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Cost of dispatchable electricity from concentrated solar power, solar tower plants, with 10 hours' molten salt thermal energy storage

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Abstract. While there is a consensus that concentrated solar power solar tower plants with thermal energy storage 10 hours may permit the production of dispatchable electricity at 6 c/kWh, without a single plant utility size produced and operated featuring this technology at this cost, the recent experience of Crescent Dunes has clearly shown that this is not the case. Crescent Dunes started operation in October 2015 demonstrating since the very beginning the lack of maturity of this specific technology, with lack of production or no production at all, every single month since then. As the 110 MW plant of cost about 1 billion $ US has been shut down after less than 4 years of operation, and a total production of only 418,849 MWh, that is less than the 500,000 MWh expected every year for 25 years, this translate in a total cost, excluding repairs and maintenance costs incurred in the 4 years, of 2.38 $ per kWh of unpredictable electricity. This experience suggests that every estimation of costs and performances should be based on data of plants built and operated, and to avoid the use of models not yet validated to predict performances of novel plants. There is a mature solar thermal technology, and this is the parabolic trough.

1. Introduction

Surprisingly NREL [1] suggests as the best option presently available for Concentrated Solar Power the Solar Tower technology with 10 hours of two tanks thermal energy storage by molten salt. They candidly state that Crescent Dunes was the first large molten-salt power tower plant in the United States. It was commissioned in 2015 with a reported installed CAPEX of 8.96 c US$/kW. They forget to mention that Crescent Dunes was also the first and only plant utility size of this kind built in the world and that Crescent Dunes never operated as expected during the lifetime, with many months without production, and annual production well below 25% of the expected, every year since commissioning, for a delivered capacity factor of 13% vs. an expected capacity factor of 52%.

Based on their "experts" surveys, but as explained in [2], [3], [4] and [5] no real plant data, NREL claims that this specific technology had a cost in 2017 of 7,800 US$/kW, Fig,.1. a. As Crescent Dunes had a cost in 2015 of 0.975 billion US$, corresponding to 8,864 US$/kW, this number was already largely optimistic. Furthermore, NREL was suggesting a large reduction of costs since 2017 with the CAPEX of 2020 further down to 6,500 US$/kW. This estimation was turning from optimistic to outrageous once also the capacity factor was considered. CAPEX is the cost per installed capacity (nominal power). The capacity factor is the ratio of actual generating power to nominal power. As the resource is not constant, capacity factors are very far from unity. Similarly based on "experts" opinions, NREL is providing the false representation that the specific technology of Concentrated Solar Power the Solar Tower technology with 10 hours of two tanks thermal energy storage by molten salt was delivering in 2017 capacity factors from 50% to 64%, Fig.1.bThis range is attributed to different resources. A fair resource is Abilene, Texas, with about 6.16 kWh/^{m2}/day. A good resource is Phoenix, Arizona, with 7.26 kWh/m^2/day. An excellent resource is finally Daggett, California: 7.65 kWh/m^2/day. Now, Tonopah, Nevada where Crescent Dunes is located is much closer to an excellent resource location than a good resource location, with about 7.51 kWh/m^2/day, and Crescent Dunes of much larger cost was not working at above 60%, and not even at the planned 52%, but at about ¼ of the 52% or 13%.

As explained in [2], [3], [4], [5] there was, and there is no reason that an immature technology such as concentrated solar power solar tower with thermal energy storage could work at such unbelievably high capacity factors with the cost of production so low. By oversizing the solar field and the thermal energy storage there is certainly the opportunity to have much better capacity factors working with a turbine that is much smaller than the optimal, but then the costs go up significantly.

According to [1], Fig.1 an and b, this specific technology cost today 30% less than the cost of the only sample in the population, while it produces 20% more

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than the electricity planned for the only sample in the population, or also almost 400% more than the electricity delivered by the same only sample in the population. While it is certainly wrong to work with statistical samples of one, it is even worse to work with statistical samples of zero negating the existence of the one. Additionally, the delivery of the small amount of energy produced was also unpredictable, as the plant was not even working for several months every year.

