Renewable Energy 87 (2016) 145–153

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

# Sensitivity analysis of a photovoltaic solar plant in Chile

F. Bustos, A. Toledo, J. Contreras, A. Fuentes*

*Departamento de Industrias, Universidad Técnica Federico Santa María, Av. España 1680, Valparaíso, Chile*

ARTICLE INFO

*Article history:*
Received 19 February 2015
Received in revised form
23 September 2015
Accepted 28 September 2015
Available online xxx

*Keywords:*
Solar radiation
Dual-axis PV solar plant
Risk analysis
$CO_2$ emissions
Financial/economic analysis
RETScreen

ABSTRACT

A total of 22 cities in Chile were analyzed focusing the development of a 30 MW Photovoltaic Solar Plant using RETScreen software. Results of the study indicate that Calama City presents interesting results, with a Capacity Factor of 34.0% and an Energy Production of 92523 MWh. However, with a discount rate of 12% and an evaluation of 30 years, a Net Present Value (NPV) of $-67 \times 10^6$ USD and an Internal Rate of Return (IRR) of 7.0% were obtained due to the high investment cost. Applying a 40% incentive in Calama City, the NPV reaches $11 \times 10^6$ USD, with an IRR of 13.7%, thus obtaining positive financial results.

Sensitivity analysis, without the incentive applied, considers the variation of ±30% for five parameters, indicating that the initial cost and the electricity export rate significantly influence the results of the project. A risk analysis was performed on these parameters indicating that an NPV ≤ 0 and an IRR ≥ 12% were reached for 94.0% and 7.0% of the projects, respectively considering the initial cost. Analyzing the electricity export rate, only 5.0% of the projects had positive results for NPV and only 4.0% of the projects meet the criteria established for the IRR.



## 1. Introduction

For developing countries like Chile, there is a casual relationship between energy consumption and economic growth [1]. In Fig. 1, the Gross Domestic Product (GDP) exhibits a direct relationship with the growth of electrical energy consumption, as observed in Ref. [2]. Currently the generation of electric power in Chile is mainly based on fossil fuels; which can result in important long-term environmental impacts, along with the possible depletion of the resource in the medium term [3,4]. Fig. 2 shows that for the year 2010 the percentage of electricity generation through fossil fuels was approximately 65%, according to the National Commission of Energy (CNE) [5]. This percentage will probably increase, given the projects that are currently in development and those that are being reviewed by the Chilean Ministry of the Environment [5]. A study of the CNE indicates that the participation of Renewable Energy (RE) in the Chilean energy matrix is approximately 1.15% [6]. The Chilean electrical system currently operates within a free market model. In this model, private entities make decisions regarding technology, location and time in which new projects will be developed. In this context, the Chilean Government acts as a regulator in terms of the environmental and social impacts.

The RE implementation approach in Chile are recognized in the Chilean legislation, called short law I [7]. This law classifies the RE sources as biomass, hydraulic (<20 MW), geothermal, solar, wind, tidal, and others that may be recognized in the future by the CNE.

Environmental and social impacts justify the incorporation of RE into the energy grid of any country [8], especially in Chile, due to its large dependence on imported fossil fuels. Unfortunately, there is a low level of RE development in the country and, consequently, a small involvement of RE in the Chilean electric market [9]. To promote the introduction of RE into the Chilean energy matrix, current legislation mandates that from 2010 to 2015 the 5% of the total electricity supply must be provided by RE, increasing gradually to 10% by 2024 [3].

To achieve this goal, it is essential to analyze different options from the RE currently available for implementation in Chile. Recently, there has been a growing worldwide interest in PV solar technology [10], and emerging studies have been carried out South America assessing the RE technologies [11]. Several studies evaluating the technical and financial potential of PV projects have also been conducted in other countries [12]. Several studies evaluating the technical and financial potential of PV projects have been conducted. For example, in Egypt, a 10 MW solar PV plant was evaluated in 29 areas of the country [13]. The results of this study indicate that given the high rate of solar radiation and the costs of the equipment in the country, a typical plant is financially feasible in any of the areas evaluated. Another similar case was studied in

* Corresponding author.
*E-mail address:* andres.fuentes@usm.cl (A. Fuentes).

http://dx.doi.org/10.1016/j.renene.2015.09.070
0960-1481/

**Nomenclature**

| | |
|---|---|
| $\overline{E}$ | Average energy converted by the PV system in a year, MWh |
| $\overline{H}_t$ | Annual average solar radiation on a tilted surface, kWh/m$^2$/year |
| $C$ | Total initial cost of the project, USD |
| $C_n$ | Net cash flow, USD |
| $C_{ener}$ | Annual energy revenue, USD |
| $C_{O\&M}$ | Annual cost in operation and maintenance, USD |
| $D$ | Annual debt payment, USD |
| $e_i$ | Emission factor for the $i$ combustion product, – |
| $E_p$ | Energy available from the sun in a year in a surface S, MWh |
| $f_d$ | Leverage rate, – |
| $r$ | Discount rate, % |
| $r_d$ | Interest rate of the debt, % |
| $r_e$ | Escalation rate of the fuel, % |
| $r_i$ | Inflation rate, % |
| CF | Capacity Factor, % |
| CNE | National Commission of Energy, – |
| EER | Electricity Export Rate, USD/MWh |
| GDP | Gross Domestic Product, – |
| GHG | Greenhouse Gases, – |
| GSR | Global Solar Radiation, kWh/m$^2$/d |
| GWP$_i$ | Equivalence factor for tCO$_{2_e}$, – |
| IRR | Internal Rate of Return, % |
| N | Evaluation period, years |
| N′ | Debt evaluation period, years |
| NPV | Net Present Value, USD |
| RE | Renewable Energy, – |
| S | Total area of the array, $m^2$ |
| SA | Aysén grid, – |
| SIC | Central grid, – |
| SING | Northern grid, – |
| SM | Magallanes grid, – |
| St | PV system station, – |
| Tk | PV system tracker, – |

*Greek Symbols*

| | |
|---|---|
| $\eta$ | Conversion efficiency, % |
| $\eta_p$ | PV system efficiency, % |
| $\lambda$ | Transmission and distribution losses, % |
| $\lambda_p$ | Miscellaneous losses of the PV system, % |

*Subscripts*

| | |
|---|---|
| $i$ | Combustion product in the emission model ($CO_2$, $CH_4$, $N_2O$), – |
| $n$ | Period $n$ in the evaluation period, years |

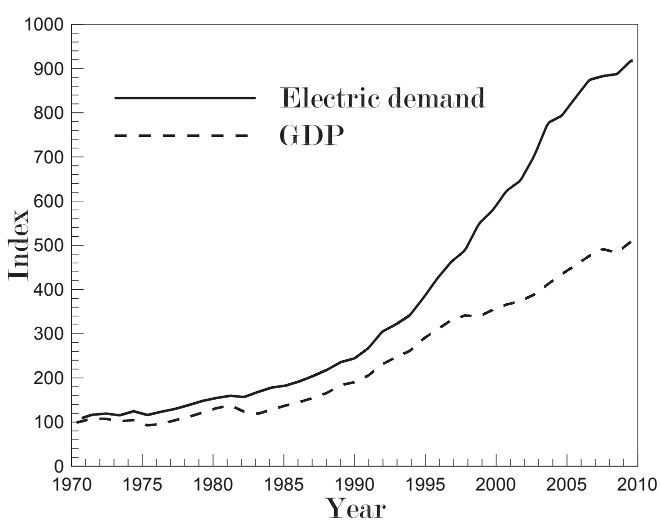


**Fig. 1.** Growth of GDP and energy demand in Chile [5].

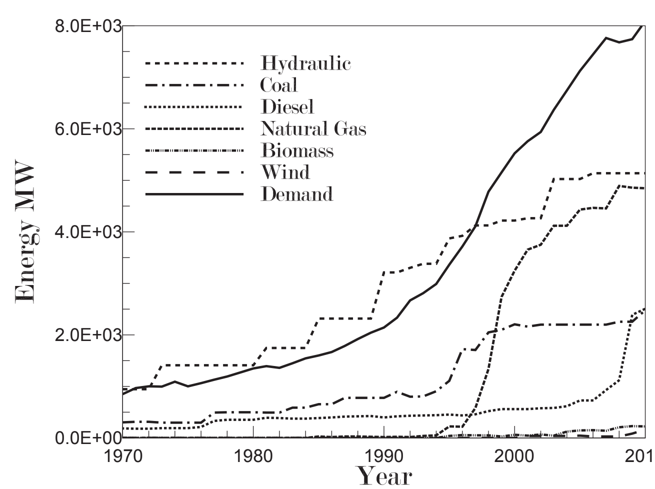


**Fig. 2.** Energy and structure of the national electrical grid [5].

Jordan [14], where a PV solar plant of 5 MW was evaluated in 24 locations. Similar to the case of Egypt, all locations exhibit financial feasibility for installation of PV solar plants. An important point is that in the case of Jordan, the variability of projects, in financial terms (NPV and IRR), is greater than in the case of Egypt. This variability is important because not only does solar radiation vary from country to country, but factors such as equipment costs, subsidies, energy needs, Electricity Export Rate (EER) and operational costs vary as well, considerably affecting the feasibility for this type of project.

Another aspect is the use of a reliable tool that allows for proper evaluation of this type of plant. Note that there are many free-access software packages available that have been used in the literature to analyze RE projects [15]. A widely accepted software used in the scientific community and engineering applications is RETScreen software. RETScreen allows the simulation of the energy production, possible savings, costs, emissions mitigations, financial viability, and risk for various types of RE sources and technologies. Fundamentally, RETScreen uses a comparison model with a base case, usually the conventional technology, and a proposed case which is typically the clean energy technology to compare. The software can be applied to any energy-system, from individual projects to global applications. All thermal generation and renewable technologies can be accounted for using RETScreen and it can incorporate energy efficiency measures relatively easily [16]. There are a series of related investigations using RETScreen in the