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LCOE Reduction Potential of Parabolic Trough and Solar Tower CSP Technology until 2025

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Abstract. Concentrating Solar Power (CSP), with an installed capacity of 4.9 GW by 2015, is a young technology compared to other renewable power generation technologies. A limited number of plants and installed capacity in a small challenging market environment make reliable and transparent cost data for CSP difficult to obtain. The International Renewable Energy Agency (IRENA) and the DLR German Aerospace Center gathered and evaluated available cost data from various sources for this publication in order to yield transparent, reliable and up-to-date cost data for a set of reference parabolic trough and solar tower plants in the year 2015 [1]. Each component of the power plant is analyzed for future technical innovations and cost reduction potential based on current R&D activities, ongoing commercial developments and growth in market scale. The derived levelized cost of electricity (LCOE) for 2015 and 2025 are finally contrasted with published power purchase agreements (PPA) of the NOOR II+III power plants in Morocco. At 7.5% weighted average cost of capital (WACC) and 25 years economic life time, the levelized costs of electricity for plants with 7.5 (trough) respectively 9 (tower) full-load hours thermal storage capacity decrease from 14-15 \$-ct/kWh today to 9-10 \$-ct/kWh by 2025 for both technologies at direct normal irradiation of 2500 kWh/(m²·a). The capacity factor increases from 41.1% to 44.6% for troughs and from 45.5% to 49.0% for towers. Financing conditions are a major cost driver and offer potential for further cost reduction with the maturity of the technology and low interest rates (6-7 \$-ct/kWh for 2% WACC at 2500 kWh/(m²·a) in 2025).

INTRODUCTION

Today, two CSP technology variants, parabolic troughs and solar towers, dominate the market of solar thermal power plant projects. Parabolic trough solar field systems are a proven technology with more than 70 utility scale power plants worldwide. While the first commercial scale solar tower systems with heliostat fields and central receivers have been recently commissioned and are operating successfully, others are currently in the process of being commissioned. CSP plants have the advantage of integrated thermal storage, allowing for very flexible and even baseload power production profiles, an important techno-economic advantage in the power system.

From the economic point of view, CSP like all renewable energy technologies is characterized by its high upfront investment and quite low running costs because of the non-existent fuel costs. For both trough and tower plants the upfront capital expenditure (CAPEX) is responsible for more than 80% of the levelized cost of electricity (LCOE), from which loan repayments account for 36-37% and interest payments for 44-47% depending on the technology. Running costs have only minor influence. Beside attractive loan interest rates the key to more competitive LCOE is consequently the reduction of the upfront capital investment which in turn reduces the financing costs. Thus, the assessment of the current and future investment costs is the main task of this study.

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METHODOLOGY

The chosen reference projects for trough and tower technology reflect the state-of-the-art for both technologies. The UltimateTrough® collector with 7.5 meters aperture width is chosen as reference parabolic trough collector [2]. The Stellio® heliostat is the reference heliostat [3]. Table 1 gives an overview of the key parameters for the reference plants in 2015 as well as for the expected future plants which are discussed in the following.

TABLE 1. Overview of the plant configuration for 2015 and 2025

	Parabolic Trough		**Solar Tower**		**Unit**
	2015	**2025**	**2015**	**2025**	
Gross electrical output	160		150		MW
Cooling Technology	Dry Cooling				
Nominal thermal output	871	843	702	684	MW
Site	Ouarzazate, Morocco				
Direct normal irradiation (DNI)	2017 / 2558 / 2935 [1]				kWh / (m²·a)
Solar collector / heliostat	Ultimate Trough	10m - Future Trough	Stellio-heliostat		
Solar field mirror aperture area[2]	1.51	1.46	1.51	1.38	km²
Heat transfer fluid (HTF)	Thermal Oil	Molten Salt	Molten Salt		
Maximum HTF temperature	393	530	565	600	°C
Storage medium	Molten Salt		Molten Salt		
Thermal energy storage capacity (full load hours)	7.5		9		h

As a first step, investment costs for both technologies in the reference year 2015 are determined based on various sources. Afterwards, a screening and assessment of technological developments and innovations within the near future until 2025 lead to the expected future plant configuration. Future component costs are closely related to the technological innovations and are estimated alongside. Finally, yield analyses are performed for both technologies for the years 2015 and 2025 using proprietary in-house simulation tools based on heat flows.