As discussed in [2], [3], [4], and [5], in the much better performing, simpler and more established parabolic trough design, without thermal energy storage it is possible to achieve much better real-world capacity factors approaching 30% (Genesis, Mojave, 28.5% in the best year so far) spending less than Crescent Dunes, or with a smaller 6 hours' thermal energy storage real-world capacity factors approaching 40% (Solana, 36.5% in the best year so far).

The one and only "world largest" concentrated solar power solar tower with thermal energy storage of Crescent Dunes got burst [6], [7], [8]. This follows the cancellation of projects by the same developer for the same technology worldwide. This has not prompted yet NREL to revise their technology forecast for concentrated solar power that is simply wrong, underrating the much better performing parabolic trough that is not considered at all, and overrating what has been so far a failure technology in the real world. Here we show as Crescent Dunes performed every month in the real world, and how Crescent Dunes should have performed if the SAM model for the plant could have been reliable.

2. Method

We analyze the electricity production by Crescent Dunes by using the data provided by the US EIA [9]. We also use the SAM model [10] to compute the performance of a concentrated solar power solar tower plant of characteristics similar to Crescent Dunes located in Tonopah, NV.

Then, we attempt validation of the molten salt solar tower model in the same SAM Version 2018.11.11, updated to Revision 4, SSC 209. Also, in this case, we compare the monthly average results of experiments and simulations for the average year. In this case, there is one solar facility only to consider. The world's largest Concentrating Solar Power solar tower with thermal energy storage, the 110 MW Crescent Dunes is also considered. Regarding the molten salt solar tower module, this is a semi-empirical model, less physically grounded than the "physical" parabolic trough model, and much more challenging. A sketch of a solar tower plant from SAM is shown in Fig. 2.

The central receiver system Concentrating Solar Power consists of a solar field of heliostats, a receiver atop of a central tall tower, the power block, and the optional thermal energy storage. The solar field is made up of the many heliostats. They are flat, sun-tracking mirrors that focus the solar DNI onto the receiver. Thermal energy is collected by the heat transfer fluid heated in the receiver and delivered to the power block. Tracking is performed on two axes. The design is much more complicated vs. the parabolic trough collectors. It is more sensitive to wind-induced forces, and other environmental variables, and it does not produce, nor maintain, the much more challenging performances very easily. The distance between the heliostats and the central receiver is very large compared to the short distance of the parabolic trough mirror and collector. Every heliostat needs very careful and demanding control and misalignments are everything but uncommon. As an advantage, the power cycle is typically medium temperature steam, Rankine cycle, with typically also a slightly higher pressure to the turbine. Receiver height and geometry, the geometry of heliostats and their layout in the solar field, and their optical, thermal and heat transfer properties dictate the operation of the molten salt solar tower system. The receiver model is based on semi-empirical equations. The receiver model is one of the weakest parts of the molten salt solar tower system model, as semi-empirical relations are dependent on the missing good experimental data. The receiver is made up of several panels. Each panel consists of a set of parallel tubes in a common heat transfer fluid header. The heat transfer fluid flows through each panel in a serpentine. Despite the number of solar tower plants built and operated is minimal, there are many different options available for the heat transfer fluid flow pattern through the receiver, such as a full circle or split path around the receiver, or split pass single cross-over.

The major difference vs the parabolic trough model in SAM is the representation of the solar field and the receiver, which is definitively much more challenging in the molten salt solar tower model. Being semi-empirical, it requires more experimental support to work properly. Having less physical background, it may only work in a limited number of cases. If the real-world data of parabolic trough plants are limited, the real-world data of solar tower plants are even in shorter supply. Also considering that the modeling of a solar tower system is much more challenging than a parabolic trough system, and the construction and operation of a solar tower system is much more challenging than the construction and operation of a parabolic trough system, the molten salt solar tower model should not be expected to work very well, being surely less accurate than the "physical" parabolic trough model.

The molten salt solar tower model is much more complicated than the "physical" parabolic trough model, it presents a larger number of variants, it is less physical and more empirical, it necessitates a much larger number of good experimental data to work well over a limited number of circumstances.

