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A Learning Curve for Solar Thermal Power

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Abstract. Photovoltaics started its success story by predicting the cost degression depending on cumulated installed capacity. This so-called learning curve was published and used for predictions for PV modules first, then predictions of system cost decrease also were developed. This approach is less sensitive to political decisions and changing market situations than predictions on the time axis. Cost degression due to innovation, use of scaling effects, improved project management, standardised procedures including the search for better sites and optimization of project size are learning effects which can only be utilised when projects are developed. Therefore a presentation of CAPEX versus cumulated installed capacity is proposed in order to show the possible future advancement of the technology to politics and market. However from a wide range of publications on cost for CSP it is difficult to derive a learning curve. A logical cost structure for direct and indirect capital expenditure is needed as the basis for further analysis. Using derived reference cost for typical power plant configurations predictions of future cost have been derived. Only on the basis of that cost structure and the learning curve levelised cost of electricity for solar thermal power plants should be calculated for individual projects with different capacity factors in various locations.

INTRODUCTION

It is important to convince decision makers that solar thermal electricity costs can substantially decrease in future. The competitive situation with conventional generation but also with other renewable generation as wind and PV is critical for the further development of the markets. Therefore a provocative argumentation is developed here.

Photovoltaics (PV) has been extremely successful in following a cost degression of modules and installed systems described by the so-called learning curve. However there are arguments that large scale mature technologies like heat engines do not show any cost degression with increasing markets. On the other side solar thermal flat plate collectors have proven to show a similar production cost reduction as PV modules with a learning rate of 22% [1]. Therefore we want to develop an approach using a simplified analysis of data to derive a learning curve for CSP technology. This will in turn help to give better estimates of future costs depending on the installation rate.

What is a “learning curve” which better should be called experience curve when it deals with cost reduction versus production numbers? It is an empirical law first described by Henderson [4], usually shown as double-logarithmic linear function, which says that whenever the cumulated production doubles, the production cost is reduced by a certain percentage. What are the reasons for that? Which effects contribute to the cost degression? We may note the following:

- Labour efficiency (in production as well in project engineering)
- Automatization of production
- Standardization, specialization and methodological improvements
- Innovation and technology improvements
- More efficient use of materials and equipment
- Location specific effects

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Also the classical scaling effects are reflected in the experience curve. It is important to acknowledge that an "experience curve" for a technology may combine individual technological approaches when the whole industry is being described and not only the cost within one company. Moreover it is possible to analyse either the complete system or individual subsystems for example the solar thermal collector, the receiver part or the thermal energy storage (c.f. **FIGURE 1**).

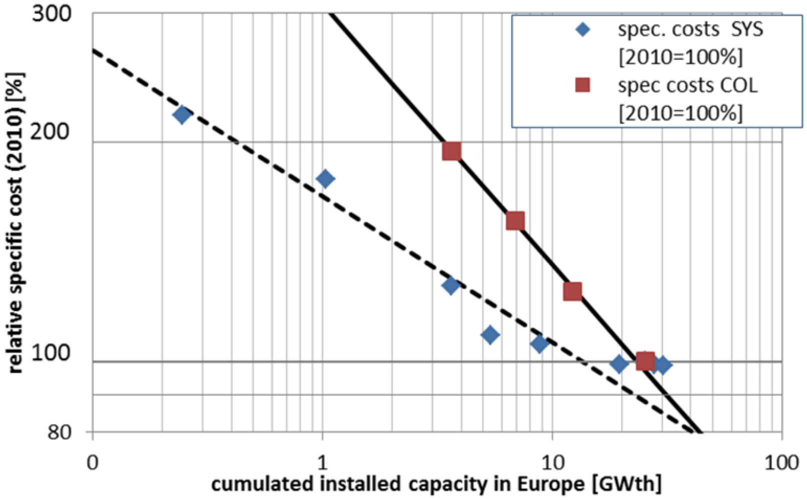

FIGURE 1: Learning curve for flat-plate solar collectors [1] (Curve COL) and low temperature solar system costs (curve SYS) having different learning rates: SYS: 13% and COL: 22%