All cost estimations in this study are given in 2015 US-$ and are based on the assumption that the total installed CSP capacity in 2025 is about 20 GW[3]. If less capacity is added, learning effects cannot be put into effect in the given time frame and cost reductions will be lower. Especially for tower technology, EPC contractors are currently building their first or second plant. In order to realize the estimated cost reductions about 10 to 15 plants of similar kind have to be built by a single contractor until 2025.

COMPONENT COST AND PERFORMANCE ANALYSIS

Parabolic Trough Solar Field

Almost all commercial parabolic trough collectors including the Ultimate Trough® rely on steel structures. The design of those structures is quite mature and has limited potential for further cost reductions. Current R&D activities investigate collector concepts based on alternative materials such as concrete. At this moment it is not possible to seriously estimate the cost reduction potential of those approaches. Therefore, it is assumed that the future collector is the next evolutionary step of the current design with an increased aperture width of 10 meters instead of 7.5 meters. Due to the wider aperture 25% less collectors (with the same length as collectors today) are required to reach the same aperture area.

The second important technical innovation is the introduction of molten salt as heat transfer fluid (HTF) in parabolic troughs. First loops in demonstration size are already in operation and it is expected that this technology

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[1] Meteorological data is taken from Meteonorm 7 Software, http://www.meteonorm.com

[2] Subject to LCOE optimization for trough technology; values for DNI = 2558 kWh / (m²·a)

[3] This CSP capacity target represents only 50% of the 180 TWh value published by the International Energy Agency (IEA) in [4] for the 2DS scenario. Assuming a capacity factor of 50% the IEA target requires a CSP capacity of 41 GW.

will be mature until 2025 [5]. This allows higher HTF temperatures up to 530°C with the corresponding advantages of a higher ΔT in the thermal storage.

According to internal expertise and other sources the solar field turn-key cost in 2015 are estimated at 231 $ per m² aperture [6]. The cost distribution on individual sub-components of the Ultimate Trough® collector as well as site preparation and HTF system costs are based on [7]. The complete cost breakdown is shown in Tab. 2.

TABLE 2. Current and future specific CAPEX for parabolic trough field by component ($ per m² aperture)

Parabolic trough solar field	**Costs 2015 [$/m²]**	**Cost variation [%]**	**Costs 2025 [$/m²]**
Site preparation	25	-20	20
Collector structure (incl. assembly)	66	-20	52
Pylons & foundations	22	-20	18
Drives	7	-20	5
Mirrors	22	-15	19
Receivers	27	-30	19
Cabling	4.2	-10	3.7
HTF system (fluid)	21	-88	3
HTF system (excl. fluid)	38	0	38
TOTAL	**231**	**-23.5**	**177**

The total cost reduction potential for the parabolic trough field is estimated at 23% spread quite evenly over all sub-components except for the HTF system (excl. fluid). In the same time it is expected that the optical efficiency of 79.1% [2] can be kept constant even with increased aperture width. This requires accuracy enhancements of collector structure, mirrors and assembly procedures.

Additional experience leads to individual, more cost-effective site preparation concepts for drainage and wind protection. Depending on the site, the levelling effort may be reduced because advanced control systems allow some slope of the terrain.

The collector structure is the most costly sub-component and cost reduction potential is estimated at 20%. Important cost drivers will be lower assembly costs due to the reduced number of collectors. Bigger plants and higher market volumes allow advanced industrialized assembly procedures and automatization in manufacturing. (Sub-) supplier standards and standardized designs will lead to a more dynamic market environment and thus falling costs.

