AIP Conference Proceedings

RESEARCH ARTICLE | JUNE 27 2017

Assessment of mid-term growth assumptions and learning rates for comparative studies of CSP and hybrid PV-battery power plants FREE

Christian Breyer; Svetlana Afanasyeva; Dietmar Brakemeier; Manfred Engelhard; Stefano Giuliano; Michael Puppe; Heiko Schenk; Tobias Hirsch; Massimo Moser

AIP Conf. Proc. 1850, 160001 (2017)
https://doi.org/10.1063/1.4984535

Assessment of Mid-Term Growth Assumptions and Learning Rates for Comparative Studies of CSP and Hybrid PV-Battery Power Plants

Christian Breyer[1,a)], Svetlana Afanasyeva[1], Dietmar Brakemeier[2], Manfred Engelhard[3], Stefano Giuliano[4], Michael Puppe[4], Heiko Schenk[4], Tobias Hirsch[4], Massimo Moser[5]

[1] *Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland.*
[2] *Fichtner GmbH, Sarweystraße 3, 70191 Stuttgart, Germany.*
[3] *M + W Group GmbH, Lotterbergstraße 30, 70499 Stuttgart, Germany.*
[4] *German Aerospace Center, Institute of Solar Research, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany.*
[5] *German Aerospace Center, Institute of Engineering Thermodynamics, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany.*

[a)]Corresponding author: christian.breyer@lut.fi

Abstract. The main objective of this research is to present a solid foundation of capex projections for the major solar energy technologies until the year 2030 for further analyses. The experience curve approach has been chosen for this capex assessment, which requires a good understanding of the projected total global installed capacities of the major solar energy technologies and the respective learning rates. A literature survey has been conducted for CSP tower, CSP trough, PV and Li-ion battery. Based on the literature survey a base case has been defined for all technologies and low growth and high growth cases for further sensitivity analyses. All results are shown in detail in the paper and a comparison to the expectation of a potentially major investor in all of these technologies confirmed the derived capex projections in this paper.

INTRODUCTION

Concentrating Solar Power (CSP) plants have been for many years the first choice for future energy system policy-making and energy system modeling [1,2]. In addition recent years have shown very high growth rates for solar photovoltaic (PV) power plants that are sized up to 575 MW for single power plants [3,4]. Plants larger than 1 MW account currently for slightly more than 50% of the global annual PV market [5]. Globally, the cumulative installed PV system capacity reached about 230 GW by end of 2015 [6,7] and the new PV installations are expected to reach 60 GW in 2016 and 70 GW in 2017 [8], while the cumulative installed CSP capacity accounted for 5.0 GW by the end of 2015 [9]. However, CSP plants can follow any required load curve using thermal energy storage (TES) with a respective solar multiple (SM) and using fossil fuel such as natural gas as a backup or for seasonal balancing. This valuable generation flexibility is not yet known from PV power plants, mainly due to a lack of requirement in tenders, but also due to a lack of an energy system requirement up to a substantial share of intermittent renewable electricity generation, since other flexibility options can be used [10]. The requirement in more flexibility for both the tenders and energy system operation may lead to an equivalent technical flexibility of CSP and PV power plants. This would create a need for PV power plants to also integrate a storage component and a backup option available throughout the year. Fast cost decline in Lithium-ion battery technology offers such an electricity storage option as well as the well-known gas turbines (GT) as a backup option. Other research has focussed on the techno-economic comparison of the available technical options [11], whereas this work discusses in detail the cost assumptions for

SolarPACES 2016
AIP Conf. Proc. 1850, 160001-1–160001-9; doi: 10.1063/1.4984535
Published by AIP Publishing. 978-0-7354-1522-5/$30.00

CSP and hybrid PV-Battery-GT power plants until the year 2030. These assumptions are based on the experience curve approach driven by technology specific learning rates and respective growth rates, for which various studies have been reviewed for the future growth projections.

