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BROADER PERSPECTIVES

Learning curve analysis of concentrated photovoltaic systems

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ABSTRACT

Price declines and volume growth of concentrated photovoltaic (CPV) systems are analysed using the learning curve methodology and compared with other forms of solar electricity generation. Logarithmic regression analysis determines a learning rate of 18% for CPV systems with 90% confidence of that rate being between 14 and 22%, which is higher than the learning rates of other solar generation systems (11% for CSP and 12 to 14% for PV). Current CPV system prices are competitive with PV and CSP, which, when combined with the higher learning rate, indicates that CPV is likely to further improve its marketability. A target price of 1 $/W in 2020 could be achieved with a compound growth rate of 67% for the total deployed volume between 2014 and 2020, which would realize a cumulative deployed volume of 7900 MW. Other projections of deployment volumes from commercial sources are converted using the learning rate into future price scenarios, resulting in predicted prices in the range of 1.1 to 1.3 $/W in 2020. © 2014 The Authors. *Progress in Photovoltaics: Research and Applications* published by John Wiley & Sons Ltd.

KEYWORDS

concentrated photovoltaics; learning curve; system learning rate; solar electricity costs; deployed volumes; regression analysis

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1. INTRODUCTION

Concentrated photovoltaic (CPV) technology uses optics to concentrate sunlight onto very efficient photovoltaic multi-junction cells. This combination results in the highest commercial efficiency conversion of sunlight to electricity [1]. Multi-junction cells have demonstrated remarkable year-over-year efficiency gains and have clear roadmaps to significant further improvements while simultaneous developments in the concentrating optics have also resulted in overall improvements of CPV system efficiency [2–4]. Furthermore, manufacturing improvements and optimisation of the integration of the components have also resulted in overall reductions in the cost per rated power output of a complete system, as shown in this paper. The CPV industry has had several challenges in establishing a market foothold, in particular during the 2010–2012 period. At that time, it had seemed poised to break through with significant growth but market factors dramatically cut the prices of the incumbent silicon technology [5–7]. Yet, during 2013 there were at least 141 MW of CPV projects completed [8,9], which demonstrated the developing maturity of the industry. Looking forward, because of the strong *technological* basis for continued price reductions of CPV systems, its potential to compete with other energy technologies should be strong. This paper quantifies the extent to which system price reductions in $/W can be expected, as well as the degree of uncertainty in those estimates based on a learning curve approach that relates system price to cumulated deployment volume.

This study focuses on system price as opposed to cost in order to be of value to system developers in assessing the economic viability of CPV systems. It follows the approach of [10] and enables the calculation of the levelized cost of energy

Table I. Detailed list of the CPV system prices and cumulative deployed volumes.

Year	CPV system prices ($/W) Value (range)	Ref
2007	8.5 (7-10)	[18]
2008	3.8 (3.60-4)	[19]
2008	5.75 (5.5-6)	[19]
2008	9.4 (8.68-10.12	[20]
2008	8.5 (7.1-9.9)	[12]
2009	5.76	[21]
2009	4.85 (4.7-5)	[22]
2010	4.66	[23]
2010	9.63	[24]
2010	5.15 (3.05-7.25)	[25]
2011	4.72 (4.56-4.88)	[26]
2011	3.08	[7]
2012	3.54	[27]
2012	2.3 (2.09-2.55)	[28]
2013	2.62	[27]
2013	3.02	[29]
Cumulative deployed volume		
Year	(MW)	Ref
2007	1.5	[30]
2007	3.3	[22]
2007	10.2	[31]
2008	15.6	[22]
2008	13	[31]
2009	17.7	[22]
2009	18	[31]
2010	20	[25]
2010	28	[32]
2010	29.2	[31]
2011	46	[27]
2011	86.75	[33]
2011	91.2	[31]
2012	108	[27]
2012	160	[31]
2013	160	[27]
2013	275	[25,8,9]

(LCOE), a major criterion used to compare among alternative energy technologies. LCOE sums all of the expected costs—discounted over the life of the project (capital investment and operational)—and divides by the lifetime expected energy production (also discounted) to provide the averaged lifetime cost of producing electrical energy in $/kWh. Future projections of LCOE calculations depend on many factors including capital cost and learning rate (provided by this paper) together with discount rate, operational and maintenance costs and irradiance conditions.

