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.

TABLE 1

Summary comparison of CSP ST and CSP PT plants with or without TES and PV plants. Opposite to Topaz, ISEGS, Solana, Mojave Solar Project and Crescent Dunes, the costs of Genesis and SEGS IX are estimates. NA not available or not applicable.

	ISEGS	Solana	Genesis	Mojave Solar Project	Crescent Dunes	SEGS IX	Solar Star	Desert Sunlight	Topaz
Start of production	14-Jan	13-Oct	14-Mar	14-Dec	15-Nov	Oct-90	15-Jun	15-Jan	14-Nov
Construction cost m$	2200	2000	1250	1600	975	NA	NA	NA	2500
Type of plant	ST	PT	PT	PT	ST	PT	PV	PV	PV
Thermal energy storage	no	yes	no	no	yes	no	NA	NA	NA
Boost by natural gas	yes	no	no	no	no	yes	NA	NA	NA
Nameplate capacity MW	377	250	250	250	110	80	597	550	550
Planned electricity generation MWh/year	1,079,232	944,000	580,000	600,000	500,000	NA	NA	NA	NA
Actual electricity generation MWh/year (2015)	653,176	718,790	621,514	503,562	3,566	163,295	1,620,464	1,287,015	1,301,415
Actual electricity generation MWh/year (2016)	703,039	643,670	624,142	624,907	127,308	157,969	1,447,006	1,346,282	1,265,760
Actual electricity generation MWh/year (2017)	720,210	724,047	627,865	594,023	42,018	151,661	1,673,719	NA	1,237,814
Planned capacity factor	32.68%	43.11%	26.48%	27.40%	51.89%	NA	NA	NA	NA
Actual capacity factor (2017)	21.81%	33.06%	28.67%	27.12%	4.36%	21.64%	33.00%	NA	25.69%
Actual capacity factor (2016)	21.29%	29.39%	28.50%	28.53%	13.21%	22.54%	28.53%	27.94%	26.27%
Actual capacity factor (2015)	19.78%	32.82%	28.38%	22.99%	0.37%	23.30%	31.95%	26.71%	27.01%
Natural gas combustion MMBtu/year (2016)	1,290,308	NA	NA	NA	NA	200,635	NA	NA	NA
Capacity factor corrected for the consumption of natural gas in a CCGT (2016)	14.42%	NA	NA	NA	NA	17.51%	NA	NA	NA
Construction cost $/kW (2017)	6084	8258	5213	6672	9227	NA	NA	NA	4739