METHODOLOGY AND DATA

The applied methodology is the well-known experience curve approach [12], which enables projecting of the development of capital expenditures (capex) for industrial products for future periods based on historic cumulative production, future expected growth, and technology specific learning rates. The learning rate expresses the cost decrease in percent of the capex per doubling of historic cumulative capacity. A summary of the mathematical formulation is shown in Equation (1) [13], where the abbreviations stand for cost at historically cumulated output level P_x (c_x), cost at initial output level P_0 (c_0), historically cumulated output level (P_x), initial output level (P_0), unity minus learning rate defined as (*progress ratio*), annual production of a specific year (P_t), growth rate of a specific year (GR_t) and the period (T) taken into account. The experience curve can be also formulated using the progress ratio, which is mathematically unity minus the learning rate (1.3). Equations (1.2) and (1.5) are equivalent. In this paper the *capex* and c_x are identical and describe the specific investment cost. Combination of Equations (1.1) and (1.5) effectively transforms the cost function from production volume dependence to time dependence, which is often more convenient for scenario analyses, in which the impact of the future growth and learning rates are investigated on an already achieved cost level.

$$c_x = c_0 \cdot \left(\frac{P_x}{P_0}\right)^{\frac{\log progress\ \ ratio}{\log 2}} = c_0 \cdot \left(\frac{P_x}{P_0}\right)^{\frac{\log (unity\ -\ learning\ \ rate)}{\log 2}} \tag{1.1}$$

$$P_x = \sum_{t=0}^{T} P_t \tag{1.2}$$

$$progress\ \ ratio = unity - learning\ \ rate \tag{1.3}$$

$$P_t = P_{t-1} \cdot (1 + GR_t) \quad \text{for} \quad t \geq 1 \tag{1.4}$$

$$P_x = P_0 \cdot \prod_{t=0}^{T} (1 + GR_t) \tag{1.5}$$

The learning rate for CSP power plants discussed in literature is typically between 10-12% [12,14-17], whereas Trieb et al. [18] show also a breakdown for the key components such as solar field (10%), thermal energy storage (8%) and power block (2%). The learning rate for PV modules is well documented and the derived range is typically between 20.0 – 21.5% [19-21], PV inverters show a comparable learning rate as the PV modules [21], whereas PV power systems show a slightly lower learning rate [22]. There is increasing indication that the learning rates for PV modules achieved a substantially higher learning rate of more than 30% [23] in recent years and a reduction of this high learning rate back to the long-term historical level is not expected in the near-term [24]. The learning rate of Li-ion based stationary battery systems is derived to about 20%, compared to about 15% for Li-ion batteries for mobile automotive applications and up to 25% for consumer electronics [25,26]. Data for the historic cumulative capacities of the technologies and expectations on the future growth are shown in the results section.

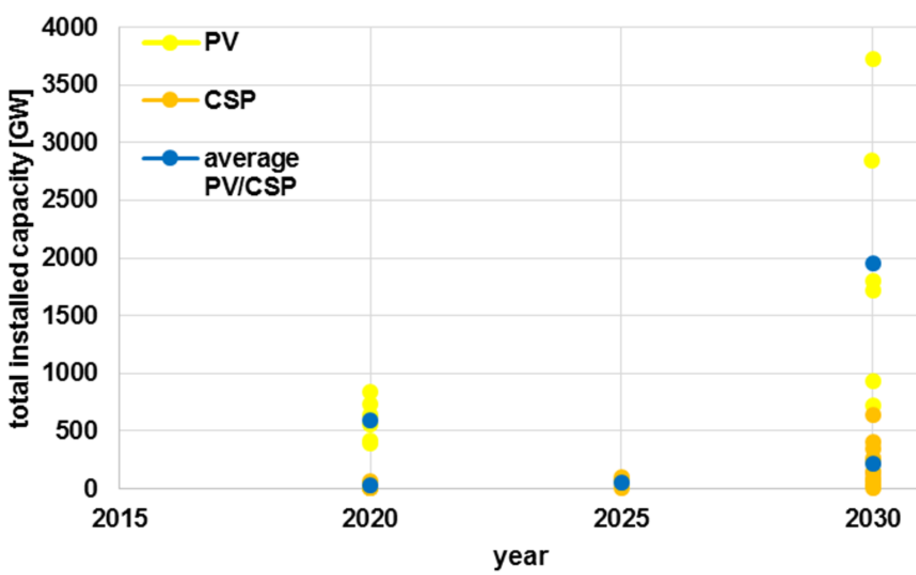
RESULTS

The cumulative capacity for CSP was 5.0 GW at end of 2015, thereof 603 MW of solar tower CSP plants were built and almost all of the rest were parabolic trough CSP plants [9]. The cumulative capacity for PV systems was 230 GW at the end of 2015 [6,7]. The experience curve approach can be applied in two ways to derive the future doublings of the historic cumulated capacity. Firstly, the future capacity projections, and secondly, the annual growth rates can be used to establish the experience curve. For PV and CSP the future capacity projections of major studies are taken into account. Cumulative capacity for Li-ion batteries is not taken into account, but the expected compound annual growth rates (CAGR), which can also be used for future cost projections, are shown by Equation (1.1) and (1.5).