LCOE has been calculated for silicon cell photovoltaics (PV) [11] and, more recently, for both PV and Concentrating Solar Power (CSP), including the use of learning rates [10]. For CPV systems, the LCOE has only been calculated [12–14] using assumed single point values for CPV cost, without learning rates. The results of this paper enable the calculation of evolving LCOEs for CPV, taking into account future trends in deployment volumes and system costs which will be of value to system developers, installers and government policy makers [15].

This paper examines the turn-key system price as a function of time for a fully installed CPV system in United States dollars per watt ($/W). It updates the price and deployed volume data found in [16], derives a learning rate with confidence interval (CI) and further presents a comparison with learning rates of CSP and PV systems. In addition, CPV prices are projected into the future and compared with projections of other authors.

For this work, the price of a CPV system is defined to include:

(i) CPV modules, which includes optic(s) that collect and concentrate sunlight, a high efficiency multi-junction photovoltaic cell mounted on an electrical carrier, the module framing and heat sinks
(ii) dual-axis tracker(s);
(iii) inverter(s) to convert DC photovoltaic output into AC;
(iv) all wiring and other balance-of-systems components;
(v) all labour and regulatory costs associated with the construction and connection of the system to the electricity grid.

We will contain this study to high concentration systems with >200× concentration.

2. HISTORIC CPV SYSTEM PRICES AND DEPLOYMENT VOLUMES

There is no commodity market or industry mechanism that tracks CPV system prices, so the first contribution of this work is to create a dataset for CPV prices. Publically released values for prices over the time period of 2007 to 2013 are collected with their sources in Table I. They are also displayed graphically by year in Figure 1. When a

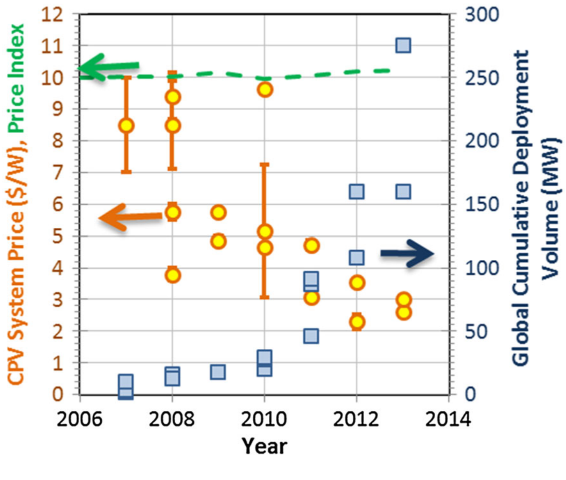

Figure 1. Graphical representation of the data for system price, *P*, (orange circles) and cumulative deployed volume, *V*, (blue squares) as contained in Table I. Error bars on price data are used to represent the range of values given by a particular reference. The dashed green line is the price index for private fixed investment in non-residential equipment set to 10 in 2006 [34].

reference provides a range of prices, this is displayed graphically in Figure 1 as a data point of the average value with error bars stretching across the range. Cost data are confidential to the CPV system supplier and developer and cannot therefore be used in a published study of this type. We follow the approach of [17] by using price instead of cost. CPV is an emerging technology for which price may be discounted compared to cost in order to compete with more established technologies such as PV and CSP. However the use of price enables the calculation of LCOE, as in [10], of interest to system developers.

