criteria of optimization

Earlier in this paper, the critical situation of the electricity market in Chile and the necessities for improvement were discussed. With that in mind, also the idea of using hybrid systems combining PV and storage together with the traditional existing diesel generation to improve Chile's supply of electricity in the mining sector of was introduced. This improvement can be seen from a technical, economical and/or environmental point of view. To maximize benefits brought by hybrids the optimization of the global system is needed. But to understand the concept of an "optimum system", it is first of all necessary to define the criterion that makes the system "optimal":

- **Technical criterion:** The system must be technically feasible and generate the maximum yield possible in a cost-effective way. The concept of "cost effectiveness" brings up the economical approach and the concept of LCOE.

- **Economical criterion:** The levelized cost of energy *(LCOE)* must be as low as possible. LCOE represents the per-kilowatt-hour cost (in real currency) of building and operating a generating plant over an assumed financial life and duty cycle. It is often cited as a convenient summary measure of the overall competiveness of different generating technologies. The Optimum from the economical point of view will be the one with the lowest LCOE.

- **Load of demand:** This is the energy demand in kWh necessary to cover in the case under study; it is the energy demand of the mine type, 24 hours a day 365 days per year. The top criterion of the design is that 100% of the demand must be covered in a reliable way.

- From the **environmental point of view**, the optimal system allows a reduction of the carbon foot print of the system.

The optimum system that will be presented in this work will consider a proper combination of diesel generation, storage and PV production with the proper design and combination of components that will target to fulfill all the above mentioned criteria.

The scope of the next chapter is to discuss the different possible combinations of components and technologies and to find the optimum system by identifying until what extend substituting diesel generation for PV green energy can be interesting.

6.2 Solar resources in Chile

Considering PV as a reliable source of energy for a country, one of the first questions one comes up with are, why PV and, what the sunlight availability in the country is.

With a longitude of around 4.500 km , Chile has a large variety of different climates and radiation which goes from the deserts of Arica and Atacama regions in the North to the Antarctic region of the South.

Figure 6.1 shows the direct normal distribution of solar radiation on horizontal surface in South America. It is easy to recognize that the region of the Arica desert on the North of Chile presents the highest values in the whole continent.

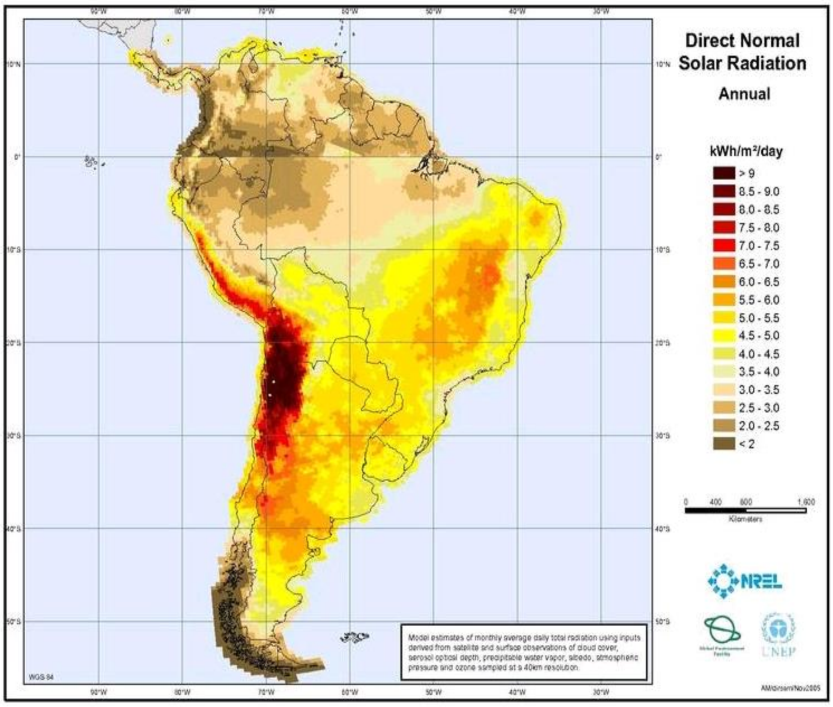


Figure 6.1: Direct Solar Radiation in South America

(NREL, 2011)

Even further, the Northern regions of the country are among the most radiated areas in the world and present some of the most extreme conditions in the Planet. This is also where the main mining activities take place, since the largest and most important mineral deposits are located there. Considering for example the area of Chuquicamata and Calama in the Tarapacá region, it can be observed that the solar resources are excellent and among the highest in the country and in the world.

This factor together with the fact that there are no hydro resources on the region and therefore, about 99% of the energy production comes from fossil fuel, grants the optimum conditions for the deployment and development of solar installations. Furthermore, the decentralized capacity of solar PV energy makes it ideal to distribute the generation center among the different mining center activities (extraction, transport, cleaning, refinery, purification, etc.) which are usually several kilometers away from each other.

Table 6.1 shows the monthly average radiations and average temperature in some of the most important regions in the North of Chile: the regions of Arica and Parinacota, Tarapacá, Antofagasta and Atacama.

Table 6.1: Monthly and Yearly Global Horizontal radiation and temperatures in the Northern Regions of Chile (kWh)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Sep	Oct	Nov	Dec	Total Year
Chuquicamata/Calama												
Gh (kWh/m2 day)	9,04	8,50	7,71	6,58	5,53	4,98	5,21	7,55	8,69	9,43	9,49	2.705
T24	14,9	15,0	14,3	12,4	10,0	8,6	8,4	11,0	12,8	13,6	14,4	12,1
San Diego de Almagro												
Gh (kWh/m2 day)	8,51	7,95	7,02	5,66	4,51	4,01	4,30	6,67	7,81	8,64	8,76	2.405
T24	21,6	21,4	20,6	18,7	16,8	15,3	14,8	17,4	19,0	20,3	21,1	18,6
Copiapo												
Gh (kWh/m2 day)	8,25	7,70	6,69	5,13	4,09	3,67	3,99	6,20	7,31	8,14	8,40	2.263
T24	21,2	21,1	20,1	18,7	17,1	15,9	15,4	17,6	18,7	19,7	20,5	18,5
Pica												
Gh (kWh/m2 day)	8,39	7,83	7,29	6,38	5,45	4,97	5,14	7,27	8,27	8,85	8,81	2.573
T24	20,3	20,4	20,0	18,9	17,5	16,2	15,8	18,0	18,7	19,3	20,0	18,5
Iquique												
Gh (kWh/m2 day)	8,22	7,71	7,11	5,95	5,05	4,45	4,58	6,39	7,55	8,31	8,46	2.405
T24	21,6	21,8	21,1	19,7	18,4	17,0	16,5	17,8	18,6	19,6	20,8	19,1
Santiago de Chile												
Gh (kWh/m2 day)	9,03	7,94	6,37	4,39	2,97	2,34	2,73	4,77	6,32	8,04	9,07	2.040
T24	18,8	18,4	17,9	15,5	11,1	8,9	7,3	10,8	13,5	16,0	17,9	13,7

Source: http://solargis.info/imaps/

6.3 Definition of the case study and assumptions

To better understand the interest of hybrid systems and their potential to bring down the high LCOE in the mining sector in Chile, and considering that this work is not based on a specific project, but rather tries to be as general as possible, it is necessary to take some assumptions for this specific application. Further, also to define the case study, it is necessary to check the results and analyze the impact of the different assumptions on them.

It is important to mention that part of the assumptions made below are the result of different research and interviews with different companies, entities and persons related to the PV sector and the technology. Others however are based on my own experience after working as an engineer in the PV business for more than seven years. Nonetheless, all assumptions will be duly checked and discussed further on.

In the following sections the base case study is defined and described.

6.3.1 Mine description and selection of the site

To define the case study it is necessary first of all to define the mine where the analysis will be carried out. A hypothetical open-pitch copper mine with a yearly production **Q_{MT} of 50.000 metric Tons per year** is assumed. This mine would hypothetically be located in the region of San Diego de Almagro, in the province of Chañaral, belonging to the region of Atacama, 150km away from the principal urban center of Copiapó (26°23'14.81"S, 70° 2'44.22"W – see Figure 6.2.

Figure 6.2: Location of Diego de Almagro in the Arica desert

Source: Google Earth

This particular place has been selected for the following reasons:

- It has intense mining activity, which is based mainly on the extraction and refinery of copper, gold and silver.

- This location belongs to the SIC, which has the most critical situation with the supply of electricity (see Figure 2.3 and 2.4).

- Diego de Almagro is located near the emblematic place of Potrerillos, a city that used to be prosperous due to the wealth of their mines, but that was abandoned in 2000 because of the high air pollution (Wikipedia: Potrerillos). Many inhabitants emigrated from Potrerillos to Diego de Almagro and other cities in the surroundings, so pollution and environment are very sensitive topics in this region.

- This area is located on the South of the Arica desert, so the radiation levels are high, though not the highest. In this region also significant differences in temperature and radiation level happen in the different seasons, which allow a more general analysis without going to extreme values of other locations more centered in the Arica desert like Chuquicamanta for example. Table 6.2 shows radiation data over the year for the Diego de Almagro location.

Table 6.2: Radiation data for the Diego de Almagro location

Diego de Almagro								
Month	**GHId**	**GHIm**	**Diffd**	**Diffm**	**DNId**	**DNIm**	**T24**	**TOTAL**
Jan	8,5	264,0	2,2	68,0	8,5	264,0	21,6	**3106,2**
Feb	8,0	223,0	2,0	56,0	8,2	230,0	21,4	**2901,8**
Mar	7,0	218,0	1,6	50,0	8,1	250,0	20,6	**2562,3**
Apr	5,7	170,0	1,3	40,0	7,2	217,0	18,7	**2065,9**
May	4,5	140,0	1,1	33,0	6,6	205,0	16,8	**1646,2**
Jun	4,0	120,0	1,0	29,0	6,3	189,0	15,3	**1463,7**
Jul	4,3	133,0	1,0	30,0	6,7	207,0	14,8	**1569,5**
Aug	5,3	165,0	1,1	35,0	7,4	229,0	16,0	**1941,8**
Sep	6,7	200,0	1,4	42,0	8,1	243,0	17,4	**2434,6**
Oct	7,8	242,0	1,7	53,0	8,7	269,0	19,0	**2850,7**
Nov	8,6	259,0	1,8	54,0	9,4	281,0	20,3	**3153,6**
Dec	8,8	272,0	2,1	64,0	9,1	281,0	21,1	**3197,4**
Year	6,6	2406,0	1,5	554,0	7,9	2865,0	18,6	**2405,4**

Source: www.solargis.info/imaps/

With:

GHi_d: Average daily sum of global horizontal irradiation (kWh/m^2)

GHI_m: Average monthly (yearly) sum of global horizontal irradiation (kWh/m^2)

Diffd: Average daily sum of diffuse horizontal irradiation (kWh/m^2)

$Diff_m$: Average monthly (yearly) sum of diffuse horizontal irradiation (kWh/m^2)

DNI_d: Average daily sum of direct normal irradiation (kWh/m^2)

DNI_m: Average monthly (yearly) sum of direct normal irradiation (kWh/m^2)

T24: Average diurnal (24-hour) air temperature (°C)

6.3.2 Yearly load of demand

As described in section 3.2 and shown in table 3.4, to produce one metric ton of refined and pure material, 7,245 MWh of electricity are needed in the copper industry of Chile. Assuming a production $\mathbf{Q_{MT}}$ of 50.kMT as mentioned above, it will be necessary to supply **362,25 GWh** per year to the mine. It is assumed that, in principle, 100% of this energy comes from diesel plants, which is almost the only energy source present in the area.

The mining activity never stops and is running 24 hours a day, 365 days per year. Since the extraction and refining processes are independent from the seasons and the time of the year, a constant and homogeneously distributed through time of 362,25 / 365 = **992,47MWh/day** is assumed.

Additionally, discussions and meetings with different entities and companies related to the sector confirmed that the typical daily distribution of electricity consumption is also quite steady and distributed in **40% during the day and 60% during the night**. This is due to the fact that during the day main activities of extraction take place and during the night activities are more concentrated in refining the mineral, not to forget the necessity of lighting, so that the balance is slightly leant to the night and the electricity consumption is a bit higher during this period (Alamo, 2013). A further analysis will be done to study the impact of modifying these assumptions though when making the sensitivity analysis later on.

6.3.3 Technology selection

a. Configuration of the hybrid system

There are basically two different configurations for hybrid systems that combine PV with storage (PV-Magazine, 2013):

- ***The DC connection***, where the storage is connected to the photovoltaic system on the DC part via a charge regulator. This configuration has the advantage of the simplicity, price efficiency (as it is cheaper) and a higher efficiency since the DC current is directly used into the inverters or storage without previous transformation steps. On the negative side, a lower flexibility for the utility or the final consumer from the AC side to interact with the storage and/or control it has to be mentioned. The global DC-AC efficiency is around 85%.

- ***The AC connection***, where the battery system is connected on the AC part. This configuration requires a standard DC-AC inverter and a bidirectional DC-AC converter since batteries can only store DC current. Compared to the DC connection configuration, this one is characterized by a lower efficiency, higher costs and a more complex configuration and operation, but brings also more flexibility and control to the final user, who can interact in a more direct way with the system. This configuration presents also the advantage that the energy from the grid can be used to charge the batteries if required. Since different transformation steps are required (DC→AC, AC→DC and again DC→AC) the global DC-AC efficiency falls to 75-80%

Figure 6.3 shows both configurations.

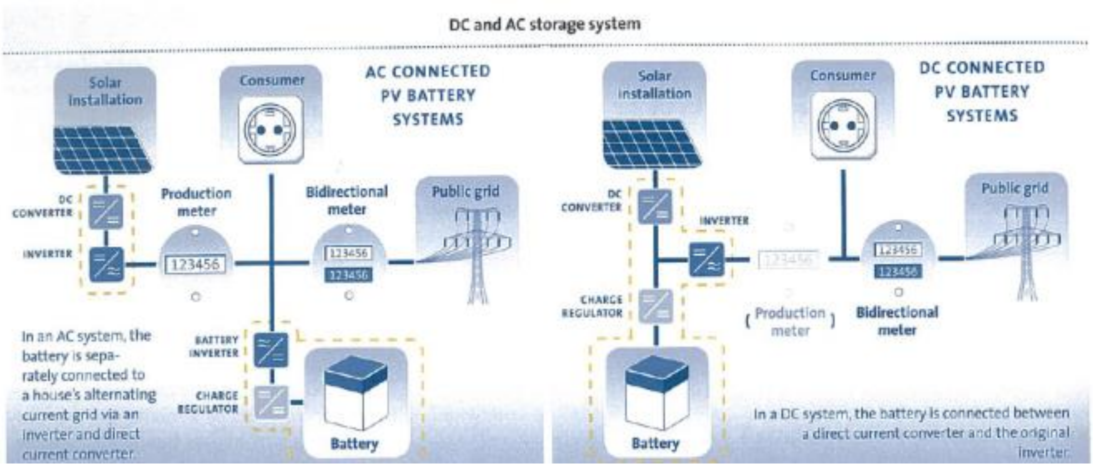


Figure 6.3: DC and AC configuration for PV & storage systems

Source: (PV-Magazine, 2013)

For this particular case study a **DC connection** is assumed, ideal for this application since a) the model is extremely sensitive to the efficiency of the conversion as it will be shown further on and b) because this kind of application does not require the flexibility and complex control that the AC-connection grants, which is more focused to quality of the grid applications while DC connection is more focused on load shifting applications.

b. Modules

As shown in table 4.2, around 91% of the power installed in the world is done with crystalline modules. That makes them a reliable and well proven technology. On the other hand, thin-film presents some advantages in hot climates and desert conditions due to their lamination process of manufacturing and to the lower temperature coefficient, which keeps low the high losses due to temperature in such climates. However, they are available only in relatively small amounts and their reliability is still under study, especially due to the degradation they suffer, which under certain circumstances is still not well understood and unexpectedly high. This is the case for example with First Solar, the biggest thin-film manufacturer in the world, as previously mentioned (Enkhardt, 2011). Although thin-film modules might certainly present some advantages for this case study and eventually show a better performance in comparison to standard crystalline ones, they would add a new level of uncertainty and lack of reliability to a technology that itself is not yet well tested and proved. Therefore the decision is made to use polycrystalline modules for this case study. Point 6.6.4 will compare the performance of each technology and analyze the impact of this decision.

c. Inverters

The selected configuration among those described in point a. (DC connected) only requires standard inverters, able to convert DC into AC current. No bidirectional inverters are required. Central inverters will be selected (vs. string ones) since a) they usually present a higher global efficiency, parameter that is critical to make the hybrid system competitive, b) because they allow better control on critical parameters such as reactive power and harmonics and c) because they are easier and more effectively integrated into the system with the batteries. This decision though will have no relevant impact into the model.

d. Mounting systems

The chosen area presents wide and vast extensions of terrain to properly deploy the PV system, and in general it is assumed that space will not be a problem. On the other hand, high ratios of direct radiation vs. horizontal radiation indicate that the use of trackers will probably present advantages vs. fix mounting systems and will certainly generate more electricity. CAPEX will also be higher, but the delta will be paid off by the increased yield as will be discussed further on. Among the different type of trackers, the horizontal trackers are chosen because of their reliability, simplicity, lower OPEX and well proven track record in areas like California and South Africa. Again, this assumption will be analyzed and discussed in section 6.6.4

e. Storage

Considering resources available for the selected location, the information presented in chapter 5 and the state of maturity of the different storage technologies, electrochemical storage (batteries) is considered to be the most suitable one to apply in this case. Among the different battery technologies (lead-acid, lithium-ion,

flow REDOX and NaS), vanadium REDOX flow batteries and LFP Lithium-ion are considered to be the most suitable ones.
The reasons are:

a) Although they certainly present very high CAPEX, higher than other technologies, they do not suffer degradation with the different charge and discharge cycles and for high capacity applications they become more cost effective since it is not necessary to replace them, or at least the degradation process is softer.

b) DoD can achieve values of 100% or close to that, so their capacity is not "wasted".

c) They are easily scalable.

The best technology to achieve low power/energy ratios is to use flow batteries as once installed the stacks for a defined power, the capacity of the battery can be easily extended by increasing the amount of electrolyte. For ratios of one to two, one to four or even one to eight, this technology presents the performance and cost efficiency balance (see figure 6.4 and 6.5).

Mainly due to a) and b), the CAPEX per kWh goes lower and lower in comparison with other technologies when increasing the capacity since it is not necessary to change the batteries after a certain number of cycles, which makes this technology ideal for large capacities and long life cycles. Figures 6.5 and 6.6 show the results of a study carried out by the Fraunhofer Institute in Germany. It shows the evolution of cost per kWh through the life of the system for lead-acid, lithium ion and REDOX flow, considering different prices for the stack and the evolution of the investment cost with the capacity for the different battery technologies.

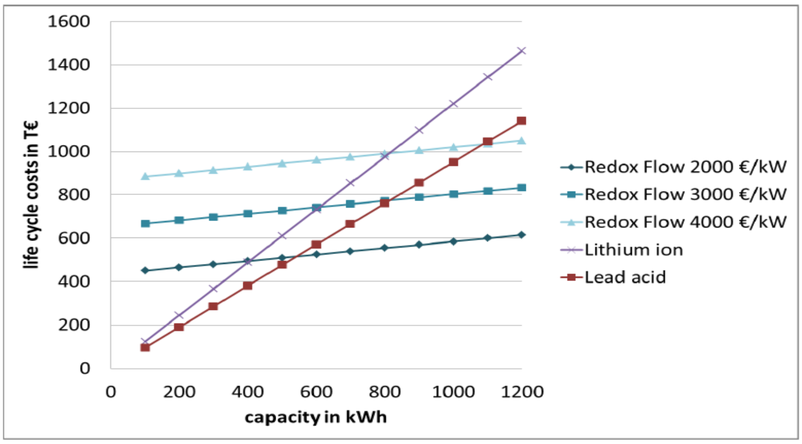


Figure 6.4: Evolution of life cycle costs (in T€) with the capacity for different battery technologies

Source: Fraunhofer Institute

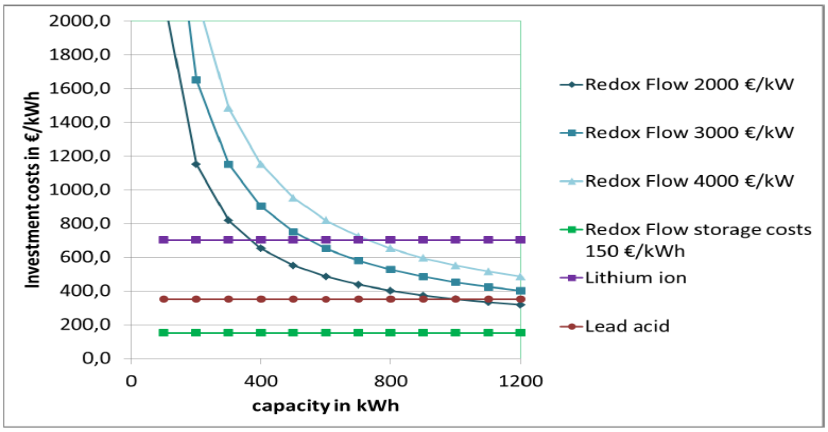
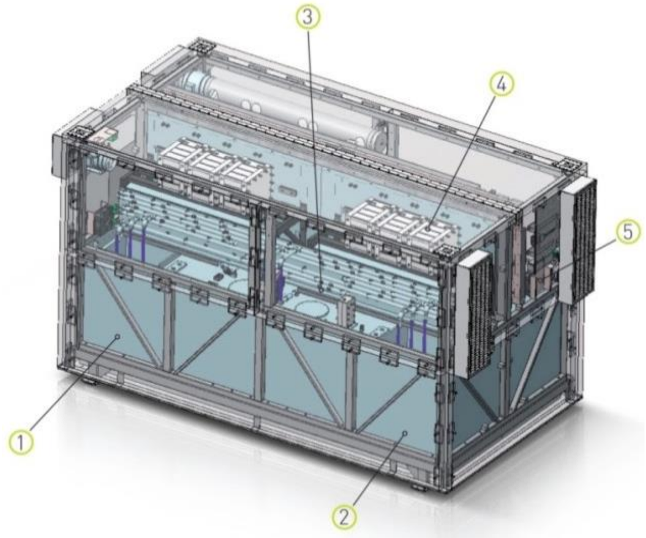


Figure 6.5: Investment cost (in €/kWh) with the capacity (in kWh) for different battery technologies

Source: Fraunhofer Institute

Additionally, c) is also a big advantage and it can be done in a very cost effective way, especially for flow REDOX batteries which are ideal for "energy oriented" applications where a large amount of energy needs to be delivered for long periods with a more or less steady power (Möllenhoff, 2013). In fact for a given price of the stacks, cost of Redox systems asymptotes to the price of the electrolyte when increasing the energy as seen in figure 6.5. For stack prices below 2.000 €/kW, which nowadays is perfectly achievable, the technology can be very competitive.