Major studies providing total global installed capacity for PV and CSP until the year 2030 are summarized in Table 1 and visualized in Fig. 1. Several other studies had to be excluded due to a lack of global capacity projections, in particular studies focussing the US market only.

TABLE 1: Total global installed capacity for PV and CSP for the years 2020, 2025 and 2030 as projected in the respective studies. Several other studies had to be excluded due to a lack of global capacity projections.

Study	**year**	**ref**	PV 2020 [GW]	PV 2030 [GW]	CSP 2020 [GW]	CSP 2025 [GW]	CSP 2030 [GW]
Greenpeace - E[R]	2015	[27]	732	2839	31		405
Greenpeace - Adv E[R]	2015	[27]	844	3725	42		635
Estela, ATK - min	2010	[28]			30	60	
Estela, ATK - max	2010	[28]				100	
Estela, Greenpeace - moderate	2016	[9]			21.8		131
Estela, Greenpeace - advanced	2016	[9]			42		350
IEA - WEO, NPS	2015	[29]	397	728	9		28
IEA - WEO, 450	2015	[29]	420	938	10		61
IEA - Roadmap STE	2014	[30]					261
BNEF - New Energy Outlook 2015	2015	[31]	636	1799	8.2	8.9	9.5
IEA - Roadmap PV	2014	[32]		1721			
ITRPV - Int Techn Roadmap PV	2015	[20]	559				
FhG-ISE, LCOE RE techn - Sarasin 2010	2013	[16]			32		91
FhG-ISE, LCOE RE techn - Greenpeace 2009	2013	[16]			68		231
FhG-ISE, LCOE RE techn - Trieb 2009	2013	[16]			15		150
min			397	728	8	9	10
average			598	1958	28	56	214
max			844	3725	68	100	635



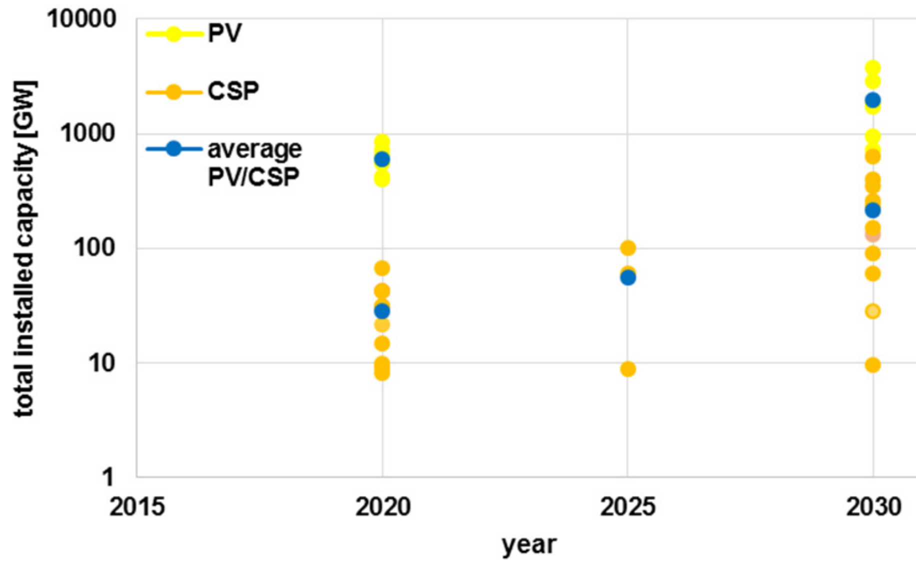


FIGURE 1. Visualised total installed capacity for PV and CSP in linear (top) and logarithmic (bottom) scaling. The data are based on the studies in Table 1.

The studies show no consensus in capacity projection, neither for PV nor for CSP. However, for PV the ratio of minimum to maximum projected capacities is smaller, by factors of 2.1 to 5.1 for the years 2020 and 2030, respectively, compared to CSP with ratios of 8.3 and 66.8 for the years 2020 and 2030, respectively. The minimum numbers for PV are due to the World Energy Outlook (WEO) [29] of the International Energy Agency (IEA). The minimum numbers for CSP are from Bloomberg New Energy Finance (BNEF) [31]. The maximum numbers are in both cases from the Energy [R]evolution scenario from Greenpeace [27]. The smaller deviation of PV reflects the already higher installed capacity and a lower market uncertainty as compared to CSP. BNEF expects a continued growth of installations of PV but only very low installations of CSP, close to a stop of further installations, after the year 2020. The projections of the WEO for PV can be regarded as a very conservative lower limit, since all projections of the last two decades have been substantially too low [33] and the installation projections to the year 2040 are continuously and substantially lower than already expected for years 2016 and 2017 [8,29,34]. This is due to the fact that PV is the least cost source of electricity on a LCOE basis in a fast growing number of regions around the world [35,36].