Cost reductions for pylons and foundations as well as drives are mainly justified by the smaller number of collectors. The construction of the residual pylons and foundations has to be more massive. Therefore the final cost reduction is estimated at about 20%.

CSP mirror technology is already quite mature. Nevertheless, small performance gains regarding accuracy due to improved production techniques are expected. Cost reductions can reach 15% thanks to standardisation and development of a competitive market.

The performance of the receiver tubes is a decisive factor for the heat losses of the solar field. The increase of heat losses due to the higher temperature level are confined by the technical improvement of the absorber tubes (e.g. absorber coating) and compensated by the higher concentration factor of the collector due to the increased aperture width. Overall heat losses at nominal operating temperature are expected in the same range for 2015 and 2025 (30-35 W/m²). Thanks to the bigger aperture width 25% less absorber tubes are required. Additionally, standardisation and a competitive market environment lead to an overall cost reduction potential of 30%.

Cost reductions for cabling are estimated at 10% and are justified with the reduced number of collectors. Wireless controls and power supply could entail further cost reductions.

HTF costs are expected to decrease from 21 to 3 $/m² due to the switchover to molten salt as HTF. In addition to the lower price of molten salt (1 $/kg vs. 5 $/kg), the HTF mass content of the solar field (incl. headers) is reduced significantly from 4.1 to 2.5 kg per m² aperture, even though the density is about 2.4 times bigger. Main factors for HTF volume reduction are the smaller HCE diameter (70 vs. 90 mm) and header diameters enabled by the higher heat capacity of the molten salt. Costs of the HTF system are assumed constant since, on the one hand the usage of the same fluid in field and storage makes the design of the HTF system much simpler and saves heat exchangers between thermal oil and molten salt, but on the other hand antifreeze measures must be taken, which more or less offset the savings on heat exchangers.

Solar Tower System

Heliostat Solar Field

According to DLR and industry expertise turn-key costs of 143 $ per m² reflective surface are representative for state-of-the-art heliostat designs. The reference tower plant design is based on the Stellio® heliostat, which is one of the latest designs [3]. The distribution of the sub-component costs depends on the actual design of the heliostat. Since detailed sub-component costs for the Stellio® heliostat are not publicly available, NREL data from [8],[9] was used with a 0.73 scaling factor. Table 3 gives an overview of the cost distribution.

TABLE 3. Current and future specific CAPEX for the heliostat field by component ($ per m² reflective surface)

Heliostat field	**Costs 2015 [$/m²]**	**Cost variation [%]**	**Costs 2025 [$/m²]**
Site preparation	11	-50	5.5
Mirrors	26	-35	16.9
Drives	45	-25	33.8
Structure & foundation	42	-25	31.5
Controls	4	-20	3.2
Installation (wiring/foundation labor)	15	-20	12.0
TOTAL	**143**	**-28**	**103**

The overall cost reduction potential is estimated at 28% and distributed quite evenly over all sub-components except for site preparation which is expected to decrease by 50%. Current state of the art site preparation and foundation is quite extensive. Alternative concepts like earth screw or pile-driven foundations are investigated and can result in much lower site preparation efforts.

Even though mirror production technology is very mature, small accuracy gains due to improved production techniques are expected. Additional potential could be unveiled by innovative sandwich solutions integrating backing and support structure or thin glass with higher reflectivity. In 2015 flat mirrors for heliostats are still considered to be slightly more expensive than bended trough mirrors. Thanks to the development of a competitive market, product standardization and improved canting procedures the overall cost reduction potential is estimated at 35%.

Drives are the biggest cost driver of the heliostat. Costly slewing drives can be replaced by linear drives with limited angular flexibility or alternative innovative concepts. Closed loop control by an optical sensor reduces the accuracy requirements of the components while increasing the overall accuracy of the heliostat. Maintenance programs can reduce downtimes. The total expected cost reduction for drives is 25%.