This data covers a range of system sizes from kWs to MWs. Table I and the right hand axis of Figure 1 also include values for global cumulative deployed volume for CPV systems. Volume data is in general more reliable than price data since developers disclose project size more readily than the project price. A confidence interval approach is used in this study to track the impact of price variability. There is a clear trend of significant price decrease over the past seven years; in contrast, the price index for private fixed investment in non-residential equipment [34], also shown in Figure 1, has been very flat.

For both price and volume data, the power rating is dependent on the test condition employed, but the data sources used herein did not specify the power rating, which could therefore range between 850 W/m^2 and 1000 W/m^2. As of September 2013, the International Energy Agency published the 62-670-1 concentrated standard test condition of 1000 W/m^2 at 25 °C; thus, all power values in 2014 and thereafter are assumed to be to this rating.

Looking at the dataset, it is clear that prices have dropped from an average of 7–10 $/W in 2007 to 2.6–3.0 $/W in 2013. At the same time, the cumulative volume of globally deployed CPV systems has been increasing steadily, starting from 5 MW in 2007 and reaching 160–275 MW in 2013. The trends in both of the parameters are non-linear—the nature of the relationships will be examined in the next sections.

3. LEARNING CURVE ANALYSIS

3.1. CPV learning rate with confidence interval

The decline in CPV system prices illustrated in Figure 1 is due to technological progress in the various components of the integrated system including: better performing components (higher efficiency cells and optics), lower costs of manufacturing and more effective integration and deployment methods. Most, if not all of these factors, will improve with increasing deployment volumes because production volumes motivate investment in research and development budgets. They also result in economies of scale in manufacturing as well as more efficient deployment methods.

We can investigate the relationship between CPV deployment volume and system price using a learning curve analysis (also known as experience curve analysis), which has been used to model prices of many technologically intensive products including automobiles, aircraft, military equipment [35] and energy systems [36–39].

A learning curve models price, *P*, as a function of cumulated deployment volume, *V*, as:

$$P = \alpha V^{\beta} \tag{1}$$

or

$$\log(P) = \log(\alpha) + \beta \log(V) \tag{2}$$

The parameters α and β are found from a linear regression of log(*P*) against log(*V*). If the deployment volume, *V* doubles, the price can be seen from Equation (1) to change by the ratio 2^{β}. Typically β is negative, resulting in a price reduction. The learning rate (*LR*) is defined as:

$$LR = 1 - 2^{\beta} \tag{3}$$

and represents the proportional reduction in price associated with a doubling in volume.

To evaluate the learning rate for the data in Table I we must create (*V*,*P*) pairs of data but not every source gives both price and volume. When there is a single price but multiple volumes for a given year, each volume is paired with the same price, (e.g. in 2007 this results in three (*V*,*P*) data points). When there are multiple values of both, prices are attributed to volumes pairwise, (e.g. in 2008, four prices are attributed to two volumes resulting in four (*V*,*P*) data points).

Where our dataset includes multiple prices and/or volumes for a single year, the prices are sequenced to decline and the volumes to increase. No method of associating prices and volumes from independent sources is perfect but our method follows a clear and rational protocol. The sensitivity of the analysis to this pairing methodology was tested: other methods gave results within 1–3% of those reported herein.

The pairing method resulted in 19 data points, which exhibited a non-linear “L”-shaped relationship in a simple *P* as a function of *V* graph (not included). When plotted on a log(*P*) versus log(*V*) graph in Figure 2 (orange circles)"", a linear relationship is evident. Furthermore, a uniform variability throughout the data range (homoscedasticity) indicates that linear regression may be employed. Therefore, Equation (2) is appropriate as a model for these data, and the fitted line is included in Figure 2. The variable β is found to be −0.288 with a standard error of 0.044. Using Equation (3), we obtain an estimate of the learning rate of 18%.

The validation criteria of the learning curve methodology for energy technologies provided in [40] indicate that it is inappropriate for technologies that have (i) non-linear or discontinuous learning curves or (ii) costs that increase after some initial deployment instead of decreasing. It can be seen from Figure 1 that CPV does not suffer from these issues.