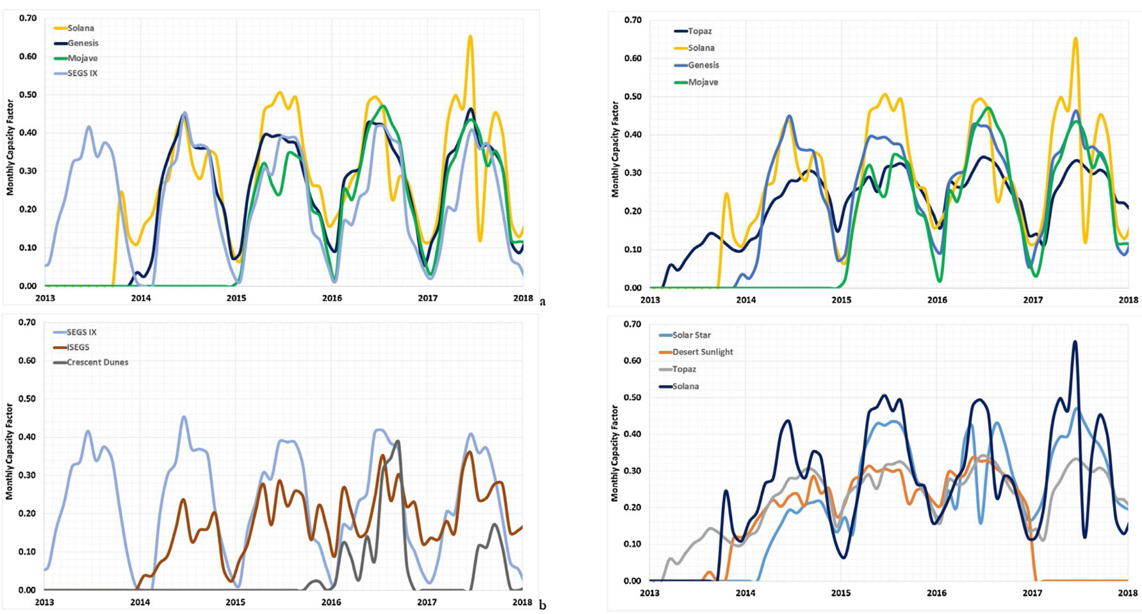

FIGURE 1

Comparison of monthly capacity factors of CSP ST and PT plants with or without TES and PV. Data are shown from January 2013 to December 2017. (a) Latest CSP PT plants of Solana, Genesis and Mojave vs. the SEGS IX CSP PT plant. (b) Latest CSP ST plants of ISEGS and Crescent Dunes vs. the SEGS IX CSP PT plant. (c) Latest CSP PT plants of Solana, Genesis and Mojave vs. the Topaz PV plant. (d) Latest PV plants of Topaz, Desert Sunlight and Solar Star vs. the Solana CSP PT plant.

In a very scattered data set, we look at costs, nameplate capacity and expected production [13], plus actual production [14], as the key performance indicators. For CSP featuring boost by NG combustion, NG consumption is also included.

Comparison of CSP ST and PT plants with or without TES

Recent CSP plants, especially the more sophisticated ST with TES, apart from having larger specific costs per unit capacity installed, have capacity factors by far smaller than the expected, and by far smaller than the capacity factors of base-load conventional plants such as combined cycle gas turbine (CCGT) plants [11]. Better real-world performances and reduced costs are generally provided by the more consolidated PT plants with or without TES [11]. Natural gas (NG) combustion then provides, in absence of TES, a boost, albeit questionable, as NG could be better used in a CCGT plant and NG combustion produces CO_2 emissions [11].

The technology of ISEGS is ST, without TES, with NG boost.

The technology of Solana is PT, with TES 6 hours and no NG boost.

Genesis and Mojave Solar Project are PT without TES and no NG boost.

Crescent Dunes is ST, with TES 10 hours and no NG boost.

SEGS IX is PT without TES but with NG boost.

Crescent Dunes and Solana are the most advanced projects. ISEGS is the largest CSP plant in the world.

From Table 1 and Figure 1, a learning rate is hard to be identified, and certainly there is a significant non-uniformity across the different offers depending on the maturity of the technology.

ISEGS had a cost (2014 values) of 2200 m$ for 377 MW of capacity, or 59836 $/kW. In terms of 2017 values, this corresponds to 6084 $/kW. The latest production data of ISEGS indicates 2016–2017 capacity factors of 21.29%-21.81% despite burning substantial amounts of NG, translating in significant additional generating costs and pollution.

The actual capacity factors drastically reduce of more than one third, to less than 15%, once the consumption of NG is properly accounted for at the fuel energy conversion efficiency of a reference CCGT plant [4].

In 2014, the plant emitted 46,084 metric tons of CO_2 by burning NG, that is twice the pollution threshold at which power plants and factories in California are required to participate in the state's cap and trade program. In the same year, ISEGS was approved to further increase NG combustion from 328 to 525 million ft^3 of NG per year.

The actual data for the years 2014, 2015, 2016 and 2017 indicate a production of only 419,085, 653,122, 703,039and 720,138 MW h/year, despite the huge consumption of NG of 774,525 (but NG consumption of two months of 2014 is missing), 1,245,986, 1,290,308 and 1,217,912 MMBtu to boost production. Burned in a 60% efficiency CCGT, the NG of 2016 could have generated 226,836 MW h of electricity.

