Energy Conversion and Management 174 (2018) 88–100

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Modeling of a small parabolic trough plant based in direct steam generation for cogeneration in the Chilean industrial sector

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ARTICLE INFO

Keywords:
Solar thermal energy
Industrial process
Parabolic trough
Direct steam generation
TRNSYS
Biogas heater

ABSTRACT

The concentrated solar power technology used in schemes of cogeneration for the production of power and heat, or power and cooling is an interesting option to develop in Chile, mainly due to the high solar potential. Besides, cogeneration is an option to face the demand for energy in terms of electricity, industrial heat or cooling, which is increasing in Chile in recent years. A concentrated solar power cogeneration plant based in parabolic trough technology with a backup system of a biogas heater and a direct steam generation scheme is proposed. The cogeneration study considers two different plants, one for power and heat, and other for power and cooling, which were studied in Santiago, Chile. The results show a benefit in fossil fuels replacement when the cogeneration plant is compared to a conventional plant for production of industrial heat. In the case of cooling, electricity savings are achieved when the cogeneration plant is compared to a conventional vapor-compression system. The cooling demand can be supplied totally using an absorption chiller in the cogeneration scheme, reaching electricity energy saving of up to 99%. For cogeneration of power and heat the energy replacement in the industrial heat process are as minimum 69% depending on the demand and configuration of the plant, and can reach up to 100%. Finally, when the biogas heater is disconnected from the plant to consider a case only based in the concentrated solar power plant, the cogeneration scheme for cooling can reach an electricity saving of 4%. The cogeneration scheme for heat can reach an energy replacement of 14% as minimum.

1. Introduction

Nowadays the global energy demand is increasing, in terms of electricity, heat for industrial processes and other kinds of energy needs, such as, cooling and water treatment. An important quantity of this demand is supplied with fossil fuels, nearby a 82% of global energy needs [1]. The implication of the greenhouse gas emissions in the climate change has been confirmed [2], for this reason is important for each country to reduce the production of greenhouse gas emissions, and therefore, its consumption of fossil fuels. Chile is in the same line that the global trend, with a sustained growth in its energy consumption in the last years, and government efforts to boost renewables energies [3].

Chile has planned its sustainable development through a long-term energy policy to 2050 and the non-conventional renewable energy (NCRE) law [4]. Particularly, this law establishes that 20% of electricity generation by 2025 must be produced with NCRE sources. However, in November 2017 the goal was achieved for this particular month [5]. An important fact that must be in consideration is that the solar irradiation in northern Chile is the highest in the world, which is very useful to use solar energy conversion technologies. Moreover, Chile has direct normal irradiation (DNI) levels of more than 3000 kWh/m^2 yr, and most of the territory has DNI levels of more 2000 kWh/m^2 yr [6]. These DNI levels are particularly useful for concentrating solar power (CSP).

According to the energy balance of Chile, the industrial sector is the main energetic consumer in the country. Fossil fuels play a significant role in satisfying the industrial energy demand, mainly focused on process heat generation. Mining, paper & wood, and food industries concentrate most of the consumption of fuels [7]. Despite the fast growth of NCRE in the national electricity system, there is yet a little market penetration by renewable energy sources in heat for industrial

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https://doi.org/10.1016/j.enconman.2018.08.026
Received 4 June 2018; Received in revised form 30 July 2018; Accepted 8 August 2018

Nomenclature

COP	Coefficient of performance
CSP	Concentrating solar power
DNI	Direct normal irradiation
DISS	Direct solar steam
DSG	Direct steam generation
HTF	Heat transfer fluid
IAM	Incident angle modifier
MAE	Mean absolute error
NCRE	Non-conventional renewable energy
ORC	Organic Rankine Cycle
PTC	Parabolic-trough collectors
TRNSYS	Transient System Simulation Program

processes.

Cogeneration is proposed in order to reduce the use of fossil fuels in the industrial sector. It allows one way to obtain two products from one source of energy, such as, electricity and heat for industrial processes, or electricity and cooling. These processes take advantage of the residual energy or decrease the energetic losses in a plant, to optimize the use of energy. CSP technology is an option to develop cogeneration schemes, due to the high levels of DNI in Chile. Several integration options with CSP technology has been studied in order to perform the cogeneration process involving electricity and process heat, or electricity and cooling [8].