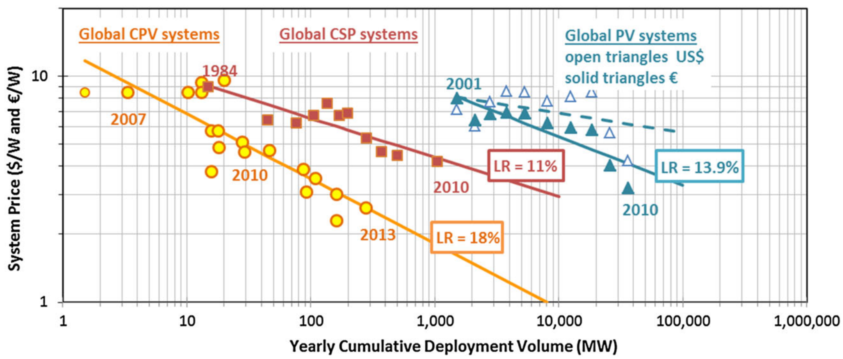

Figure 2. Learning curve plot, also known as log/log relationship between system price, *P*, and cumulated deployment volume, *V*, for CPV, CSP, [38], and PV, [40] systems. For PV systems, solid line is the fit to €, dashed line is the fit to US$.

Ref. [40] also comments that "uncertainties in future technology costs are reflected in uncertainties in the learning coefficient". As such, we can now assess the accuracy associated with our learning rate as 18%. The significant scatter in the data resulted in a relatively low R^2 value of 0.72. If, instead, the average *V* and *P* values for each year are analysed, there is less scatter and the R^2 is found to be 0.94 with the same learning rate. However, improving R^2 in this way does not improve the forecast accuracy.

We propose an approach based on maintaining the information contained in the raw data [41,42] and using regression analysis. We use the standard error on β to obtain a 90% confidence interval (CI) on β, which converts into a 90% CI on the learning rate of 14 to 22%. This indicates that, with our data sample, we are 90% confident of the learning rate being above 14% and lower than 22%. The width of the CI reflects the scatter in the data.

3.2. Comparison of learning rates and current prices among solar technologies

The above learning rate of 18% for CPV *systems* is similar to the learning rate for PV *modules* [10,17,43], which depending on methodology and time span, shows a value between 18 and 20%. However, a fully installed system is much more integrated than a module. There is significantly less research on system learning rates; however, from the point of view of implementation, system price is the more relevant metric. This paper compares the learning rate for CPV *systems* with the learning rate for PV and CSP *systems*, as summarized in Figure 2 and Table II.

Ref. [44] employs global data from the International Energy Agency (in Euros, €) to determine a learning rate of 13.9% for PV systems. When we convert into $ to include on the same plot as our CPV data, the *LR* is 5.8% due to the exchange rate trend between the two currencies. Since the majority of the manufacturing and deployments were in Europe during the time period in that study, we suggest that the *LR* of 13.9% better reflects the real learning effects.

The value for the *LR* of Dutch PV systems, [17], also in €, is similar at 12%. [10] provides an aggregation of CSP data in $ and an associated *LR* of 11%. For the sake of completeness, converting our CPV system prices from $ to €, the learning rate is essentially unchanged at 17% because the exchange rates were more stable in the 2007–2013 time period.

It should be noted that a number of factors can affect the above comparison, including:

(a) the timespan of the dataset—a long time span is desired. The CPV dataset spans 2007 to 2013—seven

Table II. Summary of learning rates and system prices reported for the three commercial solar power technologies. For global CPV systems, as derived in this paper, the range is the 90% CI, whereas for CSP and PV systems the range is the maximum and minimum values reported in those studies.