The planned electricity generation was an optimistic 1,079,232 MW h/year, corresponding to a planned capacity factor of 32.68%, with a much-limited boost by burning of NG.

Crescent Dunes had a cost of 975 m$ 2015 values, corresponding to 8864 $/kW. This translates into 9227 $/kW 2017 values. While the planned electricity generation was 500,000 MW h/year, for a capacity factor 51.89%, the actual electricity produced in 2016 when the plant was operational January to October was only 127,308 MW h/year, for a capacity factor of 13.21%. Since November 2015, the plant has been out of service due to a leak in a TES molten salt (MS) tank until July 2017. The capacity factor of 2017 has been only 4.36%.

In the much simpler and reliable PT technology, CSP is certainly performing much better.

Solana had a 2013 cost of approximately 2000 m$, 10% less than the ISEGS facility completed only two months later, however for 34% less net capacity. The 2017 specific cost is 8258 $/kW. The production data of Solana is much better than Crescent Dunes and ISEGS, even if still less than the planned values. While the planned electricity generation was 944,000 MW h/year, for a capacity factor of 43.11%, the actual electricity produced in 2016 was 643,670 MW h/year, for a capacity factor of 29.34%. The electricity production has drastically improved in 2017 to 724,047 MW h/year, for a capacity factor of 33.06%.

Genesis and Mojave Solar Project, also featuring the more established PT technology but without any TES, are possibly performing even better. The 2016–2017 productions were 624,142–627,865 and 624,907–594,023 MW h/year vs. the planned 580,000 and 600,000 MW h/year. The actual capacity factors were 28.50–28.67% and 28.53–27.12%, exceeding the planned capacity factors of 26.48% and 27.40%.

While the cost of Genesis is lower but based on a projection, the actual cost of Mojave Solar Project is 1600 m$ 2014 values for 250 MW of capacity, translating in a 2017 specific cost of 6672 $/kW that is larger than the specific cost of ISEGS.

The actual electricity production of the latest, more sophisticated plants such as ISEGS and Crescent Dunes is not that far from the CSP plants of the 1980s, for example the 80 MW SEGS IX. Completed in 1990, this plant is still delivering after almost 30 years same if not better capacity factors (when the NG consumption is factored) than ISEGS [4].

The actual data for the years 2014, 2015, 2016 and 2017 indicate a production of 159,803, 163,276, 157,969and 151, 663 MW h/year, with a consumption of NG of 159,821, 242,736, 200,635and 272,706 MMBtu to boost production. In 2016–2017, the capacity factors were 22.54–21.64%%. These capacity factors were achieved by burning proportionally much less NG than ISEGS.

The actualized costs of SEGS IX are not known with accuracy, but they may be estimated in the range 4400–6600 $/kW.

While there was a significant learning curve during the SEGS experience in the 1980s, as the costs reduced drastically from SEGS I to SEGS IX, and, at the same time, the production increased significantly, we do not see same sign of promising, uniform learning rate following the new builds of the last 5 years in the United States, that are the world largest, proposed in Table 1. The costs per MWh/year of electricity produced, more than MW of capacity, and the reliability of the CSP plants, are everything but clearly improving.

The costs per kW of installed capacity for CSP are much higher than the NREL estimates.

Comparison of CSP PT plants with or without TES and PV

In 2017, Solar Star had an annual output of 1,673,719 MW h, for a capacity factor of 33.0%. In 2016, Solar Star had an annual output of 1,447,006 MW h, for a capacity factor of 28.5%. In 2015, the annual output was 1,620,291 MW h for a capacity factor of 31.9%.

In 2016, Desert Sunlight had an annual output of 1,346,282 MW h, for a capacity factor of 27.9%. In 2015, the annual output was 1,286,763 MW h for a capacity factor of 26.7%. No data are available for 2017.