Higher accuracy of the heliostat structure and higher solar field efficiency due to optimized heliostat and field design for reduced shading and blocking are the major performance improvements until 2025. The cost reduction potential is estimated at 25% and borne by bigger market volumes in combination with standardized and optimized designs for low material consumption and advanced industrialized and automated assembly procedures.

Advanced control algorithms allow higher precision and additional experience leads to the minimization of unnecessary safety margins. In the same time, wireless power supply and control reduces the costs for field control by 20%.

Finally, the installation process profits from advanced installation and assembly procedures with a high degree of automation resulting in a 20% cost reduction.

Tower

Several cost functions for the central tower are available from literature. For this study an approximate value of 90,000 $/m for typical tower heights of about 200 m is used. It results in total tower costs of 20 Mio. $ which is in between values from [10] and [8]. Further standardization and additional experience can lower the cost by 20% until 2025. Meanwhile, innovations like recovery of potential energy in the downcomer as well as usage of the tower as natural draft chimney for dry coolers could become market-ready.

Central Receiver

The commercial introduction of thermal storages for direct steam generation plants (e.g. using phase change materials) is not expected in the given time frame. Therefore, molten salt technology is expected to be the standard HTF for future tower plants.

The performance of central receivers is expected to improve because of an improved thermo-hydraulic design that allows higher solar flux as well as higher HTF outlet temperatures. Innovative selective coatings and enhanced tubing can increase the receiver efficiency. The operation of tower plants has much room for improvements that can be unlocked with additional operational experience and research. Real time aim point strategy for homogenous receiver temperatures increases the life time of the receiver. Further important research topics are solar preheating, faster startup procedures and avoidance of receiver drainage during cloud transition.

The total costs for the receiver are estimated at 125 $/kW with a reduction potential of 20% mainly driven by improved material concepts and optimized utilization of the absorber surface (e.g. fractal receiver). Furthermore, higher average solar flux on the receiver reduces the required absorber area.

Thermal Energy Storage

The storage medium (sodium-potassium nitrate mixture) currently makes up for about 50% of the total storage costs for parabolic trough technology with thermal oil. The increase of the available temperature difference between the equally sized hot and cold tanks almost proportionally reduces the required storage fluid mass and the volume of the tanks. Therefore the switchover to molten salt for trough technology in 2025 discloses massive cost reduction potential because the available temperature difference is more than doubled (resulting in a storage fluid mass reduction of 50%). Due to the higher temperature level which requires higher grade steels the cost reduction for tanks is expected lower than for the storage medium itself. Heat exchangers are no longer required because the salt is heated directly in the solar field.

For towers in 2025, maximum HTF temperature increases to 600°C which equally results in minor cost savings for storage medium and tanks. Both technologies could benefit in the future from the development of adapted storage materials, single tank thermocline storage, innovative storage concepts (e.g. sand storage) or the acceptance of salts with lower purity and costs. The cost distribution on the sub-components for both trough and tower technology is listed in Tab. 4.

TABLE 4. Current and future specific capital cost for thermal storage in trough and tower systems in $ per kWh_{th}

	Costs 2015 [$/kWh]		**Cost variation [%]**		**Costs 2025 [$/kWh]**	
	Trough	**Tower**	**Trough**	**Tower**	**Trough**	**Tower**
Storage medium	23	10.4	-50	-10	11.6	9.4
Tanks	12	12	-10	-25	10.8	9
Pumps & heat exchangers	5	2	-64	-10	1.8	1.8
Balance of plant storage	2	2	-10	-10	1.8	1.8
TOTAL	**42**	**26**	**-38**	**-17**	**26**	**22**

Power Block

The power block technology is mature and cost reduction potential is low for the next 10 years. Dry cooling technology has been assumed for 2015 and 2025. With 1270 $/kW the power block for tower systems is 50 $/kW more expensive than for trough systems in 2015 due to the higher temperature and pressure level. In 2025 the costs are estimated at 1100 $/kW for both technologies. The live steam temperature is increased for both technologies enabling higher power block efficiencies (trough: 383°C/38.4% to 520°C/42.7%; tower: 550°C/42.8% to 580°C/43.9%).