For further analyses, the authors of this research decided on the basis of the literature survey (Table 1 and Fig. 1) to set the future growth expectations as follows, grouped as a base case, a low growth case, and a high growth case for sensitivity analyses (capex numbers for the year 2015 are also provided):

- CSP plants: cumulative capacity for the year 2020 of 15.4 GW (low: 9.0 GW, high: 21.8 GW) and for the year 2030 of 79.5 GW (low: 28 GW, high: 131 GW). The results are mainly based on [9,29]. Capex 2015 of 5431 €/kW (parabolic trough) and 4618 €/kW (solar tower) for a 100 MW power plant, SM 2.4 and TES of 10 hours.
- PV plants: cumulative capacity for the year 2020 of 598 GW (low: 397 GW, high: 844 GW) and for the year 2030 of 1958 GW (low: 728 GW, high: 3725 GW). The results are based on studies [20,27,29]. Capex 2015 of 1250 €/kWp for single-axis tracking power plants.
- Li-ion battery plants: experience curve analysis is based on a CAGR of 25% (low: 10%, high: 40%) for the period 2015 – 2030. Capex 2015 of 400 €/kWh plus 200 €/kW applied for an energy to power ratio of 6.

The capex numbers for the year 2015 are based on market numbers and confirmed by the authors of this research based on confidential market insights, real projects and offers of technology providers. The results for the base, low growth and high growth case assumptions are summarized in Table 2, applying a learning rate range. The capex for CSP tower and CSP trough are derived by the arithmetic mean of the cases that all new CSP capacities are equally distributed between tower and trough systems as well as the alternative that all new capacities are either tower or trough technology. The reasons for this approach are the uncertainty of future market development, the impact of higher relative growth for tower and lower relative growth for trough technology due to different proportions of installed capacity by end of 2015, and the fact that the trough technology is more mature than the tower technology.

TABLE 2: Solar power plants and their learning rates, doublings based on base, low growth and high growth case assumptions as well as resulting capex results for the years 2020 and 2030. Capex for CSP and PV are in the unit of €/kW for the power capacity and for the battery plant in the unit of €/kWh for the energy storage capacity assuming an energy to power ratio of 6. The capex are given in a range of minimum – average – maximum values based on the learning rate range.

Plants	Learning Rate Range	Doublings 2015-2020	Doublings 2020-2030	Capex 2020 [€/kW; €/kWh]	Capex 2030 [€/kW; €/kWh]
base case					
CSP, Tower	10-12%	1.62	2.37	3645 – 3722 - 3798	2826 – 2939 - 3052
CSP, Trough	10-12%	1.62	2.37	4222 – 4318 - 4415	3285 – 3425 – 3565
PV plant	15-20%	1.35	1.71	924 - 964 - 1003	631 – 693 – 760
Battery Plant	15-20%	1.61	3.22	303 – 318 - 334	148 – 173 – 198
low growth case					
CSP, Tower	10-12%	0.85	1.64	4031 – 4081 - 4131	3298 – 3393 – 3489
CSP, Trough	10-12%	0.85	1.64	4624 – 4692 - 4760	3836 – 3954 – 4073
PV plant	15-20%	0.76	0.87	1054 – 1079 - 1104	867 - 913 – 958
Battery Plant	15-20%	0.69	1.38	372 – 380 - 388	273 – 292 – 310
high growth case					
CSP, Tower	10-12%	2.12	2.59	3435 – 3523 - 3612	2643 – 2760 – 2876
CSP, Trough	10-12%	2.12	2.59	3990 – 4101 - 4211	3065 – 3211 - 3357
PV plant	15-20%	1.85	2.14	827 – 876 - 925	513 – 583 – 653
Battery Plant	15-20%	2.43	4.85	252 – 272 - 292	85 – 108 – 133