1.1. CSP technology and direct steam generation

There are four different CSP technologies, namely, solar power tower, parabolic dish-Stirling, parabolic-trough collectors (PTC) and lineal Fresnel collectors. Usually these systems heats a heat transfer fluid (HTF) in their focus. The HTF usually corresponds to water, thermal oil or molten salts. The most known application of CSP plants is electricity generation, although they are also being used in applications that require heat at high temperatures.

PTC technology concentrates DNI in a linear focus, using a series of parabolic mirrors in whose focus is placed a tube where the HTF circulates. This technology has expansive commercial development with a 85% market share in CSP [9]. The operating temperature of PTC could achieve temperatures between 300 and 400 °C when uses thermal oil as HTF [10]. Another possibility in the PTC technology is to use water as HTF, in this case the system can also use the water as working fluid in the power cycle using a direct steam generation (DSG) scheme. DSG advantages can be summarized in the following main points:

- Higher temperatures can be achieved with water as HTF, and therefore better plant efficiency since the thermodynamic cycle operates at higher temperature [11,12]. No limit in steam temperature, where the limitation are the structural materials. Moreover, less solar field is needed in order to produce the same amount of useful heat.
- Water is a cheap and highly available HTF, and therefore cost-efficient. In addition, water is neither inflammable nor harmful to the environment. Compared to molten salts, water is cheaper and less corrosive [13].
- No heat exchangers are required between the solar field and the power cycle, which increases the exergy efficiency, reduces investments costs and reduces operation and maintenance costs [14].
- Simpler overall plant configuration, which is very important in order to propose this solution to the industrial sector [15].

There are several studies related to perform a DSG using the PTC technology to produce electricity using a power cycle, with different configurations [13,16–19]. Anyway, a challenge in the use of PTC with DSG is the potential thermal bending issue due to the two-phase stratified flow pattern in the evaporation stage of the loop. The presence of the stratified flow pattern could cause strong circumferential thermal gradients mainly on the absorbent tube surface, and therefore, deformation of the tube due to thermal stresses, decrease in the system efficiency and glass tube breakage when heavy bending occurs. These consequences are deeply discussed in [20,21]. However, with a correct design, the thermal gradients are kept below critical values and the absorber tube does not have any damage.

1.2. Cooling technology

Nowadays the main cooling technologies used in the industry are divided in two major types: cooling based in mechanical processes, such as, vapor-compression cooling scheme, and cooling based in thermal processes, such as, absorption, adsorption and jet-ejector chillers, however, for this work, it was made for absorption chiller machines. This technology uses the same principle of operation than the vapor compression machines, the cooling and heating effect are produced by the change phases in the refrigerant fluid. While, the electric power drive a vapor compression systems, the absorption chiller machines are driven by a high temperature fluid (greater than 60 °C) [22].

The main difference between these technologies lies in the method used to raise the pressure of the evaporated refrigerant. In the technology based in a vapor-compression scheme the pressure is raised using a compressor, and in the cooling system based in thermal processes the pressure is raised using a thermochemical process [23]. The thermochemical process used in the cooling systems based in thermal process implies the absorption of the refrigerant by a transport fluid. In the case of the absorption chiller technology there is an absorber for this reason, in which the refrigerant is dissolved into the transport fluid forming a solution with high concentration of refrigerant through an exothermic reaction. Then this solution is pumped to the generator of the system, raising the pressure of the fluid, where trough an endothermic reaction, adding heat from an external source, the refrigerant vapor is separated to the transport fluid with the required operating pressure in the condenser [23].

There are important advantages of use a cooling system based in a thermal process. These systems are free of noise and vibrations, durable, and they have low maintenance and operational costs [24]. The main advantage is the possibility of use residual heat from industrial processes or solar energy to reach the generator's heat requirements. However it must be taken into consideration the high investment costs to acquire one of these systems [25].

1.3. Biogas

In this work the concept of biomass refers to the organic material that can be used to produce biogas, this may come from different sources, such as, crops, animal manure, organic waste from cities or industries, and other sources [26]. The biomass used to obtain biogas must have some quantities of nutrients that could be converted in biogas. The calorific value of the biogas depends of its methane (CH_4) content, and could reach values of 5500 kcal/m^3 [27].

One idea behind the use of biomass is to integrate the biogas in CSP plants to solve the problem of intermittence availability of the solar resource at the plant location. In Chile, the share of biomass is only behind oil and carbon in the primary energy supply [7]. There are several studies related to hybridize CSP plants with biomass [28–31].