In 2017, Topaz had an annual output of 1,237,814 MW h, for a capacity factor of 25.7%. In 2016, Topaz had an annual output of 1,265,760 MW h, for a capacity factor of 26.3%. In 2015, the annual output was 1,301,337 MW h for a capacity factor of 27%.

While the actual cost of Solar Star and Desert Sunlight are unknown, the cost of Topaz was 2.5 b$. For what concerns other sample PV costs, the 200 MW Mount Signal 1 solar power station completed in May 2014 had a possibly strongly underestimated actualized specific cost of only 1823 $/kW (data mining of costs is much more difficult than data mining of electricity production, as they are not reported by any governmental agency). Conversely, the 266 MW Antelope Valley Solar Ranch 1 (AVSR1) completed in April 2014 had a much larger actualized specific cost of 5327 $/kW. Finally, the 290 MW Agua Caliente Solar Project completed in April 2011 had an even larger actualized specific cost of 6803 $/kW. To explain this cost, this latter project is much older than the others.

From Table 1, the PV power plants are certainly cheaper than the CSP PT installations. The costs per kW of installed capacity are much higher than the NREL estimates also for PV.

The cost per kW of installed capacity of Topaz (as written before, we do not have any data for Solar Star and Desert Sunlight) is 9% cheaper than Genesis and 29% cheaper than Mojave Solar. However, the capacity factors of Genesis and Mojave Solar are 8% better than Topaz.

While Solar Star, Desert Sunlight and Topaz, same of Genesis and Mojave Solar, are producing as expected, it must be mentioned that the present production of Solana, featuring thermal energy storage (TES), is well below the planned capacity of 43.11%. As shown in Figure 1, apart from maturity issues, the CSP with TES of Solana may permit much higher capacity factors. The latest summer monthly capacity factors for Solana exceeding 60% represent indeed the fact that the CSP technology may benefit of the significant learning curve that the PV technology had in the past, with the subsequent drastic cost reduction and possibly improved performance.

Discussion

Once the cost and reliability issues of TES will be addressed, CSP PT with TES will become competitive with PV in hypothesis of mass production, as TES theoretically permits the baseload 24/7 operation presently unaffordable with PV and batteries, in addition to much larger capacity factors. Without TES, CSP PT is already competitive with PV in hypothesis of mass production, as it delivers slightly better capacity factors. Clouds coverage of a specific location may certainly change the picture, as CSP suffer much more of clouds coverage.

While in principle the specific costs for both CSP and PV should depend on the capacity, this is not yet the case at least for CSP, that is by far a technology less mature than PV. This is clear if we consider the actualized specific costs of the 250 MW Genesis, Mojave Solar and Solana CSP plants rated at 5213, 6672 and 8258 $/kW, or the actualized specific costs of the 377 MW ISEGS and the 110 MW Crescent Dunes rated at 6084 and 9227 $/kW.

As discussed in [5], CSP plants are usually listed by installed capacity (power), and the information on the actual electricity production (energy) is mostly missing, or replaced by optimistic design figures.

In the latest NREL Annual Technology Baseline data [16], the CSP workbook is based on hypothetical power towers (ST) plants with direct two-tank 10 hours TES combined with a steam-Rankine power cycle. These power plants are expected to deliver capacity factors in locations of insulation class 1 (Abilene regional), 3 (Las Vegas, NV) and 5 (Dagget, CA) respectively 42%, 56% and 59%, corresponding to an annual electricity production per unit capacity of 3679, 4906 and 5168 kW h/kW. If we look at the operational CSP power stations of capacity above even only 50 MW in the world, this list includes 34 stations, 31 of them are PT, 1 is Fresnel reflector (the 125 MW Dhursar power station in India), and only 2 of them are ST. These two power stations are the 377 MW ISEGS and the 110 MW Crescent Dunes analyzed in the prior section. The ISEGS CSP ST plant has no TES but NG combustion to achieve about 20% capacity factors with the help of NG combustion. The Crescent Dunes CSP ST with 10 hours TES is therefore the only plant on Earth featuring something like the NREL current technology. This power plant does not deliver capacity factor more than 50%, but at the best less than 15%.