The overall plant costs as depicted in Table 2 are useful when always considering the same plant configuration, i.e. the same ratio of power block, solar field and thermal energy storage. If variations, e.g. in the solar multiple, should be analysed, a cost breakdown is required since the components show significant different learning rates. The results for the CSP plants can be further separated into the main components based on the individual learning rates as provided by Trieb et al. [18]: solar field (10%), thermal energy storage (8%) and power block (2%). In order to reach the assumed learning rate range for the entire CSP plant of 10-12%, as derived by most of the respective experience curve publications, the individual component learning rates are scaled taking into account their contribution in the 2015 plant cost breakdown. The capex numbers of Table 2 are separated in Table 3 for CSP tower and in Table 4 for CSP trough into the main CSP plant cost components: power block, thermal energy storage, engineering and project management cost, and solar field with receiver and tower for CSP tower. The specific cost for the thermal energy storage for the year 2030 are identical for both technologies, only adjusted for the different temperature difference levels of 260 K for CSP trough and 310 K for CSP tower. The learning rates assumed for the indirect cost (EPC) are assumed to be identical to the total plant. The resulting plant costs are the sum of the component costs and are identical to those listed in Table 2. The tables illustrate that any variation from the reference configuration is best calculated from these component costs assumptions. Whereas the power block costs are reduced only slightly, the impact on EPC, solar field, and thermal energy storage costs can be significant for respective growth rates.

TABLE 3: Breakdown of CSP tower plant capex into the main components for the base, low growth and high growth cases for the average value of the learning curve range. The assumptions are based on a 100 MW_{el} plant at a solar multiple (SM) of 2.4 and with 10 h of thermal energy storage. Abbreviations: power block (PB), thermal energy storage (TES), engineering and project management cost also called indirect cost (EPC), capex (inv), solar field (SF) and receiver (Rec).

	Plant	PB	TES		EPC		SF	mirror	Rec	Tower
	€/kW_{el}	€/kW_{el}	€/kW_{el}	€/kWh_{th}	€/kW_{el}	% of inv	€/kW_{el}	€/m^2	€/kW_{th}	€/kW_{el}
2015										
cost	4618	1000	588	25	1066	30	1964	130	125	160
2020										
base	3722	968	523	22.6	658	25.6	1574	103.7	96.8	122

low	4081	983	553	23.9	828	30.4	1718	113.2	105.6	133
high	3523	958	504	21.8	567	22.9	1495	98.5	91.9	116
2030									
base	2939	923	440	19.3	327	14.9	1249	89.9	77.9	97
low	3393	951	491	21.5	509	21.1	1442	103.8	89.9	112
high	2760	909	418	18.3	264	12.6	1168	84.1	72.8	90

TABLE 4: Breakdown of CSP trough plant capex into the main components for the base, low growth and high growth cases for the average value of the learning curve range. The assumptions are based on a 100 MW_{el} plant at a solar multiple (SM) of 2.4 and with 10 h of thermal energy storage. Abbreviations: power block (PB), thermal energy storage (TES), engineering and project management cost also called indirect cost (EPC), capex (inv) and solar field (SF).

	Plant	**PB**	**TES**		**EPC**		**SF**	
	€/kW_{el}	€/kW_{el}	€/kW_{el}	€/kWh_{th}	€/kW_{el}	% of inv	€/kW_{el}	€/m^2
2015								
cost	5431	1000	1067	40	1155	27	2209	220
2020								
base	4318	968	941	33.0	719	26.7	1690	172.2
low	4692	983	999	35.1	901	31.9	1808	184.2
high	4101	958	905	31.8	622	23.9	1616	164.6
2030								
base	3425	923	784	23.0	362	15.7	1357	144.1
low	3954	951	880	25.6	560	22.0	1563	166.0
high	3211	909	741	21.8	294	13.4	1266	134.5

The base case assumptions derived by applying the experience curve approach can be compared to expectations in the market. A recent market expectation by one of the potentially largest solar energy investors in the world, Saudi Aramco, revealed that the findings of this study match quite well the market insights of Saudi Aramco on all three technologies (CSP, PV fixed tilted and battery) [37] as depicted in Fig. 2. Saudi Aramco starts with slightly higher battery capex but assumes a faster decline in the capex. PV capex for fixed tilted systems (capex are about 15% less than for PV single-axis tracking plants) are identical. The capex assumptions in this work for CSP towers are, by 2-6%, slightly lower than those of Saudi Aramco. However, it was not disclosed for how many hours the TES is designed, so even that could explain the deviation.

