Economic and technical evaluation of solar assisted water pump stations for mining applications: A case of study

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Abstract

Nowadays energy and water are some of the most important issues facing mining industry. Many mines are located in desert areas and they need to pump water from isolated wells or from the ocean. Therefore in order to satisfy the water demand many high power water pump stations are required. The operation of these systems is expensive due to the high-energy cost. This paper presents a case of study of a solar photovoltaic system to assist the operation of a water pump station of a mineral processing operation in Chile. An economical analysis is carried out with respect to different design variables and the percentage of the total power required for operating the system in the less favorable conditions (degree of assistance). It is demonstrated that the maximum net present value is obtained for the maximum assistance, i.e. supplying the full energy in the less favorable conditions. However, the internal rate of return will be maximized at the point where the system only supplies the energy to satisfy the full demand at the most favorable conditions. Finally the study shows that from an economical point of view PV technology is an attractive alternative to support the mining operation at present time.

Mining industry, Power generation economics, Pumps, Solar power generation.

1 Introduction

Mining operations located in remote deserted areas are facing important challenges in order to deal with scarce water resources and high-energy cost. According to Ernst & Young [1], the access to water and energy is within the 10 most important risks facing the mining industry especially for projects in South America and Africa. In Chile the energy costs have increased by 11% annually since 2000, being the electricity price one of the highest in Latin American due to the reliance on fossil fuels. Water consumption in Chile's copper mining industry will increase 66 percent by 2025 [2]. In order to satisfy this increasing demand the industry is committed to seek new sources such as seawater. Nowadays the water from the sea constitutes only the 8% of the total fresh-water withdrawals made by Chilean copper industry, value which is expected to increase in the near future. As a matter of fact seawater consumption in copper mining increased 37% between 2012 and 2011, and by 2021 it will account 23.9% of the total fresh-water consumption [2]. In order to transport water, mining companies have invested in water pump stations located in distant places in the desert and on the ocean shores. These pump stations require several MW due to water volume, altitude and distances involved.

Renewable energies are becoming an attractive alternative for mining companies as a cost-efficient energy source to address the challenge of improving their cost structure and diminishing the risk associated to the volatility of the energy prices [3]. Chile has a privileged position in terms of the abundance of solar resources and recently many mines have started to adopt thermal and PV technologies in their operations [4, 5].

In order to decrease the operational costs associated to the electrical energy required to drive pumps, photovoltaic (PV) solar plants represent an attractive solution. This work proposes the use of PV systems to assist the operation of pumps stations; i.e. they do not replace existing systems but only supply energy during those periods with solar radiation.

Techno-economic analysis of large PV system addressing different scenarios has been carried out by several researchers. For instance a performance evaluation and cost-benefits analysis of large solar PV installations for dwelling units in a Western Australia mining company in terms of carbon tax and mounting methods is presented in [6]. In [7] Monte Carlo methods along with investment models have been proposed to analyze large-scale solar PV projects for Ontario, Canada. This work analyzes the expected profitability in terms of Internal Rate of Return (IRR) and Net Present Value (NPV) of a PV project to assist the operation of pump stations in a regulated system. In this case, the incomes of the project will be associated to substitution of energy bought at a marginal cost and selling of energy excess at the average market price.

This paper is organized as follows: Section II describes the methodology to be used. Section III presents the design specifications and main considerations imposed by this applications. Section IV describes the main component of the proposed system. Section V presents the economic evaluation and sensitivity analysis. In section VI some final remarks are given.

2 General methodology

In order to carry out the technical and economical analysis the following steps were developed:

i) Gathering preliminary information: Collect information related to the power demand, solar radiations, average temperatures and cloudiness over several years of operation. Analyze the variability of the data and define regions of operations. In addition, it is necessary to know the cost of the energy at the locations of pump stations and the market price of the energy at the same point, since the excess of energy can be sold.

ii) Technical analysis: Based on the information obtained in step i), the design of a PV system considering a given level of assistance must be carried out. At this stage, it is necessary to define the architecture, PV panels, supporting structures, inverters, and transformers.

iii) Economical model and analysis: Based on the cost structure and the estimated benefits an economical evaluation can be carried out by considering different profitability indices.

3 Preliminary Information

This section describes the main considerations that have to be taken into account in order to design the solar assisted system. We will consider a Chilean mine located in the north of the country, which has several water pump stations to transport seawater to their processes as described in the following sections.