In terms of cost, Ref. [16] reports a capacity specific capital expenditure (CAPEX) of 8133 $/kW for 2015, that is then reducing to 7765/kW for 2016, $7407 $/kW for 2017 and $7039 $/kW for 2018, same for class 1, 3 or 5 insulation locations, and low, medium and high scenarios. After 2018, the CAPEX is supposed to vary to 2050 in the low and medium scenarios values only, but not across the class, up to 2805 and 5285 $/kW for 2050. As it is shown in Table 1, the actual cost of Crescent Dunes is 9227 $/kW if actualized to 2017.

This contribution does not discuss the operating and maintenance costs. The fixed operation and maintenance expenses of 66 $/kW-year for every year 2015 to 2050 of [16], and the variable operation and maintenance expenses of only 4 $/MWh for every year 2015 to 2050, are largely underrated. Crescent Dunes has requested extensive and lengthy maintenance to bring back to production the power plant after a major TES failure with costs unknown, but certainly largely exceeding the 4 $/MWh. The sources of [16] for CSP are other NREL works, such as [18] for the available capacity (GW), [17] for the net capacity factors, and finally [19] for the overnight capital cost and fixed and variable operating expenses.

The levelized cost of energy $/MWh of [16] are very optimistic for CSP.

Regarding the absolute value of the capacity factors, it must be noted that the design capacity factor depends on the relative sizing of solar field and power block, within the technological constraints, taking into consideration the strongly variable sun energy over the year. If for example the solar field is sized to generate twice the flowrate of hot fluid needed to run the power plant at nameplate capacity at the autumnal equinox, the average capacity factor of the operation during typical summer, winter and shoulder (spring/autumn) conditions will be larger than for a smaller solar field. However, the cost will be much higher. Therefore, what is important in Table 1 and Figure 1, is the difference between design and actual capacity factors more than the absolute value of the capacity factor, or the consideration of both capacity factor and capacity specific cost.

Regarding solar utility scale PV, [16] considers net capacity factors of 14%, 20% and 28%. From Table 1, even slightly higher capacity factors are delivered, for example by Solar Star. In terms of cost, [16] reports a capacity specific capital expenditure (CAPEX) of 2014 $/kW independent of the net capacity factor class for 2015, reducing to 1513 $/kW for 2016. After 2016, the CAPEX is supposed to vary to 2050 in the low and medium scenarios values only, but not across the class, up to 403 and 726 $/kW for 2050. Topaz had an actualized construction cost of 4739 $/kW. While the fixed operation and maintenance expenses are 13 $/kW-yr, there are no variable operation and maintenance expenses. The sources of [16] for PV are other NREL works except one. [18] is used for the available capacity (GW), [17] for the net capacity factors, [20] for the overnight capital cost, [21] for the fixed operating expenses and [22] for the variable operating expenses.

The levelized cost of energy $/MWh of [16] are still optimistic, but certainly more approximate than for CSP.

The experience of countries like China, which is pioneer in mass production of PV systems and thus their cost reduction, may have significant impact on the cost of electricity production by CSP. A mass production of a CSP system, possibly in the more established PT technology, without or even with a TES properly designed, may pave the way to a more relevant contribution of the CSP technology to the global energy mix, in the United States and elsewhere. As soon as a simple but efficient and reliable CSP mass product could be defined, mass production may certainly drastically reduce energy production costs.

The emphasis of this work is mainly on the electricity production and its cost based on United States data, a country with a well-developed electricity production and distribution system, but with a relevant fossil fuels contribution. Developing counties, where the solar is even more abundant, but the electricity production and distribution system is not well developed, would have even more stringent requirements of affordability. For developing countries, CSP must be made even more affordable, and it must be carefully integrated with the other energy sources, to become a cost-effective contributor to the growing energy needs. Cost-effectiveness must translate in certainty of production at costs smaller, or comparable, with conventional or renewables alternatives.