	Global CPV Systems (Current paper)	CSP Systems	PV Systems	
Learning Rate (%) Mid pt: (range)	18% (14%, 23%)	11% [10]	12% [17]	14% [44]
Time period	2007-2013	1984-2010	1992-2002	2001-2010
2012-2013 Systems Price ($/W) Mid pt: (range)	2.8 (2.3, 3.4):	5.9 (3.8, 8.0) [45]		
			2.7: (1.3, 6.0) [46]	
			3.3: (1.6, 5.0) [47]	
			2.5: (1.5, 3.5) [45]	
			1.9 [48]	

years—the entire time period of commercial CPV deployment.

(b) system sizes—larger systems have lower $/W prices due to buying power and being able to spread a project's fixed costs over a larger system. All published analyses of which we are aware use equal weighting independent of the system size,and we have followed this approach.

(c) non-learning factors affecting price—for example policy and incentives or market factors. This has primarily affected PV systems since silicon module pricing stalled due to a polysilicon shortage in 2003–2006 and experienced dramatic drops in pricing in 2010–2013 due to major increases in manufacturing supply and high competition.

(d) geographic specificity—while the equipment market is very global in extent, the non-equipment costs of a system deployment are likely to be more regionally dependent (e.g. labour costs, regulatory costs, etc.).

We did not observe a systematic influence from the above factors on our CPV learning rate. As more CPV projects are deployed it should be possible to disaggregate the data to analyse for these effects.

3.3. Comparison of current system prices among solar technologies

The regression fit also provides a price for CPV systems in 2013 (as an overall estimate instead of a value from one source) of 2.8 $/W, with 90% confidence of being between 2.3 and 3.4 $/W. This compares competitively with the global prices for PV system prices which were, at the end of 2012, on the order of 2.7 $/W with a range of 1.3 to 6.0 $/W [46] (these are the prices for PV systems larger than 10 kW in 19 countries). Global aggregated values for 2013 were estimated to be 1.6 to 3.3 $/W for utility-sized systems and 2 to 4.95 $/W for distribution connected systems [47]. The IEA [45] additionally provides a 2012 range of 1.5 to 3.5 $/W for large-scale PV systems and a range of 3.8 to 8.0 $/W for CSP systems.[1] The price for utility scale PV deployment in South Africa, in 2013, was 1.9 $/W [48].

These estimates are summarized in Table II, which shows that in 2013, PV systems were—at least at the utility size and in certain countries—able to achieve the lowest pricing, followed by CPV. However, overall CPV and PV are cost competitive with each other, with the average mid-point estimate for PV being just 7% lower than that for CPV.

In a free market one would expect some similarity among PV, CPV and CSP system prices. CPV prices can be expected to be higher than PV prices, since most PV deployments are fixed tilt, while the tracking used in CPV results in higher system prices but also higher energy yields. Current CSP system prices are higher than those for both PV and CPV; however, it should be noted that CSP technologies can use hybridization and storage capability, making them attractive from the viewpoint of dispatchability, such that a higher system price is acceptable.

3.4. Current competitive position of CPV

There are three general conclusions that can be drawn from the above comparisons. First, the current CPV system price is slightly higher than the corresponding figure for PV, while the CSP figure is substantially higher. Second, the *LR* of CPV systems is stronger than the *LR* for PV and CSP systems. When these two points are considered together, they indicate that not only will the prices for CPV remain competitive, but that there is a likelihood of significant further decreases, leading towards CPV having the lowest prices of all the available solar technologies. Third, since CPV deployment volumes are currently very low when compared with the established technology of PV, only a very modest level of further investment (a relatively small volume of deployment) is required for CPV systems to achieve a lower price per watt than PV or CSP. Figure 2 shows that CPV can achieve $1/W when 7900 MW have been deployed, which is very small, for example compared to global PV deployment, projected to reach 277 GW in 2020 [49].

4. CPV SYSTEM PRICE PROJECTIONS

Accurate predictions of future prices of CPV technology versus *time* are clearly desirable, but extrapolation of historic trends typically results in a high degree of uncertainty [22,50]. The learning curve can provide a more robust price forecast since it can be associated with projected deployment volumes versus time, which are more commonly and easily studied, as will be shown below.