COST OVERVIEW

The project cost structure accords to the proposed appendix *cost structures* for the *SolarPACES Guideline for Bankable STE Yield analysis* [11], [12]. Profit margin and contingencies in 2015 are accounted with 19% for tower technology compared to 10% for trough technology. This reflects the fact that today's tower plants are mostly first of their kind and have to deal with several issues in construction and commissioning phase causing additional costs. In 2025, these costs can be avoided with future experience how those issues can be overcome. Table 5 gives an overview of the total project costs. Both technologies have similar capital expenditure (CAPEX) and a reduction potential of about 35%.

TABLE 5. CAPEX overview for trough and tower technology

	Unit	**2015**		**Cost variation [%]**		**2025**	
		Trough	**Tower**	**Trough**	**Tower**	**Trough**	**Tower**
Total Direct EPC costs	**Mio. $**	**675**	**598**	**-24**	**-23**	**508**	**459**
Engineering, management, add. EPC services	% on direct EPC	5				2	
Profit margin and contingencies	% on direct EPC	10	19			6	
Total Indirect EPC cost	**Mio. $**	**101**	**144**	**-60**	**-74**	**41**	**37**
Project development	% on dir.+indir. EPC	10				4	
Land cost	$ / m² land	1				1	
Infrastructure	Mio. $	6				6	
Additional owner's cost	% on dir.+indir. EPC	3				2	
Total Owner's cost	**Mio. $**	**112**	**113**	**-61**	**-60**	**44**	**46**
Capital expenditures (CAPEX)	**Mio. $**	**888**	**854**	**-33**	**-37**	**593**	**541**
Operational expenditures (OPEX)	% of CAPEX	2.2	2.3			2.1	1.9

The operational expenditures (OPEX) are expected to decrease slightly stronger than the CAPEX due to several technical innovations and learning effects like optimized O&M schedules, innovative field surveillance methods (e.g. UAVs), automated cleaning equipment, less collectors due to higher aperture width (trough) or more reliable equipment.

RESULTS

The annual total net electrical output of the parabolic trough configuration is 576 GWh for 2015 and 625 GWh for 2025[4]. This corresponds to capacity factors (CF) of 41.1% respectively 44.6% and an increase of the overall net plant efficiency from 15.1% to 17.0%. The overall efficiency gain is mainly achieved by the increased power block efficiency (42.7% vs. 38.4%) while the overall solar field efficiency increases slightly from 51.0% to 51.4% on annual average.

The tower plant delivers 598 GWh (CF: 45.5%) for 2015 and 644 GWh (CF: 49.0%) for 2025. In the same time the solar field mirror area is reduced by 9%. The overall net plant efficiency increases by about 3% and can reach 18.3% in 2025 for the medium DNI level thanks to a higher mirror reflectance (0.912 vs. 0.893), receiver efficiency (0.905 vs. 0.876) and power block efficiency (43.9% vs. 42.8%).

The LCOEs are calculated dividing the discounted lifetime costs of the power plant by the discounted lifetime electricity production. The weighted average cost of capital (WACC) is set to 7.5% and the economic life time of the plant is 25 years. Figure 1 summarizes the results of the LCOE calculation.