Not discussed in this paper is the role of subsidy. Many countries, for example India, may certainly support CSP technologies through subsidization. This support may lead to a significant reduction of the overall cost of the electricity production, albeit artificial. In the long run, the uptake of an energy conversion technology in general, may only be based on better fundamentals. Support of further research and development is more needed than subsidy of substandard technologies. Once a technology is made competitive, there is no need of subsidy.

Not discussed is the integration of CSP with other renewable energy technologies, such as wind. Similarly, not discussed even more promising is the integration of CSP with natural gas combustion, biomass combustion, or waste-to-heat plants, in combined cycle and cogeneration plants. The integration of different renewable and conventional energy technologies may provide much better results than the focus on a single technology, especially in a decadal time window.

Integration of CSP with combustion fuels, conventional, renewable or alternative, may also address issues such as temporary cloud coverage otherwise drastically reducing the appeal of CSP in many geographical areas where the sun is abundant, but the skies are not always clear.

Conclusions

In the United States, CSP PT plants have largest capacity factors than CSP ST plants. Capacity factors of CSP PT plants, without TES, solar only, such as Genesis or Mojave Solar Project, are about 30%, close to their design values.

With 6 hours of TES, the capacity factors of the Solana plant, CSP PT, solar only, are up to 33%, however much lower than the design value of 43%. The CSP ST plants of Ivanpah, without TES but with boost by NG combustion, and Crescent Dunes, with 10 hours TES, solar only, have delivered so far much less than their planned capacity factors, and much less than the capacity factors delivered by the contemporary CSP PT plants.

PV plants have capacity factors 1–2% lower than the CSP PT plants, close to their design values.

Without TES, actualized construction costs for CSP PT are 5213–6672 \$/kW and 6084 \$/kW for CSP ST. With TES, the actualized costs of PT and ST increase to 8258 \$/kW and 9227 \$/kW respectively.

Actualized construction costs are about 4739 \$/kW for PV.

While there may be a significant CSP learning rate soon, there has been so far, no such a major, generalized, and uniform improvement of CSP over the last 5 years.

PV have grown considerably during the last few years, thanks to a well-established technology and a drastic reduction of costs following mass production. CSP still lacks a consolidated technology to be mass produced.

Presently, CSP PT without any TES has already the numbers to become competitive with solar PV once refined and mass produced, but it is being downplayed by the idea CSP ST with enhanced TES is superior. While CSP with TES may provide highly desirable 24/7 base load, or on demand electricity production, it requires further research and development. Similarly, the ST has theoretical advantages versus PT albeit difficult to translate in actual advantages within the constraints of cost and reliability of operation over prolonged time frames.

Conflicts of interest

The author declares no conflict of interest.