3.1 Pump stations

The seawater is transported through a pipeline of 145 km of length. In order to transport the water, 4 pump stations are required, one for pumping the water from the sea and the rest for transporting the water to the processes. Pump stations 1 and 2 are located 50 Km away from the water catchment and pump station no. 3 at 120 Km. Since pump station no 3 is closer to the mine site, it was selected as case of study. Each pump station has several pumps driven by a set of induction motors as summarized in Table 1. Pump station no. 3 has two set of motors, having 4 and 3 units, each connected to 3.45 kV bars.

Tab. 1: Stations and their technical characteristics

Station	Number of Motors	Power per motor [KW]
Pump station 0	9	448
(Water catchment)		
Pump station 1	8	1.865
Pump station 2	8	1.865
Pump station 3	7	1.343

Tab. 2: Operating power regimes

Power range [MW]	Hours [h]	% month
$P > 4.5$	139	57.90
$3.5 < P < 4.5$	93	38.75
$2 < P < 3.5$	6	2.5
$P < 2$	2	0.8
Total	240	100

The pump stations operate according to the required water demand, having normally two regimes, either 630 L/sec or 1200 L/sec. In order to analyze the power demand during the period with sunlight, as described in section B, a set of power consumption data for one month of operation (September) was obtained from one of the 3.45 kV bars associated to pump station no. 3, and is summarized in the histogram depicted in Figure 1.

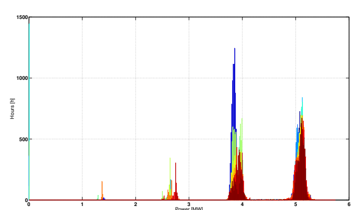

Fig. 1: Histogram of power demand during one month (September).

The histogram shows that the consumption can be classified in four regions of operations (see Figure 1). The region with power consumption higher that 4.5 MW represents the operation associated to the high water rate, while the region with consumption in the range of $(3.5MW, 4.5MW)$ is associated to the lower water rate. Regions with power consumption smaller than 3 MW are not relevant for this study. The number of hours associated to each regime during one month (September) is summarized in Table 2.

This analysis concluded that most of the time motors work at power higher than 4.5 MW. The mean value of the required power is 5.1 MW, i.e. near their rated values. Similar values were found for the other motors associated to pump station no. 3.

3.2 Solar resources

In order to have an estimate of the solar resources, it is necessary to know the exact location of the pump station no. 3. In this case, the location is Latitude: $22.98^o S$, Longitude: $69.15^o O$, Altitude: 2116 m. With this information the Global Horizontal Irradiance (GHI) can be obtained from [8], Figure 2 shows the values of GHI for one year. This index represents the radiation received from above by a surface horizontal to the ground and includes the direct and diffuse radiation. As seen in Figure 2, the minimum value is obtained in June.

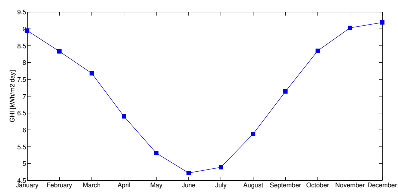

Fig. 2: Global Horizontal Irradiance at the pump station location.

In addition, it is necessary to consider the number of direct sun hours. Figure 3 shows that the total hourly radiation for June is about eight effective sun hours; i.e. the number of hours where the hourly mean radiation is higher than $197 W/m^2$. The cloudiness index is a value between 0 and 1 and provides information about the fraction of time that the site was covered by clouds during an hour or month. This index is defined as the ratio between the diffusive daily radiation and daily global radiation. It can be calculated by using different measurement methods such as direct radiative measurements, satellites images and temperature measurements [9]. The estimated cloudiness index used in this work can be obtained by the Solar resource explorer using the information of the GOES EAST and MODIS satellites [10]. The method calculates first the clear sky radiation for a given location, and a cloud index is derived from the pixel value of the satellite images. The ground global radiation is then estimated by reducing the clear sky radiation by the cloud cover. The mean value of this index for the last eight years is 0.01%; i.e. clouds do not have significant effects.

Finally, another important factor is the outdoor temperature, since it affects the efficiency of the solar panels. As seen in Figure 4, the average outdoor temperature is $20^o C$ and the variations are within $\pm 5^o C$ range.