4.1. Price projections based on learning curve and volume projections

We make use of projections of market volume from three commercial market analyses. Yole Consulting [51] provides a conservative and an optimistic market projection for CPV volume until 2020. SPV [52] provides low, conservative and high projections until 2016. IHS [27] provides a volume projection to 2020. All three volume predictions are converted into price predictions using the *LR* of section 1 and shown in Figure 3. We again use the standard error of our estimates to obtain a 90% CI on the price projections. It can be seen from Figure 3 that it is

[1]The range of prices for CSP systems is wide due to the additional costs of dry cooling in areas of water shortage and the cost of storage incorporated into some projects.

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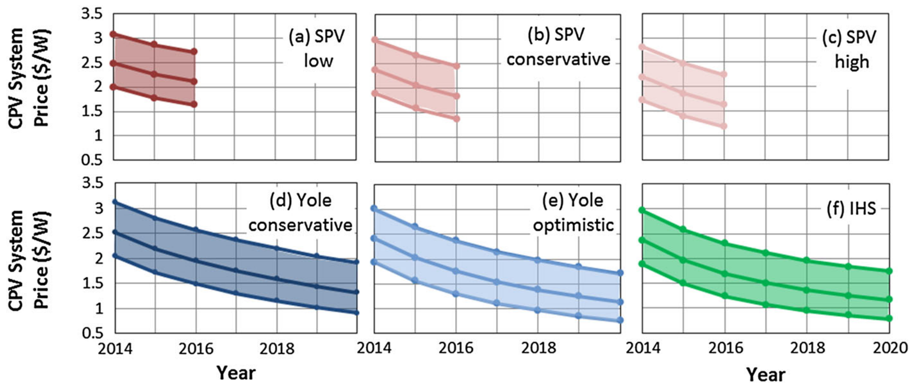

Figure 3. CPV system price projections and associated 90% confidence intervals based on volume projections found in market analyses by three companies: based on SPV volume projections for (a) "low", (b) "conservative" and (c) "high" scenarios, [52]; based on Yole Consulting volume projections for (d) "conservative" and (e) "optimistic" scenarios [51]; and based on IHS volume projections [27].

important to take into account the *LR* CI as it converts into a significant degree of uncertainty in the price projections.

The deployment volume projections from Yole, SPV and IHS and our corresponding price projections are presented in Figure 4 with a logarithmic scale. For clarity, the colour coding in Figure 3 is carried over into Figure 4, while CIs are displayed only at the end of the time period as arrowed bars. Two commercial price forecasts [7,27] (red triangles) are seen to be comparable to those obtained from the learning analysis. Although the learning analysis relies on volume projections from other sources in order to make price projections, Figure 4 shows that the expected price projections do not vary substantially from one source to another. One outcome of the *LR* relationship (in particular when $|\beta| < 1$) is that the spread of price projections is narrower than the spread of volume projections.

4.2. Price projections based on extrapolation of price trends

We now compare the above volume-derived price projections with a more conventional approach based on extrapolation of the price trends in Figure 1. Evidently Figure 1 shows a non-linear, heteroscedastic trend in CPV system prices. Log (P) as a function of time gives a linear trend with reduced heteroscedasticity, resulting in the projection given by the brown line in Figure 4. It is clear that this approach predicts extremely low prices, which means

