



## Economic viability of concentrated solar power under different regulatory frameworks in Spain

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### ABSTRACT

Between 2004 and 2013, Spain applied a series of regulations that prompted a rapid expansion of the CSP sector. Most of this capacity was based on a proven technology that involved limited technical and financial risks (50 MWe, parabolic trough, synthetic HTF, 7.5 h thermal energy storage and wet cooling). This paper provides an introduction to CSP technology and a detailed review of these regulatory frameworks. This information has been used to evaluate the economic viability of a CSP plant representative of those deployed in Spain. The results evidence the limited competitiveness of this form of CSP, which is attributable not only to its elevated capital costs but also to high fixed operating costs per unit of output and limited revenues from power sales. Although generation capacity may be increased through hybridization with NG, this is also a loss making activity due to the limited efficiency of single cycle technology. With exceptions, the policy strategy followed in Spain had limited success at promoting technology advances with potential to achieve higher generation capacity, improved revenues, reduced costs and increased dispatchability. This form of CSP may still be attractive in isolated locations, where real power generation costs may be significantly higher.

### 1. Introduction

Concentrated solar power (CSP) began its journey during the second half of the 1980's with the commissioning of nine plants (SEGS I-IX) totalling 354 MWe in the Mojave Desert (California, USA). Despite the technical success of this endeavour, once the effects of the 1970's oil crises were behind, CSP fell into a long period of oblivion [1,2]. Seventeen years later, the solar thermal energy market reopened again in Spain prompted by the approval of the national Plan for Renewable Energies 2011–2020 [3,4] setting ambitious objectives for the generation of renewable power. Between 2007 and 2013, Spain lead the international community with the commissioning of 50 new CSP plants totalling 2304 MWe [5]. The USA followed behind at a slower pace accumulating 1789 MWe in 24 projects until 2017. The latest records show 132 commercial plants currently operating worldwide for a combined capacity of 4800 MWe, 35 more under construction and 77 in project [6]. CSP is receiving special interest from emerging economies with growing electricity demands that are located in places with good solar resources like China<sup>1</sup> [7], India [8,9], Chile [10], Egypt [11], Qatar [12], South Africa [13] and Morocco [14].

Despite all this, the future of solar thermal power needs to be viewed with caution. CSP is still regarded as an immature technology

lacking competitiveness in the absence of public support [15,16]. The 4.8 GW installed worldwide up until 2017 fall far behind the values reached by other renewables like photovoltaic (303 GW), wind (487 GW) or hydropower (1096 GW) [17]. Projects like Desertec [18,19] and the Mediterranean Solar Plan [20], which envisaged the mass production of solar electricity in desert areas and its transmission to high consumption centres, have not become a reality. In this context of slow growth, CSP is unlikely to meet the objectives set by the International Energy Agency (IEA) for 2020 (147 GW) and there is high uncertainty with regards to 2050 (1089 GW) [21].

Although intrinsic limitations of the technology are also to blame (such as the scale factor and limited modularity of thermal power plants [2] or the limited availability of Direct Normal Irradiation resources in locations with high electricity demand [22]), the main reason for the slow development of CSP is mainly related to its high generation costs [15,16,23]. This situation is clearly exemplified in Spain, where the solar sector came to complete stagnation when the financial crisis forced the national government to cut down on the subsidies that had prompted its rapid expansion a few years earlier [23,24].

But what levels of support or what electricity market prices are required to make CSP competitive? What subsidy structures were more effective at ensuring economic viability? How much do capital and

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<sup>1</sup> China is expected to take the lead in CSP technology by 2020 with a combined capacity of 5000 MW, as projected in its 13th five-year development plan for renewable energies.

operating costs need to be reduced to make the technology viable in the absence of public support? What is the effect of hybridizing CSP with natural gas on the economic viability of the plant? And most importantly, did the policies implemented in Spain really facilitate the transition of CSP towards competitiveness? The objective of this paper is to shed some light onto all these issues and onto the economic viability of conventional CSP.

Thus, the paper has been structured as follows: **Section 1** provides a brief introduction to CSP with the aim of describing existing and future alternatives. **Section 2** provides a review of regulatory frameworks that affected CSP in Spain between 1998 and 2014. This data is used to evaluate the economic viability of a conventional plant representing the technology most widely deployed in Spain during this period (50 MWe parabolic trough with 7.5 h TES). The analyses consider three scenarios with regards to the use of auxiliary fuels: CSP operating exclusively on solar energy (0% NG) and hybrid operation with 15% and 30% power derived from NG. **Section 3** describes the methodology and inventory data employed in this economic analysis and **Section 4** shows the results and discussion derived from this investigation. In view of these results, **Section 5** provides conclusions about the viability of CSP and the usefulness of these strategies to facilitate the transition of this technology towards competitiveness.

### 1.1. Overview of CSP technologies

The term CSP refers to a wide range of technologies designed to generate electricity from concentrated solar radiation. The operating principles and the different configurations available are well documented in various books [2,25,26] and reviews [16,27,28]. As a general introduction, CSP plants consist of two components: the solar field and the power element. The former is made of a series of mirrors (or lenses) designed to concentrate the solar radiation into a receiver, where it is transformed into high temperature thermal energy. A thermal fluid connects the receiver with the power component, where a heat engine is used to transform this thermal energy into electricity.