Figure 6.6 shows the internal configuration and distribution of a flow battery



1 – Negative electrolyte tank
2 – Positive electrolyte tank
3 – Fluid conduits
4 – Stacks
5 – Flow Battery - Controller

Figure 6.6: Typical configuration and distribution of a flow battery

Source: Cellstrom GmbH

Lithium-ion batteries on the other side are more oriented to "power" application, where the power/energy ratio is close to one, due to their way to work: the power and energy delivered depends on the inverters installed and how "quick" they take the energy away from the batteries. Although they are more expensive than for example Lead-acid batteries, they present other features that make them more suitable for large scale applications (see point 5.5.2).

Finally, although the NaS technology presents a great potential, it has not been taken into consideration for this case study since the technology compared with the others is not mature enough and has demonstrated in recent events to be extremely dangerous, i.e. when on the 21st of September of 2011 a NaS storage facility exploded in Japan and was burning during 14 days until the firefighters managed to put it down, causing severe material damages (Greentechmedia, 2011)

f. Diesel generation

Diesel generators are assumed to be of the "Diesel Standby Power" type as described in point 4.3.4 This means they can operate for long periods of time (hours) but have the capacity to start and stop when needed and work with loads below the nominal one. They are considered to be already installed and operative, so no additional investment will be required. They will be considered as "ideal", meaning that no replacement will be needed during the lifespan of the project (20 years). The idea behind these assumptions is that the only factor that will affect the

LCOE from the diesel generation point of view is the fuel cost and the O&M with its escalation through the time.

6.3.4 Economic assumptions

To carry on with the study, further assumptions on the cost of the system have to be made. Costs involved are of two kinds: initial investment costs or CAPEX (capital expenses) and running cost or OPEX (operational expenses). Again, these assumptions are the results of my detailed research, interviews conducted with different entities and persons related to the sector as well as my own experience as a photovoltaic engineer. Following are mentioned the companies involved in these discussions.

CAPEX

CAPEX are the expenses necessary to get the project ready to be operative. It is mainly driven by cost of the development and permitting process, acquisition of the equipment, logistics and transportation and construction of the facility. Needless to mention that the costs involved in this type of systems are, as per any other type of system and investment, subjected to an economy of scale. Costs below are considered for utility scale[1]

a. ***Development and permitting process***

Each project or new construction requires the authorizations of the local authorities. Additionally there is always a development cost involved. Typical cost of development are approx. **0,05 USD/Wp**

b. ***PV modules***

This is a tricky point since the PV modules represent the main investment of the system, but the current situation on the market for this component and its outlook is unclear. China, the largest manufacturer worldwide, is selling modules to the market below the cost of production (dumping), what allows them to keep the leading position among the international manufacturers. However, it has been issued different anti-dumping policies in different countries and continents, like USA and recently Europe (PV Magazine, 2013). Also India, which is an emerging market but

[1] It is hard to define what “utility scale” is, since there is no common opinion on that but in general terms, in the sector it is assumed to be a project with at least two digits when talking about the peak power. Thus a 20 – 30 MWp project onwards could be considered as such.

is getting more and more weight in the international business, is considering imposing anti-dumping duties to Chinese modules (Cleantechnica, 2013). These circumstances lead to a situation in which the price of modules is totally unclear. For the ongoing study a price of the modules of **0,60 USD/Wp.** Companies such as CNBM, Hyundai, Renesola, Hahwha, Jinko, JA Solar or Yinko can be seen here as references for the market.

c. *Inverters and bidirectional converters*

The market for PV inverters (DC→AC) is very well developed and there are many companies offering this kind of product. This grants the possibility to get very high quality inverters, very reliable and with high efficiency values in a very cost efficient and competitive way. Assumption: **0,20 USD/Wp** for a central inverter station solution. The inverter station would eventually include the inverters, step-up transformer and medium voltage switchgear. As shown in figure 6.3, the selected configuration (DC connected) does not require bidirectional converters which would add around 0,25 – 0,30USD/Wp more to the global cost of the system and penalize it. This is also one of the reasons why this configuration was chosen. Reference companies to benchmark this price are SMA, AEG, PowerOne, ABB and Advance Energy for example.

d. *Mounting systems*

For this component two different alternatives will be considered and compared:

- Fix mounting system: assumption **0,14USD/Wp.** References taken are Unirac, Mounting Systems, Schletter.

- Horizontal trackers: **0,25USD/Wp.** Unirac, ATI, SPG, Van der Valks, Martifer or Grupo Clavijo to were considered for benchmarking.

e. *Cables*

Prices of the cables are quite standard worldwide and mainly set by the cost of the raw materials (aluminum and or copper) which is regulated by the LME (London Market Exchange). Assumption: **0,10 USD/Wp.** References: Helukabel, Telefonika, SKW, HIS.

f. *Monitoring & control*

It is out of the scope of this document to explain how the monitoring and control of such a complex system works, integrating and connecting different technologies with each other and performing different strategies through the day and months, depending on the radiation and load of demand. At this point, it is enough to consider that it is very complex and that it includes SCADA systems for the management of different protocols of communication, many sensors, charge and discharge regulators for the batteries, etc. Everything is linked and interconnected via a CANBus that allows the communication between the different sub-systems. The assumed cost for this is **0,10 USD/Wp** (including the charge control and regulation of the batteries). References: Skytron, SolarLog, Meteocontrol

g. *Storage system (batteries)*

The fact that storage is very expensive is not a secret. This is the main reason why this kind of solutions are not more extended and used worldwide. Beyond the traditional pumped hydro system, all other kinds of storage solutions are costly and in most cases economically unfeasible. However, the rising price of fossil fuels and strong investment made in the last years on R&D for the different technologies are enabling the fact that they are becoming more and more competitive, specially under certain circumstances and for certain applications.

As presented in section 5, electrochemical storage is considered to be the most suitable technology for the present case study. Within electromechanical storage there are different technologies, each of them with their pros and cons. However, Li-ion and REDOX flow batteries present the biggest potential here. To be considered when defining the behavior and cost of a battery system is the C-RATE, which is basically the ratio between energy and power, or said in another way, the capacity of the battery and how quick this capacity is delivered in hours. Li-ion traditionally presents C-rates of one, denoted C/1, and although they can achieve lower c-rates, they perform better with c-rates close to the unit. Even further, some lithium technologies such as Lithium Cobalt Oxide (LCO) have a limited c-rate of C/1 for charge and discharge. Va-REDOX on the other side perform very well with higher C-RATE of C/2, C/4, C/8, (Wikipedia, 2013) etc. In the coming analyses for Li-ion (in particular LFP) a c-rate equal or close to one is considered and for Va-REDOX for ratios higher than one.

It is important to mention here that when modeling the different types of batteries, it has been taken into consideration that LFP batteries suffer from aging and degradation (see figure 5.6) and Va-Redox ones do not.

For the system cost of the batteries the following has been taken into account:

- ***Li-ion*****,** in particular **Lithium-Iron-Phosphate (LFP): 600$/kWh**. ByD, one of the main manufacturers of LFO batteries, gave and estimation of 550 and 650 $/kWh. Aging: 2% yearly. (Tong, 2013)

- ***Va-REDOX: 650$/kWh***. Different companies and entities have confirmed this estimation for large scale projects for c-rates higher than two. As examples, in his presentation about battery technologies, Prof. Stefan Kempfen from AEG presented a current investment cost for this technology of 500 €/kWh (650 USD/kWh) and a potential to reduce costs in a short/medium term up to 200€/kWh (260 USD/kWh). Additionally, the organization EPRI in their report *"Electricity Energy Storage Technology Options",* issued in December 2010*,* gives a range of $620-740kWh for the Va-REDOX (Rastler, 2011).

It is clear that the investment costs of the system, including the PV and storage subsystems are the main parameter for the economic feasibility. Slight changes on them can drastically influence it in a positive or negative way. Due to its influence, this factor will be subject of a deeper study later on with a sensitivity analysis.

h. Human power factor: Transport, logistic and construction: It refers to all human power activities, including transport of the gods, logistics, customs duties and construction of the facility. Within construction of the installation, engineering, civil works, electrical and mechanical works, assembling, montage, fencing and commissioning of the system are included. Therefore the assumed cost is **0,30 USD/Wp.**

That makes an overall cost of the system of **1,6USD/Wp** considering trackers or **1,49 USD/WP** with fix mounting system for the PV part (storage not included) which is quite in line for the estimations made by some analysts (Smith, 2012).

Figure 6.7 shows the expected evolution of the price of the balance of systems (all components except the PV modules) for the incoming years.

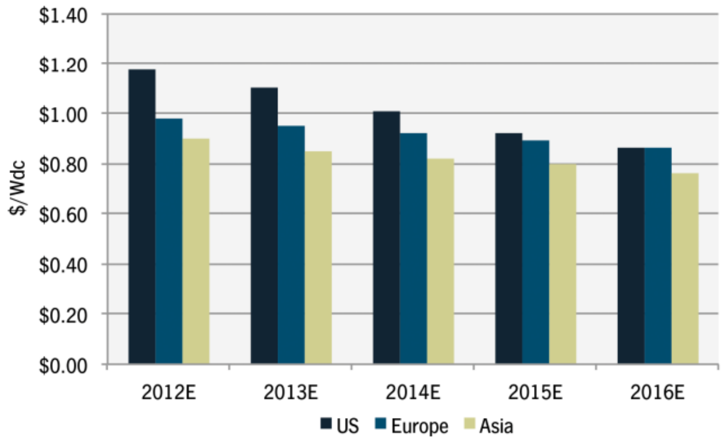


Figure 6.7: BOS Cost Comparison by Region, 10 MW Fixed-tilt c-Si System, 2012-2016

Source: GTE Research

Just as a reference, prices in Europe (Germany for example) are currently (2013) around 1€/Wp (1,3USD/Wp) for fix and around 1,1€/Wp (1,43USD/Wp) with trackers so the assumed prices are rather on the conservative side. EPC companies such as Enerparc, Phoenix Solar, Gerhlicher or Belectric can be taken as references.

OPEX

These expenses comprise all the costs for the operation of the system to provide the needed energy to the mine. It includes:

a. Fossil fuel cost

All the energy that will not be supplied by the PV system with the backup of batteries will be supplied with diesel generators. The National Commission of Energy in Chile fixes the rules to follow in order to fix prices for the energy (electricity and fuels). These fixations are regularly collected and published in the document “Fijación de Precios de Nudo” *(Fixation of the Price for the Nodes)*. As explained in section 2 each electricity system (SING, SIC, Aysén and Magallanes) is independent and with a different regulatory frame. For the SIC, system where Diego de Almagro is located, the last publication is from April 2013 (CNE, April 2013). In this document the costs for each central of energy that is supplying electricity to the system are described in detail and organized by technologies. The main table with this description can be found in appendix 3. Currently the prices for the MWh coming from diesel generator oscillate between 177,32 and 489,23 USD/MWh, depending on the size of the installation (economy of scale) and the location of the installation. In the diesel installation in Diego de Almagro (23MW) for example the price is 385,2 USD/MWh. In order to make the case study as general as possible a weighted average considering the power of the installation and the price per MWh has been calculated. The result is an average cost for diesel of **262 USD/MWh.**

Since this is also a key parameter to understand the economic feasibility of the project, a sensitivity analysis will be carried out later on as well, once the results have been presented.

b. Maintenance services

One part of the running cost expenses is the maintenance of the system. It includes labor cost of the works, spare parts, calibration and repair in the different subsystems. It is necessary to differentiate between the photovoltaic park, the batteries and the diesel generators:

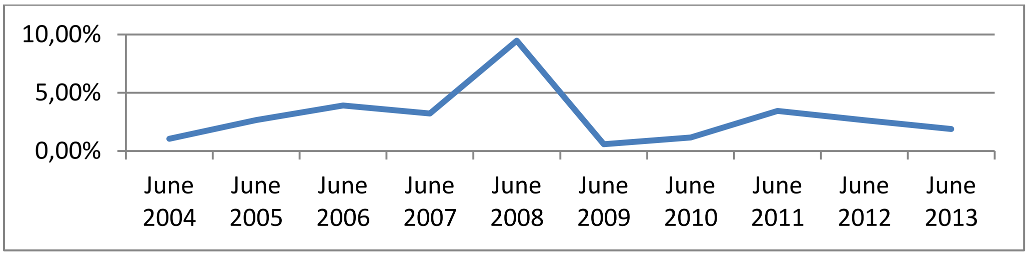
- ***Photovoltaic parks:*** Yearly **15.000 USD/MWp**, including operation, maintenance, monitoring, insurance and spare parts. References: Eosol and TSK Electrónica y Electricidad S.A., Spanish Companies that operate in the area of South America (Chile, Mexico, etc).

- ***Batteries:*** **4% of the initial investment** per year. This cost includes an O&M service from the manufacturer and a 20 years warranty, including keeping the system operative and spare parts for that period of time. References from Samsung SDI and Gildemeister.

- ***Diesel generators:*** this information is also available in the mentioned document “Fijación de Precios de Nudo” *(Fixation of the Price for the Nodes)* (CNE, April 2013). Again, it depends on the size and location of the system, oscillating from 3 to 45 USD/MWh. In the case of the central in Diego de Almagro it is 6,63 USD/MWh. In order to make it general the weighted average cost as for the fuel cost has been calculated, which is 12 **USD/MWh.**

ESCALATION OF RUNNING COSTS

The inflation in Chile in the last years is shown in figure 6.8



June 2004	June 2005	June 2006	June 2007	June 2008	June 2009	June 2010	June 2011	June 2012	June 2013
1,06%	2,67%	3,92%	3,23%	9,47%	0,59%	1,16%	3,44%	2,65%	1,90%

Figure 6.8: Evolution of the inflation in Chile in the last years

Source: http://es.global-rates.com/estadisticas-economicas/inflacion/indice-de-precios-al-consumo/ipc/chile.aspx

Considering these values, for the escalation of costs an **annual increase of 3,0%** has been assumed for the O&M services and fuel.

WEIGHTED AVERAGE COST OF CAPITAL (WACC)

In their report “Chilean Market: a Grid Parity but not without Challenges”, the Deutsche Bank establishes **7%** as a reference cost of debt in the country for PV projects (Shah, 2013). It is necessary to mention though that no large project combining PV and storage has been financed by financing entities in Chile so far. Therefore, WACC is in this case mainly driven by the cost of opportunity that the investor wants to apply here. Some banks like Deutsche Bank for example have shown their interest on this kind of solutions and are willing to study the possibility to finance them (Peters, 2013).

WACC is usually also a very sensitive parameter so a sensitivity analysis is conducted later on (see .6.8.8).

6.4 The modeling of the system

To model the system, a simple but effective tool was developed in Microsoft Excel that allows simulating the system with different configurations and dynamically interacting with it, taking into consideration all the assumptions above described. This tool also allows making sensitivities analysis to study the impact on the results when modifying the different parameters and assumptions. The main outcomes of the tool are:

- LCOE of the system for any possible configuration
- Optimum combination between diesel, PV and storage that minimizes the LCOE
- Minimum LCOE in case that decision is not to install storage, and support the diesel generation only with PV
- Energy coverage for each technology for a specific scenario
- Combination of PV, storage and diesel generation necessary to cover certain ratio of green vs. traditional generation previously given or required
- NPV and IRR of the investment for a given PPA price

It also provides secondary but still interesting and useful information such as

- Solar energy wasted due to losses that is not used by the mining company
- Seasonal, monthly and hourly prevision on when each technology will supply energy and approximately how much. This information is useful for example to pre-schedule O&M activities, hours of operation, prevision to store diesel, etc.
- PPA that generate a breakeven of the capital investment

The model is based on a daily energy balance, taking average hourly values through the year. The methodology, equations behind and algorithms will be further explained in the next points.

6.4.1 Definition of the LCOE

Levelized cost of energy has been already mentioned many times in this document, but so far, it has not been properly defined and formulated.

Levelized cost of energy (also known as levelized energy cost, LEC) is the price at which electricity must be generated from a specific source to break even over the lifetime of the project. It is an economic assessment of the cost of the energy-generating system including all costs over its lifetime, such as initial investment, operations and maintenance, cost of fuel, cost of capital and it is very useful in calculating the costs of generation from different sources (Wikipedia, 2013).

There are many ways to formulate the LCOE. For this work a simplified version with an "EBITDA" approach has been chosen, where taxations, tax credits, amortizations, depreciations and/or reinvestments are not included. When discussing about the LCOE and comparing different technologies it is very important to formulate the assumptions precisely as each of the parameters is very sensitive and only small variations can lead to completely different results.

The following definition has been considered:

$$\mathrm{LEC} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Source: (Wikipedia, 2013)

Where:

LEC or LCOE is the average lifetime levelized electricity generation cost

I_t is the investment expenditures in the year t

M_t Operations and maintenance expenditures in the year t

F_t Fuel expenditures in the year t, (diesel)

E_t Electricity generation in the year t, which needs to meet the demand of the utility

r is the rate or WACC for this case

n is Life of the system, 20 years in this case

6.4.2 Methodology for the calculations

The excel algorithm is programmed to simulate on an hourly basis of an average day of each month the balance of electrical energy between the demand required by the mine and their activities and the energy available from the different technologies, PV, storage and diesel. The global concept is

$$\boldsymbol{Production = Demand}$$

With this the total demand of energy through the year is defined. The absolute requirement that will rule all the calculations is that the demand must be 100% covered by any of the three technologies, solar, storage or diesel. On an hourly basis, the prioritization and order of utilization are set as follows:

Priority Nº 1: Solar energy. When the PV system is producing because solar radiation is available it has total priorities over the other two. All available energy generated by the PV system will be directly used by the system. If there is a surplus of supply from solar this will be stored in the batteries or wasted. If solar energy is not able to cover the demand on a specific hour, the difference will be covered by the storage first or diesel generator if stored energy is not available.

Priority Nº 2: Storage**.** If there is no solar radiation available (night time or cloudy day) the energy demand will be covered from the batteries if it is available, discharging them with the required power to fulfill the demand.

Priority Nº 3: Diesel Generators. Finally, if neither solar nor storage are available, or only partially to cover the demand, the remaining part will be covered by the diesel generators.

The methodology of the calculation has the following steps:

1) ***Calculation of PV generation:*** This is done with the help of the radiation data bases SolarGis and the simulation software PVSYST. With these the hourly average yield of the PV system for each month of the year can be determined. This results in a table with the 288 values that represent the average production of 1 MWp installation in the selected place (see appendix 5)

2) ***Calculation of the energy demand*** by considering the hourly average load of demand during the year. As previously explained, due to the lack of more detailed information, for this exercise a more or less homogenous electricity demand through the day and year has been considered, making a differentiation between the load during day and night (40% day, 60% night), equally distributed the 365 days of the year. This generates a table with 24 values corresponding to the hourly demand of energy of a standard day, which will be the same 365 days per year. It is worth to mention at this point that, in case of availability of more detailed data about the profile of consumption, it would lead to more accurate results, but the process and strategy would not change. Instead of making 288 balances of energy through the year, it would be possible to make 8760 (365x24), but the algorithm and balance of energy would always follow the formulas above described.

3) ***Programming the energy balance calculations in EXCEL:*** for a defined system configuration, that is, combination of PV storage and diesel generation, it is necessary to calculate the hourly energy balance through the year following the criteria given above. The best and simplest way to evaluate the hourly balance of energy between the demand and the available sources is to program it in an excel table. This table represents the critical part of the simulation, so more detailed description will follow in 6.4.3.

4) ***Calculate the LCOE and obtain the system with the lowest value***. To obtain the optimum combination between PV, storage and diesel it is necessary to evaluate all the different possible configurations, calculate the LCOE and compare the results. Excel facilitates this task, giving the possibility to generate a table with two variables and showing the results. For this study, the two main variables to be considered are the **PV power (MWp)** and the **storage capacity (MWh)** to be installed. Then LCOE can be easily calculated with the equation described on the last point. The optimum configuration will be the one that gives the lowest LCOE.

   This is the same evaluation process done by all commercially available software for hybrid systems such as HOMER, VIPOR or Hybrid2.

5) ***Sensitivity analysis and decision:*** Once the results are available, it is necessary to evaluate them in detail and eventually make the final decision whether it is economically and technically feasible to substitute the diesel generation by a combination of PV plus storage. A useful tool to help making

the decision is to make a sensitivity analysis of the most critical variables. That will also help to understand whether the assumptions taken are appropriate or need to be reformulated, generating an iterative process converging to the optimum.

6) ***Calculation of the economics of the system:*** With LCOE and the definition of my system (PV power and storage capacity) it is possible to calculate the IRR and NPV of the investment for a given PPA (price of the energy in USD/kWh), calculate the PPA that will create a breakeven in the investment, or to calculate what would be the price of the energy that a mining company would have to pay to give the investor a required IRR.

6.4.3 Equations

The above mentioned defines the strategy how the programming of the EXCEL sheet is set for the hourly energy balance. The complete model is based on the simple assumption, logical on the other way, that 100% of the energy demand must be covered one way or another every hour of every day, 24 hours per day 365 days per year.

Thus the main formula that defines the global energy balance is:

$$E_{Demand} = \sum_d \sum_h E_{Demanddh} = \sum_d \sum_h G_{Dieseldh} + \sum_d \sum_h G_{PVdh}$$

$$G_{Solardh} = G_{PVdh} + G_{Wastedh}$$

Where:

E_{Demand}: Total demand of electrical energy of the mine during one year in MWh.

$E_{Demanddh}$: Energy demand of the system during the day “d” and the hour “h”.