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References

[1] H.L. Zhang, J. Baeyens, J. Degrève, G. Cacères, Renew. Sustain. Energy Rev. 22 (2013) 466–481.
[2] M. Liu, N.S. Tay, S. Bell, M. Belusko, R. Jacob, G. Will, W. Saman, F. Bruno, Renew. Sustain. Energy Rev. 53 (2016) 1411–1432.
[3] D.A. Baharoon, H.A. Rahman, W.Z.W. Omar, S.O. Fadhl, Renew. Sustain. Energy Rev. 41 (2015) 996–1027.
[4] A. Boretti, in: L. Dai, R.N. Jazar (Eds.), Concentrated Solar Power Plants Capacity Factors: A Review, Nonlinear Approaches in Engineering Applications Energy: Vibrations, and Modern Applications, Springer, New York, 2017, http://dx.doi.org/10.1007/978-3-319-69480-1_2.
[5] A. Boretti, S. Castelletto, S. Al-Zubaidy, Nonlinear Eng. (2017), http://dx.doi.org/10.20944/preprints201710.0027.v2 (Online: 17.11.17/in press).
[6] J. Lilliestam, M. Labordena, A. Patt, S. Pfenninger, Nat. Energy 2 (2017) 17094.
[7] K. Williges, J. Lilliestam, A. Patt, Energy Policy 38 (2010) 3089–3097.
[8] L. Neij, Energy Policy 36 (2008) 2200–2211.
[9] P. Viehbahn, Y. Lechon, F. Trieb, Energy Policy 39 (2011) 4420–4430.
[10] Renewable Energy Policy Network for the 21st Century (REN21), Renewables Global Status Report 2017, 2017. Available at: www.ren21.net/wp-content/uploads/2017/06/17-8399_GSR_2017_Full_Report_0621_Opt.pdf (accessed 09.11.17).
[11] International Energy Agency, Key World Energy Statistics, 2016, Available at:, 2016 (accessed 09.11.17). www.iea.org/publications/freepublications/publication/KeyWorld2016.pdf.
[12] Energy Information Administration, Electricity Data Browser – Net Generation for All Sectors – United States. Available at: www.eia.gov/electricity/data/browser (accessed 09.11.17).
[13] National Renewable Energy Laboratory, Concentrating Solar Power Projects by Project Name. Available at: www.nrel.gov/csp/solarpaces/by_project.cfm (accessed 09.11.17).
[14] Energy Information Administration, Electricity Data Browser – Plant Level Data. Available at: www.eia.gov/electricity/data/browser/ (accessed 09.11.17).
[15] BP, Energy Economics, Statistical Review, Renewable Energy, Solar Energy. www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/renewable-energy/solar-energy.html (accessed 09.11.17).

[16] NREL (National Renewable Energy Laboratory), 2017 Annual Technology Baseline, National Renewable Energy Laboratory, Golden, CO. www.nrel.gov/analysis/data_tech_baseline.html (accessed 05.04.18).

[17] A. Lopez, B. Roberts, D. Heimiller, N. Blair, G. Porro, US Renewable Energy Technical Potentials: A GIS-Based Analysis, Contract, 303, 275-3000, Available at:, 2012 (accessed 05.04.18) www.nrel.gov/docs/fy12osti/51946.pdf.

[18] W. Short, P. Sullivan, T. Mai, M. Mowers, C. Uriarte, N. Blair, D. Heimiller, A. Martinez, Regional Energy Deployment System (ReEDS), Available at:, National Renewable Energy Laboratory (NREL), Golden, CO, 2011 (accessed 05.04.18) www.nrel.gov/docs/fy12osti/51946.pdf.

[19] P. Kurup, C. Turchi, Parabolic Trough Collector Cost Update for the System Advisor Model (SAM). NREL Report No. TP-6A20-65228, Available at:, 2015 (accessed 05.04.18) https://www.nrel.gov/docs/fy16osti/65228.pdf.

[20] D. Feldman, G. Barbose, R. Margolis, M. Bolinger, D. Chung, R. Fu, J. Seel, C. Davidson, N. Darghouth, R. Wiser, Photovoltaic System Pricing Trends. Historical, Recent, and Near-Term Projections (No. NREL/PR-6A20-64898), National Renewable Energy Lab. (NREL), Golden, CO (United States), 2015, Available at: www.nrel.gov/docs/fy15osti/64898.pdf (accessed 05.04.18).

[21] M. Bolinger, J. Seel, Utility-Scale Solar 2014: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States (No. LBNL-1000917), Available at:, Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States), 2015 (accessed 05.04.18) eta-publications.lbl.gov/sites/default/files/lbnl-1000917.pdf.

[22] United States Department of Energy, SunShot Vision Study: February 2012. NREL Report No. BK5200-47927. Available at: www1.eere.energy.gov/solar/pdfs/47927.pdf (accessed 05.04.18).