DATA TREATMENT AND LEARNING CURVE

Cost estimations and predictions for solar thermal power plants are extremely problematic, although a number of studies try to predict cost reduction (e.g. [2]). This is due to a number of reasons:

- Cost information for real plants is very difficult to obtain
- Cost information is structured in different ways or not presented at all
- Many design factors like solar multiple, storage capacity and locations specific solar resource influence the overall cost
- Quoted cost of electricity LCOE is even more difficult to compare as country specific conditions and financing schemes influence this value extremely

Approximate cost information on total CAPEX very often is the only publicly available information on real projects e.g. from CSP Today [5].

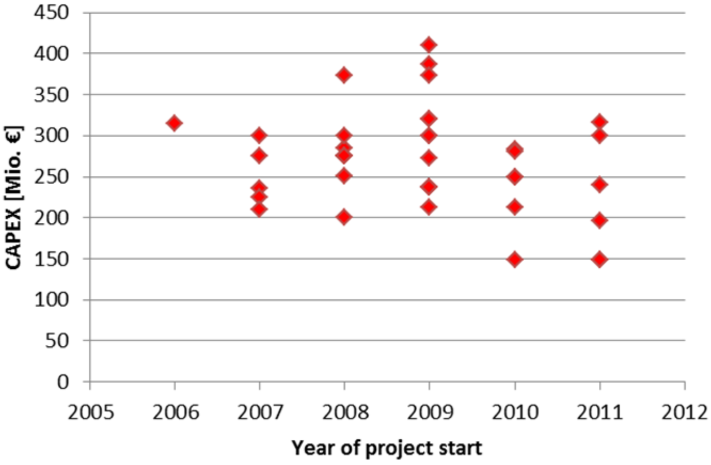

FIGURE 2: Overall CAPEX information for parabolic trough 50 MW power plants from [5] plotted over start year of project

We have retrieved and analysed data there only for the region of Spain, as this was the biggest market and rather similar configurations of parabolic trough plants with and without storage have been built there in the last years. As only CAPEX data were given, cost information on solar field or other parts of the complete project cannot be analysed directly. More than 40% of the projects include a TES with 7-8h storage capacity. As there is a large variation in the data , due to the fact that also different solar field sizes and storage are included (**FIGURE 2**), no clear trend of cost degression is visible. Only the lower limit of project cost shows such a trend over the years.

In order to extract information on the main cost categories an approach by Lovegrove [3] has been extended in a second step. Lovegrove used published relative cost breakdowns to see which cost categories were used, tried to attribute the different details to a cost structure with the following categories

- Concentrator field (excluding receiver and HTF)
- Receiver and HTF (including piping)
- Thermal storage
- Power block
- BOP and other

Analysing the numbers from both, parabolic trough and central receiver projects, Lovegrove produced synthesised estimate of fractional capital cost breakdown for 2011 CST plants of 100 MWe capacity with 5 hours of storage. For the analysis of the Spanish power plant data we wanted to be more specific and precise. We used only the 5 cases on parabolic trough projects as analysed by Lovegrove, and made two more simplifying assumptions:

- Costs for concentrator fields, receiver, HTF, site works and land are proportional to area
- Cost for thermal energy storage is proportional to storage time (all 2 Tank indirect storage)

Then two typical configurations for a parabolic trough power plant were defined, one without TES and a solar multiple of SM=1.45, the other one with 7.5h TES and a solar multiple SM=2.4. Distributing the fractional cost after scaling the original numbers by area and storage time according to the assumptions above, a rather homogeneous picture in all 5 cases evolved. Thus reasonable approximate cost breakdowns for these typical configurations have been created using the same data (see **TABLE 1**). Indirect costs which are the EPC costs plus Owner's cost have been assumed to be 20% of total costs for the plant.