***$Diesel_{dh}$*:** Energy generated by the diesel generator during the day “d” and the hour “h”.

***$Solar_{dh}$*:** Energy that the PV system can potentially supply the day “d” and the hour “h”. This energy can actually be used by the system or “wasted”.

Attending the main formula above, the calculations are implemented in EXCEL.

At a first stage it is necessary to calculate ***Demand***$_{dh,}$ and subsequently ***Demand***. Each of the 24 hours are identified as "night" or "day", and get associated a predefined value for the typical demand. For the base case study it has been considered a hypothetical copper mine that produces 50 kMT per year of pure refined copper. As discussed in point 3.2, 7,245 MWh of electricity are required in average in Chile to produce one metric ton of pure copper, so the yearly requirement of electricity is

$$E_{Demand} = E_{Specdemand} * Q_{MT}$$
$$E_{Demand} = 7,245\ MWh/MT\ x\ 50\ kMT = 362.250\ MWh/year$$

Assuming the **40 %** of the consumption occurs during the **day** and **60%** during the **night** as discussed in 6.3.2 we have:

$$E_{daytime} = Prop_{day(\%)} * E_{Demand}$$
$$E_{nighttime} = Prop_{night(\%)} * E_{Demand}$$

- Daytime: $0,4\ x\ {}^{362.250MWh}/_{365\ days} = 396,99\ \text{MWh}$
- Nighttime: $0,6\ x\ {}^{362.250\ MWh}/_{365\ days} = 595,48\ \text{MWh}$ d

"Daytime" is defined **from 6:00 to 17:59** and **"Nighttime" from 18:00 to 5:59**, splitting the 24 hours of the day in two identical time spans of 12 hours.

For the "Day" and "Night" times the hourly distribution of power required results as:

$$E_{Demand\text{dh}} = {}^{396,99\ MWh}/_{12h} = 33,08\ MWh \text{ during Day time}$$
$$E_{Demand\text{dh}} = {}^{595,48\ MWh}/_{12h} = 49,62\ MWh \text{ during Night time}$$

The maximum hourly energy requirement during the night time in this case, defines the power requirement of the system, which will be **50MW** for the modeled case. This has a significant impact in the design of the system since it defines the sizing of the diesel generators, the inverters and the stacks of the Va-REDOX batteries for example.

GSolar$_{dh}$ is calculated from the available radiation obtained with the help of the iMap tool from SolarGis http://solargis.info/imaps and processing the data with the PV software PVSYST. The annual results for the selected location considering two different versions, a system with modules assembled on a horizontal tracking system and a fix system, are summarized in table 6.3.

Table 6.3: Summary of the annual radiation and energy production of the PV system

San Diego de Almagro										
Months	Gh (kWh/m2 day)	Gh (kWh/m2 month)	Geff_Fix (kWh/m2 month)	Geff_Tr (kWh/m2 month)	PR_Fix	PR_Tr	FLH_Fix (MWh/MWp)	FLH_Tr (MWh/MWp)	Yield_Fix (MWh)	Yield_Tr (MWh)
Jan	8,51	264	231,0	331,0	0,78	0,77	181	255	16.316	22.938
Feb	7,95	223	210,3	288,8	0,78	0,77	165	222	14.839	20.014
Mar	7,02	218	229,7	298,8	0,80	0,78	184	233	16.540	20.976
Apr	5,66	170	202,0	247,8	0,82	0,79	165	196	14.866	17.619
May	4,51	140	188,3	218,1	0,83	0,80	157	174	14.122	15.703
Jun	4,01	120	169,7	189,1	0,84	0,81	143	153	12.860	13.785
Jul	4,30	133	184,5	209,7	0,84	0,82	155	172	13.979	15.476
Aug	5,32	165	207,3	285,7	0,83	0,81	173	231	15.537	20.828
Sep	6,67	200	223,4	324,8	0,82	0,80	183	260	16.442	23.386
Oct	7,81	242	236,4	331,7	0,80	0,77	190	255	17.122	22.987
Nov	8,64	259	230,6	336,8	0,79	0,77	183	259	16.470	23.340
Dec	8,76	272	230,1	336,8	0,79	0,76	181	256	16.290	23.040
ANNUAL	**6,6**	**2.406**	**2.543**	**3.399**	**0,79**	**0,79**	**2.060**	**2.668**	**185.383**	**240.091**

Source: Own elaboration

Where ***G$_h$*** is the global horizontal radiation, ***G$_{eff}$*** is the effective radiation on the modules plane, PR is the performance ratio, FLH are the full load hours of the system and yield represents the global production of the system in MWh/year.

The mentioned variables are linked with the following formula:

$$\boldsymbol{Yield = Pp\ x\ PR\ x\ ^{Geff}/_{Gref}}$$

P$_p$ is the peak power in standard conditions (1000 W/m^2, 25ºC and 1,5 of air mass) installed and ***G$_{ref}$*** the reference irradiance equal to 1000W/m^2 as defined for the standard conditions. The ***PR*** is an experimental parameter that can be measured, but not directly calculated with accuracy due to its complexity, multiple dependencies and physics effects that affect it. The PR reflects the losses due to:

- Low irradiance
- Reflection on the glass of the modules
- Losses due to shadowing
- Temperature losses
- Wiring losses
- Electrical losses in inverters and transformers

G_h values are given by SolarGis based on satellite measurements between 1994 and 2013. SolarGis gets the information from different databases (see SolarGis report in appendix 4). G_{eff} is calculated from G_h with the help of PVSYST, which calculates the gains and losses due to the position of the modules respective to the sun. It is usually a complex calculation that includes different models, methodologies and algorithms. The most common ones, generally used in commercial software are the ones by Perez and Boland/Ridley/Lauret (Lanini, 2010)

As described above:

$$G_{Solardh} = G_{PVdh} + G_{Wastedh}$$

With

G_{PVdh}**:** Energy of the PV system that is actually used to supply energy to the mine on the day “d” and at the hour “h”. This energy can be supplied directly by the PV system to the mine or be stored to be supplied later on when needed.

$G_{Wasteddh}$**:** The term “wasted” refers to the energy that proceeding from the PV installation could have been used by the mine to cover their necessities but for any reason was not used and “wasted”. It includes the losses of the charge and discharge process due to the efficiency of the process and the surplus of energy produced by the PV system that is not required by the mine.

$$G_{PVdh} = G_{PVdirectdh} + G_{Storagedh}$$

With:

$G_{PVdirectdh}$**:** Energy proceeding from the PV generator that is *directly* used by the system to supply energy to the mine the on day “d” and at the hour “h”.

***$G_{Storagedh}$*:** Energy that, although proceeding from the PV generator, is not directly used by the system but stored in the batteries the on day "d" and at time "h" to be used later on. This term is logically affected by the efficiency of the storage mechanism. That is: $\eta_{dc\text{-}st}$ which is the efficiency to store the energy from the DC-Bus connected to the PV modules into the batteries (charging efficiency) and $\eta_{st\text{-}ac}$ is the efficiency to recover the energy stored into the batteries return it into the DC-Bus (discharge efficiency) and convert it into AC. Related to the variable storage, it is also necessary to define two more intermediate variables, C_{dh}, and C_{max} which represent respectively the charge status of the batteries on the day "d" at hour "h" and the maximum capacity of the battery, both in MWh. For the hourly balance, the natural limitation below will be considered to calculate the evolution of each of the variables from dh to dh+1

$$0 \leq C_{dh} \leq C_{max} \text{ for each d and h}$$

$G_{Storagedh}$ should be physically understood as the flow of energy from or to the battery. In mathematical terms:

$$G_{Storagedh} = |C_{dh+1} - C_{dh}|$$

By calculating $G_{PVdirectdh}$ and $G_{Storagedh}$ all other necessary terms would be available to close the hourly balance of energy. For their calculation it is necessary to appeal to the main formula of the energy balance and to the prioritization described at point 6.4.2.

All in all, for each day and hour the value of **7 different variables** must be calculated to know:

- The energy demand $E_{Demanddh}$ calculated as above mentioned for each day and hour

- The solar energy available, $G_{Solardh}$ calculated with SolarGis and PVSYST. PVSYST gives the option to simulate and give an hourly breakdown of the solar production of the PV system. Appendixes 6 and 7 show the simulations for systems with fix and tracking systems respectively.

- The energy flow of each technology, to know the supply for each technology for each day and hour, $G_{PVdirectdh}$, $G_{Dieseldh}$ and $G_{Storagedh}$.

- The amount of energy lost due to the efficiency of the system and surplus of energy not consumed or stored, $G_{Wasteddh}$.

- The charge status of the battery system, C_{dh}.

For simplicity reasons, instead of calculating the 7 variables for the 365 days, a typical day for each month from the demand and solar energy production point of view has been programmed and assumed 31 typical days in January, 28 in February, etc., generating a table of "only"

$$7\ variables\ x\ 12\ months\ x\ 24\ hours = 2.016\ entries.$$

Depending on the conditions of the system in each day and hour, formulas are set in EXCEL as follows:

a) If $G_{Solardh} > E_{Demanddh}$, meaning that there is enough solar energy to cover the demand

- $G_{PVdirectdh} = E_{Demanddh}$
- $G_{Dieseldh} = 0$ No diesel generation required
- $G_{Storagedh} = (G_{Solardh} - E_{Demanddh})\ x\ \eta_{charge}$
- $C_{dh} = G_{Storagedh} + C_{dh-1}$ There is surplus of solar energy available, so the batteries charge if there is capacity available
- $G_{Wasteddh} = (1 - \eta_{charge})x\ (G_{Solardh} - E_{Demanddh}) + +\Delta Charge$ where ***ΔCharge*** represents the solar energy "wasted" that is not consumed or stored in the case the batteries would be already full.

b) If $G_{Solardh} < E_{Demanddh}$, meaning that there is NOT enough solar energy to cover the demand

b.1) If $C_{dh-1} > 0$, meaning that there is energy stored available

- $G_{PVdirectdh} = E_{Demanddh} - G_{Solardh}$
- $C_{dh} = C_{dh-1} - G_{Storagedh}$ Batteries are discharging

And additionally

b.1.1) If $C_{dh-1} > (E_{Demanddh} - G_{PVdirectdh}) / \eta_{disc}$ (storage is able to fully complement solar energy to cover all the demand)

- $G_{Storagedh} = (E_{Demanddh} - G_{PVdirectdh}) / \eta_{disch}$
- $G_{Dieseldh} = 0$
- $G_{Wasteddh} = (1/\eta_{disc} - 1) x (E_{Demanddh} - G_{PVdirectdh})$

b.1.2) If $C_{dh-1} < (E_{Demanddh} - G_{PVdirectdh}) / \eta_{disc}$ (storage is NOT able to fully complement solar energy to cover all the demand)

- $G_{Storagedh} = C_{dh-1}$ Batteries will empty completely
- $G_{Dieseldh} = E_{Demanddh} - G_{PVdirect} - G_{storagedh} \, x \, \eta_{disc}$
- $G_{Wasteddh} = (1 - \eta_{disc}) \, x \, G_{Storagedh}$

b.2) If $C_{dh-1} = 0$, meaning that energy stored is NOT available (batteries are empty) and therefore the diesel generators must fully complement the solar generation

- $G_{PVDirectdh} = G_{PVSolardh}$
- $G_{Dieseldh} = E_{demanddh} - G_{PVDirectdh}$
- $G_{Wasted} = 0$
- $G_{Stored} = 0$
- $C_{dh} = 0$

For the efficiency, values were considered as:

- $\eta_{charge} = 92\%$.
- $\eta_{disc} = 90\%$

Efficiency of discharge is slightly lower since it also includes the DC→AC conversion. Global efficiency results in approx. 83%, which are typical values in the charge and discharge processes, obtained from Gildemeister and Samsung SDI.

In practice, there is a simpler way to calculate the energy wasted since it is not necessary to record hour by hour $G_{Wasteddh}$. To have the global view of the energy lost due to the charge and discharge efficiency of batteries and eventually the energy not stored due to surplus of solar production, it is enough to make a final energy balance between $\boldsymbol{G_{Solardh}}$, $\boldsymbol{G_{Dieseldh}}$ and $\boldsymbol{E_{Demanddh}}$:

$$G_{Wasted} = \sum_{d} \sum_{h} G_{Wasteddh}$$
$$= \sum_{d} \sum_{h} G_{Solardh} + \sum_{d} \sum_{h} G_{Dieseldh} - \sum_{d} \sum_{h} E_{Demanddh}$$

For this case study it is calculated this way.

6.5 Presentation of results for the Case Study

Once the system and assumptions for the case study was described (point 6.3), the model was defined by setting the equations and parameters (point 6.4) and the formulation has been implemented in EXCEL, we are in the position to run the model, get the results and analyze them.

At a first stage and to understand the results, it is necessary to get the LCOE of the system without any kind of additional support. That is, the LCOE with just the diesel generation covering 100% of the daily electricity demand of the mine during day and night. Assuming values for the diesel generators as described in 6.3 (fuel cost, O&M and WACC) and taking the equation of the LCOE as described in 6.4 it can be calculated the breakdown of expenses and electricity generated, shown in table 6.4.

Table 6.4: Calculation of LCOE for a Diesel Generator to supply 100% of the electricity to a copper mine with a 50kMT/year production

Year	Investment	Diesel Gen. Running Costs	O&M Hybrid System	Discount Life Cycle Cost	Electricity Generation (MWh)	Discount Lifetime Energy Production
0	$ -	$ -	$ -	$ -	0	0
1	$ -	$ 105.965.370	$ -	$ 99.033.056	362.250	338.551
2	$ -	$ 109.144.331	$ -	$ 95.330.886	362.250	316.403
3	$ -	$ 112.418.661	$ -	$ 91.767.114	362.250	295.704
4	$ -	$ 115.791.221	$ -	$ 88.336.568	362.250	276.359
5	$ -	$ 119.264.957	$ -	$ 85.034.266	362.250	258.279
6	$ -	$ 122.842.906	$ -	$ 81.855.415	362.250	241.382
7	$ -	$ 126.528.193	$ -	$ 78.795.400	362.250	225.591
8	$ -	$ 130.324.039	$ -	$ 75.849.777	362.250	210.833
9	$ -	$ 134.233.760	$ -	$ 73.014.272	362.250	197.040
10	$ -	$ 138.260.773	$ -	$ 70.284.766	362.250	184.150
11	$ -	$ 142.408.596	$ -	$ 67.657.298	362.250	172.102
12	$ -	$ 146.680.854	$ -	$ 65.128.053	362.250	160.843
13	$ -	$ 151.081.280	$ -	$ 62.693.360	362.250	150.321
14	$ -	$ 155.613.718	$ -	$ 60.349.683	362.250	140.487
15	$ -	$ 160.282.130	$ -	$ 58.093.620	362.250	131.296
16	$ -	$ 165.090.594	$ -	$ 55.921.896	362.250	122.707
17	$ -	$ 170.043.312	$ -	$ 53.831.358	362.250	114.679
18	$ -	$ 175.144.611	$ -	$ 51.818.971	362.250	107.177
19	$ -	$ 180.398.949	$ -	$ 49.881.813	362.250	100.165
20	$ -	$ 185.810.918	$ -	$ 48.017.072	362.250	93.612
TOTAL	$ -		$ -	**$ 1.412.694.644**	7.245.000	**3.837.682**

Source: Own elaboration

Taking the definition of LCOE:

$$LCOE = \frac{Tot. Life\ Cycle\ Cost}{Tot. Lifetime\ Energy\ Production} = \frac{1.412.694.644}{3.837.682} = 368,11\ \$/MWh$$

It is important to make some clarifications on the table 6.4. Firstly, the investment cost for the diesel generator has been considered zero, since it is assumed that the mining company is already equipped with the necessary system to supply the energy. Additionally, it was also considered that the lifetime of that system will be 20 years, so no re-investment for this equipment is required. Both assumptions have been made for a) simplicity, in order to keep the model as simple as possible, still reflecting reality and b) to check whether the integration of the hybrid system with the diesel generation is competitive (lower LCOE) even in the best case scenario for the diesel system. If the hybrid system turns to be competitive under these circumstances, it will be even more competitive in a more pessimistic scenario (from the diesel generation point of view) in which an initial investment or replacement of the diesel generator would have to be carried out after 5 or 10 years of service.

It is also worth to remind that the running costs of this conventional system includes the fuel costs and the O&M services, considering 284 $/MWh as described in section OPEX of point 6.3.4.

Thus, if there is a combination of diesel, PV and storage that could eventually bring down the cost of energy **below 368,11 $/MWh**, in general the cost effectiveness and competitiveness of this kind of hybrid systems in the particular application of mining activities in the North of Chile would be proven.

The implemented model in EXCEL shows that the addition of PV and storage in specific proportions to partly supplement the diesel generation, or even the integration of only PV without any storage, can certainly decrease the levelized cost of energy of the system for the defined period of 20 years. Table 6.5 shows these interesting results:

Table 6.5: LCOE for different combinations of PV power (columns, in MWp) and Storage capacity (rows, in MWh) to partly supplement diesel generation to supply electricity to a copper mine with a 50kMT/year production

$ 264,4	0	10	20	30	40	50	60	70	80	90	100	110
0	$368,11	$345,64	$323,16	$300,68	$278,25	$267,67	$266,78	$269,39	$272,58	$276,06	$279,77	$283,62
20	$373,36	$350,88	$328,41	$305,93	$283,46	$268,30	$265,45	$267,99	$271,17	$274,66	$278,36	$282,22
40	$378,61	$356,13	$333,66	$311,18	$288,71	$269,76	$265,15	$266,59	$269,77	$273,25	$276,96	$280,81
60	$383,86	$361,38	$338,90	$316,43	$293,96	$273,53	$265,42	$265,23	$268,37	$271,85	$275,55	$279,41
80	$389,10	$366,63	$344,15	$321,68	$299,21	$278,78	$266,52	$264,54	$266,96	$270,45	$274,15	$278,01
100	$394,35	$371,88	$349,40	$326,92	$304,45	$284,02	$267,93	$264,81	$265,56	$269,04	$272,75	$276,60
120	$399,60	$377,12	$354,65	$332,17	$309,70	$289,27	$270,88	$265,08	$264,61	$267,64	$271,34	$275,20
140	$404,85	$382,37	$359,90	$337,42	$314,95	$294,52	$275,76	$266,38	$264,47	$266,24	$269,94	$273,79
160	$410,10	$387,62	$365,14	$342,67	$320,20	$299,77	$281,01	$267,77	$264,74	$265,09	$268,54	$272,39
180	$415,34	$392,87	$370,39	$347,92	$325,45	$305,02	$286,25	$269,81	$265,09	$264,40	$267,13	$270,99
200	$420,59	$398,12	$375,64	$353,16	$330,69	$310,26	$291,50	$273,56	$266,48	$264,65	$265,79	$269,58

Source: Own elaboration

The "greener" the cell looks, the lower the LCOE is and the more red, the higher. It can be observed that if we divide the rectangle table in two rectangle triangles from the "0, 0" coordinate to "110, 300" any combination of PV and storage on the upper right part presents a lower LCOE than the basis case with only diesel (0 PV power and 0 storage capacity installed). The minimum happens for a **90MWp** peak power installation and an installed capacity of storage of **180MWh** with Va-REDOX, achieving a **LCOE of 264,4$/MWh.** This is therefore the **optimum configuration** that gives the minimum LCOE. The detailed yearly breakdown for this specific case is presented in table 6.6.

Table 6.6: Calculation of LCOE for a Hybrid System with Diesel Generator, 90MWp of photovoltaic installation and 180MWh capacity of storage to supply 100% of the electricity to a copper mine with a 50kMT/year production

Year	Investment	Diesel Gen. Running Costs	O&M Hybrid System	Discount Life Cycle Cost	Electricity Generation (MWh)	Discount Lifetime Energy Production (MWh)
0	$261.000.000	$ -	$ -	$ 261.000.000	0	0
1	$ -	$ 50.313.907	$ 6.210.900	$ 52.826.922	362.250	338.551
2	$ -	$ 51.824.342	$ 6.397.227	$ 50.852.973	362.250	316.403
3	$ -	$ 53.380.126	$ 6.589.144	$ 48.952.788	362.250	295.704
4	$ -	$ 54.982.620	$ 6.786.818	$ 47.123.609	362.250	276.359
5	$ -	$ 56.633.228	$ 6.990.423	$ 45.362.784	362.250	258.279
6	$ -	$ 58.333.393	$ 7.200.135	$ 43.667.757	362.250	241.382
7	$ -	$ 60.084.605	$ 7.416.139	$ 42.036.071	362.250	225.591
8	$ -	$ 61.888.395	$ 7.638.624	$ 40.465.358	362.250	210.833
9	$ -	$ 63.746.343	$ 7.867.782	$ 38.953.339	362.250	197.040
10	$ -	$ 65.660.076	$ 8.103.816	$ 37.497.822	362.250	184.150
11	$ -	$ 67.631.267	$ 8.346.930	$ 36.096.694	362.250	172.102
12	$ -	$ 69.661.643	$ 8.597.338	$ 34.747.923	362.250	160.843
13	$ -	$ 71.752.980	$ 8.855.258	$ 33.449.553	362.250	150.321
14	$ -	$ 73.907.110	$ 9.120.916	$ 32.199.700	362.250	140.487
15	$ -	$ 76.125.918	$ 9.394.544	$ 30.996.551	362.250	131.296
16	$ -	$ 78.411.347	$ 9.676.380	$ 29.838.361	362.250	122.707
17	$ -	$ 80.765.396	$ 9.966.671	$ 28.723.449	362.250	114.679
18	$ -	$ 83.190.127	$ 10.265.671	$ 27.650.199	362.250	107.177
19	$ -	$ 85.687.662	$ 10.573.642	$ 26.617.053	362.250	100.165
20	$ -	$ 88.260.187	$ 10.890.851	$ 25.622.512	362.250	93.612
TOTAL	$261.000.000		$166.889.209	**$ 1.014.681.418**	7.245.000	**3.837.682**

Source: Own elaboration

$$LCOE = \frac{Tot. Life\ Cycle\ Cost}{Tot. Lifetime\ Energy\ Production} = \frac{1.014.681.418}{3.837.682} = \$264,40MWh$$

Note that the electricity generated is always the same, 362.250 MWh/Year corresponding to the required demand from the mine as calculated in section 6.4.3

This optimum configuration can bring down the LCOE from 368,11$/MWh to 264,40$/MWh, which results in a **saving of 39,22%.**

Table 6.7: Monthly Energy Balance for each technology, diesel PV and storage for the 90MWp PV and 180MWh storage capacity case, which presents the minimum LCOE

SOURCE OF SUPPLY (MWh)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	PENETRATION
PV PRODUCTION	23.358	20.423	21.590	18.345	16.530	14.490	16.051	18.839	21.089	23.528	23.551	23.841	241.635	52,7%
DIRECT PV USED	12.189	10.855	11.475	10.642	10.438	9.580	10.184	10.739	10.920	11.694	11.713	12.323	132.753	36,6%
STORAGE USED	5.022	4.536	5.022	4.860	5.022	4.065	4.858	5.022	4.860	5.022	4.860	5.022	58.171	16,1%
DIESEL	13.555	12.398	14.270	14.272	15.307	16.129	15.724	15.006	13.994	14.051	13.201	13.422	171.326	47,3%
PV ENERGY LOST	5.997	4.473	4.603	2.659	1.045	844	1.009	2.816	4.598	6.138	6.123	5.953	46.259	19,1%
TOTAL LOAD DEMAND	30.766	27.789	30.766	29.774	30.766	29.774	30.766	30.766	29.774	30.766	29.774	30.766	362.250	100,0%

Source: Own elaboration

With that optimized combination, **52,7%** of the demand can be covered with **solar energy**, split in **36,6% of direct supply and 16,1% via the storage**. The additional 47,3% would be supplied with diesel generator. 19,1% of the solar energy would be lost due to charge and discharge efficiencies and to surplus of energy not stored.