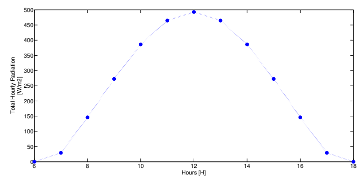

Fig. 3: Total Hourly radiation (June).

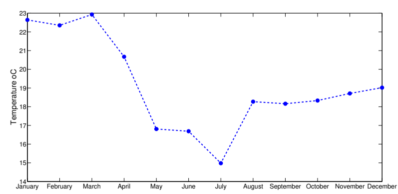

Fig. 4: Monthly average outdoor temperature.

3.3 Energy costs and prices

Since PV systems do not always generate energy, it is necessary to consider the cost of buying energy when the PV system is not able to supply it, and the price of selling energy when the PV system generates more than the required energy for pumping. Thus the Marginal Cost (MC) and the Average Market Price of MWh (AMP) should be considered. The MC represents the cost of supplying an extra generating unit to the system. It is obtained by satisfying the demand by adding generators starting from the cheapest generators, and being the generator with the highest MC that fixes the price. In this study, the monthly forecast carried out by the Chilean regulatory agency CDEC SING for the period 2015-2029, and depicted in Figure 5, is considered [11].

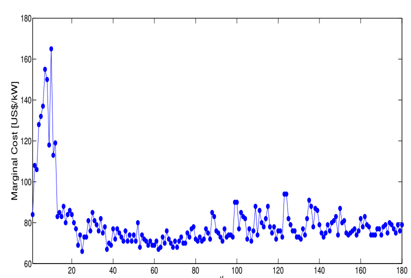

Fig. 5: Marginal Cost forecast.

The average market price is obtained from the contracts informed by the power generating company at the time of carrying out this study, and it was

97.93 [US$/MWh] [12]. The main assumption of this study is that the energy will be bought at the MC and sold at AMP.

4 Technical analysis

In order to satisfy the power demand, a PV plant is designed to supply a percentage of the total required power by the pump station during the less favorable conditions in terms of solar radiation. This percentage is defined as degree of assistance. Thus the system was initially sized considering the month with less radiation. Since the PV plant is located in the southern hemisphere June is the month with the lowest radiation. This case represents 100% of assistance; i.e. the system will supply all the energy required by the pump station during 8 hours in the less favorable conditions. The main characteristics of the design associated to the pump station no. 3 with a rated power of 9.4 MW, are:

a) Solar Panels: Polycrystalline panels of $P_p = 310$ W were considered since their cost is smaller compared with other technologies. Additionally over 80% of the big installations in Chile have selected this technology due to its favorable cost ratio in price per watt on the system level [13]. A decrease of 0.8% annually is considered for the efficiency of the panels due to aging and other factors [14].

b) Power inverters: The configuration considers centralized inverters of 1 MW, due to their smaller cost to produce one watt in AC current, it has fewer components, higher reliability and it has demonstrated to be very effective for large systems where the radiation is similar in all panels [15, 16]. In this work the inverter SG1000TS-M of SunGrow is considered. The minimum voltage for operation is 460 V and its efficiency is 0.98. Inverters have much shorter field mean time between failure than the solar panels, and the typical warranties last between 5-10 years [17, 18]. The experience of large utility scale PV generating plants in desert areas shows that the unscheduled maintenance cost associated with inverters can represent more than the 50% of the total cost [19].

c) Tracking system: this study considers just one axis tracking system. Even though a two axis could provide a 4% more power, but at expense of a higher investment cost and also surface area for the installation [20]. It is considered that the required land for the installation of the solar panels is property of the project owner and they do not have any alternative use.

d) General structure: The rated output power of the array under standard conditions, in watts, can be estimated as follows:

$$P_{array} = \frac{E_m}{PSH \cdot \eta \cdot f_d} \tag{1}$$

where E_m is the required power per day, PSH are the peak solar hours (worst month = 4.72 h/day), $\eta = 0.97$ is the efficiency of the subsystem including power transmission loss and inverters efficiency, $f_d = 0.83$ is a dimensionless de-rating factor taking into account the effect of soiling, temperature and safety margin. Thus, the number of required solar panels is given by $P_{array}/P_p = 64811$. In order to provide the minimum voltage for the operation of the inverter and deliver the required energy, the general structure was designed with 15 sectors. Each sector considers a 1 MW inverter and 4560 solar panels distributed in 240 strings of 19 panels each connected in parallel to the inverter.

