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Cost and production of solar thermal and solar photovoltaics power plants in the United States

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The costs and electricity production of concentrating solar power (CSP) parabolic trough (PT) and solar tower (ST) plants are presented and compared with photovoltaics (PV) plants in the United States. Production and costs of alternative CSP technologies are strongly non-uniform. Without thermal energy storage (TES), actualized construction costs are 5213–6672 $/kW for CSP PT and 6084 $/kW for CSP ST. With TES, the actualized costs of PT and ST increase to 8258 $/kW and 9227 $/kW respectively. The annual capacity factors of the more reliable PT plants are 28–29% without TES, and 29–33% with TES. ST plants presently deliver much smaller annual capacity factors even when boosted by natural gas (NG) combustion, or fitted with TES. ST appears to be less mature and more troublesome technology than PT. TES is still not delivering the expected improvements suffering efficiency and reliability issues. PV are less expensive than CSP, with actualized construction costs 4739 $/kW. However, as the capacity factors of PV plants are only 26.3–28.5%, CSP already deliver a 1–2% better capacity factors even without TES. In a decadal perspective, PV may certainly suffer soon of the competition by CSP, more likely PT, with the addition of TES, once this energy storage technology will mature, if a simple but reliable mass production product could be defined.

Introduction

In solar thermal, or concentrating solar power (CSP) plants, lenses or mirrors concentrate the sun light energy on a small area to be converted into heat at high temperature. This heat is then transferred to a power cycle working fluid. Recent reviews of CSP plants may be found in [1–5].

CSP is a technology still in its infantry, contributing very little to the global energy mix, with a very limited number of plants of significant size operational across the world. The present contribution of CSP to the global energy mix is negligible [4,10]. In terms of energy, presently, the total solar electricity generation is 1.05% in the world [11], and it is 1.4% in the United States [12]. As the installed capacity of CSP is only 1.5% of the total solar power capacity, the total CSP contribution to the global energy mix is still negligible in the United States and in the world [4].

Ref. [6] recently discussed the perspective of CSP, explaining that what they call the learning rate, i.e. the cost reduction following an expansion of a technology, exceeded 20% in the last 5 years. This figure is much larger than prior already optimistic estimates such as [7–9]. It also suffers of lack of robust statistics, as it is based on a very scattered population not very well characterized by objective performance indicators. Ref. [6] is based on nameplate capacity and projected costs. The most important aspects of a power plant are however the actual electricity produced, more than the nameplate capacity, and the actual costs vs. the projected costs.

The installed capacity (power) is misleading when used to indicate the actual production of electricity (energy) for solar energy. The annual capacity factor, electricity produced divided by the product of the installed capacity by the number of hours in a year, is a superior indicator [5]. This is due to the obvious statistical and periodic (annual and daily) variability of the solar energy [5]. The clouds coverage also deserves attention in CSP. Additionally, regular maintenance or repair can further reduce the actual operational time of any power plant, thus impacting on the annual energy production and eventually costs.

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Nomenclature

ε	capacity factor
E	energy
n	number of hours
P	power (capacity)
CAPEX	capacity specific capital expenditure
CCGT	combined cycle gas turbine
CSP	concentrating solar power
ISEGS	Ivanpah Solar Electric Generating System
NG	natural gas
PT	parabolic trough
PV	photovoltaics
SEGS	Solar Energy Generating Systems
ST	solar tower
TES	thermal energy storage

Here we use the actual costs and electricity production data, rather than projected costs and nameplate capacity, to produce a proper assessment of the latest, largest CSP projects in the United States of America. Further, we discuss the learning rate based on nameplate capacity specific costs and capacity factors. These data are finally compared to solar photovoltaics (PV) plants.

PV are scaling up rapidly, with capacity more than trebling over the past four years [15]. Thanks to 75 GW of new installations in 2016, the global solar PV capacity increased to 301 GW by the end of 2016. This is a 33.2% increase vs. the end of 2015. The largest increments of 2016 were mostly in China (34.5 GW) and the United States (14.7 GW). China now leads in cumulative capacity (78.1 GW), Japan (42.8 GW) is second place, Germany (41.3 GW) third place, and the United States (40.3 GW) fourth place.