Appendix 8 presents the matrix from the EXCEL model that results when calculating the energy balance though the year with the algorithm previously described. Table 6.7 contents the monthly sum of that matrix to summary the results.

6.6 Sensitivity analysis

In this section the sensitivity analysis of the main parameters and assumptions made during the discussion is presented. The idea is to show how the LCOE and optimum configuration of the system are affected when modifying the different assumptions. As above mentioned, for optimum configuration it is understood the combination between diesel, PV and storage that represents the lowest possible LCOE for the given assumptions.

For the sensitivity analysis a power requirement equal to the maximum MWh needed through each hour of the day, 50MW in general as explained when

presenting the equations is presumed. This power is taken as a reference to choose between LFP and Va-REDOX. In general, in all the incoming tables of this section it will be specified which between those two is the most convenient technology.
All the analyses are carried out with the help of the EXCEL tool developed by changing one parameter and keeping all remaining assumptions unchanged. For each analysis, a brief discussion will be carried out to comment the results.

6.6.1 Analysis of the system without storage

It was just shown how integrating storage into the system a minimum LCOE of $264,4/kWh can be achieved. Before going deeper into the analysis it might make sense at a first step to see the impact on the system by not using storage. Considering the same scenario and assumptions, the minimum LCOE without storage occurs for a **60MW PV** installation with a value of **$266,78/MWh** as shown in table 6.5 above. This is understandable considering that, attending the results showed in 6.4.3, the energy demand required during the day is 33, 08 MWh, which means (considering constant the load) a maximum power of 33,08MW. A PV installation of 60 MW can perfectly cover a large part of the demand during the day (up to 35.3% through the year). As during part of the day the demand will be lower than the energy available, especially during summer and spring seasons, part of the PV production will be lost. Non used and "wasted" energy will be of 20,6% for this particular case. The summary of the energy balance through the year is presented in table 6.8 and appendix 9 shows the complete table with monthly energy balance behind.

Table 6.8: Monthly Energy Balance for diesel and PV technologies with a 60MWp PV installation without storage

SOURCE OF SUPPLY (MWh)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	PENETRATION
PV PRODUCTION	15.572	13.615	14.393	12.230	11.020	9.660	10.701	12.559	14.059	15.685	15.701	15.894	161.090	35,3%
DIRECT PV USED	11.838	10.361	11.046	10.128	9.965	9.088	9.724	10.348	10.515	11.537	11.448	11.976	127.973	35,3%
STORAGE USED	0	0	0	0	0	0	0	0	0	0	0	0	0	0,0%
DIESEL	18.928	17.428	19.720	19.646	20.802	20.686	21.042	20.418	19.259	19.230	18.326	18.791	234.277	64,7%
PV ENERGY LOST	3.734	3.255	3.347	2.102	1.055	572	977	2.211	3.544	4.149	4.253	3.919	33.117	20,6%
TOTAL LOAD DEMAND	30.766	27.789	30.766	29.774	30.766	29.774	30.766	30.766	29.774	30.766	29.774	30.766	362.250	100,0%

Source: Own elaboration

6.6.2 Modifying the coverage of renewable energy

After presenting the results and attending to the list of requirements defined in 6.1, where not only the economical but also technical and environmental aspects were included, the natural questions to answer are: How does the LCOE change when changing the coverage of renewable energies? Is it possible to achieve 0% of diesel to cover the demand? How does the combination of PV and storage evolve when changing the targeted diesel share?

It is clear that to reduce the share of diesel generation and increase the coverage with renewable energy (solar energy, either directly or stored) it is necessary to increase the PV installed and/or the storage capacity. This clearly represents an increase on the CAPEX, what translates in an increase of LCOE. The further the target is from the minimum, the more LCOE will increase.

Table 6.9 shows the results obtained.

Table 6.9: Evolution of LCOE, IRR and optimum combination of PV and Storage when decreasing the diesel share to cover the demand

Diesel Coverage	LCOE ($/MWh)	PV Installed (MWp)	Storage installed (kWh)	CAPEX (Million $)	IRR Project (%)
100%	386,11	0	0	0,0	0,00
90%	336,64	14	0	22,4	38,82
80%	307,43	27	0	43,2	38,82
70%	276,26	41	0	65,6	38,69
60%	265,38	60	60 (LFP)	135,0	20,80
50%	264,74	80	160 (REDOX)	232,0	11,60
47%	264,40	90	180 (REDOX)	261,0	10,14
40%	265,03	100	260 (REDOX)	329,0	7,49
30%	267,24	120	380 (REDOX)	439,0	4,74
20%	271,98	140	500 (REDOX)	549,0	2,83
10%	276,74	160	620 (REDOX)	659,0	1,50
2,5%	320,28	190	840 (REDOX)	850,0	-1,76

Source: Own elaboration

As expected, the evolution of the LCOE values draw a typical “U-curve” with a minimum in $264,30/MWh, corresponding to the already described “90 – 180” value.

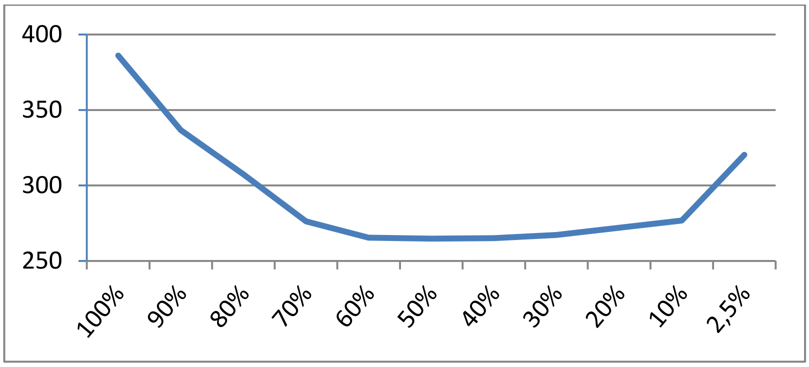


Figure 6.9: "U-Curve" of LCOE ($/MWh) in evolution with the diesel generation share

Source: Own elaboration

The explanation is, starting from a 100% share of diesel and progressively decreasing it:

1) When adding PV generation capacity to the system, the global LCOE decreases due to the lower LCOE of the PV generation in comparison with diesel generation. The expensive fuel is progressively substituted by “green energy”

2) Surpassing the threshold of 70% of diesel coverage (around 66% as to be discussed later on), it is not only convenient but necessary to install storage to decrease the LCOE. Increasing the combination PV plus storage allows a further reduction of the operating cost by a further reduction the fuel needed.

3) The minimum of the curve takes place at 90 MWp of PV and 180 MWh of capacity with a renewable coverage of 52,7%. At that point the symbiosis between diesel, PV and storage reaches the optimum and guarantees a minimum investment and operation cost to cover the demand through the lifetime of the installation

4) If a higher ratio of diesel is targeted and wants to be covered with renewable energy beyond the optimum, the investment and operation cost of the PV + storage system will not pay off the decrease of fuel needed. This creates a new raise of the LCOE

Figure 6.10 shows the evolution of CAPEX for each of the cases given in table 6.9. The investment costs of the system drastically increases when decreasing the diesel share. After the optimum, the marginal increase in the CAPEX does not cover the reduction in the OPEX.

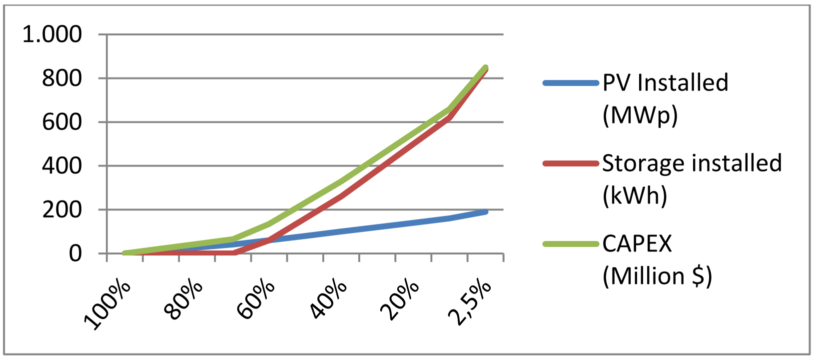


Figure 6.10: Evolution of CAPEX (Million $) with the addition of PV and storage to decrease the diesel share

Source: Own elaboration

Table 6.9 gives also information about the unlevered IRR of the project, calculated for a hypothetic PPA price of $300/MWh. This and other economic parameters will be further discussed in the economic analysis section but as a preview it can be observed that, in general, the higher the penetration of renewable energy, the lower the IRR and the inclusion of storage represents a significant reduction of this variable. This is caused by the extremely high investment cost.

With regard to the question whether it is possible to cover 100% of the demand with renewable, although conceptually it could be possible to achieve, the model and the reality shows that a certain percentage needs to be covered with diesel in order to cover:

- Initial period when the batteries are installed and not charged
- Yearly maintenance periods of the PV and/or storage system, when batteries need to be disconnected
- Eventual failures in the PV and/or storage system that require a backup from the diesel generation

That residual value is considered in the model as 2,5% based on own experiences, considering a typical 98% availability of the PV and storage system and additional

0,5% for additional losses, like initial charge of the batteries, recharge after O&M processes, etc.

Neglecting these contingencies and considering an ideal system with no O&M constrains and unexpected losses, the model shows that with a **190 MWp and 840 MWh** system of PV and storage, a 100% coverage could be achieved representing an investment of around 850M$. Although from an economical point of view this investment might not make sense (massive CAPEX required and the IRR breakeven happens only for a **$331,1/MWh PPA** price, which is very high), it is worth to analyze the table of the yearly balance of energy shown in appendix 10

It is really interesting to analyze in this case the way the system behaves. The matrix in appendix 10 shows that the combination of PV and storage would create a self-sufficient system where there is always energy in the batteries available to cover the demand and it would be possible to achieve the 100% coverage. In particular, the critical period of the year would be 7 am in the morning during the month of July, where the batteries would exhaust their capacities to almost 0 (only 4,63 MWh remaining regarding the model) but still covering the total demand through the year. On the negative side, up to 25,9% of the electricity available from the PV installation would be wasted.

6.6.3 Radiation

In section 6.2 it was described how the North of Chile is one of the areas in the world with a higher solar radiation. To make the analysis fairly general, the region of San Diego de Almagro was chosen as a reference which, within the North of Chile frame, has an average radiation, being far from highest values that can be reached in regions further to the North and to the center of the country, i.e. in the heart of the Arica Desert such as Chuquicamata or Pica. However, with values of approx. 2.405 kWh/m^2 and a yearly yield 2.668 kWh/kWp , it is clear that the yield and solar radiation are still very high in comparison to other regions in the world.

To study the impact on the radiation, the model has been adapted with a mathematical sophistry that, although it does not represent 100% the reality, it helps to get an idea of the balance of energy and it is fairly loyal to reality in regions with latitude close to the parallel 26 South (and North), where San Diego de Almagro is situated. This mathematical sophistry consists of considering that for regions with different radiation, the average yearly yield will be a proportional fraction of the yield in San Diego de Almagro. Thus, to calculate the energy balance through the year on an hourly basis the following has been considered

$$\boldsymbol{Localyield_{dh} = P_p * DdAyield_{dh} * \frac{LocalYield_{annual}}{DdAYield_{annual}}}$$

Where:

***P_p*:** installed PV peak power in kWp

$Localyield_{dh}$: yield of the PV installation at the new location on day “d” at hour “h” in kWh/kWp

$DdAyield_{dh}$: yield of the PV installation at Diego de Almagro on day “d” at hour “h” in kWh/kWp

$LocalYield_{annual}$: global yearly yield of the PV installation at the new location in kWh/kWp

$DdAYield_{annual}$: global yearly yield of the PV installation at the new location in kWh/kWp.

Table 6.10 shows the results of the analysis with this assumption:

Table 6.10: Expected variation of LCOE and optimum combination of PV and storage with the global yield

Local Annual FLH (kWh/kWp)	Minimum LCOE ($/MWh)	PV Installed (MWp)	Storage Installed (MWh)	CAPEX (Million $)	Coverage w/ Renewable (%)
1.500	285,92	90	0	144,0	34,0
1.600	283,31	90	0	144,0	34,7
1.700	280,88	80	0	128,0	34,1
1.800	278,60	80	0	128,0	34,7
1.900	276,51	80	20 (LFP)	140,0	36,7
2.000	274,91	70	0	112,0	34,4
2.100	273,16	70	20 (LFP)	124,0	36,4
2.200	271,36	70	20 (LFP)	124,0	36,9
2.300	270,15	70	40 (LFP)	136,0	38,7
2.400	268,72	70	40 (LFP)	136,0	39,1
2.500	267,54	70	60 (LFP)	148,0	40,9
2.600	265,32	80	120 (Va-REDOX)	206,0	46,9
2.668	**264,40**	**90**	**180 (Va-REDOX)**	**261,0**	**52,7**
2.700	263,94	80	140 (Va-REDOX)	219,0	48,7
2.800	262,45	90	200 (Va-REDOX)	274,0	54,7

Source: Own elaboration

As just mentioned, this approximation is only valid for similar latitudes, with similar time for dusk and dawn. The further away the location is located from the 26º South parallel, the less accurate this assumption will be.

The general conclusion of the analysis is that the higher the radiation and the yield of the PV system for a given system type (considering equal PR) the lower LCOE can be achieved with the proper system configuration. Figure 6.11 shows that the progression is almost linear with the yield.

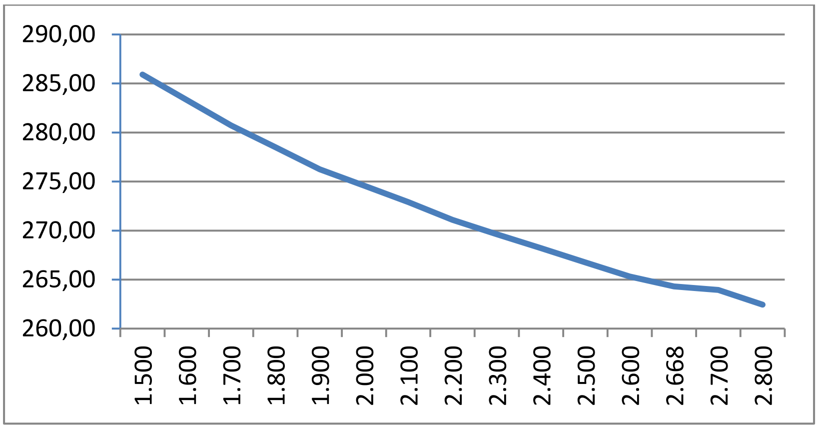


Figure 6.11: Progression of minimum LCOE (in $/MWh) achievable for different global yields (in kWh/kWp)

Source: Own elaboration

Only starting with 2.100 kWh/kWp FLH storage becomes interesting in this specific application. In the particular case of 1900, considering no storage LCOE would be $227,16/kWh, so the additional investment might not pay off the difference. In other words, there is a correlation between the full load hours and the convenience to use storage in the system, becoming only interesting for high radiation levels. The higher the radiation is, the higher the capacity convenient to install, and the lower the LCOE are. Also depending on the radiation and on the capacity required, either one technology or the other becomes interesting.

All in all, the radiation and yield analysis should be done in detail for each location and on a case by case basis in order to make a proper decision on the technology that best fits the conditions of the system. Some particular cases with different FLH will be studied in the following point when discussing the chosen technologies.

6.6.4 Chosen technologies

In order to develop the discussion of the potential use of PV and storage to support the mining activities in the North of Chile, some assumptions and decisions on the technologies to be used when introducing the case study in section 6.3 were made. In particular, decisions on the modules (polycrystalline), mounting system (horizontal trackers) and storage (Va-REDOX batteries or LFP) to be used were taken and explained. Results presented in 6.5 showed that a proper combination of those technologies can certainly manage to bring the LCOE down, up to 39,27%, creating a reliable and more cost efficient system. Now it is interesting to analyze the impact of choosing different technologies on the optimum system and on the LCOE

a. ***Modules:*** In point 6.3.3 it was explained why under criterions of reliability, availability, track record and maturity of the technology, polycrystalline modules was selected to carry out the study. In general, thin-film might also be a very interesting option. Putting apart reliability and maturity issues and considering that the required quantity is eventually available, they might represent an improvement due to their lower coefficient of temperature which is an advantage in the hot and dry climate of the North of Chile. Depending on the selected thin-film technology, amorphous, CdTe or CIS, the system could have more or less a higher yield (in kWh/kWp), so actually, following the conclusion of the previous point, a lower LCOE could be expected.

Table 6.11 shows the results of the study of comparing the different technologies, indicating the configuration of the optimum system for the lowest LCOE, CAPEX involved and coverage with renewables. It also includes allusion to the manufacturer that has been taken as a reference for each technology. Since each of them has a different behavior and performance, some comments need to be addressed to properly understand the table:

- ***Initial degradation***: amorphous Silicon and Cadmium Telluride modules present an initial degradation that needs to be considered in the model. The value of this initial degradation depends on the technology, manufacturer, climate, manufacturing process (a-Si.H simple, double, triple, tandem, etc.) and other parameters. For the study the recommendations of PVSYST to use a 10% initial degradation for Sharp's technology (μ-Si/a-Si) and a 5% for First Solar's Cd-Te (PVSYST, University of Geneva, 1999 - 2013) were followed. In the model this initial degradation has been treated as additional PV power to be installed in order to cover the power losses, which affect the PV CAPEX (excluding inverters) in 10 and 5% respectively.

- ***Annual degradation***: the value of the degradation is inherent to each technology. Based on own experience and studies referenced in 4.2, it has been considered: -0,5% for poly-crystalline, -1% for μ-Si/a-Si, -0,6% for CIS and -1% for Cd-Te. This is modeled with accumulative additional yearly diesel consumption, necessary to cover the progressive loss of PV generation.

- ***Storage degradation***: a -2% annual degradation for LFO cases has been considered. The storage capacity in MWh must be kept constant and equal to the design capacity for a proper running of the system so the degradation was modeled as an additional investment required every year to install new capacity equal to the loss (2%). No initial degradation was assumed for Va-REDOX batteries since that technology suffers none.

- ***CAPEX and system costs:*** systems that use thin-film modules usually involve higher CAPEX. The reason is the higher BOS costs caused by the lower efficiency of the modules (in general, more structures and more cables are required). Some years ago, this was partly compensated by a lower cost of the PV modules. However nowadays, due to the low price of poly-silicone, both poly-crystalline and thin-film technologies are on the same range of prices. This was confirmed during Intersolar 2013 in conversation with representatives of First Solar, Solar Frontier, Calyxo and Sharp. Taking the polycrystalline technology as a reference and its cost for the PV system (as described in 6.3.4), the update for the system cost for each technology is based on the difference in efficiencies following the formula:

$$CS_{tech} = \left(CS_{poly} - CS_{mscab}\right) * CS_{mscab} * \frac{Eff_{tech}}{Eff_{poly}} * (1 + Deg_{int})$$

Where CS_{tech} is the cost of the system for the new technologies, CS_{poly} is the system cost with polycrystalline, equal to $1,60/Wp, CS_{mscab} is united cost of mounting system and cables (elements affected by the efficiency of the modules when calculating the BOS cost) and equal to $0,35/Wp, Eff_{tech} and Eff_{poly} are the efficiencies of the correspondent technologies and its Deg_{int} initial degradation.

Table 6.10 summarizes all the relevant values.

Table 6.11: Relevant values for the simulation of each technology

Technology	Manufacturer	Model	Power (Wp)	Efficiency (%)	System Cost ($/Wp)
Poly-Crystalline	**JA Solar**	**JAP6-60-245**	**245**	**14,98**	**1,60**
μ-Si/a-Si	Sharp	NA-F100	100	8,85	2,02
CIS	Solar Frontier	SF150-S	150	12,21	1,68
Cd-Te	First Solar	FS-390	90	12,25	1,76

Source: Own elaboration

The model was run with numbers in table 6.11, obtaining results shown in table 6.12.

Table 6.12: Comparison of different module technologies and effect on the optimum system and LCOE

Modules Technology	Annual FLH (kWh/kWp)	Minimum LCOE ($/MWh)	PV Installed (MWp)	Storage Installed (MWh)	CAPEX (Million $)	Coverage w/ Renewable (%)
Poly-Crystalline	**2.668**	**264,40**	**90**	**180 (REDOX)**	**206,0**	**52,7**
μ-Si/a-Si	2.738	271,32	60	40 (LFP)	155,0	38,9
CIS	2.776	264,57	80	140 (REDOX)	225,4	49,0
Cd-Te	2.816	265,57	70	100 (REDOX)	188,2	44,9

Source: Own elaboration

As expected, results show that the annual FLH for thin-film technologies is significantly higher. However, apart from µ-Si/a-Si, LCOE for all the technologies is fairly equal, with still a small advantage for poly-Si. That shows that the additional yield of thin-film is somehow compensated with the higher cost per Wp, resulting in very similar LCOE. The initial and progressive degradation of µ-Si/a-Si and their low efficiency represent a disadvantage that translates in a significantly higher LCOE. Also in terms of "green energy" coverage poly-Si represents an improvement against other technologies, with an optimum configuration able to cover up to 52,7% with renewable energy.