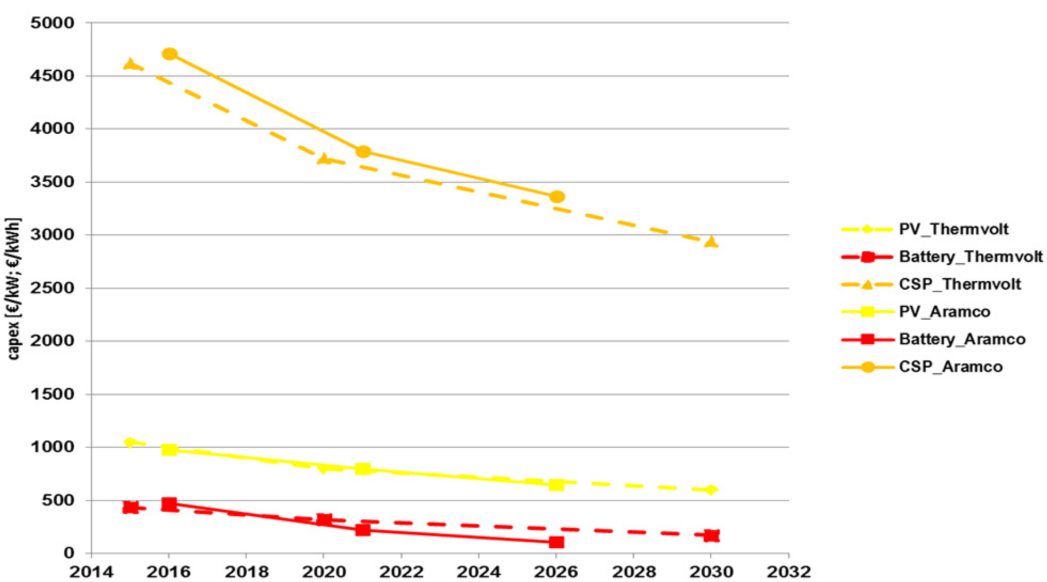


FIGURE 2. Comparison of capex projections of this work and Saudi Aramco based on the base case assumptions for CSP towers, PV fixed titled power plants and utility-scale battery storage for the period of mid-2010s to mid-2020s.

The key intention of this work was to provide capex numbers for the major solar energy technologies for the period up to the year 2030 based on transparent literature assumptions and the broadly accepted experience curve approach. The range of capacity projections and the range of learning rates have been used to define a base case and for sensitivity analyses low growth and high growth cases. The derived capex values can be used for various analyses of the core solar energy technologies.

The capex range for CSP tower plants for 2030 is found to be 2826-3052 €/kW and for CSP parabolic trough plants to be 3285-3565 €/kW for the base case, each of 100 MW of size, a SM of 2.4 and a TES of 10 h. For a comparable hybrid PV-Battery-gas turbine (GT) power plant one needs 282 MWp PV, 448 MWh battery capacity and 100 MW GT (capex of 475 €/kW) for assumed identical solar resource conditions, accounting in total to capex of 2917-3505 €/kW. Detailed hourly modeling using fine-tuned technical composition of all components, such as solar field, TES and power block as well as PV, battery and GT plant allows well balanced levelized cost of electricity (LCOE) comparisons to derive the most competitive set-up. However, such analyses are beyond this paper. Nevertheless, the comparison of the capex already shows that CSP tower, CSP trough and hybrid PV-Battery-GT plants can emerge as technically equivalent solutions in the years to come, even the combination of all of these components to hybrid CSP-PV plants, as already discussed earlier [38]. It needs to be noted that lower or higher growth rates of the key technologies would increase or decrease the relative competitiveness.

SUMMARY

A literature survey on the installed capacity projections until the year 2030 has been conducted and combined with literature findings on the learning rates of the major solar energy technologies, namely CSP tower, CSP trough, PV and Li-ion battery, to define base case assumptions for all technologies as well as low growth and high growth cases for sensitivity analyses. It had been found that the uncertainty in market projections is the highest for CSP. The strength of the growth for batteries cannot yet be estimated well. However, it can be expected to be substantial due to three major drivers, which are batteries for electric vehicles, small-scale PV prosumer storage and large utility-scale storage. The capex estimates derived in this research matches the expectation of potentially major investors, such as Saudi Aramco. The capex for CSP tower is expected to be lower than CSP trough, which may lead to a switch of a higher market share among the CSP technologies from CSP trough to CSP tower. For the year 2030 the capex projections of CSP tower and hybrid PV-Battery-GT plants, which are technically fully equivalent, are comparable. More detailed analyses of combinations of the different components are needed to obtain a more detailed understanding of the relative competitiveness on a LCOE level.

ACKNOWLEDGEMENTS

The authors would like to thank the German Federal Ministry for Economic Affairs and Energy for the financial support of the project THERMVOLT (contract no. 0325760) and Michael Child for proofreading.