TABLE 1: Approximate direct cost breakdown for typical parabolic trough plant configurations

Subsystem	Fractional cost w/o storage SM 1.45	Fractional cost with storage SM 2.4 7.5 h TES
Solar field (incl. Rec./HTF/pip)	63.0%	56.5%
Thermal storage	0.0%	18.9%
Power block and BOP	28.5%	16.4%
Civil and site works	8.5%	8.2%

Using this approximate cost breakdown for parabolic power plants the overall CAPEX for all projects in in Spain was split up in the categories solar field (SF), thermal storage (TES), power block and balance of plant (PB), civil and site works (CW) and indirect costs. For these fractional costs, labour should be included, i.e. the cost for the solar field includes the installation.

For all projects in Spain, which are 50 MW power plants, the average CAPEX has been taken, and according to the fractional cost, the average cost for the individual categories was calculated. The results were dependent on the solar multiple SM, which varies between 1.3 and 1.9 for plants without storage and is between 2.4 and 2.6 for plants with storage.

In order to get specific results on the solar field costs, all projects had been analysed, assuming 20% indirect costs. From the direct total costs the fractional costs according to solar multiple were taken and divided by the aperture area. The cumulated installed capacity was determined using the start dates of the projects. Different start dates within a year could not be resolved on the time axis. Inflation was not taken into account as the period of activity in Spain was only several years. However a more extended experience curve analysis should consider that.

The resulting specific solar field costs are presented in **FIGURE 3**. There is a large spread between projects of the same year. This may be attributed to the fact that many companies developed projects starting from different background in engineering. Experience effects would be visible when a company has executed several projects in a row. Taking the lower costs for the solar field as best practise, the red line was drawn as a lower limit experience curve. A guide for the eye indicating the upper limit is then plotted as a black parallel line.. The learning rate is 16%

for the lines shown (**FIGURE 3**). The problem in this approach is that for all cost categories the same learning rate is implicitly assumed. If one wants to analyse solar field alone, we also took only data for plants without thermal energy storage and assumed as an alternative a constant power block cost. This yielded similar specific solar field costs but a higher learning rate of 18% (**FIGURE 4**). This reflects similar experience from PV and low temperature solar thermal systems, that learning rates for systems are always a bit lower than for the collectors or modules.

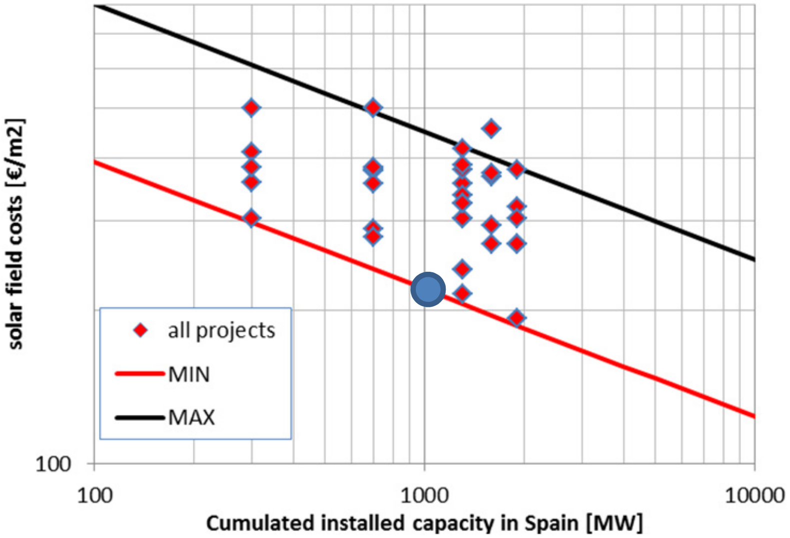

FIGURE 3: Simplified evaluation of learning curve for specific solar field cost (collector incl. receivers, HTF, piping,) based on approximate CAPEX data for 38 Spanish Parabolic Trough plants with and without storage. (Learning rate is 16%, Progress ratio 0.84)
NB: blue circle: average cost for 3 GW - reference case