The comparison with published data from existing plants is difficult since cost and financing data are usually not publicly available. Instead, the most reliable indicators are power purchase agreements (PPA), which contain tariffs of 14 respectively 15 $-ct/kWh for NOOR II/III. Those values are lower than the calculated LCOEs at medium DNI level which is expected at this site (trough: 16.5 $-ct/kWh, tower: 16.1 $-ct/kWh). The difference between LCOE and PPA tariff can be explained by the financing conditions. When using WACC of 5.4% for troughs and 6.5% for towers the calculated LCOEs are equal to the PPA tariffs. Since such favorable financing conditions are quite possible it is concluded that the estimated cost for 2015 match quite well to the cost of realized projects.

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[4] If not stated otherwise the given values refer to the medium DNI level of 2558 kWh/(m²·a).

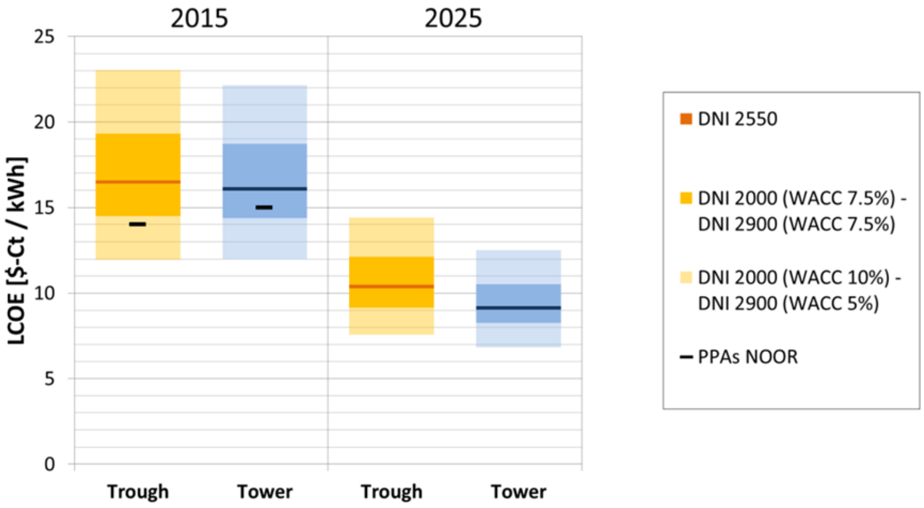
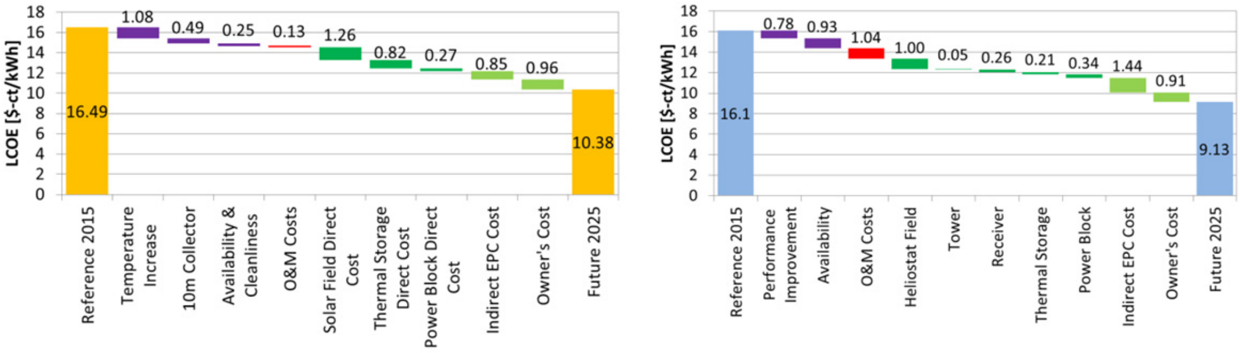


FIGURE 1. Estimated LCOE for trough and tower technology in 2015 and 2025, and real PPA data for NOOR II/III

Cost Driver Analysis

As shown in the previous section both parabolic trough and tower technology offer significant cost reduction potential. However, the cost drivers for both technologies are quite different as shown in Fig. 2.