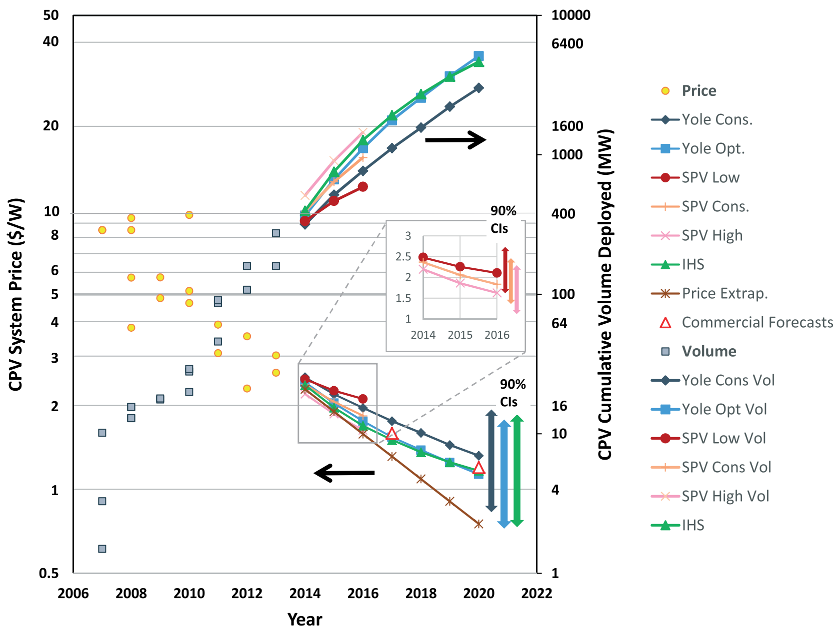

Figure 4. Projections of CPV system prices (left axis) and volumes (right axis) using multiple methodologies. The commercial forecasted prices are from [7,27].

that volume growth would need to be substantially higher than even the most aggressive scenario included here. This highlights that a second advantage of the learning approach lies not only in estimating the learning rate, but also in providing a “sanity check” on future price projections [41].

4.3. Discussion of learning curve projections

Learning curve analysis relates price to cumulative deployment volume, which can be both an advantage and a disadvantage. In the absence of volume projections it cannot be used to forecast prices but remains useful for comparing historical learning rates of alternative technologies, as was done in Section 3.

Furthermore, the learning curve method can be used to estimate the rate of growth of deployment that would be necessary to achieve a given future price target. For instance, in order to achieve a price of $1/W in 2020, the cumulative deployment volume requires a cumulative annual growth rate (CAGR) of 67%, reaching a cumulative deployed volume of 7,900 MW. These growth rates, although high, are nevertheless lower than the historical CAGR of 88% during the period 2007-13 (found by fitting this paper’s volume data) and have a possibility of being realised since CPV LCOE is particularly competitive in high-sun climates, which is where solar industry growth rates are the highest.

The main approach used in this paper is based on volume projections provided by market analysts, which are likely to be more realistic since they are based on interviews with major industry players. and therefore incorporate information about the status of future possible deployment contracts. When volume projections are available, the learning curve method can be used to derive price projections, which are less variable than the volume projections upon which they are based, since $|\beta| < 1$. Several scenarios for market growth can be considered and compared. For example, from Yole’s “conservative” volume projection the predicted price in 2020 would be $1.32/W, whereas from Yole’s “optimistic” volume projection the same price would be $1.13/W. Furthermore, deployed volume data are typically more accessible and more commonly tracked than price data, thus in the future one can use the learning rate analysis to translate actual volume growth into current pricing and pricing predictions.

5. CONCLUSIONS

This paper provides a comprehensive aggregation of CPV system prices and volumes. Using the fit to the historic and 2013 data, the price of CPV systems in 2013 was found to be 2.8 $/W with a confidence of 90% being within 2.3 - 3.4 $/W, which is competitive with PV systems (1.3–6.0 $/W) and lower than CSP systems (3.8–8.0 $/W).

The dataset enabled the evaluation of CPV system learning rate, which was found to be 18% and between 14% and 22% with a 90% confidence value. CPV system prices can therefore be expected to drop by 18% for every doubling of cumulative deployment volumes. This learning rate is higher than the learning rates for global CSP systems (11%) and PV systems (12%–14%). