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ORIGINAL RESEARCH ARTICLE

Concentrating solar power for less than USD 0.07 per kWh: finally the breakthrough?

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The cheap power purchase agreements (PPAs) for two recent concentrating solar power (CSP) projects in Australia (Aurora) and Dubai (DEWA IV) raise questions of how such low costs can be achieved, and whether this could mark the commercial breakthrough of this technology. Here, we investigate these projects with the information available, and seek reasons for the low PPAs. Both projects have low technology costs – which are prerequisites but insufficient as explanations for the low bids. For Aurora, a key explanation is its business model that allows it to sell power outside the PPA, during high-price times when the sun sets and the growing PV fleet goes offline, revealing the market value of CSP. For DEWA IV, a key factor is its extraordinarily long PPA duration, but we expect that it also has very low financing costs. We conclude that both projects can probably be replicated, either in places with an increasing PV fleet and strong ''duck curve'' problems (replicating Aurora) or in places with low policy risks and access to cheap capital (replicating DEWA IV); such places could include the US, Southern Europe, or the Gulf region.

Introduction

In August and September 2017, two new power plant deals caused a stir of amazement across the concentrating solar power (CSP) community. In Australia, SolarReserve (USA) signed a 20-year power purchase agreement (PPA) with the South Australian government to supply up to 125 MW power from the 150 MW tower station *Aurora* at a maximum price of USD 0.06 per kWh (AUD 0.078 per kWh) [1,2]. In Dubai, a consortium of ACWA (Saudi Arabia) and Shanghai Power (China) was the preferred bidder for the 700 MW combined tower and trough station *DEWA IV*, at a PPA price of USD 0.073 per kWh (AED 0.27 per kWh) [3–5].

Not only are these projects important as being the first large CSP station in sun-blessed Australia (Aurora) and the world's largest CSP station (DEWA IV): the PPAs paid for these projects are the by far lowest – roughly half of the next lowest – in the history of CSP [6], also [7]. Hence, voices have been heard that this marks the breakthrough of CSP: at these costs, dispatchable solar thermal power could step out of its niche and conquer the markets, offering a renewable source of dispatchable power and paving the way for renewable power systems across the world [8]. Indeed, if the plants perform as the bids promise, and if these bids can be generalised to other markets, these projects could mark a turning point for CSP. Here, we analyse the techno-economics of the two projects, as far as details are known, and seek the reasons for the low prices and whether these reasons are generalisable, or if there are project-specific factors that are not easily transferable to other projects and countries.

What we know about Aurora and DEWA IV

At the time of writing, in May 2018, not many details are known about these projects as they are both in early realisation phases: the ground-breaking ceremony for DEWA IV took place in mid-March 2018 [9], whereas Aurora recently received the necessary permits [10] and construction is expected to start in mid-2018. All data is thus uncertain and may change as the projects progress. However, some key data are known (see Table 1) and allow for a rough analysis and reverse engineering of the economic cases of these projects. In this, we speculate and test possibilities for explaining

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TABLE 1

Key data for the Aurora and DEWA IV CSP stations. Data in italic are inferred from performance of other similar CSP stations. *Sources*: **[1–5,26,23,27,12].**

	Size MW	Storage	DNI (kWh/m^2/year)	Investment cost (million)	Spec. inv. cost (USD/kW)	Exp. gen. (GWh/year)/ load factor	PPA (USD/kWh) Duration
Aurora	150	8 h	2400	650 AUD (500 USD)	3300	495/38%	0.061 (for $\leq$125 MW) 20 years
DEWA IV	700 (100 tower; 3 × 200 trough)	Tower: 15 h Trough: 10 h	2000	14,200 AED (3870 USD)	*5500*	*3500/56%*	0.073 (for 4 pm–10 am) 35 years

the costs based on publicly available information, but we do not know the business cases of the two projects and we have not discussed our analysis with the involved companies.

Importantly, we do not know the expected generation of DEWA IV, and we infer load factors based on similar projects. Towers with similar storage sizes can reach 55% (e.g. Redstone, South Africa, 12 h; under development) to 65% (e.g. Golmud, China, 15 h; under construction) load factors; whereas trough plants with 10 hours storage may achieve 50–55% (e.g. Bokpoort, South Africa, 9.3 h). Assuming that DEWA IV achieves the best of these load factors, its aggregated load factor would be about 56%, giving an expected generation of some 3500 GWh/year.

How can these projects achieve such low costs?

