Renewable and Sustainable Energy Reviews 59 (2016) 583–596

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Review and multi-criteria assessment of solar energy projects in Chile

M. Grágeda [a,b,*], M. Escudero [a], W. Alavia [a], S. Ushak [a,b], V. Fthenakis [c]

[a] Department of Chemical Engineering and Minerals Processes and Center for Advanced Study of Lithium and Industrial Minerals (CELiMIN), University of Antofagasta, Campus Coloso, Av. Universidad de Antofagasta, 02800 Antofagasta, Chile
[b] Solar Energy Research Center (SERC-Chile), University of Chile, Av Tupper 2007, Piso 4, Santiago, Chile
[c] Columbia University, Center for Life Cycle Analysis, USA and Brookhaven National Laboratory, New York, NY 10027, USA

A R T I C L E I N F O

Article history:
Received 9 October 2014
Received in revised form
17 December 2015
Accepted 17 December 2015

Keywords:
Solar energy
PV
Solar heat plants
NCRE
Multicriteria analysis

A B S T R A C T

Chile needs to increase its installed electric capacity to support economic growth. Currently, the total demand is 67,564 GW h and an additional 22,508 GW h will be needed by 2020 to meet the energy demand of industrial projects. The Chilean mining industry is a major electricity consumer in the country accounting for one third total consumption over today. Solar energy has the highest potential for growth in northern Chile as the north of the country hosts the highest solar resources of the world. In this paper we present a comprehensive review of the energy supply and demand status, planning and prospects in the country with focus on solar photovoltaic- and solar thermal-projects. As of the end of 2014, a solar capacity of 2384 MW are operational and under construction, and more than 10,000 MW of solar power plants have been proposed; most solar projects are located in northern regions where the mining takes place. Considering a conservative scenario where one half of the proposed solar projects would be operational before 2020, solar technology could cover a great part of the country's energy requirements. We evaluated eight operating PV plants and three operating solar thermoelectric plants based on a multi-criteria assessment to offer a reference point for assessing future projects.

Contents

Abbreviations: CAP, Compañía de Acero del Pacífico; CDEC, Centro de Despacho Económico de Carga (Center for Economic Load Dispatch); CER, Centro de Energias Renovables (Center of Renewable Energy); CF, Capacity Factor; CNE, Comisión Nacional de Energía (National Energy Commission); COCHILCO, Comisión Chilena del Cobre (Chilean Copper Commission); CODELCO, Corporación Nacional del Cobre (Chile State Copper Company); CORFO, Corporación de Fomento de la Producción de Chile (Production Development Corporation); CPC, Compound Parabolic Collector; CSP, Concentrated solar power; DNI, Direct Normal Irradiance; ER, Electrorefined cathode (pyrometallurgy); ETC, Evacuated Tube Collector; EW, Electrowinning; FP, footprint CO_2; FPC, Flat Plate Collector; GHG, Greenhouse Gas; GHI, Global Horizontal Irradiation (GHI); HFC, Heliostats Field Collector; IEA, International Energy Agency; INV, Investment; LFR, Lineal Fresnel Reflector; LU, Land Use; LX, Leaching; MTF, Metric ton refined copper; NCRE, Non conventional renewable energy; OECD, Organisation for Economic Co-operation and Development; PC, Parabolic-trough Collector; PDR, Parabolic Dish Reflector/Sterling Dish; PF, Performance; PPA, Power purchase agreement; PSF, Planta solar fotovoltaica (Photovoltaic Solar Plant); PV, Photovoltaic; TES, Thermal Energy Storage; SEIA, Servicio Evaluación Impacto Ambiental (Environmental Impact Assessment System); SIC, Sistema Interconectado Central (Central Interconnected System); SING, Sistema Integrado del Norte Grande (Northern Interconnected System); SX, Solvent extraction

* Corresponding author at: Department of Chemical Engineering and Minerals Processes and Center for Advanced Study of Lithium and Industrial Minerals (CELiMIN), University of Antofagasta, Campus Coloso, Av. Universidad de Antofagasta, 02800 Antofagasta, Chile.
E-mail address: mario.grageda@uantof.cl (M. Grágeda).

http://dx.doi.org/10.1016/j.rser.2015.12.149
1364-0321/

1. Introduction

Currently, there is no single report that compiles all the information related to the development of solar energy in Chile. One of the sources for project-specific information is the Environmental Impact Assessment System (SEIA). However, projects below or equal to 3 MW do not make declarations of environmental impact. Our review includes all large and small projects with nominal power < 3 MW for which there is published information about its location and consumer. We include data for economic and technical analysis of solar plants, such as technology, irradiation levels, investment, and capacity factors. This comparative review offers a tool to assess rates of return and cost of electricity, applied to all solar technologies (e.g., PV, CSP without storage, combined cycle.) installed in Chile. Thus, this article offers a source of useful data for the evaluation of solar projects in Chile and illustrates the application of multi-criteria assessment to the evaluation of PV and solar thermal plants. The results of this assessment that can be used as reference points for assessing future projects.