Considering the LCOE and "green energy" coverage discussion, together with the reliability, availably, maturity and track record arguments, poly-crystalline is still considered the best option for this application, so the initial assumption turns to be appropriate.

b. ***Mounting systems:*** Table 6.3 shows the monthly average values of radiation, PR, full load hours and final yield for a system with trackers and with fix mounting system with a 25° tilt. For the calculations, selected tracker is a combination of horizontal and polar one. In particular, it has the same concept, components and assembling that a horizontal tracker, but the southern pile of each table is longer than the northern one, giving up to 10° tilt to the structure. Because of that, it can be considered a "semi-polar" tracker, allowing to achieve higher yields but with the robustness and reliability of horizontal trackers. Table 6.12 shows the comparison for the mentioned technologies. Results indicate that the selection of this kind of trackers is a good decision, since it grants the lowest LCOE.

For fix tilt CAPEX has been presumed $1,49 /Wp (7,5% lower than the reference system) and OPEX 15% lower (lower O&M cost for the structures with no moving parts). For horizontal trackers it was considered 2,5% lower CAPEX (all poles will have same length) but equal O&M expenses.

Table 6.13: Comparison of different mounting system technologies and effect on the optimum system and LCOE

Mounting System Technology	Annual FLH (kWh/kWp)	Minimum LCOE ($/MWh)	PV Installed (MWp)	Storage Installed (MWh)	CAPEX (Million $)	Coverage w/ Renewable (%)	Comments
Fix Tilt System (25° Tilt)	2.060	270,51	80	40 (LFP)	145,2	38,9	CAPEX PV: -7,4% OPEX PV: -15%
Horizontal Tracking (0° Tilt)	2.571	264,96	80	120 (REDOX)	202,8	46,7	CAPEX PV: -2,5% OPEX PV: Same
Semi-Polar Tracking (10° Tilt)	**2.668**	**264,40**	**90**	**180 (REDOX)**	**206**	**527**	**Reference**

Source: Own elaboration

c. ***Battery technology:*** points 5.5 and 6.3.4 already gave a wide description and reasonable explanations why the selected technologies, LFP and Va-REDOX, have been chosen depending on the c-rate. Looking into figure 5.8, it can be seen that the calculated optimum system still lies within the recommended limits of Va-REDOX and Li-ion which reinforces the fact that it is a right selection even more. The selection of one or the other is basically an economical one since for C/1 c-rates Va-Redox is too high ($2.000 – $3.000/MWh as previously discussed).

6.6.5 Size of the mine and profile of demand (Day & Night distribution)

When in point 6.3 the case study was described, a hypothetical 50.000 mT production mine with a consumption profile of 40% during the day and 60% during the night, considering a constant and steady load of electricity along the year was defined. It was also described in section 3.2 how to produce one metric ton of refined and pure material in Chile in average 7,245 MWh are needed. Tables 6.14 and 6.15 show how these assumptions affect the LCOE and the configuration of the optimum system. Both both show very interesting results.

Table 6.14: Variation of LCOE and optimum configuration with the capacity of the mine for a 40% day consumption

Mine Production (mT/year)	Yearly Energy Consumption (GWh)	Minimum LCOE ($/MWh)	PV Installed (MWp)	Storage Installed (MWh)	Coverage w/ Renewable (%)
10.000	72,45	265,7	20	60 (REDOX)	62,2
20.000	144,90	265,8	30	40 (LFP)	45,0
30.000	217,35	264,6	50	100 (REDOX)	50,8
40.000	289,80	264,5	70	140 (REDOX)	52,0
50.000	**362,25**	**264,4**	**90**	**180 (REDOX)**	**52,7**
60.000	434,70	264,4	100	180(REDOX)	49,7
70.000	507,15	264,4	120	220 (REDOX)	50,5
80.000	579,60	264,3	130	220 (REDOX)	48,6
90.000	652,05	264,4	150	260 (REDOX)	49,3

Source: Own elaboration

Table 6.15: Variation of LCOE and optimum configuration with the profile of demand (day & night distribution) for a 50.000 mT/year production mine

Load Profile Day/Night (%)	Minimum LCOE ($/MWh)	PV Installed (MWp)	Storage Installed (MWh)	Coverage w/ Renewable (%)
0/100	368,1	0	0	0,0
10/90	342,3	20	40 (REDOX)	12,5
20/80	316,4	40	60 (REDOX)	23,5
30/70	291,2	50	40 (LFP)	30,4
40/60	**264,4**	**90**	**180 (REDOX)**	**52,7**
50/50	238,4	100	160 (REDOX)	59,6
60/40	211,7	130	240 (REDOX)	76,5
70/30	184,6	120	120 (REDOX)	74,0
80/20	158,4	150	200 (REDOX)	90,7
90/10	131,7	130	60 (LFP)	85,7
100/0	110,7	150	60 (LFP)	93,9

Source: Own elaboration

On one side, table 6.14 shows that there is no correlation between the size of the mine and the minimum achievable LCOE. Considering the different optimum configurations, LCOE remains fairly stable keeping all other assumptions constant. Also coverage with REN remains quite steady in general.

Table 6.15 however shows that the higher the proportion of the load during the day is the lower the LCOE becomes, achieving values really low and in general the higher the renewable coverage is. This is understandable since a higher proportion of energy can be supplied directly with PV during the day, which has a very low

LCOE (see 6.6.8). Particularly interesting is the case when 100% of the energy is consumed during the night. In this case the most efficient way (lower LCOE) to cover the demand is only with the diesel generators, meaning that in is not economically convenient storing solar energy during the day and supplying during the night for this particular case and application.

6.6.6 Initial cost of the system (PV and storage)

The initial cost of the system is driven by two different concepts: the cost of the PV system, including all components and construction as described in 6.3.3 and the initial investment required for the storage system. Although both are part of the CAPEX and their value heavily affects the LCOE and optimum configuration, a separate analysis has been carried out to differentiate between the impacts that each of them causes in the results. Observing the definition of LCOE in 6.4.1, there is no doubt that this is one of the variables that affects it most as it changes directly the numerator of the equation.

a. Initial costs of the PV system

The full turn-key initial investment to have the PV installation fully operative is well known and market prices described in 6.3.4. Nonetheless there is a tendency for these initial expenses to decrease through the time. In the last years the sector has seen an important reduction of the CAPEX mainly driven for the dramatic decrease in the cost of poly-silicone and therefore the modules. Based on own experiences, although that sharp reduction has been somehow moderated via different measures, the tendency is still there mainly because of the hard and aggressive competition of many companies in the market.

Table 6.16 gives the results of the sensitivity analysis when changing the PV system cost and letting all other parameters unchanged (including the cost of storage system) and figure 6.12 shows the graphic with the evolution of LCOE. For a clearer and more comprehensive analysis of the results for both PV storage analysis the reference value ($1,6/Wp and $650 /kWh) was taken and increased and decreased the values by 5% steps.

Table 6.16: Variation of LCOE and optimum configuration with the cost of the PV system (keeping storage cost constant)

PV System Cost ($/Wp)	Minimum LCOE ($/MWh)	PV Installed (MWp)	Storage Installed (MWh)	Total CAPEX	Coverage w/ Renewable (%)
1,28	255,6	120	340 (REDOX)	374,6	67,7
1,36	258,1	120	340 (REDOX)	384,2	67,7
1,44	260,4	110	280 (REDOX)	340,4	62,3
1,52	262,5	90	180 (REDOX)	253,8	52,6
1,60	**264,4**	**90**	**180 (REDOX)**	**261,0**	**52,7**
1,68	266,0	70	80 (REDOX)	169,6	42,9
1,76	267,5	70	80 (REDOX)	175,2	42,9
1,84	269,4	60	40 (LFP)	134,4	38,6
1,92	270,7	60	40 (LFP)	139,2	38,6
2,00	271,9	60	40 (LFP)	144,0	38,6

Source: Own elaboration

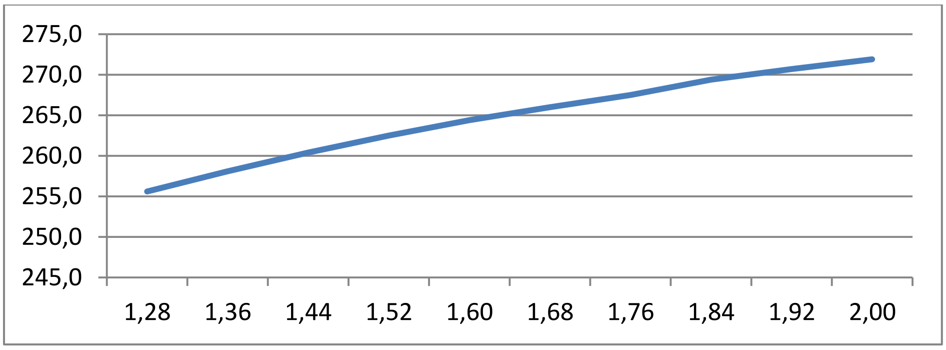


Figure 6.12: Variation of LCOE ($/MWh) with the cost of the PV system (keeping storage cost constant)

Source: Own elaboration

b. Initial cost of the storage system

The cost of the batteries on the other side is not as well defined as for the PV system. In their report *"Electricity Energy Storage Technology Options"*, issued in December 2010, the organization EPRI gives a range of $620-740kWh for the Va-REDOX technology but also rates the confidence of cost estimations for it as "C", based on vendors quotes and system installation estimations which means an accuracy of -20 and +25%. Also Li-ion is rated with "C", giving the clear message the system cost is not well defined yet as the technologies, although in a commercial level, are not yet fully mature (Rastler, 2011).

Table 6.17 collects the data for LCOE and optimum system when changing the cost of the storage system (and keeping all other assumptions) and figure 6.13 shows the evolution of LCOE with that parameter.

Table 6.17: Variation of LCOE and optimum configuration with the cost of the storage system (keeping PV cost constant)

Storage System Cost ($/Wp)	Minimum LCOE ($/MWh)	PV Installed (MWp)	Storage Installed (MWh)	Total CAPEX	Coverage w/ Renewable (%)
520	243,8	170	640 (REDOX)	604,8	92,3
553	252,2	140	440 (REDOX	467,1	76,3
585	256,6	120	340 (REDOX)	390,9	67,7
618	261,1	120	340 (REDOX)	402,0	67,7
650	**264,4**	**90**	**180 (REDOX)**	**261,0**	**52,7**
683	265,6	70	80 (REDOX)	166,6	42,9
715	266,8	60	20 (LFP)	110,3	37,1
748	268,8	60	0	96,0	35,3
780	268,8	60	0	96,0	35,3

Source: Own elaboration

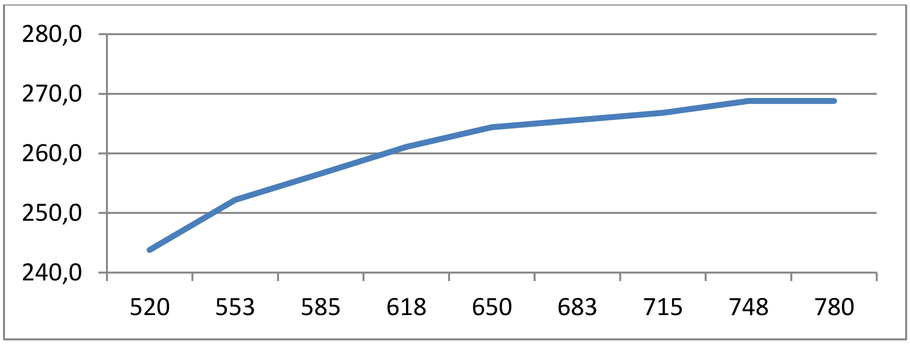


Figure 6.13: Variation of LCOE ($/MWh) with the cost of the storage system (keeping PV cost constant)

Source: Own elaboration

Analyzing both tables and charts the significant impact that both factors have on the LCOE can be seen. The cost of PV has a quasi-linear effect on LCOE and shows that storage remains interesting for a wide range of the PV system cost. A 5% change on the PV system cost represents approximately 2.84% variation in LCOE, resulting in a derivative of 0,54. The cost of the storage system on the other hand is more sensitive, resulting on a logarithmic or fractional function with a clear asymptote in $268,8/kWp, reaching that value for a storage system cost of $718/kWh. That means, for a storage system cost higher than $718/kWh the use of storage is not interesting anymore since it does not contribute to decrease the

LCOE and a system with only PV integrated with diesel represents the lowest possible value achievable for the given system and the taken assumptions.

6.6.7 Cost of fuel

The assumption of 284$/kWh of cost for diesel was calculated as a weighted average cost of the diesel among all the thermal generator present in the area and adding the weight average for the fix O&M cost diesel plants as explained in point 6.3.4. This is clearly another of the most critical parameters when evaluating the potential of using storage combined with renewables since it affects enormously the total LCOE. Table 6.18 gives the results of the analysis of how this parameter affects the system. As expected, the use of storage only becomes interesting starting with a certain cost of fuel.

Table 6.18: Variation of LCOE and optimum configuration with the cost of fuel

Load Profile Day/Night (%)	LCOE only Diesel ($/MWh)	Minimum LCOE ($/MWh)	PV Installed (MWp)	Storage Installed (MWh)	Coverage w/ Renewable (%)
220	285,2	212,7	50	0	33,8
230	298,1	221,3	50	0	33,8
240	311,1	229,8	60	20 (LFP)	37,1
250	324,0	238,0	60	20 (LFP)	37,1
260	337,0	246,1	60	20 (LFP)	37,1
270	350,0	254,3	60	20 (LFP)	37,1
280	362,9	261,6	70	80 (REDOX)	42,9
284	**368,1**	**264,4**	**90**	**180 (REDOX)**	**52,7**
290	375,9	267,9	110	280 (REDOX)	62,3
300	388,8	272,3	120	340 (REDOX)	67,7
310	401,8	276,4	120	340 (REDOX)	67,7
320	414,8	280,5	170	600 (REDOX)	89,9

Source: Own elaboration

The clear tendency of the cost of diesel to increase, together with the expected reduction in the system cost, especially for the batteries, will make the use of storage more and more interesting in a short/medium term, up to the point that if the cost of diesel becomes extremely high, massive storage would be required to cover up to 90% of the demand. It is quite unlikely that such a situation will occur. Before that happens, other sources of energy will be put in place to substitute the diesel generation (coal, nuclear, gas, etc.) but the important is the clear message of the analysis: combination of PV with storage becomes interesting for high cost of diesel, and becomes more and more interesting to cover the demand with renewables against traditional generation the higher those costs are.

6.6.8 Cost of capital, WACC

Finally, although the economic study will follow on the next section, it is still interesting to study the effects of this critical parameter on LCOE and optimum configuration. Following the discussion in 6.3.3, it is hard to predict what would be the cost of debt for this kind of projects since there are no references in Chile. Because of that, although a 7% has been considered, the real WACC will be strongly driven by the expectations of the investor and the maturity of the technology and might be higher than that. Table 6.19 shows the result of the analysis.

Table 6.19: Variation of LCOE and optimum configuration with the WACC

WACC (%)	Minimum LCOE ($/MWh)	PV Installed (MWp)	Storage Installed (MWh)	Coverage w/ Renewable (%)
6,0	258,7	120	340 (REDOX)	67,7
6,5	262,1	120	340 (REDOX)	67,7
7,0	**264,4**	**90**	**180 (REDOX)**	**52,7**
7,5	265,3	70	80 (REDOX)	42,9
8,0	265,9	60	20 (LFP)	37,1
8,5	266,1	60	20 (LFP)	37,1
9,0	266,3	60	20 (LFP)	37,1
9,5	266,5	60	20 (LFP)	37,1
10,0	266,7	50	0	33,8

Source: Own elaboration

WACC has a significant impact on the optimum configuration. However, the minimum LCOE stays almost unchanged due to the flexibility of the system to adapt different scenarios. Thus, we can conclude that although WACC is an important parameter to consider when designing the installation, the use of storage is still interesting for a wide range of values.

6.7 Economic analysis

At first, it is important to remark that the idea of this work is not to present an exhaustive and detailed economic analysis of one particular project, but rather to give an idea of the convenience and feasibility of integrating different solutions to serve electricity to a specific application. That is the reason why for the following analysis an "EBITDA" approach was considered, not taking into account economic factors such as taxes, depreciation and/or amortization. The only relevant economical factor that has been considered is the WACC, being one of the main drivers as just presented.

When discussing the specific application under study, different approaches from an investment point of view can be taken:

- On the one hand, it could be interesting for the utility/mining company to invest on these technologies to decrease their high running cost. By integrating the PV and storage systems they would eventually bring the LCOE from $386,11 /MWh to $264,40 /MWh, a reduction of almost 40%. In this case the minimum LCOE, optimized relation between minimum investment and running costs with maximum production, would guarantee the maximum IRR for equality of assumptions. By integrating the configuration of system that represents the minimum LCOE (90 MWp and 180 MWh of storage) they would get maximum return to their investment. However this approach is not usual and the utilities (mining companies in this case) tend to look for external capital through an investment from external IPPs, negotiate the price of the energy and sign a PPA to be supplied with electricity for a defined period of time.

- On the other hand, a more interesting approach is from the IPP point of view. Being conscious of the high prices that the mining companies have to pay for the electricity, IPP might approach them with the idea of reducing the price of the energy. Points 6.7.1 and 6.7.2 will deepen into this approach, analyzing until what extend and under which circumstances it might be interesting for an IPP company to sign a PPA with a utility.

6.7.1 PPA price, IRR and NPV of the project

The natural way to understand how interesting it is for an external investor to invest into this kind of applications is by analyzing the internal rate of return of the project. The IRR must be calculated in based of the levelized value of the cash flow through the lifespan of the project, which is 20 years in this case. The value of WACC (7%)

is considered for the discount rate The critical value that is necessary to define is the PPA price or value in which the energy will be sold.

Generally speaking, within the renewable sector the definition of the price for the PPA is a process that involves mainly two countered parties: on one side, the IPP wants to sell the energy as high as possible to maximize their IRR. On the other side, the utility desires to buy the electricity as cheap as possible. This requires a negotiation process between the IPP and utility to achieve an agreement. In the end, if there is an agreement, it will be defined a PPA price that will generate an IRR.

Table 6.20 shows how the IRR changes with the PPA for the optimum system, to know, 90 MWp of PV and 180MWh of storage. This combination allows the lowest LCOE for the utility, but it does not mean that it maximizes the IRR for the IPP. The project IRR (non-levered) has been calculated also with help of the EXCEL tool developed for this study by keeping all assumptions unchanged and modifying the PPA price

Table 6.20: Variation of project IRR and NPV with the PPA price

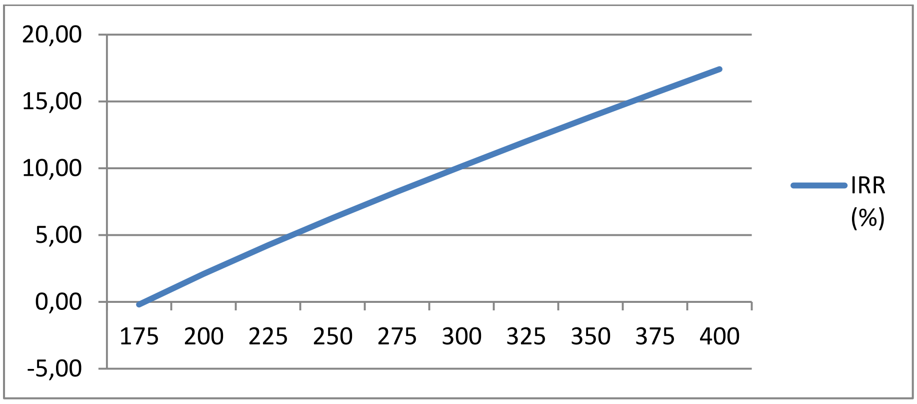
PPA ($/MWh)	**IRR (%)**	**NPV**
175	-0,20	$ -4.160.367
200	2,09	$ 44.359.813
225	4,24	$ 92.879.994
250	6,28	$ 141.400.174
275	8,24	$ 189.920.354
300	10,14	$ 238.440.534
325	12,01	$ 286.960.715
350	13,84	$ 335.480.895
375	15,64	$ 384.001.075
400	17,42	$ 432.521.255

Source: Own elaboration

The breakeven of IRR =0% and NPV=$0 occurs for a PPA of **$ 177,14/MWh.** That is, at least on the paper, a PPA higher than $177,14 /MWh, could be interesting for an investor from the economic point of view. The experience says though, that investors seek an IRR several basic points above the WACC to find the investment interesting and get a proper margin on it. Thus, and just guessing, the final PPA price would probably lie somewhere **between 260 and $300 /kWh.** Figure 6.14

shows the correlation practically linear between the PPA price and the IRR and NPV with a derivative of approximately 3,12 and 3,43 respectively.

Appendix 11 shows the table with the numbers to calculate the IRR for the optimum configuration (90 MWp and 180MWh) and a PPA of $300/MWh.