Here, we investigate the key parameters – solar resource, expected generation, technology cost, financing cost, and the terms of the PPA – for their likely impact on costs of the two projects – both the known factors, which we relate to past CSP developments, and the unknown, which we investigate for their possible impact on cost. The LCOE is calculated as

$$\mathrm{LCOE} = \sum_{t=1}^{n} \frac{I_t + O\&M_t/(1+r)^t}{E_t/(1+r)^t},$$

where I_t is the investment expenditures in year t, assuming the same expenditures each year over the lifetime n (standard assumption: 25 years; for Aurora and DEWA IV, we assume the PPA duration as their lifetime), $O\&M_t$ are the operation costs (1.5% of the investment cost per year), E_t is the expected yearly generation, and r is the weighted cost of capital[1] (5%, except where stated otherwise) [6,11].

Aurora

Despite being located in Australia, which has among the best solar resources in the world, the solar resource at the Aurora site is good but not exceptional: the direct normal irradiation (DNI) is about 2400 kWh/m^2/year, which is only 10% higher than the average of all CSP projects in the last 5 years [7]. The expected generation of Aurora is not exceptionally high, and is identical to Noor III (Morocco, 7 h storage) despite Noor's smaller storage and worse solar resource. Thus, neither of these two factors can help explain the low PPA of Aurora.

The technology cost of towers of similar configurations have decreased by 40% in the last three years, from USD 9200 per kW (Crescent Dunes, USA, 2015; 10 h storage) to USD 5750 (Noor III, Morocco, under construction, 2018; 7 h storage). Aurora continues that trend (see Figure 1), its USD 3300 per kW marking the currently last point of a 60% investment cost reduction of this station configuration over 5 years; three similarly configured Chinese solar towers under construction fit almost perfectly in this trend as well. It seems that others (e.g. SunCan in China) are able to build at similar cost, and that the investment cost reduction pace necessary for Aurora is both realistic and replicable; furthermore, other CSP segments (e.g. troughs without storage, 2011–2014) have seen similarly fast cost reductions in the past [6].

The low technology cost however only explains parts of the low PPA: with the figures from SolarReserve and standard assumptions as described above, the LCOE would be USD 0.096 per kWh – 3.5 cents higher than the PPA. Hence, at least one of two things must come into play: very low capital costs, and/or additional revenue beyond the PPA. Both factors are known to be present.

First, SolarReserve has received a AUD 110 million government equity loan, covering 1/6 of the total investment [12]. This should lower the total financing cost, but probably not very far below the already low 5% we assumed above: hence, the additional revenues must be significant to the business case. A minor contribution towards cost-competitiveness is the deal with OzMining to share the construction and operation cost of the 35 km transmission line signed in March 2018 [13].

Second, the PPA covers only 125 MW of Aurora's 150 MW capacity: SolarReserve can sell the remaining capacity on the power market. The South Australian demand curve is relatively flat during daytime, with a strong peak between 17:00 and 21:00, just as the sun sets will become. With rapidly increasing solar PV shares during daytime, this peak become more pronounced, requiring the other generators to ramp up both far and fast as the sun sets and demand soars – the system has an increasing "duck curve" problem [14]. It is thus likely that the daytime electricity price will be low if the PV expansion continues, affecting the profitability of generators – except Aurora, which has a fixed PPA price for these times. With its 8 hours of storage, Aurora can maximise its output under "favourable conditions, such as in the evening" [2] and sell its 25 MW capacity not under the PPA during peak time prices. SolarReserve may speculate on scarcity prices during these times [15], and possibly on profiting from being able to ramp up faster than most fossil fuel stations when the sun sets and PV generation ceases. To us, this seems to be a good bet: South Australian peak prices are usually above AUD 100 per MWh (USD 75 per MWh), often reach twice that, and occasionally go up to 1000 or several thousand AUD per MWh, such as the peak price of AUD 8000 per MWh in February 2018 [16,17]. In May 2018, SolarReserve sought permission to augment Aurora by

[1] We use the WACC and the discount rate as synonyms.