(a) Trough (b) Tower

FIGURE 2. Contributing factors to the LCOE reduction from 2015 to 2025 for trough and tower systems: Performance improvement (violet), OPEX reduction (red), direct CAPEX reduction (dark green) and indirect CAPEX reduction (light green).

For both technologies, the cost reductions (CAPEX and OPEX) are responsible for more than two thirds of the total LCOE reduction. The residual third is achieved with technical performance improvements.

For trough technology, two major cost drivers can be identified. First, the increase of the temperature level enabled by the switchover to molten salt as HTF leads to higher cycle efficiency of the power block and lower investment costs for the thermal storage, accounting for 1.9 ct/kWh of LCOE reduction. The second important cost driver is the reduction of the solar field cost which is closely related to the newer trough collector with wider aperture area and thus less collector units, leading to LCOE reductions by 1.75 $-ct/kWh. Further LCOE reduction is mainly achieved by the lower indirect EPC and owner's cost.

For tower technology, the major cost driver is the gain of experience. While many of the EPC contractors and project developers build their first tower projects in 2015, risk margins are still high. The lack of experience in 2015 is represented by three factors that deviate from the trough values. The expected plant availability in 2015 is only 0.93 instead of 0.99 in order to account for longer outages due to unscheduled additional maintenance and replacement of broken components. Extended commissioning phases with replacement of broken components could be seen for several tower projects built today. Additional maintenance and commissioning efforts are also responsible for the assumption of increased O&M costs (2%, later 1%). Indirect EPC costs are expected to be 9%-points higher in 2015 due to additional risk surcharges within the supply chain. In 2025 indirect cost and availability are the same as for troughs which reduces the LCOE by 3.4 ct/kWh.

CONCLUSION

Levelized cost of electricity is the major criterion chosen for the economic comparison of different electricity generation technologies. Concentrating solar power currently reaches LCOEs in the range of 15 to 19 $-ct/kWh with reference values of 16.5 ct/kWh for trough and 16.1 ct/kWh for tower technology at 7% WACC and 25 years economic life time. Those values match very well to the published power purchase agreements for NOORII/III when accounting for favorable financing conditions.

The future development of parabolic trough technology is dominated by the switchover to molten salt as heat transfer fluid, which allows much higher live steam temperatures of 530°C compared to 383°C for the currently used thermal oil. The higher temperature level increases the power block efficiency and the thermal storage volume can be reduced by 50% due to the higher temperature difference between hot and cold tank. The second important development for troughs is the further collector upscale towards aperture widths of about 10 meters. Less loops for the same aperture area cuts investment costs for several components, such as number of foundations, receivers, pylons and controls. In total, CAPEX reductions of 33% from 5550 $/kW down to 3700 $/kW for a configuration with 7.5-full-load-hours storage are expected until 2025. The overall plant efficiency of trough plants is expected to increase from 14.9% to 16.6% (net electricity/DNI on aperture area) while the CF rises from 41.1% to 44.6%.

Tower technology still looks back on a much shorter track record compared to trough technology. In 2015, less than ten tower plants are in operation or commissioning phase and most EPC contractors have built first-of-their-kind plants. The lack of experience results in higher indirect EPC cost, lower expectable plant availability and higher operational costs in 2015. The learning effects will bring these values to the same level as for trough plants. The project CAPEX reductions are estimated at 37% (from 5700 $/kW down to 3600 $/kW) for a configuration with 9 full-load-hours storage, while the plant efficiency increases from 15.5% to 18.3% and the CF from 45.5% to 49.0%.

By 2025 the levelized costs of electricity reach 9-12 $-ct/kWh for troughs and 8-11 $-ct/kWh for towers under the financing assumptions 7.5%/25 years, which corresponds to 37% and respectively 43% reduction. Financing conditions are a major cost driver and offer potential for further cost reduction to 6-7 $-ct/kWh for 2% WACC and 2500 kWh/(m²·a) DNI.

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