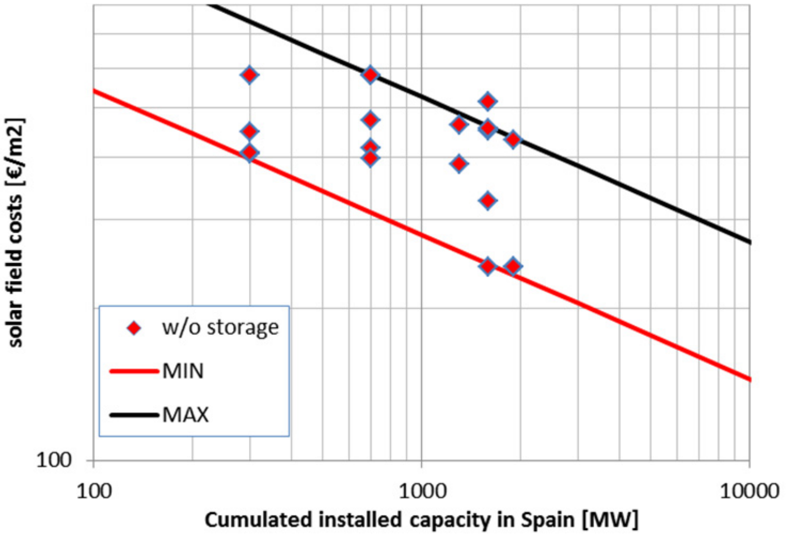

FIGURE 4: Simplified evaluation of learning curve for specific solar field cost (collector incl. receivers, HTF, piping,) based on approximate CAPEX data for 20 Spanish Parabolic Trough plants without storage under the assumption of identical power block cost (Resulting Learning rate is 18%, Progress ratio 0.82)

Due to the fractional cost breakdown the learning rates cannot be distinguished between categories such as power block and thermal energy storage. In any category a cost decrease can be seen, however it is not clear whether the progress is due to the total project management or some individual cost category. For prediction of system cost decrease in the future we therefore assume an overall learning rate of 16%. The same innovation rate should at least be possible in the case of concentrating collector fields. As a reference point for present cost we take the average cost numbers for a cumulated capacity of 3 GW as the world wide installations are beyond this level. For the solar field the value taken is represented by the blue circle in **FIGURE 3**. We determine the direct specific costs for the reference plant as the average of maximum and minimum curve – which border the majority of all cost data - at 3 GW cumulated capacity and present it in **TABLE 2.**

TABLE 2: Direct specific cost for reference plant 50 MW for cumulated capacity 3 GW

Subsystem	Unit	Reference (3 GW)
Solar field (incl. Rec./HTF/pip)	€/m^2	254
Thermal storage	€/kWh	40
Power block and BOP	€/kW	762
Civil and site works	€/m^2	35

Using these data the complete project cost for a 100 MW solar power plant with and without storage TES has been calculated as an example. Indirect cost such as EPC cost, owners cost are included (**TABLE 3**)

TABLE 3: Total cost breakdown for reference 100 MW parabolic trough plant configurations (SM 1.45: 640000 m^2 aperture, SM2.4: 1020000 m^2 aperture)

Subsystem	Cost w/o storage SM 1.45 [Mio. €]	Fractional cost with storage SM 2.4 7.5 h TES [Mio. €]
Solar field (incl. Rec./HTF/pip)	162.6	259.1
Thermal storage	0.0	80.0
Power block and BOP	76.2	76.2
Civil and site works	22.4	35.7
Indirect cost	52.2	90.2
Total	**313.4**	**541.2**

Any other cost case with other combinations of storage and solar filed size could be similarly calculated. The values compare well with other cost estimations for different parabolic power plants (see e.g. [2,6,7]).