REFERENCES

[1] J. M. Weingart, The Helios Strategy: An Heretical View of the Potential Role of Solar Energy in the Future of a Small Planet, Technological Forecasting and Social Change, **12**, 273-315 (1978)
[2] [WBGU] – German Advisory Council on Global Change, World in Transition – Towards Sustainable Energy Systems, Berlin (2003)
[3] K. Komoto and C. Breyer, Renewable Energy Mix and Economics of Northeast Asia Supergrid, 3rd Northeast Energy Forum Asia Security - Sustainable Energy, Energy Interconnection and Regional Energy Cooperation, Seoul (17 December 2015)
[4] pvresources, Large-Scale PV Power Plants – Top50, Jesenice, Slovenia (2016), www.pvresources.com/en/pvpowerplants/top50pv.php [accessed: 28.07.2016]
[5] [IEA PVPS] - International Energy Agency Photovoltaic Power Systems Programme, Trends 2015 in PV Applications, Paris (2015)

[6] [IEA-PVPS] - International Energy Agency Photovoltaic Power Systems Programme, Snapshot of Global PV Markets 2015, St. Ursen (2016), www.iea-pvps.org/fileadmin/dam/public/report/statistics/IEA-PVPS_-__A_Snapshot_of_Global_PV_-_1992-2015_-_Final.pdf
[7] C. Werner, A. Gerlach, C. Breyer, G. Masson, Global Photovoltaics in 2015 – Analysis of Current Solar Energy Markets and Hidden Growth Regions, 32nd EU PVSEC, Munich (20-24 June 2016), DOI: 10.4229/32ndEUPVSEC2016-7DO.14.2
[8] PV Market Alliance, The PV Market Alliance forecasts a growing global PV market exceeding 60 GW in 2016 and 70 GW in 2017, Hong Kong, Brussels, Madrid, Tokyo, San José (16 June 2016), http://pvmarketalliance.biz/
[9] [ESTELA] – European Solar Thermal Electricity Association, Solar Thermal Electricity – Global Outlook 2016, study published together with SolarPACES and Greenpeace International, Brussels (2016),
[10] D. Bogdanov and C. Breyer, The Role of Solar Energy towards 100% Renewable Power Supply for Israel: Integrating Solar PV, Wind Energy, CSP and Storages, 19th Sede Boqer Symposium on Solar Electricity Production (23-25 February 2015)
[11] S. Giuliano, M. Puppe, H. Schenk, T. Hirsch, M. Moser, T. Fichter, J. Kern, F. Trieb, D. Brakemeier, J. Kretschmann, U. Haller, R. Klingler, M. Engelhard, S. Hurler, A. Weigand, C. Breyer, S. Afanasyeva, Techno-Economic Analysis and Comparison of CSP and Hybrid PV-Battery Power Plants, SolarPACES, Abu Dhabi (11-14 October 2016)
[12] L. Neij, Cost development of future technologies for power generation – A study based on experience curves and complementary bottom-up assessments, Energy Policy, **36**, 2200-2211 (2008)
[13] C. Breyer and A. Gerlach, Global Overview on Grid-Parity, Progress in Photovoltaics: Research and Applications, **21**, 121-136 (2013)
[14] J. E. Haysom, O. Jafarieh, H. Anis, K. Hinzer, D. Wright, Learning curve analysis of concentrated photovoltaic systems, Prog. Photovolt: Res. Appl., **23**, 1678-1686 (2015)
[15] [NEEDS] – New Energy Externalities Developments for Sustainability, Cost development – an analysis based on experience curves, Deliverable D 3.3 – RS 1a, Lund University (2006)
[16] Fraunhofer ISE, Levelized Cost of Electricity - Renewable Energy Technologies, Freiburg (November 2013), www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/study-levelized-cost-of-electricity-renewable-energies.pdf
[17] Sargent & Lundy, Assessment of Parabolic Trough, Power Tower and Dish Solar Technology Cost and Performance Forecasts – 2008, study on behalf of US Department of Energy and Sandia National Laboratory prepared by Sargent & Lundy, Chicago (2009)
[18] F. Trieb, C. Schillings, M. O'Sullivan, T. Pregger, C. Hoyer-Klick, Global Potential of Concentrating Solar Power, SolarPACES, Berlin (15-18 September 2009)
[19] R. M. Swanson, A Vision for Crystalline Silicon Photovoltaics, Prog. Photovolt: Res. Appl., **14**, 443-453 (2006)
[20] [ITRPV] – International Technology Roadmap for Photovoltaic, 2015 Results, 7^{th} Ed. ITRPV and VDMA, Frankfurt a.M. (March 2006)
[21] Fraunhofer ISE, Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems, study on behalf of Agora Energiewende and carried out by Fraunhofer ISE, Freiburg, Berlin (2015), www.agora-energiewende.de/fileadmin/Projekte/2014/Kosten-Photovoltaik-2050/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf
[22] F. Kersten, R. Doll, A. Kux, D. M. Huljić, M. A. Görig, C. Breyer, J. Müller, P. Wawer, PV-Learning Curves: Past and Future Drivers of Cost Reduction, 26th EU PVSEC, Hamburg (5-9 September 2011), DOI: 10.4229/26thEUPVSEC2011-6CV.1.63
[23] G. Masson, Solar PV: A tale of two markets, IRENA workshop on Solar PV: Changing our energy system, 32nd EU PVSEC, Munich (22 June 2016)
[24] P. J. Verlinden, Perspectives for cost decline in the PV industry, IEA-PVPS Workshop on Enhancing PV Competitiveness with Energy Storage, 32^{nd} EU PVSEC, Munich (20 June 2016)
[25] W. Hoffmann, Importance and evidence for cost effective electricity storage, 29th EUPVSEC, Amsterdam (22-26 September 2014)
[26] B. Nykvist and M. Nilsson, Rapidly falling costs of battery packs for electric vehicles, Nature Climate Change, **5**, 329–332 (2015)
[27] Greenpeace International, energy [r]evolution – A sustainable world energy outlook 2015, Amsterdam (2015), www.greenpeace.org/international/en/campaigns/climate-change/energyrevolution/