Unlike photovoltaic (PV) cells, which may use all forms of solar radiation (direct, diffuse and reflected), the primary energy resource for CSP is direct normal irradiance (DNI). This type of radiation prevails in subtropical latitudes, usually coincidental with desert climate zones [22]. Another key difference with PV relates to the limited modularity of CSP. Due to the thermal nature of the technology, CSP plants need large scales to achieve high efficiencies.

CSP plants can be divided into two broad categories, depending on whether the solar collectors concentrate the sunlight along a linear receiver or on a single focal point. In the linear receiver category, the most commercially proven technology is based on parabolic trough (PT) collectors while the use of Fresnel linear collectors is still under development. Point-focusing systems, which may achieve significantly higher concentration ratios, include central tower (CT) solar plants and dish/engine systems.<sup>2</sup>

#### 1.1.1. Parabolic trough CSP technology

PT-CSP technology was used in the primigenial SEGS I-IX plants and it still remains the most dominant in the market by far. As a reference, 45 out of the 50 solar plants built in Spain are based on this technology, representing 96.5% of the capacity installed in this country [5]. PT collectors are made of curved mirrors forming a linear parabolic shape that concentrates the solar radiation onto a receiver that runs along its focal point. Individual collectors are grouped into solar collector assemblies (SCA), each one equipped with its own single-axis tracking mechanism. These SCAs are in turn arranged into a series of loops whose total lengths and aperture areas are adapted to the capacity of

the plant (including power block and storage system). Electric pumps force the circulation of a heat transfer fluid (HTF) inside the receiver, which absorbs the concentrated radiation to increase its temperature as it moves along the solar field. This thermal fluid evacuates its thermal energy into the power block using a multiple stage heat exchanger, producing steam that is used to drive a turbine for power generation. Alternatively, some of this energy may be transferred to a thermal energy storage (TES) system for later use, as will be discussed below.

The operating conditions of PT-CSP plants are constrained by the physical-thermal properties of the HTF connecting the solar field with the power block. Commercial fluids for indirect heat transfer applications like Dowtherm or Therminol VP-1 are made of eutectic mixtures of two very stable synthetic compounds: diphenyl oxide ( $C_{12}H_{10}O$ ) and biphenyl ( $C_{12}H_{10}$ ) [29]. To be used in CSP plants, these fluids need to comply with strict standards with regard to thermal stability, vapour pressure, freeze point, heat transfer coefficient and viscosity [30]. The maximum operation temperatures of these fluids (around 400 °C) limit the enthalpy of the steam generated in the power block (typically below 380 °C and 90–100 bar), thus typically reducing the energy efficiency of the thermodynamic cycle to less than 30%.

The first commercial CSP plant based on parabolic trough technology outside the USA was the 50 MWe Andasol 1. It was designed and built by ACS-Cobra in Guadix (Granada, Spain), and entered into operation in 2008. The plant incorporates an indirect TES system based on molten salts with a capacity for 7.5 h of full load operation. The company reported a cycle efficiency of 38% and a net power generation capacity of 158,000 MWh/yr, yielding a capacity factor of 36%. Under the influence of subsequent Spanish regulatory systems promoting renewable energies (between 2007 and 2014), the same plant design was replicated 16 times (with minor variations in terms of generation capacity and TES capacity) and 27 additional CSP projects were based on the same size and configuration but without TES.

The development and application of working fluids with higher thermal stabilities and lower toxicity complications is an area of increasing importance in the CSP sector [30,31]. The practical application of water/steam in Direct Steam Generation (DSG) technology has been investigated in various EU funded projects including the Direct Solar Steam (DISS) [32] and the subsequent Integration of DSG Technology for Electricity Production (INDITEP) [33]. Despite its potential, Direct Steam Generation technology has not reached a commercial stage in PT-CSP due to problems with pressure control inside the receivers and also to air tightness limitations in the elements of the HTF circuit connecting the solar collectors [34–36].

The use of molten salts (typically eutectic mixtures of sodium and potassium nitrates) as the primary thermal fluid in PT-CSP plants is also the subject of various projects [37–39]. These salts may sustain operating temperatures up to 650 °C, which are sufficient to drive supercritical (600 °C and 300 bar) steam cycles with efficiencies up to 40–45%. The main drawbacks with molten salts relate to their higher freezing temperatures (200–250 °C) compared to synthetic oils (10 °C), which would require extra insulation and external heating of the solar field during the night. Additional downsides include increased maintenance costs and energy pumping requirements, longer start-up and shut-down times and also technical challenges related to corrosion and material compatibilities [38,40]. The lack of moving parts in the HTF circuit may benefit CSP plants based on linear Fresnel collectors in the adoption of DSG and molten salts technologies [41].

#### 1.1.2. Central tower technology

The solar field in a CSP plant based on central tower (CT) technology consists of an array of mirrors (heliostats) equipped with two-axis tracking systems. These elements concentrate the radiation onto a point receiver situated on top of a central tower where the radiative energy is transformed into high temperature thermal energy. A thermal fluid is then used to transfer this thermal energy into the power block where it is transformed into electricity using a heat engine.

<sup>2</sup> Due to their reduced commercial significance and difference in nature, dish/engine systems will not be further considered in this introduction.

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