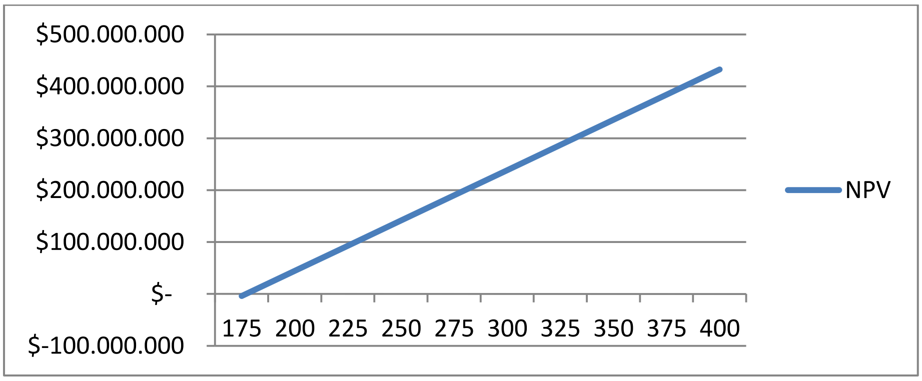


Figure 6.14: Variation of project IRR and NPV with the PPA price

Source: Own elaboration

6.7.2 Use vs. no use of storage

In 6.6.1 it was introduced the idea of a minimum LCOE without storage occurring for a 60MWp PV installation with a value of $266,78/MWh, which represents a difference of $2,38 /MWh over the minimum with storage of $264,40 /kWh. This difference is less than 1% so, it might be thought that the difference between including and not storage is not significant enough to pay off the additional investment and risk of including a not 100% mature technology. In fact, considering a PPA range of 260 to $300 /kWh as estimated in the last point, it would represent a project IRR (non-levered) between 24,12% and 29,14%, which is a very attractive for an investor. Explaining this the other way around, to get the same IRR that including storage (10,14% for example considering a PPA of $ 300/kWh with storage) the IPP can offer a much lower price of $151,85 /MWh or even lower by decreasing the expected IRR; for a targeted 7% IRR they can offer as low as $129,2 /kWh. So actually, this might lead a potential investor to the idea that the integration of storage into the system is not interesting, and that it is much more profitable and with a lower risk to integrate only PV with the diesel generation.

However, this decision would not take into consideration additional benefits of including storage in the system and their economic impact which are not so obvious and not so straight forward to evaluate. Beyond the economics of a project, the utilities look into other factors that bring additional value to the projects and to their companies.

A common way to make business nowadays in the renewable sector is that one utility, the mining company in this case, who for whatever reason wants to cover part of its energy demand with renewable energy, normally issues a tender or opens a bidding process in which different companies can openly offer their best proposal. The driver for that is usually a commitment from the utility side with the environment and with a sustainable development or some strict environmental regulations that push them to search alternative sources of energy in order to decrease its carbon footprint. At the end of the process, the utility chooses one company and awards it with the PPA contract for a certain period. This is the way it works currently in California and South Africa for example and it will be soon implemented in other areas such as MENA region. Own experiences reflect that these tender processes are extremely competitive and the companies have to be extremely aggressive to be awarded with a PPA contract.

But sometimes the utilities are not only looking for competitive and adjusted prices, but are also seeking into other factors such as reliability, dispatchability, carbon footprint reduction, etc. The energy sources must guarantee a steady and consistent supply of energy. Any inconvenience or disruption in the energy supply activity is usually tremendously painful for them and results in an imbalance of their production.

The idea of this paper was to present the combination of PV with storage as a tool to differentiate one project presented to one utility and make one step further to cover exactly those factors. The integration of PV and storage into the system brings additional value to the negotiation table and sometimes granting the possibility to pass through the tender or bidding process and enabling a bilateral negotiation with the utility in a more “personal” and direct negotiation, where the proposal can be fully customized to the necessities of the application.

Additionally, when defining the criteria to select the optimum system in 6.1, additional factors beyond the economics were considered. Integration of storage into the system together with the PV and the traditional diesel generation represents an improvement in all those critical factors, adding value to the project. If we take the optimum configuration calculated for the case study, 90 MWp of PV and 180 MWh of storage with all the assumptions described we have:

- From the economic point of view, it is an improvement vs. the use of PV only. As shown in chapter 6.5, it can decrease the LCOE further than only with PV.

- It improves the reliability of the system by increasing the diversity of sources of energy. In case of disruption in the service of PV and/or diesel generation, storage can still cover totally or partially the demand. Although the integration of large scale storage installations is not 100% developed, it has already been tested in many applications and installations and it is a state of the art technology, fully commercialized and available in the market with proper guarantees and warranties from reliable and bankable companies. The company Mitsubishi for example has already installed a large utility scale storage facility in the North of Chile (Mitsubishi Corporation, 2012)

- It also brings additional stability and reliability to the global supply on energy since it represents a decentralized way to generate electricity, undertaking and overcoming the problems with the grid explained in section 2.

- It represents also an improvement from the dispatchability’s point of view. Thanks to the inclusion of storage “green energy” can be used even during hours where natural sources are not available. This has special importance for utilities whose main activities are during the night like in the case of mining companies.

- It grants an additional reduction of CO_2 covering up to 52,7% of the demand vs. only 35,3% for the 60 MWp and no storage case. Following the calculations in 3.3 this results in 14.568 MT of CO_2 yearly emissions.

7 Conclusions

In this master thesis an overview on the electricity sector in Chile as well as some of the challenges they need to overcome in order to keep their excellent economic and population growth was presented. In particular, the critical problems in the generation, transmission and distribution of electricity due to different geographic, political and methodological factors that evolved in dramatic increase in the price of the electricity, and the necessity to integrate more flexible and decentralized sources of energy into the system have been addressed.

It was also shown the mining activity as one of the main drivers for the good economic situation, but also as one of the most affected by this rise of prices, is majorly influencing Chile's competitiveness.

As one possible solution to face the mentioned challenges, a hybrid system was proposed to overcome the problems. In particular, the combination of PV and storage together with diesel generation for one particular application was discussed and shown that the dispatchbility and reliability of the system can be improved by sourcing energy from different sources throughout the day. Further it was also demonstrated how the integration of storage with a renewable source of energy can reduce even more the carbon footprint of the energy system which otherwise would be limited to the availability of the natural sources, such as wind or sun in this case.

Even more, it was shown that these improvements in reliability, dispatchability and CO_2 emissions can be done in a feasible way from a technical and economical point of view. On one side, the technologies used to complement the diesel generation, to know PV systems, Vanadium-REDOX batteries or Lithium-Ion batteries (depending on the optimum configuration) are all in a commercialized level and although they are not yet widely spread (mainly because of high costs) they are nowadays state of the art technologies. On the other side, it was proven that a proper design and a smart combination of the three technologies can mean an important economic improvement by reducing the levelized cost of the system through the life time up to approximately 40%.

To support the study and the analysis, a base case was introduced where a hypothetical copper mine was defined and different assumptions, concerning production, profile of demand, location, radiation, etc. were made. With the help of an own-made EXCEL tool, the optimum combination of PV, storage and diesel generation that minimizes the LCOE, based on a daily balance of energy where the main criteria is that 100% of the demand must be cover for one of the available technologies was calculated.

Supporting the results also a sensitivity analysis of the main parameters and variables was conducted to know, renewable energy coverage, radiation, chosen technologies, size of the mine, profile of demand, cost of capital and CAPEX and OPEX of the system: In this detailed analysis all of those factors proved to have a significant impact on the LCOE and the configuration of the system that minimizes it.

Finally, during the economical discussion the integration of a hybrid system for this particular application was introduced. This did not only show as an economical improvement with interesting IRR for potential investors, but also proved to be a tool to differentiate the projects against the competition and bring additional value to the mining companies, to the investors themselves and to the environment.

This work did not intend to study the feasibility of a specific project but rather to introduce a problematic and present a possible solution to it. The idea was to explain the methodology to be applied for this specific environment and conditions to overcome the problem with that possible solution, to know, the integration of photovoltaics and storage with the traditional generators to improve the system. To support the methodology it was introduced a case study with hypothetical values and assumptions. Next step would be to apply this methodology to one specific project with real values and conditions to study its feasibility, technical and economical.

Discussing about the economics of the project, next level would be to cover more in detail all the economic parameters that affect the final result of a project, to know, taxes, tax credits, amortization, depreciation, etc.

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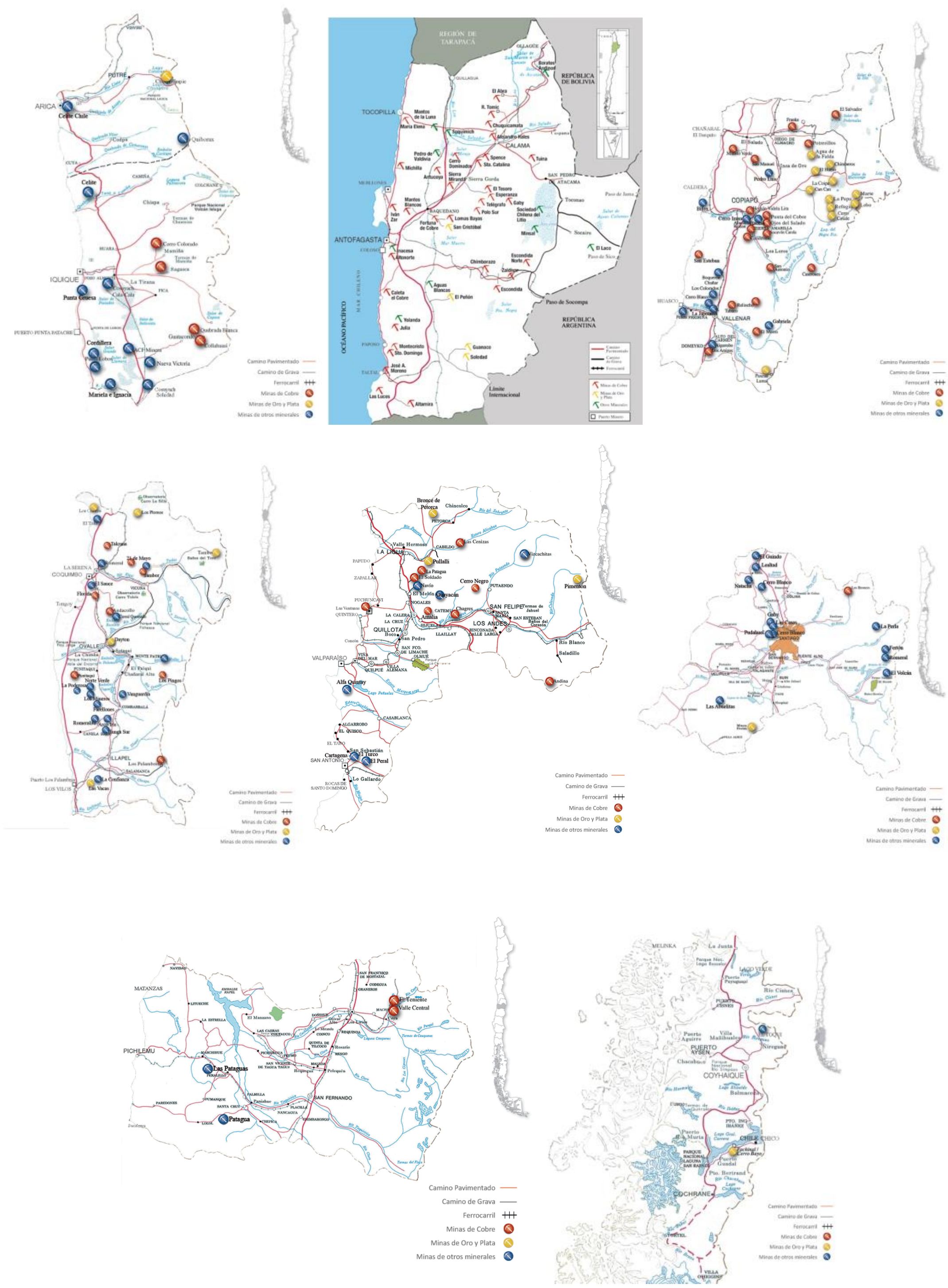
Appendixes

1 Distribution and location of the main mining center in Chile



Source: http://mineriachile.com/2012/01/ubicacion-de-minas-por-regiones/

2 Technical and economical features of power storage technologies

Storage technology	PHS	CAES	Hydrogen	Flywheel	SMES	Supercap	Conventional Batteries		Advanced Batteries			Flow batteries	
							Pb-acid	NiCd	Li-ion	NaS	NaNiCl ZEBRA	VRB	ZnBr
Power rating, MW	100-5000	100-300	0.001-50	0.002-20	0.01-10	0.01-1	0.001-50	0.001-40	0.001-0.1	0.5-50	0.001-1	0.03-7	0.05-2
Energy rating	1-24h+	1-24h+	s-24h+	15s-15min	ms-5min	ms-1h	s-3h	s-h	min-h	s-hours	Min-h	s-10h	s-10h
Response time	s-min	5-15 min	min	s	Ms	ms						ms	ms
Energy density, Wh/kg	0.5-1.5	30-60	800-104	5-130	0.5-5	0.1-15	30-50	40-60	75-250	150-240	125	75	60-80
Power density, W/kg			500+	400-1600	500-2000	0.1-10	75-300	150-300	150-315	90-230	130-160		50-150
Operating temp (°C)				-20 - +40		-40- +85				300-350	300	0-40	
Self-discharge (%/day)	~0	~0	0.5-2	20-100	10-15	2-40	0.1-0.3	0.2-0.6	0.1-0.3	20	15	0-10	1
Round-trip efficiency	75-85	42-54	20-50	85-95	95	85-98	60-95	60-91	85-100	85-90	90	85	70-75
Lifetime (years)	50-100	25-40	5-15	20+	20	20+	3-15	15-20	5-15	10-15	10-14	5-20	5-10
Cycles	$2x10^4$-$5x10^4$	$5x10^3$-$2x10^4$	10^3 +	10^5-10^7	10^4	10^4-10^8	100-1000	1000-3000	10^3-10^4+	2000-4500	2500+	10^4+	2000+
Power cost €/kW	500-3600	400-1150	550-1600	100-300	100-400	100-400	200-650	350-1000	700-3000	700-2000	100-200	2500	500-1800
Energy cost €/kWh	60-150	10-120	1-15	1000-3500	700-7000	300-4000	50-300	200-1000	200-1800	200-900	70-150	100-1000	100-700

(Directorate-Generale for Energy, 2013)

3 Distribution of cost of generation per technologies

Central	Potencia Neta [MW]	Entrada en Operación	Salida de Operación	Tasa de salida forzada (%)	Tipo de Combustible	Costo de Combustible *	Unidades de costo de combustible	Consumo Especifico	Unidades de consumo especifico	C. Var. no comb. [US$/MWh]	C. Var. [US$/MWh]
Eolica Punta Colorada	20.0	*	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Canela 01	18.2	*	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Canela 02	60.0	*	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Monte Redondo	48.0	*	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Totoral	46.0	*	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Talinay Oriente	90.0	MesAbr-2013	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Negrete Cuel	33.0	MesAgo-2013	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
El Arrayán	115.0	MesMar-2014	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica IV Region 03	50.0	MesAgo-2018	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Concepcion 02	50.0	MesDic-2018	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica IV Region 04	50.0	MesDic-2019	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Concepcion 04	50.0	MesEne-2022	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica IV Region 01	50.0	MesDic-2015	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Concepcion 01	50.0	MesNov-2016	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica IV Region 02	50.0	MesDic-2017	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica IV Region 05	50.0	MesMar-2020	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Concepcion 03	50.0	MesOct-2020	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Geotermica Calabozo 01	40.0	MesOct-2017	*	4.3%	Geotermia	0.00	[US$/MWh]	1.000		2.00	2.00
Geotermica Potrerillos 01	40.0	MesJun-2018	*	4.3%	Geotermia	0.00	[US$/MWh]	1.000		2.00	2.00
Geotermica Calabozo 02	40.0	MesSep-2020	*	4.3%	Geotermia	0.00	[US$/MWh]	1.000		2.00	2.00
Geotermica Calabozo 03	40.0	MesEne-2021	*	4.3%	Geotermia	0.00	[US$/MWh]	1.000		2.00	2.00
Geotermica Potrerillos 02	40.0	MesEne-2022	*	4.3%	Geotermia	0.00	[US$/MWh]	1.000		2.00	2.00
Taltal 01 GNL	121.5	*	MesJun-2016	5.0%	GNL	668.75	[US$/dam3]	0.303	[dam3/MWh]	4.00	206.64
Taltal 02 GNL	123.4	*	MesJun-2016	5.0%	GNL	668.75	[US$/dam3]	0.303	[dam3/MWh]	4.00	206.64
Taltal CC GNL	360.0	MesJul-2016	*	5.0%	GNL	7.16	[US$/Mbtu]	6.909	[Mbtu/MWh]	3.19	52.63
Nehuenco 01 GNL	340.1	MesAbr-2015	*	2.1%	GNL	264.09	[US$/dam3]	0.197	[dam3/MWh]	0.00	52.10
Nehuenco 01 FA GNL	21.4	MesAbr-2015	*	2.1%	GNL	264.09	[US$/dam3]	0.248	[dam3/MWh]	0.00	65.36
Nehuenco 01 GNL TP	295.0	*	MesAbr-2013	2.1%	GNL	0.00	[US$/dam3]	0.197	[dam3/MWh]	0.00	0.00
Nehuenco 02 GNL	384.2	MesAbr-2016	*	2.1%	GNL	264.09	[US$/dam3]	0.181	[dam3/MWh]	0.00	47.85
Nehuenco 02 GNL TP	384.2	*	MesMar-2015	2.1%	GNL	0.00	[US$/dam3]	0.181	[dam3/MWh]	0.00	0.00
San Isidro GNL	350.0	*	*	2.1%	GNL	187.01	[US$/dam3]	0.203	[dam3/MWh]	3.87	41.83
San Isidro FA GNL	20.0	*	*	2.1%	GNL	187.01	[US$/dam3]	0.337	[dam3/MWh]	2.82	65.75
San Isidro 02 GNL	392.0	*	*	2.1%	GNL	187.01	[US$/dam3]	0.184	[dam3/MWh]	3.71	38.04
Quintero 01 CA GNL	128.0	MesEne-2014	MesMay-2019	2.1%	GNL	264.09	[US$/dam3]	0.317	[dam3/MWh]	3.80	87.64
Quintero 02 CA GNL	129.0	MesEne-2014	MesMay-2019	2.1%	GNL	264.09	[US$/dam3]	0.317	[dam3/MWh]	3.80	87.64
Quintero CC FA GNL	35.0	MesJun-2019	*	2.1%	GNL	264.09	[US$/dam3]	0.266	[dam3/MWh]	2.50	72.88
Quintero CC GNL	350.0	MesJun-2019	*	2.1%	GNL	264.09	[US$/dam3]	0.198	[dam3/MWh]	2.50	54.73
Nueva Renca GNL	312.0	MesAbr-2014	*	2.4%	GNL	264.09	[US$/dam3]	0.202	[dam3/MWh]	3.85	57.25
Nueva Renca Int GNL	30.0	MesAbr-2014	*	2.1%	GNL	264.09	[US$/dam3]	0.253	[dam3/MWh]	0.00	66.68
Candelaria CA 01 GNL	125.3	MesOct-2018	MesDic-2019	2.1%	GNL	264.09	[US$/dam3]	0.322	[dam3/MWh]	0.00	84.96
Candelaria CA 02 GNL	128.6	MesOct-2018	MesDic-2019	2.1%	GNL	264.09	[US$/dam3]	0.322	[dam3/MWh]	0.00	84.96
Candelaria CC GNL	360.0	MesEne-2020	*	5.0%	GNL	7.16	[US$/Mbtu]	6.909	[Mbtu/MWh]	3.19	52.63
Nueva Aldea 03	37.0	*	*	3.3%	Licor Negro-Petróleo N°6	0.00	[US$/MWh]	1.000		0.00	0.00
Diego de Almagro TG	23.0	*	*	5.0%	Petróleo Diesel	1123.36	[US$/Ton]	0.337	[Ton/MWh]	6.63	385.20
San Lorenzo 01	28.5	*	*	2.1%	Petróleo Diesel	1220.38	[US$/Ton]	0.342	[Ton/MWh]	25.00	442.37
San Lorenzo 02	26.0	*	*	2.1%	Petróleo Diesel	1220.38	[US$/Ton]	0.380	[Ton/MWh]	25.00	489.23
Emelda 01	33.3	*	*	5.0%	Petróleo Diesel	1215.68	[US$/Ton]	0.292	[Ton/MWh]	14.50	369.48
Emelda 02	36.0	*	*	5.0%	Petróleo Diesel	1215.37	[US$/Ton]	0.314	[Ton/MWh]	14.50	396.13
El Salvador TG	23.8	*	*	5.0%	Petróleo Diesel	1082.56	[US$/Ton]	0.337	[Ton/MWh]	41.72	406.55
Cardones	153.0	*	*	5.0%	Petróleo Diesel	1178.11	[US$/Ton]	0.239	[Ton/MWh]	22.41	303.98
Cenizas	13.9	*	*	5.0%	Petróleo Diesel	763.87	[US$/Ton]	0.230	[Ton/MWh]	13.81	189.73
Termopacifico	81.2	*	*	5.0%	Petróleo Diesel	1110.70	[US$/Ton]	0.225	[Ton/MWh]	22.43	272.34
El Peñón	81.0	*	*	2.1%	Petróleo Diesel	1154.39	[US$/Ton]	0.221	[Ton/MWh]	28.50	283.62
Espinos	124.0	*	*	5.0%	Petróleo Diesel	1146.15	[US$/Ton]	0.221	[Ton/MWh]	45.30	298.88
Olivos	115.2	*	*	5.0%	Petróleo Diesel	1146.15	[US$/Ton]	0.225	[Ton/MWh]	43.10	301.28
Los Vientos	132.0	*	*	2.1%	Petróleo Diesel	1122.54	[US$/Ton]	0.267	[Ton/MWh]	2.95	302.67

Source: (CNE, April 2013)