3. Results

Table 1 presents the capacity factor in Crescent Dunes. Data are from [9]. By taking for Crescent Dunes a capacity factor of 52% and a CAPEX equal to the actual construction cost of 975 million US$ divided by a capacity of 110 MW, or 8863 $/kW this could have translated into a production of 501,072 MWh per year that repeated over 25 years of life of the plant, could have translated in a cost of 0.0778 US$/kWh. By considering a fixed O&M cost of 66 $/kW/yr. [1], to be added to the CAPEX, this could have brought the cost per kWh to 0.0923 US$/kWh. As the Crescent Dunes plant has been shut down after less than 4 years of operation, having produced only 418,849 MWh, without considering the O&M costs, and the repairs incurred to rectify damages to the plant, the US taxpayers thus paid unpredictable electricity from the sun 2.38 US$/kWh.

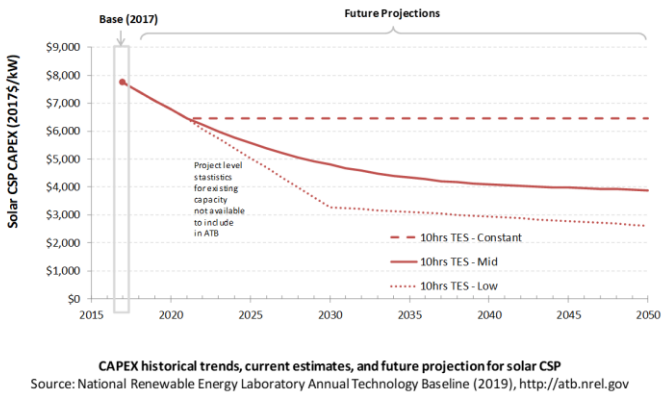
A CAPEX reduced to 6500 $/kW to deliver a much better capacity factor of 62% could have translated into a construction cost of 715 million $US, and a cost per kWh of 0.0479 US$/kWh without O&M costs, and 0.0600 US$/kWh. These 6 c per kWh were the numbers then circulated in the peer review commenting the power purchase agreement for a similar plant by the same developer in Port Augusta, canceled shortly afterward for lack of any investor believing the numbers [5].

Fig.2 presents, in a the expected performances of the plant over a typical day of every month in the typical year for which the resource and weather parameters are provided. Fig. 2 then presents in b the comparison of the measured and predicted performances. A plant of characteristic similar to Crescent Dunes could have performed even better of the 52% expected annual average capacity factor, at 54%, if the different components of the plant could have delivered as modeled in SAM.

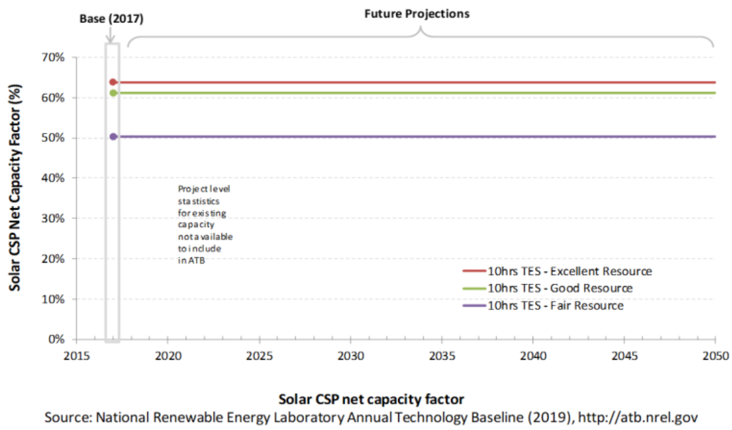
As SAM is a system of semi-empirical models, it is not possible to expect from SAM a good accuracy if the different models are not carefully tuned vs. the experiments. Here comes the problem with solar towers with thermal energy storage. Until the time high-frequency data – 1 minute or less – will be made available for both the resource and the weather, as well as for all the components of the solar plant, up to the turbine and the generator, for a plant built and operated, attempted of a never validated software will never deliver results that could be trusted.