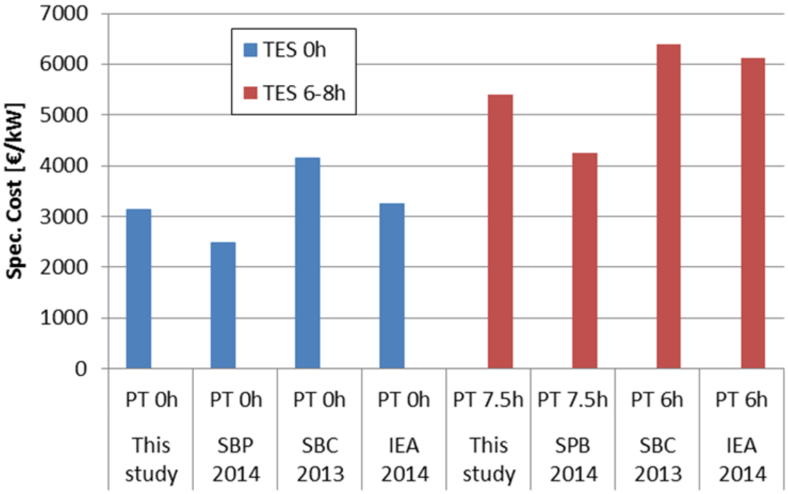

FIGURE 5: Comparison of specific cost data for a 100 MW parabolic trough plant (Source: SBP [7], SBC [6], IEA [2])

FUTURE COST DEVELOPMENT

How will costs develop in future? The learning rate for the conventional power block cost will probably be smaller in the beginning than for the specific innovative components of the solar field and the thermal energy storage, which is still under development. However supercritical cycles and other efficiency improvements might also drive the costs down here. We assume therefore the following limits for learning rates for the four categories in order to show a development scenario.

TABLE 4: Upper and lower assumed limits for the learning rates

Subsystem	Upper limit	Lower limit
Solar field (incl. Rec./HTF/pip)	20%	10%
Thermal storage	20%	10%
Power block and BOP	10%	0%
Civil and site works	10%	5%

Using these learning rates and the cost data of our reference plant defined in TABLE 3 we calculated the theoretical cost degression for plants with storage which are shown in the following figures:

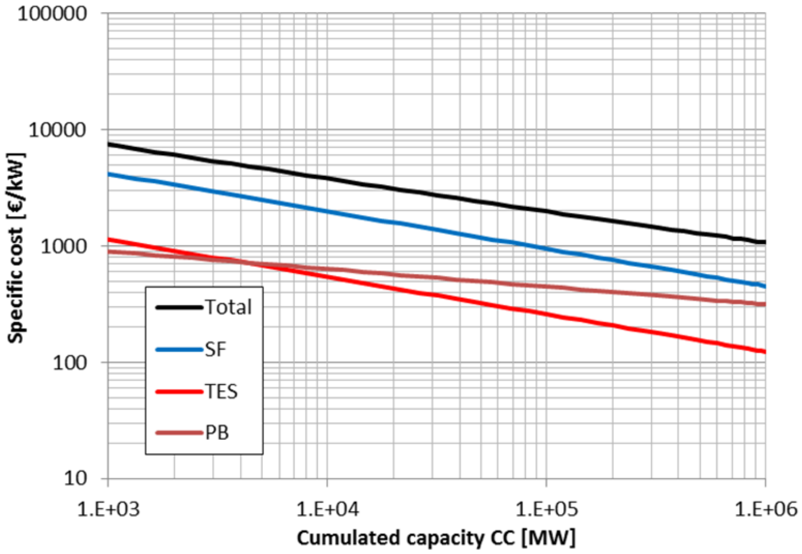

FIGURE 6: Optimistic Scenario using maximum learning rates for all 3 main components
Specific cost per kW for power plant with 7-8 h storage time