Central	Potencia Neta [MW]	Entrada en Operación	Salida de Operación	Tasa de salida forzada (%)	Tipo de Combustible	Costo de Combustible *	Unidades de costo de combustible	Consumo Especifico	Unidades de consumo especifico	C. Var. no comb. [US$/MWh]	C. Var. [US$/MWh]
Eolica Punta Colorada	20.0	*	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Canela 01	18.2	*	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Canela 02	60.0	*	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Monte Redondo	48.0	*	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Totoral	46.0	*	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Talinay Oriente	90.0	MesAbr-2013	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Negrete Cuel	33.0	MesAgo-2013	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
El Arrayán	115.0	MesMar-2014	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica IV Region 03	50.0	MesAgo-2018	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Concepcion 02	50.0	MesDic-2018	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica IV Region 04	50.0	MesDic-2019	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Concepcion 04	50.0	MesEne-2022	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica IV Region 01	50.0	MesDic-2015	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Concepcion 01	50.0	MesNov-2016	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica IV Region 02	50.0	MesDic-2017	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica IV Region 05	50.0	MesMar-2020	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Eolica Concepcion 03	50.0	MesOct-2020	*	0.0%	Eolica	0.00	[US$/MWh]	1.000		7.70	7.70
Geotermica Calabozo 01	40.0	MesOct-2017	*	4.3%	Geotermia	0.00	[US$/MWh]	1.000		2.00	2.00
Geotermica Potrerillos 01	40.0	MesJun-2018	*	4.3%	Geotermia	0.00	[US$/MWh]	1.000		2.00	2.00
Geotermica Calabozo 02	40.0	MesSep-2020	*	4.3%	Geotermia	0.00	[US$/MWh]	1.000		2.00	2.00
Geotermica Calabozo 03	40.0	MesEne-2021	*	4.3%	Geotermia	0.00	[US$/MWh]	1.000		2.00	2.00
Geotermica Potrerillos 02	40.0	MesEne-2022	*	4.3%	Geotermia	0.00	[US$/MWh]	1.000		2.00	2.00
Taltal 01 GNL	121.5	*	MesJun-2016	5.0%	GNL	668.75	[US$/dam3]	0.303	[dam3/MWh]	4.00	206.64
Taltal 02 GNL	123.4	*	MesJun-2016	5.0%	GNL	668.75	[US$/dam3]	0.303	[dam3/MWh]	4.00	206.64
Taltal CC GNL	360.0	MesJul-2016	*	5.0%	GNL	7.16	[US$/Mbtu]	6.909	[Mbtu/MWh]	3.19	52.63
Nehuenco 01 GNL	340.1	MesAbr-2015	*	2.1%	GNL	264.09	[US$/dam3]	0.197	[dam3/MWh]	0.00	52.10
Nehuenco 01 FA GNL	21.4	MesAbr-2015	*	2.1%	GNL	264.09	[US$/dam3]	0.248	[dam3/MWh]	0.00	65.36
Nehuenco 01 GNL TP	295.0	*	MesAbr-2013	2.1%	GNL	0.00	[US$/dam3]	0.197	[dam3/MWh]	0.00	0.00
Nehuenco 02 GNL	384.2	MesAbr-2016	*	2.1%	GNL	264.09	[US$/dam3]	0.181	[dam3/MWh]	0.00	47.85
Nehuenco 02 GNL TP	384.2	*	MesMar-2015	2.1%	GNL	0.00	[US$/dam3]	0.181	[dam3/MWh]	0.00	0.00
San Isidro GNL	350.0	*	*	2.1%	GNL	187.01	[US$/dam3]	0.203	[dam3/MWh]	3.87	41.83
San Isidro FA GNL	20.0	*	*	2.1%	GNL	187.01	[US$/dam3]	0.337	[dam3/MWh]	2.82	65.75
San Isidro 02 GNL	392.0	*	*	2.1%	GNL	187.01	[US$/dam3]	0.184	[dam3/MWh]	3.71	38.04
Quintero 01 CA GNL	128.0	MesEne-2014	MesMay-2019	2.1%	GNL	264.09	[US$/dam3]	0.317	[dam3/MWh]	3.80	87.64
Quintero 02 CA GNL	129.0	MesEne-2014	MesMay-2019	2.1%	GNL	264.09	[US$/dam3]	0.317	[dam3/MWh]	3.80	87.64
Quintero CC FA GNL	35.0	MesJun-2019	*	2.1%	GNL	264.09	[US$/dam3]	0.266	[dam3/MWh]	2.50	72.88
Quintero CC GNL	350.0	MesJun-2019	*	2.1%	GNL	264.09	[US$/dam3]	0.198	[dam3/MWh]	2.50	54.73
Nueva Renca GNL	312.0	MesAbr-2014	*	2.4%	GNL	264.09	[US$/dam3]	0.202	[dam3/MWh]	3.85	57.25
Nueva Renca Int GNL	30.0	MesAbr-2014	*	2.1%	GNL	264.09	[US$/dam3]	0.253	[dam3/MWh]	0.00	66.68
Candelaria CA 01 GNL	125.3	MesOct-2018	MesDic-2019	2.1%	GNL	264.09	[US$/dam3]	0.322	[dam3/MWh]	0.00	84.96
Candelaria CA 02 GNL	128.6	MesOct-2018	MesDic-2019	2.1%	GNL	264.09	[US$/dam3]	0.322	[dam3/MWh]	0.00	84.96
Candelaria CC GNL	360.0	MesEne-2020	*	5.0%	GNL	7.16	[US$/Mbtu]	6.909	[Mbtu/MWh]	3.19	52.63
Nueva Aldea 03	37.0	*	*	3.3%	Licor Negro-Petróleo N°6	0.00	[US$/MWh]	1.000		0.00	0.00
Diego de Almagro TG	23.0	*	*	5.0%	Petróleo Diesel	1123.36	[US$/Ton]	0.337	[Ton/MWh]	6.63	385.20
San Lorenzo 01	28.5	*	*	2.1%	Petróleo Diesel	1220.38	[US$/Ton]	0.342	[Ton/MWh]	25.00	442.37
San Lorenzo 02	26.0	*	*	2.1%	Petróleo Diesel	1220.38	[US$/Ton]	0.380	[Ton/MWh]	25.00	489.23
Emelda 01	33.3	*	*	5.0%	Petróleo Diesel	1215.68	[US$/Ton]	0.292	[Ton/MWh]	14.50	369.48
Emelda 02	36.0	*	*	5.0%	Petróleo Diesel	1215.37	[US$/Ton]	0.314	[Ton/MWh]	14.50	396.13
El Salvador TG	23.8	*	*	5.0%	Petróleo Diesel	1082.56	[US$/Ton]	0.337	[Ton/MWh]	41.72	406.55
Cardones	153.0	*	*	5.0%	Petróleo Diesel	1178.11	[US$/Ton]	0.239	[Ton/MWh]	22.41	303.98
Cenizas	13.9	*	*	5.0%	Petróleo Diesel	763.87	[US$/Ton]	0.230	[Ton/MWh]	13.81	189.73
Termopacifico	81.2	*	*	5.0%	Petróleo Diesel	1110.70	[US$/Ton]	0.225	[Ton/MWh]	22.43	272.34
El Peñón	81.0	*	*	2.1%	Petróleo Diesel	1154.39	[US$/Ton]	0.221	[Ton/MWh]	28.50	283.62
Espinos	124.0	*	*	5.0%	Petróleo Diesel	1146.15	[US$/Ton]	0.221	[Ton/MWh]	45.30	298.88
Olivos	115.2	*	*	5.0%	Petróleo Diesel	1146.15	[US$/Ton]	0.225	[Ton/MWh]	43.10	301.28
Los Vientos	132.0	*	*	2.1%	Petróleo Diesel	1122.54	[US$/Ton]	0.267	[Ton/MWh]	2.95	302.67

Source: (CNE, April 2013)

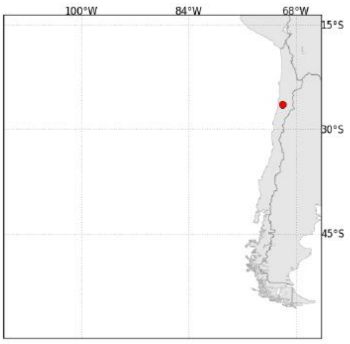
4 Long term monthly averages of solar radiation and air temperature for the region of San Diego de Almagro

Site info

Site name:	Diego de Almagro Provincia de Chañaral, Región de Atacama, Chile
Coordinates:	**26° 23' 26.76" S, 70° 02' 20.96" W**
Elevation a.s.l.:	796 m
Slope inclination:	2°
Slope azimuth:	220° southwest

Location on the map: http://solargis.info/imaps/#loc=-26.3907679,-70.039156=Google:Satellite=14

Geographic position



Google Maps © 2013 Google

Climate data

Month	Gh_d	Gh_m	Dh_d	Dh_m	Dn_d	Dn_m	T_{24}
Jan	8.51	264	2.20	68	8.50	264	21.6
Feb	7.95	223	1.99	56	8.23	230	21.4
Mar	7.02	218	1.62	50	8.05	250	20.6
Apr	5.66	170	1.34	40	7.22	217	18.7
May	4.51	140	1.06	33	6.61	205	16.8
Jun	4.01	120	0.96	29	6.30	189	15.3
Jul	4.30	133	0.96	30	6.67	207	14.8
Aug	5.32	165	1.14	35	7.39	229	16.0
Sep	6.67	200	1.41	42	8.11	243	17.4
Oct	7.81	242	1.70	53	8.69	269	19.0
Nov	8.64	259	1.81	54	9.38	281	20.3
Dec	8.76	272	2.05	64	9.05	281	21.1
Year	**6.59**	**2406**	**1.52**	**554**	**7.85**	**2865**	**18.6**

Long-term averages:

Gh_d	Daily sum of global horizontal irradiation (kWh/m^2)
Gh_m	Monthly sum (annual) of global horizontal irradiation (kWh/m^2)
Dh_d	Daily sum of diffuse horizontal irradiation (kWh/m^2)
Dh_m	Monthly sum (annual) of diffuse horizontal irradiation (kWh/m^2)
Dn_d	Daily sum of direct normal irradiation (kWh/m^2)
Dn_m	Monthly sum (annual) of direct normal irradiation (kWh/m^2)
T_{24}	Daily (diurnal) air temperature (°C)

Source: http://solargis.info/pvplanner/#tl=Google:Satellite

5 Hourly average solar generation distribution in kWh/kWp for 1MWp

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL AVERAGE
00:00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
01:00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
02:00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
03:00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
04:00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
05:00	43,0	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,8	98,2	178,5	139,0	38,6
06:00	525,4	389,1	318,7	264,4	162,7	7,6	4,5	173,2	366,4	590,4	607,2	586,7	332,8
07:00	699,5	657,2	655,6	588,9	532,6	442,8	474,9	602,5	693,9	755,6	784,2	737,5	635,3
08:00	792,3	781,3	766,3	721,2	640,3	567,4	578,7	696,1	790,0	822,7	839,4	810,1	733,5
09:00	816,7	795,6	795,3	709,2	633,1	590,0	645,9	726,9	802,0	829,4	844,6	829,2	751,3
10:00	810,8	803,8	794,8	713,1	635,0	606,7	649,4	707,5	799,6	827,7	828,4	820,8	749,5
11:00	793,2	791,0	786,2	712,6	641,5	596,8	623,1	708,5	795,0	816,4	819,7	806,9	740,6
12:00	778,7	770,0	772,2	692,0	639,4	598,5	630,2	708,8	784,8	815,4	811,6	783,4	731,9
13:00	766,5	762,8	754,8	683,8	626,5	617,1	630,9	699,0	774,8	801,5	805,0	761,8	723,4
14:00	752,5	750,4	740,0	692,9	611,1	601,0	616,4	676,5	774,2	783,7	789,0	743,6	710,6
15:00	713,8	724,6	696,8	616,3	532,2	506,2	561,5	625,5	717,1	701,4	726,5	712,8	652,4
16:00	597,2	614,3	539,3	398,8	270,2	232,5	337,6	428,0	510,6	540,9	572,1	579,1	467,6
17:00	282,6	263,4	118,4	1,4	0,0	0,0	0,0	0,0	1,6	49,7	116,4	234,5	88,2
18:00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
19:00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
20:00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
21:00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
22:00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
23:00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Source: Own elaboration with data from SolarGis

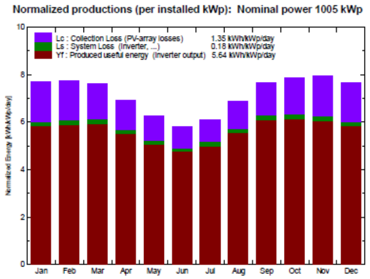
6 PVSYST simulation for a fix system with 25° tilt

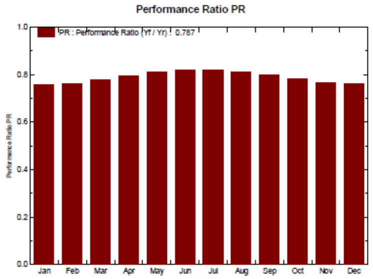
Grid-Connected System: Main results

Project : **San Diego de Almagro**
Simulation variant : **1,005MWp Fix PowerOne**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	25°	azimuth	0°
PV modules	Model	JAP6-60-245	Pnom	245 Wp
PV Array	Nb. of modules	4100	Pnom total	**1005 kWp**
Inverter	Model	PVI-Central-500-TL	Pnom	500 kW ac
Inverter pack	Nb. of units	2.0	Pnom total	**1000 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results
System Production — **Produced Energy** **2069 MWh/year** — Specific prod. 2060 kWh/kWp/year
Performance Ratio PR 78.7 %





1,005MWp Fix PowerOne
Balances and main results

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	EffArrR %	EffSysR %
January	264.0	21.60	239.0	231.0	188.1	182.2	11.74	11.37
February	222.0	21.50	216.8	210.3	170.9	165.7	11.76	11.40
March	217.0	20.70	236.2	229.7	190.8	184.7	12.05	11.67
April	169.0	18.80	207.5	202.0	171.3	166.0	12.31	11.94
May	140.0	16.90	193.6	188.3	162.6	157.7	12.53	12.15
June	120.0	15.40	174.3	169.7	148.2	143.6	12.68	12.29
July	133.0	14.90	189.4	184.5	161.1	156.1	12.68	12.29
August	164.0	16.10	212.9	207.3	179.0	173.5	12.55	12.16
September	200.0	17.50	229.2	223.4	189.6	183.6	12.34	11.95
October	241.0	19.10	243.4	236.4	197.7	191.2	12.11	11.72
November	259.0	20.40	237.8	230.6	188.9	182.9	11.85	11.47
December	271.0	21.20	237.9	230.1	187.8	181.9	11.77	11.40
Year	2400.0	18.66	2617.9	2543.3	2135.9	2069.1	12.17	11.79

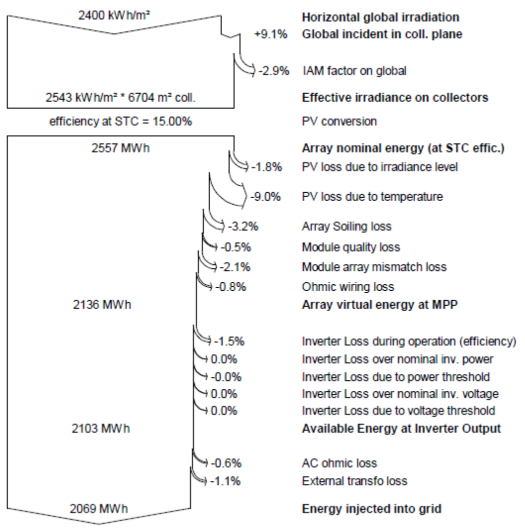
Legends:
- GlobHor — Horizontal global irradiation
- T Amb — Ambient Temperature
- GlobInc — Global incident in coll. plane
- GlobEff — Effective Global, corr. for IAM and shadings
- EArray — Effective energy at the output of the array
- E_Grid — Energy injected into grid
- EffArrR — Effic. Eout array / rough area
- EffSysR — Effic. Eout system / rough area

Grid-Connected System: Loss diagram

Project : **San Diego de Almagro**
Simulation variant : **1,005MWp Fix PowerOne**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	25°	azimuth	0°
PV modules	Model	JAP6-60-245	Pnom	245 Wp
PV Array	Nb. of modules	4100	Pnom total	**1005 kWp**
Inverter	Model	PVI-Central-500-TL	Pnom	500 kW ac
Inverter pack	Nb. of units	2.0	Pnom total	**1000 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



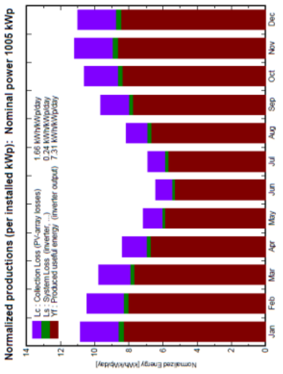
7 PVSYST simulation for a system with trackers

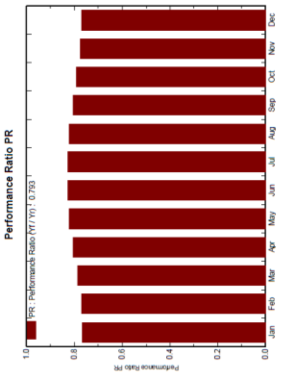
Grid-Connected System: Main results

Project : **San Diego de Almagro**
Simulation variant : **1,005MWp Tracker PowerOne**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tracking, tilted axis, Axis Tilt	10°	Axis Azimuth	0°
PV modules	Model	JAP6-60-245	Pnom	245 Wp
PV Array	Nb. of modules	4100	Pnom total	**1005 kWp**
Inverter	Model	PVI-Central-500-TL	Pnom	500 kW ac
Inverter pack	Nb. of units	2.0	Pnom total	**1000 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**2680 MWh/year**	Specific prod.	2668 kWh/kWp/year
	Performance Ratio PR	79.3 %		





1,005MWp Tracker PowerOne
Balances and main results

	GlobHor	T Amb	GlobInc	GlobEff	EArray	E_Grid	EffArrR	EffSysR
	kWh/m²	°C	kWh/m²	kWh/m²	MWh	MWh	%	%
January	264.0	21.60	335.9	331.0	268.0	259.2	11.90	11.51
February	222.0	21.50	292.9	288.8	234.2	226.6	11.92	11.54
March	217.0	20.70	303.1	298.8	247.5	239.5	12.18	11.79
April	169.0	18.80	251.7	247.8	210.0	203.5	12.45	12.06
May	140.0	16.90	222.4	218.1	189.0	183.3	12.67	12.29
June	120.0	15.40	193.1	189.1	165.6	160.6	12.79	12.40
July	133.0	14.90	213.8	209.7	183.5	177.9	12.80	12.41
August	164.0	16.10	253.6	249.4	215.7	208.9	12.69	12.29
September	200.0	17.50	289.4	285.7	241.9	234.0	12.47	12.06
October	241.0	19.10	329.2	324.8	270.1	261.1	12.24	11.83
November	259.0	20.40	336.4	331.7	270.3	261.3	11.98	11.59
December	271.0	21.20	341.9	336.8	273.4	264.6	11.93	11.54
Year	2400.0	18.66	3363.4	3311.7	2769.1	2680.4	12.28	11.89

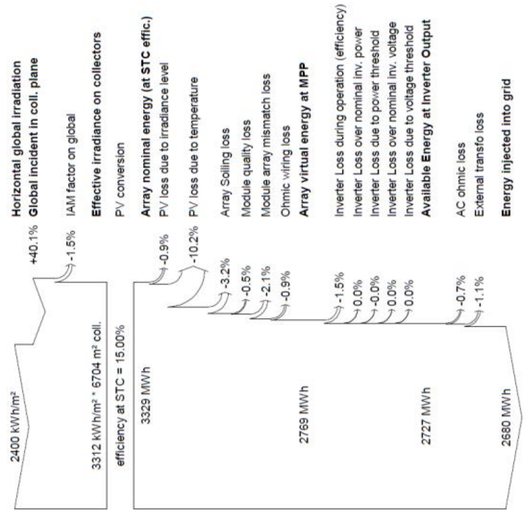
Legends:			
GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
T Amb	Ambient Temperature	E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area

Grid-Connected System: Loss diagram

Project : **San Diego de Almagro**
Simulation variant : **1,005MWp Tracker PowerOne**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tracking, tilted axis, Axis Tilt	10°	Axis Azimuth	0°
PV modules	Model	JAP6-60-245	Pnom	245 Wp
PV Array	Nb. of modules	4100	Pnom total	**1005 kWp**
Inverter	Model	PVI-Central-500-TL	Pnom	500 kW ac
Inverter pack	Nb. of units	2.0	Pnom total	**1000 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



8 Yearly energy balance with the optimum system to minimize the LCOE: 90MWp PV and 180MWh storage system

HOUR	TIME FRAME LOAD	LOAD (MWh)	SOURCE OF SUPPLY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
00:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
01:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
02:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
03:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
04:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
05:00	Night	49,62	PV	3,87	0,08	0,00	0,00	0,00	0,00	0,00	0,00	0,07	8,84	16,07	12,51
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	45,75	49,55	49,62	49,62	49,62	49,62	49,62	49,62	49,55	40,79	33,55	37,11
06:00	Day	33,08	PV	47,28	35,02	28,68	23,80	14,64	0,68	0,41	15,59	32,97	53,13	54,65	52,80
			PV ENERGY LOST	1,14	0,16	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,60	1,73	1,58
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	4,40	9,28	18,44	32,40	32,68	17,50	0,11	0,00	0,00	0,00
07:00	Day	33,08	PV	62,95	59,15	59,00	53,00	47,93	39,85	42,74	54,23	62,45	68,00	70,58	66,38
			PV ENERGY LOST	2,39	2,09	2,07	1,59	1,19	0,54	0,77	1,69	2,35	2,79	3,00	2,66
			STORAGE AVAILABLE	13,07	1,79	0,00	0,00	0,00	0,00	0,00	0,00	0,00	18,45	19,84	18,14
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