5 Economical analysis

The profitability of the investment is analyzed in terms of the IRR and NPV. The analysis considers 20 years for the project life time and also a discount rate of 10%, which is normally used for project associated to renewable energies [4] The MC and AMP are the ones obtained in section II. The income (I) produced by the project at month k considers the energy used to drive the pumps and the surplus sold at AMP:

$$I(k) = E_p(k) \cdot MC + \gamma(E_p(k) - E_m) \cdot AMP \tag{2}$$

where E_m is the demanded energy, $E_p(k)$ is the energy generated by the PV system during month k. Function $\gamma(E_p(k) - E_m)$ is defined as follows:

$$\gamma(E_p(k) - E_m) = \begin{cases} E_p(k) - E_m & (E_p(k) - E_m) \geq 0 \\ 0 & (E_p(k) - E_m) < 0 \end{cases} \tag{3}$$

The energy generated by the system depends on the panel's efficiency ($\eta_p(k)$), the power transmission and inverter efficiency (η_{ti}), the Global Horizontal Irradiance, and the surface covered by the P-V panels (S_p):

$$E_p(k) = \eta_p(k) \cdot \eta_{ti} \cdot S_p \cdot GHI(k) \tag{4}$$

The percentage of assistance is defined as

$$A = \frac{\hat{E}_p}{E_m} \cdot 100 \tag{5}$$

where $\hat{E}_p = E_p(\hat{k})$ is the energy generated at the less favorable conditions obtained at month $\hat{k}$. The different conditions along the months for different degrees of assistance are illustrated in Figure 6. For 100% assistance there will be no need to buy energy during the PV operation.

The detailed cost structure for a PV project can be found for instance in [21, 22], and in this study it was considered the following investment costs:

$$C = N_{sp} \cdot P_{sp} + N_{inv} \cdot P_{inv} + N_{st} \cdot P_{st} + C_e + I_s + C_{eng} \tag{6}$$

where C is the total investment cost, N_{sp} is the number of solar panels, P_{sp} is their price, N_{inv} in the number of inverters, P_{inv} is the associated price, N_{st}

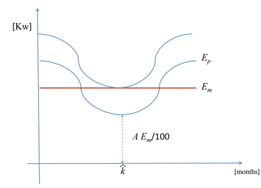

Fig. 6: Generated Energy for different degrees of assistance.

Tab. 3: Investments and Operational costs

Item	US$/unit	item	US$	item	US$/month
P_{sp}	164	C_e	847000	T_s	5760
P_{inv}	165000	C_{eng}	45000	C_s	5000
P_{st}	2200	I_s	571500		

is the number of solar trackers and mounting systems, P_{st} is their price, C_e is the cost of electrical system (wire and cables, grounding, system protection equipments, conduits, junction boxes, disconnect switches), C_{eng} is the engineering cost, and I_s is the installation cost including site preparation, mechanical mounting, support structures and stacking. The operational cost is given by:

$$O_C = T_s + C_s + R \tag{7}$$

where T_s is the cost associated with the technical staff, C_s the cleaning staff and R is the replacement cost associated to inverters and panels. The replacement costs consider preventive maintenance schedules considering replacements of key components associated to inverters, tracking systems and protections. The anual cost associated to maintenance is estimated as the 0.07% of the capital investment [19]. The replacements of 60 panels per year and 50% of the inverters are also considered. The replacement of inverters is considered at the 7th and 15th year of operation of the system.
Table 3 summarizes the values of the operational and investments costs. The prices for solar panels, inverters, solar trackers and electrical system are estimated considering market prices. The engineering cost is estimated based on local engineering rates.The installation cost is estimated as the 0.5% of the panels cost. The cost associated to technical and cleaning staff considers the labor cost for a team of 25 cleaning people and 4 technical staff.

The results for 100% of assistance ; i.e. $A = 100$; are summarized in table 4. The project has a positive NPV and the IRR is higher than the discount rate and the payback of the project is 6.5 years.

It is necessary to analyze how the profitability of this project is affected by the different factors such as: operational costs, initial investment, panel cost

Tab. 4: Main Financial Indicators

Indicator	value
NPV	6500000 US$
IRR	14.01
Payback	6.48 years

and energy prices.