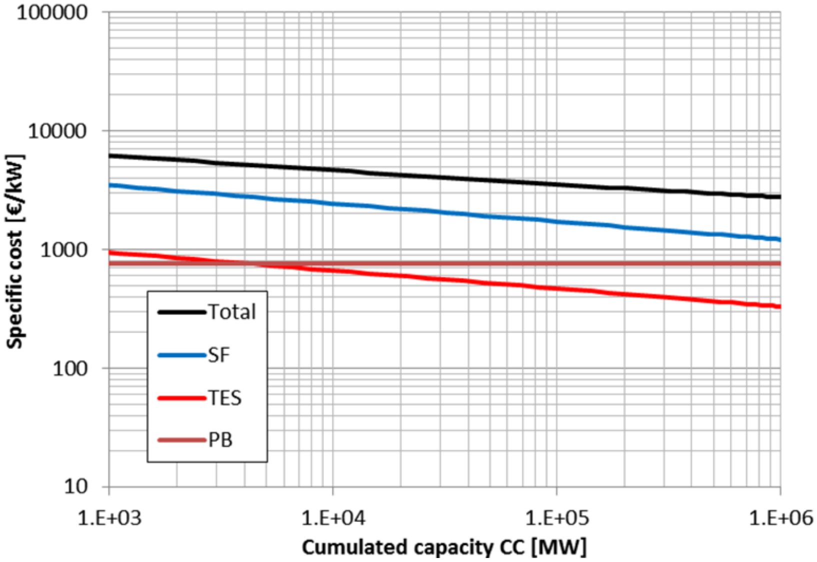

FIGURE 7: Pessimistic Scenario using minimum learning rates for all 3 main components
Specific cost per kW for power plant with 7-8 h storage time

According to **FIGURE 6** in near future reaching 10 GW installed capacity the cost should drop down to 3825 €/kW CAPEX. The overall learning rate for the total cost is 17%. For 1000 GW installed the cost could drop down to 1000 €/kW which seems to be unrealistic as power block cost alone today may exceed this value. It is a question whether e.g. more compact supercritical turbines will be a solution. Learning curves also will be limited by material cost as a lower limit. For a negative scenario using the lower limits of the learning rates, the corresponding numbers would be 4650 €/kW (10 GW) and 2750 €/kW (1000 GW).

However how fast will the market grow? That certainly depends on policies and removal of market barriers. Which growth can be assumed from historic development? Which growth would be required then when the IEA CSP Roadmap 2014 should be followed? If the market develops one might use a theory applied first to energy generation technologies by Marchetti in 1996 using the logistic function [8]. Taking the prediction of the IEA technology roadmap 2014 as guide we show the predicted growth over the years according to the logistic function in **FIGURE 8**.

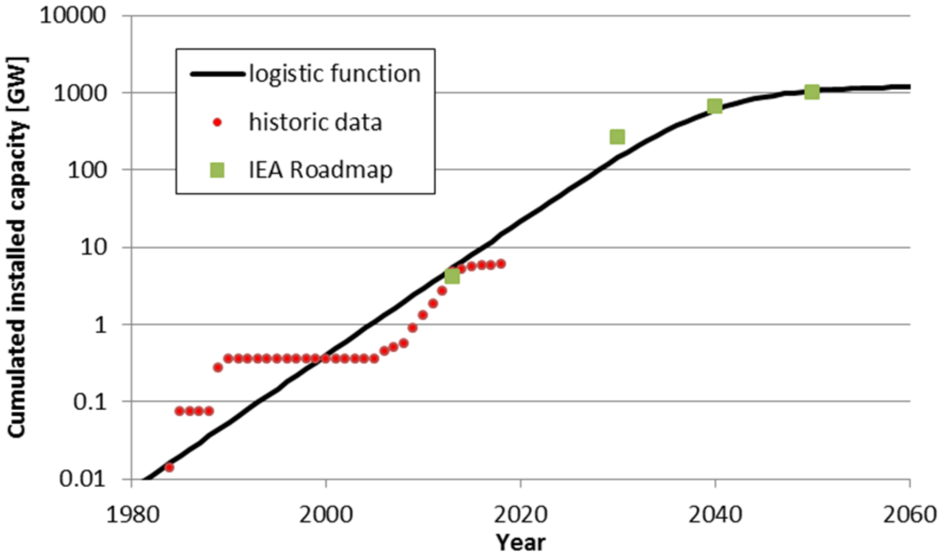

FIGURE 8: Installed capacity for CSP according to the logistic function fitted to IEA Roadmap data and historic data After 2050 saturation is reached in this approach at about 1200 GW; repowering is not included in the data