Table 1 – Measured capacity factor for Crescent Dunes. Data are from [9]

Year	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*average*
2015.										0.021	0.023	0.000	**0.015**
2016	0.018	0.123	0.087	0.027	0.140	0.078	0.312	0.345	0.385	0.066	0.000	0.000	**0.132**
2017	0.000	0.000	0.000	0.000	0.000	0.000	0.115	0.112	0.173	0.113	0.006	0.000	**0.043**
2018	0.010	0.070	0.072	0.174	0.130	0.422	0.290	0.405	0.399	0.260	0.103	0.100	**0.203**
2019	0.157	0.195	0.245	0.035	0.000	0.000	0.000	0.000	0.000	0.000	0.000		**0.058**
												average	**0.104**



a



b

Fig. 1 – CAPEX and capacity factor of concentrated solar power solar tower with 10 hours of thermal energy storage. Credit NREL.

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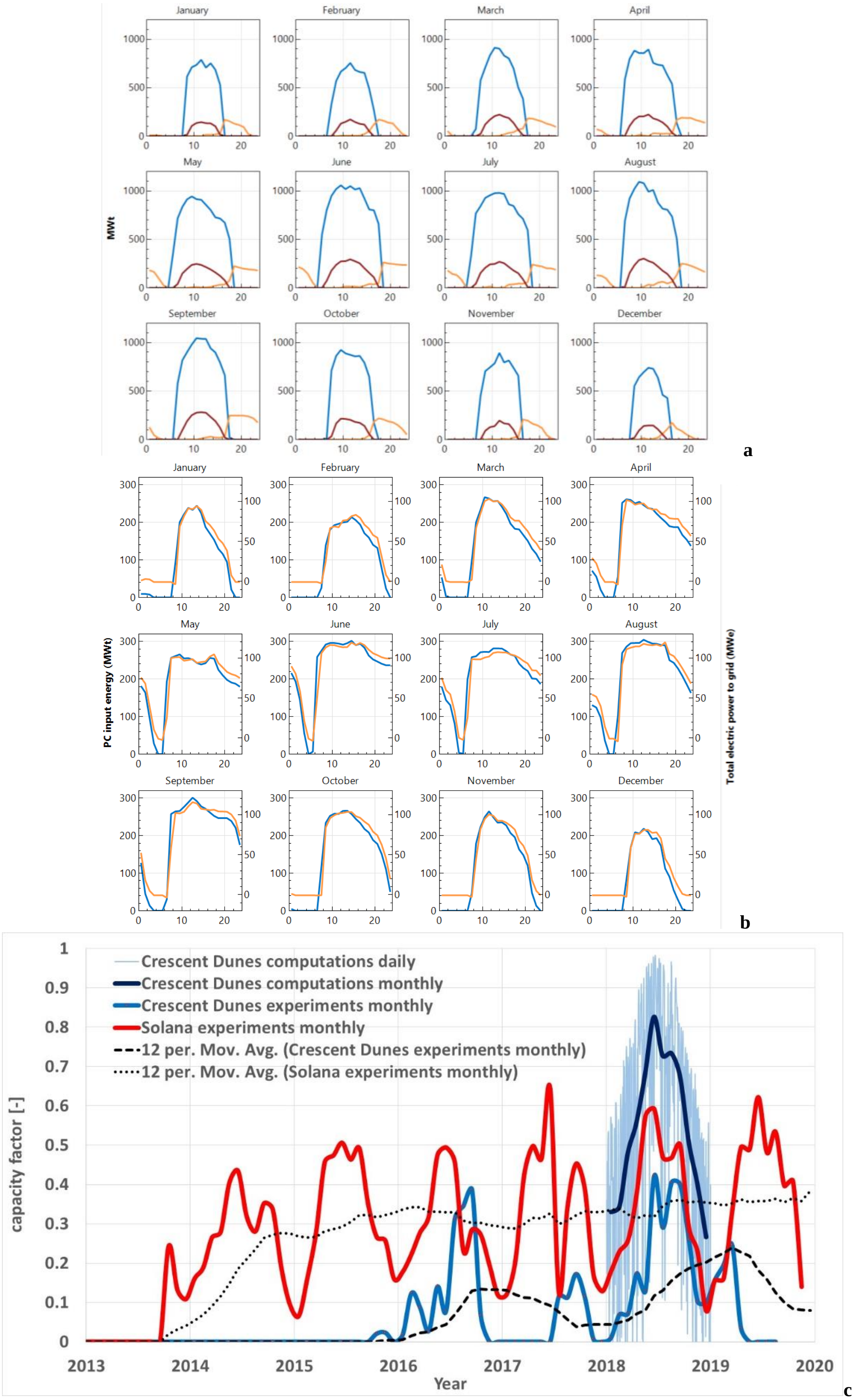