CSP plants are now receiving a growing interest, especially when coupled with TES, for the hypothetical ability to produce electricity partially decoupled from the sun energy without any battery, as otherwise needed with PV. While CSP plants have been built mostly in the PT technology, ST installations are considered more promising than PT for the opportunity to achieve higher sun energy concentration and temperatures, and therefore better efficiencies in the power cycle.

Materials and methods

Costs and electricity production data of CSP projects, both ST and PT, and PV plants in the United States have been obtained through collection of public domain information mostly from the United States Energy Information Administration [13,14].

The data of [14] are available on an annual, quarterly or monthly basis as net generation in MWh, and eventually NG use in MMBtu. From the net installed capacity (power) P in MW, annual and monthly capacity factors ε are computed by diving the annual and monthly electricity production by the product of capacity and number of hours in a year or a month.

$$\varepsilon = \frac{E}{P \cdot n}$$

where n is the number of hours in a year or in the specific month.

The time series of the monthly capacity factors are used to supplement the synthetic information provided by the annual capacity factors to indicate advantages and possible improvements of a technology. Cost data are proposed per unit capacity and actualized to 2017.

While the population is certainly minimal to infer statistically significant trends in the power industry, this approach is certainly superior to analyses only based on projections of costs and electricity production openly conflicting with the real-world data, as recently discussed in [5].

Results

The latest list of CSP projects worldwide of [13] includes 184 projects. However, 10 projects are currently non-operational, and 78 are under construction, contract or development. Of the 96 operational, only 7 have net capacity more than 100 MW. Only 4 of the 7 have a net capacity exceeding 150 MW. They are all in the United States.

The 4 projects are the 377 MW Ivanpah Solar Electric Generating System (ISEGS) and the 250 MW each Solana Generating Station, Genesis Solar Energy Project and Mojave Solar Project.

The 7th largest CSP plant in the world, the 110 MW Crescent Dunes Solar Energy Project, is also in the United States.

ISEGS started production January 2014, Solana October 2013. Genesis March 2014, Mojave Solar Project December 2014 and Crescent Dunes November 2015. Hence, all of them are very recent.

Solar Energy Generating Systems (SEGS) IX, a PT plant with NG boost but no TES operational since October 1990 is also included as an historical reference. The SEGS complex, made up of plants I to IX, with a combined capacity from three separate locations, has a total capacity of 354 MW. It has been the largest CSP complex in the world until recently, and the world's second largest after ISEGS was completed.

Solar Star, Desert Sunlight and Topaz were in 2016 the three largest solar PV power plants in the world by capacity.

Solar Star is a 579 MW_{AC} PV power station near Rosamond, California. It was completed in June 2015. It was at the time the world's largest solar farm in terms of capacity. It uses 1.7 million solar panels spreading over 13 km^2. Compared to other PV plants of similar size, such as Desert Sunlight and Topaz, Solar Star uses a smaller number of large form-factor, high-power modules, mounted on single axis trackers. Solar Star uses crystalline silicon technology.

As an alternative to Solar Star, the Desert Sunlight and the Topaz plants, 550 MW_{AC} each, use about 9 million of smaller form-factor, lower power modules on fixed-tilt arrays. Desert Sunlight and Topaz use thin film CdTe technology. Desert Sunlight and Topaz spread over a larger area of about 25 km^2. The Desert Sunlight Solar Farm is near Desert Center, California, in the Mojave Desert. It uses approximately 8.8 million CdTe modules. It was completed in January 2015. The Topaz Solar Farm is in San Luis Obispo County, California. It was completed in November 2014. The project uses 9 million CdTe modules.

Table 1 is a summary of costs and annual capacity factors for the years 2015, 2016 and 2017, while Figure 1 presents the monthly capacity factors, from January 2013 to December 2017. The results include the recent CSP plants of ISEGS, Solana, Genesis, Mojave Solar Project and Crescent Dunes, the historical CSP plant of SEGS IX, plus the PV plants of Solar Star, Desert Sunlight and Topaz.