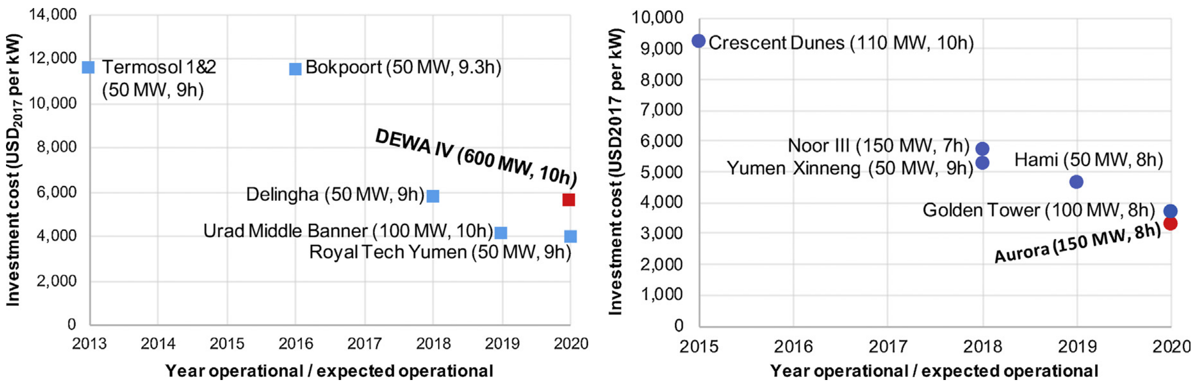

FIGURE 1

Investment costs of Aurora (left) and DEWA IV (right; only the trough part) compared to the global trend of similar CSP stations. The figure for DEWA is estimated based on assumed costs for the tower part of USD 5000 per kW. All stations except DEWA IV, Aurora and Golden Tower are operational or under construction. Data: [7].

70 MW PV capacity [18]; although the decision has not been made at the time of writing, we interpret this as a further measure to increase the possibility to store heat and ramp up during peak time.

In sum, the low PPA of Aurora can be explained in part by its low technology cost and advantageous financing conditions. The key reason, we suspect, is the flexibility offered by their hybrid PPA model: by selling a part of the capacity under a fixed-price PPA, SolarReserve can get a steady and low-risk revenue stream and then seek to recover the remainder of their costs by speculating on very high peak prices for a few hours per day after sunset.

DEWA IV

The DEWA IV project has a 10% lower solar resource than the CSP stations built in the last 5 years or currently under construction [7]. Hence, a particularly good solar resource is not the reason for the low cost – it achieves low costs *despite* the low DNI in Dubai.

We do not know the investment costs of the tower and trough parts separately but believe that they are low compared to other projects. If the 100 MW tower follows the Crescent Dunes-Noor III trend, its costs should be below USD 5000 per kW (Aurora presents much lower costs, USD 3300 per kW). In this case, the 3 × 200 MW trough parts would cost around USD 5600 per kW, which is much lower than ACWA's most recent and quite similar trough station Bokpoort (South Africa) despite the much worse solar resource in Dubai, but similar to Chinese projects under construction (see Figure 1). Reasons for this low cost could include the very large station (700 MW is twice the second largest operating CSP station, Ivanpah, US), which leads to economies of scale, and opportunities to profit from cheap component manufacturing by the Chinese project partners. Indeed, the EPC is the Chinese company Shanghai Electric, which would support this hypothesis, but the parabolic trough solar field will be built by Spanish Abengoa and the tower solar field by the US company Brightsource [19–21].

Using standard assumptions and the highly uncertain load factor of 56% (see above), we estimate the LCOE of DEWA IV to be USD 0.084 per kWh, almost 1.5 cents per kWh higher than the PPA. This would be the lowest LCOE of any existing CSP station or under construction (except Aurora), due to its extraordinarily long PPA duration of 35 years: with a more standard 20-year PPA, the LCOE would be USD 0.106 per kWh, which is about the same as declared by many Chinese stations under construction [7]. The long PPA duration thus directly reduces the LCOE by some 2 cents per kWh; in addition, it could help de-risking the investment by giving a very long-term perspective for investors, thus reducing the cost of capital.

Hence, to be profitable, DEWA IV must have extraordinary financing conditions, and/or additional streams of revenue. One such source of revenue could be additional generation during daytime (the PPA is for power generated between 4 pm–10 am), if sufficient heat can be collected for the night-time operation. It could also be an escalating PPA over time, or inflation and/or currency fluctuation adjustments; we have no information whether this is the case, but it would change the economics of DEWA IV substantially. In the following, we assume that escalation measures are not present.