1.1. Thermal energy background

In Chile, delivering heat and electricity to households and industry has involved the burning of fossil fuels, and subsequently, the emissions of greenhouse gases (GHG) that are a great concern worldwide. By joining in 2010 the Organisation for Economic Cooperation and Development (OECD), Chile made a commitment to mitigate climate change by incorporating goals to reduce greenhouse gas emissions (GHGs) [1]. The country started doing that in 2008 by establishing Law 20.257 (known as 20/20) [2] that introduced amendments to the general electric services on generating electrical power from nonconventional renewable energy sources where power generators must introduce a quota of NCRE-generated electric power. Therein, solar technology preponderated as a source of energy for the electrical- and thermal- supply. In 2009, law 20365 established a franchise tax for thermal-solar systems, promoting the installation of solar thermal collectors for heating water in buildings (i.e., low-temperature solar-thermal systems) [3]. Solar water heating has been the most popular solar system in Chile, greatly reducing peak electrical-load [4]. Due to familiarity with the technology, large-scale solar heat for industrial processes (SHIP) plants are considered for the northern regions of Chile where the solar resources are the greatest. In the Atacama Desert (Northern Chile) there is a remarkable annual global irradiation (GHI) of 3300 kW h/m^2 on latitude tilt surfaces, almost 4000 kW h/m^2 on one-axis tracking planes, and annual direct normal irradiation (DNI) of 3000 kW h/m^2 on two-axis tracking. One-axis tracking systems receive 3000 h of sun per year, resulting to capacity factors up to 34% [5].

1.2. Background on electricity demand

Chile faces huge challenges in developing its energy planning policy to assure the sustainability required to meet increasingly higher annual consumption by industrial companies [6,7]; presently, its electric matrix is vulnerable to fluctuations in energy supply. Chile [8] is highly dependent on imported fossil fuels, whose high prices have increased the marginal costs of power generation and, consequentially, the price of electricity.

The price of energy is a key cost driver within industrial production. For this reason, companies focus on systematically optimizing energy efficiency in their production processes, so to increase the country's industrial competitiveness.

According to the International Energy Agency (IEA), electricity tariffs paid by the Chilean industry and households (Fig. 1a and b) are higher, during recent years, than the average OECD tariffs [9]. Electricity prices increases have in general followed oil increases; in the late 90s, the world average oil price stood at nominal levels of around US$10 a barrel, whereas in 2012, that price was over $100 a barrel [10], and this raised the cost of producing electricity to both industry and households (Fig. 1a and 1b). However, the rate of electricity price increases has been higher in Chile than in other OECD countries, as Chile is almost entirely dependent on imported fossil fuels. This dependency was exacerbated by lower rainfall and drought that reduced the share of hydropower in the country, natural gas shortages (2004 onwards), earthquakes that affected the output of the electric matrix, and high level of concentration in the electricity market of few generator actors [11].

OECD members, after the oil crisis of the 1970s, started to reduce their consumption and explore new resources, while they also embarked in a long term effort to decouple economic growth from the expansion of energy demand [12,13]; they achieved this by using energy more efficiently, aided by the development of new technologies and equipment, by diversifying energy sources, incorporating non-conventional renewable energy (NCRE), and by orienting a restructuring of the economy towards services. Similarly, after the financial crisis of 2007–2008, Chile decreased its consumption of fossil fuels and introduced more hydropower, thus lowering the rate of rise in electricity prices, but the period of drought in 2010–2012 lowered the production of hydroelectric power from South Chile. However, Chile's gross domestic product is greatly dependent on the revenues of the metals and minerals industries which require high amounts of energy, thus, making decoupling of economic growth from energy demand growth more problematic than in other OECD countries.

The current study considers two scenarios for predicting future prices [10]. Over the short term, the prediction will depend on the changes in international market fuel prices and the evolution of hydrological scenarios that may affect the hydropower potential; in the long term, price evolution will depend on diversified technologies e.g., non-conventional renewable energy (NCRE) into the energy mix, and its reliability in satisfying the growth of the country's electricity requirements.

1.2.1. NCRE policy integration into energy matrix

Chile is privileged in having conditions geared to the potential of non-conventional renewable energy (NCRE); the State has prioritized the diversification and sustainability of energy matrix