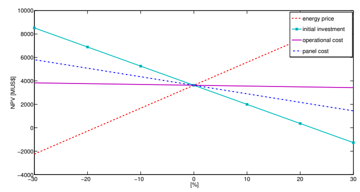

Fig. 7: Sensitivity analysis.

The effects of these factors in terms of percentage variations over the NPV are depicted in Figure 7. As seen in Figure 7, the profitability of the project is influenced mainly by the initial investment and the energy prices. Both variables are critical, variations larger than 20% can compromise the economical feasibility of the project. The panel price is also an important cost since the 60% of the initial investment is associated with the solar panels. The rest of the variables have less impact, but they are also important and they need to be considered in the analysis since they may have larger variations.

Since the system was designed to provide the full power at the less favorable conditions, it will provide a surplus of energy at the most favorable conditions; which will be sold at the AMP. Thus, it is interesting to analyze the profitability of the project with respect to the percentage of the full power required in the less favorable conditions; i.e. degree of assistance. The ANV has a monotonic behavior with respect to the percentage of assistance since an increase of the investment in solar panels will increase the production of energy. As seen in Figure 8 at 50% there is an inflection point, since the system starts to sell energy to the power distribution system and the slope of the curve decreases slightly as a result of the small value of the AMP with respect to the MC. The maximum value for the NPV is obtained for a system designed to satisfy the full power requirement in the less favorable conditions; i.e. 100% of assistance.

The IRR, however, presents a maximum around 50% corresponding precisely to the inflection point of the NPV, as seen in Figure 9. This result is obtained since the selling price (AMP) is smaller than MC associated to the saved energy. It is worth pointing out that this level of assistance means that no energy will be sold at the most favorable irradiation conditions. These results have shown that the optimal size of the system to assist the pump operations will depend on the selling and buying electricity prices and financial criteria considered for

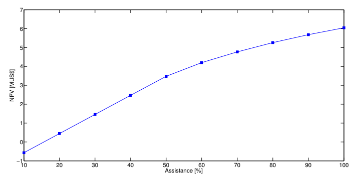

Fig. 8: NPV for different percentages of assistance.

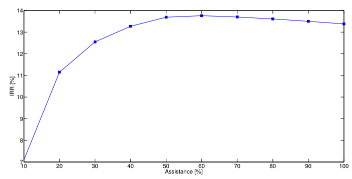

Fig. 9: IRR for different percentages of assistance.

carrying out the evaluation. Therefore solar assisted energy sources are an attractive solution to be considered by the mining companies, irrespective of the financial criteria used for the evaluation.

6 Conclusion

The current importance of water and energy issues in the mining sectors is leading to consider the use of nonconventional energy and water sources. In Chile, in particular, this problem is more acute due to the location of the most important mines and the high cost of the electrical energy. This work has presented the design and economic evaluation of an alternative system to assist the operation of pump stations based on PV panels. The analysis shows that this strategy is attractive from a technical and economical point of view. The level of assistance defined as the percentage of energy to be supplied for the PV system will depend on the economic criteria used. If the NPV is considered, then the 100% of assistance during hours with daylight will be attractive. However if IRR is considered, the maximum value is obtained when the level of assistance is such that at the less favorable conditions some energy must be bought to the network and in the most favorable conditions no energy is sold to the network. The sensitivity analysis shows that the prices of energy and investment costs are the most important variable to be considered. The results demonstrate the potential of the solar energy to address the main challenges associated to the water end energy availability in the mining industry, and in particular for the Chilean one.

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References

[1] Ernest-Young, “Business risks facing mining and metals 2014–2015,” Ernest & Young, Tech. Rep., 2014.

[2] C. Montes, “Fresh water demand forecast by the copper mining industry, 2013-2021,” Cochilco, Tech. Rep. DE/23/2013, December 2013.

[3] N. Consulting, “Renewable energy for the mining industry revenue by technology, aggressive investment scenario, world markets: 2013-2022,” Navigant Consulting, Inc, Tech. Rep., 2013.

[4] G. Jimenez-Estevez, R. Palma-Behnke, R. R. Latorre, and L. Moran, “Heat and dust: The solar energy challenge in Chile,” *Power and Energy Magazine, IEEE*, vol. 13, pp. 71–77, 2015.