Keeping all other things constant, our results suggest that DEWA IV would need a WACC of 3% or less to remain below the PPA. For other solar energy projects in Dubai, debt costs around 5% have been quoted [22]: if ACWA's statement of a 30:70 equity:debt ratio is true [23], that interest rate would require a negative return on equity to reach 3% WACC, which is unlikely. If we instead assume an interest rate of 2.5%, the cost of equity can be up to 4%, which is still low, but reasonable if there is a perception of very low policy, off-taker and technology risks. Arguably, all three can apply in Dubai, offering a plausible explanation to a large part of the low cost of DEWA IV, but not why the ACWA bid was so much lower than other bids: the risk environment in Dubai is similar for all bidders.

Often, claims are heard that ACWA benefits from Saudi state money [23], allowing them to access cheaper capital than its competitors; also Chinese companies are rumoured to be backed by state institutions, raising the credit-worthiness of projects. We do not know whether any of the involved companies are state-backed and receive preferential finance conditions, but we expect that they do not. We do however know that Chinese banks provide most or all of the external finance of DEWA IV, and that an unknown share of the finance comes from Chinese state-backed Silk Road Fund [9,24].

However, with more or less close state ties and being financially very strong, the winning Saudi-Chinese DEWA IV consortium may not need, or get very good conditions, for bank guarantees to cover the EPC production guarantee. If this is the case, it could give them a cost advantage of several tens of millions of dollars compared to other bidders. Even so, however, this is not a main explanation for the low price.

In sum, we find that DEWA IV has low technology cost, compensating for the comparatively weak solar resource. We believe that there are two additional key reasons that enable the low PPA of the DEWA IV project: an extraordinarily long PPA duration of 35 years, and very good financing conditions and production guarantee conditions.

Discussion and conclusion

In both cases, we could identify specific reasons for the very low PPAs. For both projects, the low – for Aurora very low – technology costs are key explanatory factors: if these prove realistic and attainable also in other places, there is good reason to be optimistic about a continued expansion of CSP. As none of the projects happen in a low-cost environment, there is reason to believe that these costs could be replicated elsewhere: similarly low bids have been submitted in Chile [25], and the investment costs of both stations are similar to ongoing projects in China. In both cases, however, even the low technology cost cannot fully explain the low price: with standard-low assumptions, both would have LCOEs exceeding the PPAs, so that additional factors must play a role.

Aurora is supported by 1/6 concessional finance, which lowers its financing cost. In particular, however, SolarReserve has exempted a part of the capacity of Aurora from the PPA, allowing it to sell electricity on the market during peak time: with increasing PV generation, the duck curve of South Australia will become increasingly prominent, and market prices around sundown – which coincides with the demand peak – can be expected to increase sharply. Thus, speculatively, Aurora can supply this high-price market niche *and* its PPA commitment; the PPA is thus a sort of hedge, whereas the key cost recovery would happen during peak times. If this explanation holds, it would be one of the first cases where the market value of CSP, as opposed to its mere cost, is reflected in the business model of a project.

For DEWA IV, in contrast, the key factor is the extraordinarily long PPA duration of 35 years, which strongly decreases the LCOE. Further, DEWA IV must profit from exceptionally good financing conditions, as the total WACC cannot exceed 3% for an LCOE below the PPA level: for low-risk investments in stable environments, and in a low-interest world, this seems low, but perhaps not wholly unfeasible.

In sum, our rough and somewhat speculative reverse-engineering analysis of costs shows that there are specific factors that enable the very low PPA bids of Aurora and DEWA IV: the existence of a strong ''duck curve'' and the exemption of some capacity from the PPA (Aurora) and a very long PPA duration and access to very cheap finance (DEWA IV). These conditions may to some extent be replicated elsewhere: strong duck curves exist and are expected to gain importance, for example, in south-western US or Australia, and both these regions are stable, low-risk environments where access to (relatively) cheap capital could be possible. Cheap capital is available in many economically and politically stable regions, including Europe, where interest rates remain at all-time lows, or in the Middle East. In addition, one should keep in mind that the solar resource in particular in Dubai is far from excellent – other countries, like Chile or South Africa, have up to 40% higher insolation, which could allow for even lower PPAs, if the financial risk can be handled to give good conditions. Overall, if Aurora and DEWA IV are built on time and on budget, thereby demonstrating that such low costs are both feasible and sustainable, these enabling factors may be generalised to other places: if this happens, these two projects may indeed mark the break-through point of concentrating solar power as a commercially viable technology for dispatchable renewable electricity.

Conflicts of interest

None declared.

Acknowledgements

Johan Lilliestam is funded by the Horizon2020 project MUSTEC (Market uptake of solar thermal electricity through cooperation, contract number 764626). The European Commission was not involved in any step of the work leading to this article.

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