The logistic function takes into account also the market penetration needs time for building capacities, that information sharing and distribution have to be developed. Certainly in the beginning also supporting policies are needed to reach the goals. But assuming a smooth development we arrive at the following numbers for cost and market size (**TABLE 5**), which are certainly optimistic and need some stimulation. Especially the short term goal for 2020 might be at stakes if markets stagnate. However one might also note that these numbers should not only reflect only parabolic trough power plants but the development of costs for all technologies, as the learning rate includes also changes in design of components and power plants. For example the Fresnel power plant in Rajasthan reaches also the 2010 cost level. Therefore it seems more likely that a time lag of 5 years may reflect better the development due to the stagnation of market in Spain.

TABLE 5: Future cost and capacity development according to the optimistic (first value) and pessimistic scenario (second value) and logistic curve in **FIGURE 8**

Year	Installed capacity [GW]	CSP 0h TES [€/kW]	CSP 7.5h TES [€/kW]
2010	3.0	3051	5415
2020	21.6	1918 / 2491	3053 / 4236
2030	143.0	1300 / 2097	1800 / 3406
2040	600.0	1004 /1866	1223 / 2918
2050	1057.0	915 / 1787	1054 / 2753

CONCLUSIONS

A simple derivation of a learning curve is not possible with existing information. A fractional cost distribution assumes similar learning rates for all cost categories, solar field, thermal storage and power block. For solar field installation only comparing available data for power plants with and without storage allow a better estimation. Experience from low temperature collector development indicate that a possible learning rate of 20% for the solar field seems feasible, whereas at least 10-15% should be possible for the complete capital cost. Actual project data lie within a parallel upper and lower limit curve. An interpretation of that could be that there is an experience time lag between actors entering the market and those already active for some time.

Using the fractional cost breakdown and the calculations for 3 GW reference costs have been developed for each component which should present representative cost data for today. A comparison with other studies showed that we are in the plausible range as well for the CSP power plant without storage as well with storage size 6-8 full load hours. They certainly do not reflect demand situations as have occurred in the Spanish market development e.g. for turbines or solar salt leading to higher prices.

Predictions for the future rely on the learning rates. Learning rates are dependent on the aggregation level of cost. Thus assuming different learning rates for different parts of CSP (like concentrator field, receivers, storage, power block, engineering etc.) and a resulting combined rate for the total cost was proposed.

Using the theoretical data for a pessimistic and an optimistic cost development one may infer that project costs including storage (being the ones producing dispatchable electricity) for 2050 may vary between 1.050 and 2750 €/kW, but realistically we believe that 1500 €/kW may be achievable. Also the timely development of the market is important. The theory of the market share development according to the logistic curve indicates that there is already a time lag when we want to reach the target data for CSP development described in the IEA Technology Roadmap. Especially the short term target 2020 may not be reached but a time lag of 5 years is plausible. Historic data show that also in the past these time lags have happened, and that in a more intensive market phase (as for instance during the years 2008-2012) the market penetration was faster. This would indicate that the 2030 and 2050 targets still may be reached.

Although a number of uncertainties is inherent in the present publication we think that this approach allows to better structure predictions of future CSP cost and market development using the experience curves which have been successfully used by PV analysts in the past. It is of course important to arrive a more precise estimation of learning rates for the different component categories. It is suggested that cost information on these categories including material and installation labour should be published in a more standardised way for future projects.

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