Fig. 2 – a) Crescent Dunes, incident sun power and power to and from the storage during typical days for every month. From SAM computations to be noted the dispatchability during the summer, with the production of electricity extended after the sunset. b) power to the cycle (left axis) and electric power output (right axis) also from computations. c) Comparison of predicted and measured capacity factors for Crescent Dunes and measured capacity factors of Solana. Computations performed by using SAM.

4. Discussion and Conclusions

The best performing large concentrated solar power plant in the world is Solana. It features the more established and reliable parabolic trough technology, plus 6 hours of molten salt thermal energy storage. The 250 MW plant, completed in 2013, had a construction cost of 2 billion $US. This translates into a CAPEX of 8,000 $US/kW, which is less than the 8863 $US/kW of Crescent Dunes. The capacity factor of Solana is also increasing, presently at 36.5%. Working 25 years at this capacity factor would translate into a cost of 0.100 US$/kWh. By adding O&M cost, that should be dramatically less for a parabolic trough than a solar tower, we may take for example fixed O&M cost of 33 $/kW/yr., this would translate into a final cost of 0.1100 US$/kWh. The cost of a plant-like Solana is expected to dramatically reduce as soon as the design could converge towards an industrial product, and some issues especially with the energy storage, that is the most delicate part, could be finally addressed. (as mentioned before, since the start of operation in 2013, the annual capacity factors of Solana have been continuously improving).

While an alternative concentrated solar power technology, the much simpler and reliable parabolic trough, is reasonably performing in real world, there was a single plant of decent size built and operated worldwide featuring the proposed "superior" technology, solar tower with thermal energy storage of 10 hours, Crescent Dunes, and that plant was performing very badly.

Theories without the support of experiments are not science nor engineering, but just speculations. A parabolic trough is a much simpler, reliable and well-established technology. Thus, good plants can be produced at low costs. Conversely, the solar tower, especially with the addition of larger thermal energy storage, is a much more difficult and delicate design, still lacking technology readiness, and good plants are hard to be made at reduced costs.

Fully dispatchable solar power cannot be made with the specific technology solar tower with molten salt thermal energy storage of 10 h at 6 c/kWh. Thanks to the savvy energy administrators of the Obama era, backed by NREL and the high impact peer review, the US taxpayers have thus paid unpredictable electricity from the sun 2.38 $ per kWh. Taxpayers of other countries of similarly savvy energy administrators, South Africa, Chile, and Australia, were just spared same waste of money by the lack of investors willing to contribute off –their-pockets the additional money needed. Investors do not trust NREL, nor the high impact peer review.

Renewable energy (as everything else) may only progress through the scientific method, where theories, no matter how popular they are, are always verified experimentally, before being called science.

Only by continuing to operate the Crescent Dunes power plant, collecting back to back high-frequency resource, weather, and component operating parameters, there is the opportunity to learn from this failure, and grow up a technology that definitively needs more and better research and development, and less overselling.

Presently, the best opportunity for concentrated solar power is to further refine the parabolic trough design with molten salt thermal energy storage, up to the definition of an industrial product that if mass-produced could bring to the cost down to the 0.060 US$/kWh.

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