HOUR	TIME FRAME LOAD	LOAD (MWh)	SOURCE OF SUPPLY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
08:00	Day	33,08	PV	71,30	70,31	68,96	64,91	57,63	51,06	52,08	62,65	71,10	74,05	75,54	72,91
			PV ENERGY LOST	3,06	2,98	2,87	2,55	1,96	1,44	1,52	2,37	3,04	3,28	3,40	3,19
			STORAGE AVAILABLE	40,55	25,76	23,85	18,32	13,66	6,23	8,88	19,45	27,02	50,57	54,34	48,77
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
09:00	Day	33,08	PV	73,50	71,60	71,57	63,83	56,97	53,10	58,13	65,42	72,18	74,65	76,02	74,63
			PV ENERGY LOST	3,23	3,08	3,08	2,46	1,91	1,60	2,00	2,59	3,13	3,33	3,43	3,32
			STORAGE AVAILABLE	75,71	60,02	56,86	47,60	36,24	22,77	26,37	46,65	62,00	88,26	93,40	85,41
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
10:00	Day	33,08	PV	72,97	72,34	71,53	64,18	57,15	54,60	58,45	63,67	71,96	74,49	74,55	73,87
			PV ENERGY LOST	3,19	3,14	3,08	2,49	1,93	1,72	2,03	2,45	3,11	3,31	3,32	3,26
			STORAGE AVAILABLE	112,89	95,45	92,27	75,89	58,22	41,19	49,41	76,40	97,97	126,50	132,90	123,64
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
11:00	Day	33,08	PV	71,39	71,19	70,76	64,14	57,74	53,71	56,08	63,77	71,55	73,48	73,77	72,62
			PV ENERGY LOST	3,06	3,05	3,01	2,48	1,97	1,65	1,84	2,45	3,08	3,23	3,26	3,16
			STORAGE AVAILABLE	149,59	131,58	127,65	104,49	80,37	60,99	72,75	104,55	133,74	164,60	171,05	161,16
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
12:00	Day	33,08	PV	70,08	69,30	69,50	62,28	57,54	53,87	56,72	63,79	70,63	73,39	73,04	70,51
			PV ENERGY LOST	37,00	2,90	2,91	2,34	1,96	1,66	1,89	2,46	3,00	40,31	39,96	37,42
			STORAGE AVAILABLE	180,00	166,63	162,31	133,06	103,05	79,96	93,91	132,78	169,13	180,00	180,00	180,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
13:00	Day	33,08	PV	68,99	68,65	67,94	61,54	56,38	55,54	56,78	62,91	69,73	72,14	72,45	68,56
			PV ENERGY LOST	35,91	35,57	34,85	2,28	1,86	1,80	1,90	2,39	36,65	39,06	39,37	35,48
			STORAGE AVAILABLE	180,00	180,00	180,00	159,92	125,56	99,09	115,65	161,03	180,00	180,00	180,00	180,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
14:00	Day	33,08	PV	67,73	67,54	66,60	62,36	55,00	54,09	55,47	60,88	69,68	70,53	71,01	66,92
			PV ENERGY LOST	34,65	34,46	33,52	29,28	1,75	1,68	1,79	27,80	36,59	37,45	37,92	33,84
			STORAGE AVAILABLE	180,00	180,00	180,00	180,00	147,00	119,75	137,45	180,00	180,00	180,00	180,00	180,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
15:00	Day	33,08	PV	64,24	65,22	62,71	55,46	47,90	45,56	50,53	56,29	64,54	63,13	65,39	64,15
			PV ENERGY LOST	31,16	32,14	29,63	22,38	1,19	1,00	1,40	23,21	31,45	30,04	32,30	31,07
			STORAGE AVAILABLE	180,00	180,00	180,00	180,00	167,16	139,07	158,06	180,00	180,00	180,00	180,00	180,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

HOUR	TIME FRAME LOAD	LOAD (MWh)	SOURCE OF SUPPLY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
16:00	Day	33,08	PV	53,75	55,29	48,54	35,89	24,32	20,92	30,38	38,52	45,95	48,68	51,49	52,12
			PV ENERGY LOST	20,66	22,21	15,46	2,81	0,97	1,35	0,30	5,44	12,87	15,60	18,40	19,04
			STORAGE AVAILABLE	180,00	180,00	180,00	180,00	180,00	150,55	174,11	180,00	180,00	180,00	180,00	180,00
			STORAGE USED	0,00	0,00	0,00	0,00	8,76	12,16	2,70	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
17:00	Day	33,08	PV	25,43	23,71	10,65	0,12	0,00	0,00	0,00	0,00	0,15	4,47	10,47	21,10
			PV ENERGY LOST	0,85	1,04	2,49	3,66	3,68	3,68	3,68	3,68	3,66	3,18	2,51	1,33
			STORAGE AVAILABLE	180,00	180,00	180,00	180,00	170,27	137,04	171,11	180,00	180,00	180,00	180,00	180,00
			STORAGE USED	7,65	9,38	22,43	32,96	33,08	33,08	33,08	33,08	32,94	28,61	22,61	11,98
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
18:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	171,50	169,58	155,08	143,38	133,51	100,28	134,36	143,24	143,40	148,21	154,88	166,69
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
19:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	4,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	116,37	114,45	99,94	88,24	78,37	45,15	79,22	88,11	88,27	93,07	99,74	111,55
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	40,63	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	8,99	0,00	0,00	0,00	0,00	0,00	0,00
20:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	4,48	3,31	2,32	0,00	2,41	3,30	3,31	3,79	4,46	5,51
			STORAGE AVAILABLE	61,23	59,31	44,80	33,11	23,24	0,00	24,08	32,97	33,13	37,93	44,61	56,41
			STORAGE USED	49,62	49,62	40,32	29,80	20,91	0,00	21,67	29,67	29,82	34,14	40,15	49,62
			DIESEL	0,00	0,00	9,30	19,83	28,71	49,62	27,95	19,95	19,81	15,48	9,48	0,00
21:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,61	0,42	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,13
			STORAGE AVAILABLE	6,09	4,17	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,28
			STORAGE USED	5,48	3,75	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,15
			DIESEL	44,14	45,87	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	48,47
22:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
23:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62

Source: Own elaboration

9 Yearly energy balance with the optimum system without storage: 60MWp

			PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
0:00	Night	49,62	STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
1:00	Night	49,62	STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2:00	Night	49,62	STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3:00	Night	49,62	STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4:00	Night	49,62	STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			PV	2,58	0,05	0,00	0,00	0,00	0,00	0,00	0,00	0,05	5,89	10,71	8,34
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5:00	Night	49,62	STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	47,04	49,57	49,62	49,62	49,62	49,62	49,62	49,62	49,58	43,73	38,91	41,28
			PV	31,52	23,35	19,12	15,87	9,76	0,46	0,27	10,39	21,98	35,42	36,43	35,20
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,34	3,35	2,12
6:00	Day	33,08	STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	1,56	9,73	13,96	17,22	23,32	32,63	32,81	22,69	11,10	0,00	0,00	0,00
			PV	41,97	39,43	39,34	35,33	31,95	26,57	28,49	36,15	41,64	45,33	47,05	44,25
			PV ENERGY LOST	8,88	6,35	6,25	2,25	0,00	0,00	0,00	3,07	8,55	12,25	13,97	11,17
7:00	Day	33,08	STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	1,13	6,51	4,59	0,00	0,00	0,00	0,00	0,00

8:00	Day	33,08	PV	47,54	46,88	45,98	43,27	38,42	34,04	34,72	41,76	47,40	49,36	50,36	48,60
			PV ENERGY LOST	14,45	13,79	12,89	10,19	5,34	0,96	1,64	8,68	14,32	16,28	17,28	15,52
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
9:00	Day	33,08	PV	49,00	47,73	47,72	42,55	37,98	35,40	38,76	43,61	48,12	49,77	50,68	49,75
			PV ENERGY LOST	15,92	14,65	14,63	9,47	4,90	2,32	5,67	10,53	15,04	16,68	17,60	16,67
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
10:00	Day	33,08	PV	48,65	48,23	47,69	42,78	38,10	36,40	38,96	42,45	47,97	49,66	49,70	49,25
			PV ENERGY LOST	15,57	15,15	14,60	9,70	5,02	3,32	5,88	9,37	14,89	16,58	16,62	16,17
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
11:00	Day	33,08	PV	47,59	47,46	47,17	42,76	38,49	35,81	37,39	42,51	47,70	48,98	49,18	48,41
			PV ENERGY LOST	14,51	14,38	14,09	9,67	5,41	2,73	4,31	9,43	14,62	15,90	16,10	15,33
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
12:00	Day	33,08	PV	46,72	46,20	46,33	41,52	38,36	35,91	37,81	42,53	47,09	48,93	48,70	47,00
			PV ENERGY LOST	13,64	13,12	13,25	8,44	5,28	2,83	4,73	9,44	14,01	15,84	15,61	13,92
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
13:00	Day	33,08	PV	45,99	45,77	45,29	41,03	37,59	37,02	37,85	41,94	46,49	48,09	48,30	45,71
			PV ENERGY LOST	12,91	12,69	12,21	7,95	4,51	3,94	4,77	8,86	13,40	15,01	15,22	12,63
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
14:00	Day	33,08	PV	45,15	45,03	44,40	41,57	36,67	36,06	36,98	40,59	46,45	47,02	47,34	44,61
			PV ENERGY LOST	12,07	11,94	11,32	8,49	3,58	2,98	3,90	7,51	13,37	13,94	14,25	11,53
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
15:00	Day	33,08	PV	42,83	43,48	41,81	36,98	31,93	30,37	33,69	37,53	43,02	42,08	43,59	42,77
			PV ENERGY LOST	9,74	10,40	8,73	3,89	0,00	0,00	0,61	4,45	9,94	9,00	10,51	9,68
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	1,15	2,71	0,00	0,00	0,00	0,00	0,00	0,00

16:00	Day	33,08	**PV**	35,83	36,86	32,36	23,93	16,21	13,95	20,26	25,68	30,64	32,45	34,32	34,75
			PV ENERGY LOST	2,75	3,78	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,24	1,66
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,72	9,16	16,87	19,13	12,83	7,40	2,45	0,63	0,00	0,00
17:00	Day	33,08	**PV**	16,96	15,80	7,10	0,08	0,00	0,00	0,00	0,00	0,10	2,98	6,98	14,07
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	16,13	17,28	25,98	33,00	33,08	33,08	33,08	33,08	32,99	30,10	26,10	19,01
18:00	Night	49,62	**PV**	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
19:00	Night	49,62	**PV**	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
20:00	Night	49,62	**PV**	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
21:00	Night	49,62	**PV**	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
22:00	Night	49,62	**PV**	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
23:00	Night	49,62	**PV**	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE AVAILABLE	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62

Source: Own elaboration

10 Yearly energy balance for a hybrid system with 190MWp PV and 840MWh storage to cover 100% of the demand with green energy

HOUR	TIME FRAME LOAD	LOAD (MWh)	SOURCE OF SUPPLY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
00:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	510,00	509,18	509,18	497,41	472,71	472,42	371,25	337,55	472,42	472,76	482,90	496,99
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
01:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	454,86	454,04	454,04	442,27	417,57	417,28	316,12	282,41	417,28	417,62	427,77	441,85
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
02:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	399,73	398,90	398,90	387,14	362,44	362,15	260,98	227,27	362,15	362,49	372,63	386,72
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
03:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	344,59	343,77	343,77	332,00	307,30	307,01	205,84	172,14	307,01	307,35	317,49	331,58
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
04:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	289,45	288,63	288,63	276,86	252,16	251,87	150,70	117,00	251,87	252,21	262,36	276,44
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
05:00	Night	49,62	PV	8,17	0,16	0,00	0,00	0,00	0,00	0,00	0,00	0,15	18,66	33,92	26,41
			PV ENERGY LOST	4,61	5,50	5,51	5,51	5,51	5,51	5,51	5,51	5,50	3,44	1,74	2,58
			STORAGE AVAILABLE	234,32	233,49	233,49	221,72	197,03	196,74	95,57	61,86	196,74	197,08	207,22	221,30
			STORAGE USED	41,45	49,46	49,62	49,62	49,62	49,62	49,62	49,62	49,47	30,97	15,70	23,22
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
06:00	Day	33,08	PV	99,82	73,94	60,55	50,24	30,91	1,44	0,86	32,91	69,61	112,17	115,37	111,47
			PV ENERGY LOST	5,34	3,27	2,20	1,37	0,24	3,52	3,58	0,02	2,92	6,33	6,58	6,27
			STORAGE AVAILABLE	188,25	178,53	178,36	166,59	141,89	141,60	40,43	6,73	141,76	162,67	207,99	195,51
			STORAGE USED	0,00	0,00	0,00	0,00	2,17	31,64	32,22	0,18	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
07:00	Day	33,08	PV	132,90	124,86	124,56	111,88	101,19	84,14	90,23	114,48	131,84	143,56	149,00	140,13
			PV ENERGY LOST	7,99	7,34	7,32	6,30	5,45	4,08	4,57	6,51	7,90	8,84	9,27	8,56
			STORAGE AVAILABLE	249,66	216,12	203,63	182,37	139,48	106,44	4,63	6,53	175,37	235,43	283,70	267,62
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

HOUR	TIME FRAME LOAD	LOAD (MWh)	SOURCE OF SUPPLY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
08:00	Day	33,08	PV	150,53	148,44	145,59	137,03	121,66	107,80	109,96	132,25	150,11	156,32	159,48	153,91
			PV ENERGY LOST	9,40	9,23	9,00	8,32	7,09	5,98	6,15	7,93	9,36	9,86	10,11	9,67
			STORAGE AVAILABLE	341,48	300,56	287,79	254,87	202,13	153,41	57,20	81,42	266,23	337,07	390,34	366,11
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
09:00	Day	33,08	PV	155,17	151,16	151,10	134,74	120,28	112,10	122,72	138,11	152,38	157,59	160,48	157,55
			PV ENERGY LOST	9,77	9,45	9,44	8,13	6,98	6,32	7,17	8,40	9,54	9,96	10,19	9,96
			STORAGE AVAILABLE	449,54	406,69	391,30	350,50	283,62	222,15	127,92	172,65	373,89	450,45	506,63	477,27
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
10:00	Day	33,08	PV	154,05	152,72	151,01	135,48	120,66	115,27	123,39	134,42	151,92	157,26	157,39	155,95
			PV ENERGY LOST	9,68	9,57	9,43	8,19	7,01	6,57	7,22	8,11	9,51	9,93	9,94	9,83
			STORAGE AVAILABLE	561,86	515,32	499,88	444,03	363,84	294,85	210,39	269,28	483,64	565,00	623,83	591,79
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
11:00	Day	33,08	PV	150,71	150,29	149,38	135,40	121,89	113,39	118,40	134,62	151,05	155,12	155,74	153,31
			PV ENERGY LOST	9,41	9,38	9,30	8,19	7,10	6,42	6,83	8,12	9,44	9,76	9,81	9,62
			STORAGE AVAILABLE	673,15	625,39	608,37	538,24	444,41	370,46	293,48	362,51	592,98	679,24	738,20	704,83
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
12:00	Day	33,08	PV	147,95	146,29	146,71	131,48	121,48	113,72	119,74	134,67	149,11	154,93	154,20	148,85
			PV ENERGY LOST	9,19	9,06	9,09	7,87	7,07	6,45	6,93	8,13	9,28	9,75	121,12	9,26
			STORAGE AVAILABLE	781,36	733,22	715,36	632,37	526,12	444,34	371,96	455,93	701,51	791,51	840,00	815,44
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
13:00	Day	33,08	PV	145,64	144,94	143,42	129,93	119,03	117,25	119,87	132,81	147,21	152,29	152,95	144,74
			PV ENERGY LOST	112,56	8,95	8,83	7,75	6,88	6,73	6,94	7,98	9,13	119,21	119,87	111,66
			STORAGE AVAILABLE	840,00	837,37	819,90	722,90	607,45	518,53	451,69	549,38	808,26	840,00	840,00	840,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
14:00	Day	33,08	PV	142,98	142,58	140,61	131,64	116,11	114,18	117,11	128,53	147,10	148,89	149,90	141,28
			PV ENERGY LOST	109,90	109,50	107,53	7,88	6,64	6,49	6,72	7,64	114,01	115,81	116,82	108,19
			STORAGE AVAILABLE	840,00	840,00	840,00	811,99	686,52	595,96	531,53	641,13	840,00	840,00	840,00	840,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
15:00	Day	33,08	PV	135,62	137,68	132,40	117,09	101,12	96,18	106,68	118,84	136,24	133,27	138,04	135,43
			PV ENERGY LOST	102,53	104,60	99,32	84,01	5,44	5,05	5,89	6,86	103,16	100,18	104,95	102,34
			STORAGE AVAILABLE	840,00	840,00	840,00	840,00	762,91	670,58	608,84	728,94	840,00	840,00	840,00	840,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

HOUR	TIME FRAME LOAD	LOAD (MWh)	SOURCE OF SUPPLY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
16:00	Day	33,08	PV	113,47	116,72	102,47	75,77	51,35	44,17	64,14	81,32	97,01	102,77	108,69	110,03
			PV ENERGY LOST	80,38	83,64	69,39	42,68	1,46	0,89	2,48	3,86	63,93	69,69	75,61	76,95
			STORAGE AVAILABLE	840,00	840,00	840,00	840,00	825,50	728,63	676,55	807,83	840,00	840,00	840,00	840,00
			STORAGE USED	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
17:00	Day	33,08	PV	53,69	50,05	22,49	0,26	0,00	0,00	0,00	0,00	0,31	9,44	22,11	44,55
			PV ENERGY LOST	20,61	16,96	1,18	3,65	3,68	3,68	3,68	3,68	3,64	2,63	1,22	11,46
			STORAGE AVAILABLE	840,00	840,00	840,00	840,00	840,00	738,83	705,13	840,00	840,00	840,00	840,00	840,00
			STORAGE USED	0,00	0,00	10,59	32,82	33,08	33,08	33,08	33,08	32,78	23,65	10,97	0,00
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
18:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	840,00	840,00	828,23	803,53	803,24	702,07	668,37	803,24	803,58	813,73	827,81	852,74
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
19:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	784,86	784,86	773,09	748,40	748,11	646,94	613,23	748,11	748,45	758,59	772,67	797,60
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
20:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	729,73	729,73	717,96	693,26	692,97	591,80	558,10	692,97	693,31	703,45	717,54	742,46
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
21:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	674,59	674,59	662,82	638,12	637,83	536,66	502,96	637,83	638,17	648,32	662,40	687,33
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
22:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	619,45	619,45	607,68	582,99	582,69	481,53	447,82	582,69	583,03	593,18	607,26	632,19
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
23:00	Night	49,62	PV	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
			PV ENERGY LOST	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51	5,51
			STORAGE AVAILABLE	564,32	564,32	552,55	527,85	527,56	426,39	392,69	527,56	527,90	538,04	552,13	577,05
			STORAGE USED	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62	49,62
			DIESEL	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Source: Own elaboration

11 Calculations of IRR and NPV for a PPA of $300/MWh

NPV and LRGC for a PV PLANT with STORAGE

Year	Discounted Cash Flow	Nominal Cash Flow	Electricity sale	Investment / Replacement	Fuel	O&M	Costs	Discounted Costs
0	-$ 261.000.000	-$ 261.000.000		-$ 261.000.000			$ 261.000.000	$ 261.000.000
1	$ 47.457.873	$ 50.779.924	$ 56.990.824		$ -	-$ 6.210.900	$ 6.210.900	$ 5.804.579
2	$ 43.941.517	$ 50.308.643	$ 56.705.870		$ -	-$ 6.397.227	$ 6.397.227	$ 5.587.586
3	$ 40.678.732	$ 49.833.196	$ 56.422.340		$ -	-$ 6.589.144	$ 6.589.144	$ 5.378.704
4	$ 37.651.481	$ 49.353.410	$ 56.140.229		$ -	-$ 6.786.818	$ 6.786.818	$ 5.177.631
5	$ 34.842.996	$ 48.869.105	$ 55.859.527		$ -	-$ 6.990.423	$ 6.990.423	$ 4.984.075
6	$ 32.237.700	$ 48.380.094	$ 55.580.230		$ -	-$ 7.200.135	$ 7.200.135	$ 4.797.754
7	$ 29.821.112	$ 47.886.189	$ 55.302.329		$ -	-$ 7.416.139	$ 7.416.139	$ 4.618.399
8	$ 27.579.778	$ 47.387.193	$ 55.025.817		$ -	-$ 7.638.624	$ 7.638.624	$ 4.445.748
9	$ 25.501.194	$ 46.882.906	$ 54.750.688		$ -	-$ 7.867.782	$ 7.867.782	$ 4.279.552
10	$ 23.573.742	$ 46.373.119	$ 54.476.934		$ -	-$ 8.103.816	$ 8.103.816	$ 4.119.569
11	$ 21.786.625	$ 45.857.620	$ 54.204.550		$ -	-$ 8.346.930	$ 8.346.930	$ 3.965.566
12	$ 20.129.810	$ 45.336.189	$ 53.933.527		$ -	-$ 8.597.338	$ 8.597.338	$ 3.817.321
13	$ 18.593.976	$ 44.808.601	$ 53.663.859		$ -	-$ 8.855.258	$ 8.855.258	$ 3.674.617
14	$ 17.170.463	$ 44.274.624	$ 53.395.540		$ -	-$ 9.120.916	$ 9.120.916	$ 3.537.248
15	$ 15.851.221	$ 43.734.019	$ 53.128.562		$ -	-$ 9.394.544	$ 9.394.544	$ 3.405.015
16	$ 14.628.775	$ 43.186.540	$ 52.862.920		$ -	-$ 9.676.380	$ 9.676.380	$ 3.277.725
17	$ 13.496.178	$ 42.631.934	$ 52.598.605		$ -	-$ 9.966.671	$ 9.966.671	$ 3.155.193
18	$ 12.446.977	$ 42.069.941	$ 52.335.612		$ -	-$ 10.265.671	$ 10.265.671	$ 3.037.242
19	$ 11.475.177	$ 41.500.292	$ 52.073.934		$ -	-$ 10.573.642	$ 10.573.642	$ 2.923.700
20	$ 10.575.207	$ 40.922.714	$ 51.813.564		$ -	-$ 10.890.851	$ 10.890.851	$ 2.814.403
TOTAL	**$ 238.440.534**	**$ 659.376.252**	**$ 1.087.265.461**	**-$ 261.000.000**	**$ -**	**-$ 166.889.209**	**$ 427.889.209**	**$ 343.801.628**

Concept	Number	Units
DC Power	90	
Storage Installed	180	
Energy Sold	190.924	MWh
Degradation Panels	0,5%	
CAPEX	$ 261.000.000	
OPEX	$ 6.030.000	
WACC	7%	
Cost Fuel	$ -	
Escalation Fuel	3%	
Escalation O&M	3%	
PPA	300	$/MWh

NPV	$ 238.440.534	Annuity of Costs	$ 32.452.442		
Annuity	$ 22.507.100	Yearly El. Generation	190.924	MWh	IRR 10,14%
NPV Costs	$ 343.801.628	LRGC	$ 169,98	$/MWh	

Source: Own elaboration