[28] [ESTELA] – European Solar Thermal Electricity Association, Solar Thermal Electricity 2025, study prepared by AT Kearney on behalf of Estela, Brussels (June 2010), www.estelasolar.org/wp-content/uploads/2015/11/2010-Solar-Thermal-Electricity-2025-ENG.pdf
[29] [IEA] – International Energy Agency, World Energy Outlook, IEA, Paris (2015)
[30] [IEA] – International Energy Agency, Technology Roadmap - Solar Thermal Electricity, 2014 edition, Paris (2014), www.iea.org/publications/freepublications/publication/technologyroadmapsolarthermalelectricity_2014edition.pdf
[31] [BNEF] - Bloomberg New Energy Finance, New Energy Outlook 2015, BNEF, London (23 June 2015)
[32] [IEA] – International Energy Agency, Technology Roadmap - Solar Photovoltaic Energy, 2014 edition, Paris (2014), www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarPhotovoltaicEnergy_2014edition.pdf
[33] M. Metayer, C. Breyer, H. J. Fell, The projections for the future and quality in the past of the World Energy Outlook for solar PV and other Renewable Energy technologies, 31st EU PVSEC, Hamburg (14-18 September 2015), DOI: 10.4229/31stEUPVSEC2015-7DV.4.61
[34] [EWG] – Energy Watch Group, IEA creates misleading future scenarios for solar power generation, Berlin (27 November 2015), http://energywatchgroup.org/iea-creates-misleading-future-scenarios-solar-power-generation/
[35] C. Breyer, D. Bogdanov, A. Gulagi, A. Aghahosseini, L. S. N. S. Barbosa, O. Koskinen, M. Barasa, U. Caldera, S. Afanasyeva, M. Child, J. Farfan, P. Vainikka, On the Role of Solar Photovoltaics in Global Energy Transition Scenarios, 32nd EU PVSEC, Munich (20-24 June 20-24 2016), DOI: 10.4229/32ndEUPVSEC2016-7DO.13.1
[36] G. Agostinelli, Scaling Solar Power, International Finance Corporation, 32nd EU PVSEC, Munich (20-24 June 2016)
[37] Energy Storage Update, Saudi Aramco sees PV storage as most economic at under 4 hours, article is based on a presentation of Saudi Aramco at Menasol 2016, May 25-26 in Dubai, London (1 June 2016), http://bit.ly/2aqbVDR
[38] M. Hlusiak, H. A. Bedoya Díaz, M. Götz, C. Breyer, Hybrid Photovoltaic (PV) - Concentrated Solar Thermal Power (CSP) Power Plants: Modelling, Simulation and Economics, 29th EU PVSEC, Amsterdam (22-26 September 2014), DOI: 10.4229/29thEUPVSEC2014-7AV.6.20