[5] V. Fthenakis, A. Atia, M. Perez, A. Florenzano, M. Grageda, M. Lofat, S. Ushak, and R. Palma, “Prospects for photovoltaics in sunny and arid regions: A solar grand plan for chile -part i-investigation of pv and wind penetration,” in *IEEE 40th Photovoltaic Specialist Conference (PVSC)*, 2014, pp. 1424–1429.

[6] D. Liyanage and S. Rajakaruna, “Performance evaluation and cost-benefit analysis of a large solar PV installation at a mine site in Western Australia,” in *Innovative Smart Grid Technologies Asia (ISGT) IEEE PES*, 2011, pp. 1–8.

[7] W. Muneer, K. Bhattacharya, and C. Canizares, “Large-scale solar PV investment models, tools, and analysis: The ontario case,” *Power Systems, IEEE Transactions on*, vol. 26, pp. 2547–2555, 2011.

[8] CNE, “Solar irradiance in Chilean territories,” CNE/PUND/UTFSM, Tech. Rep., 2008.

[9] S. Armstrong and W. Hurley, “A new methodology to optimise solar energy extraction under cloudy conditions,” *Renewable Energy*, vol. 35, pp. 780–787, 2005.

[10] A. Molina and R. Rondanelli. Solar energy resources explorer: User’s manual, Facultad de Ciencias Fisicas y Matematicas, Universidad de Chile, Chile. (in Spanish). [Online]. Available: http://ernc.dgf.uchile.cl/Explorador/Solar2/

[11] CDEC, “Marginal cost forecast 2015-2019,” CDEC-SING Chile, Tech. Rep., October 2014.

[12] Systep, "SING prices: Electrical sector monthly report," Systep, Tech. Rep., November 2014.

[13] A. Sharma, "Top solar power industry trends for 2015," IHS Technology, Tech. Rep., 2015.

[14] D. C. Jordan and S. R. Kurtz, "Photovoltaic degradation rates—an analytical review," *Progress in Photovoltaics: Research and Applications*, vol. 21, no. 1, pp. 12–29, 2011.

[15] A. Solar, "Advantages of distributed and central architectures in solar array," AE Solar Energy, Tech. Rep., 2014.

[16] P. Suskis, "Overview of the photovoltaic system topologies," Riga Technical University, Tech. Rep., 2013.

[17] J. Flicker, R. Kaplar, M. Marinella, and J. Granata, "Pv inverter performance and reliability: What is the role of the bus capacitor?" in *IEEE 38th Photovoltaic Specialists Conference (PVSC)*, vol. 2, 2012.

[18] P. Zhang, W. Li, S. Li, Y. Wang, and W. Xiao, "Reliability assessment of photovoltaic power systems: Review of current status and future perspectives," *Applied Energy*, vol. 104, pp. 822–833, 2013.

[19] L. M. Moore and H. N. Post, "Five years of operating experience at a large, utility-scale photovoltaic generating plant," *Prog. Photovolt: Res. Appl.*, vol. 16, no. 3, pp. 249–259, 2008.

[20] M. Mehrtash, G. Quesada, and Y. Dutil, "Performance evaluation of sun tracking photovoltaic system in Canada," Shiraz University, Shiraz, Iran, Tech. Rep., 2012.

[21] G. Shushnar, J. Caldwell, and R. Reinoehl, "Balance of system costs for a 5 MW photovoltaic generating station," *IEEE Power Engineering Review*, vol. PER-5, p. 29, 1985.

[22] K. Kurokawa, K. Kato, M. Ito, K. Komoto, T. Kichimi, and H. Sugihara, "A cost analysis of very large scale PV (VLS-PV) system on the world deserts," in *Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference*, 2002, pp. 1672–1675.

[23] L. Moore, H. Post, H. Hayden, S. Canada, and D. Narang, "Photovoltaic power plant experience at arizona public service: A 5-year assessment," *Prog. Photovolt: Res. Appl.*, vol. 13, no. 4, pp. 353–363, 2005.

[24] E. Fuentealba, P. Ferrada, F. Araya, A. Marzo, C. Parrado, and C. Portillo, "Photovoltaic performance and LCoE comparison at the coastal zone of the Atacama desert, Chile," *Energy Conversion and Management*, vol. 95, pp. 181–186, 2015.

[25] A. Marinopoulos and P. Bakas, "Techno-economic evaluation of alternative configurations for very large scale PV power systems including energy storage," in *2014 Ninth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, 2014, pp. 25–27.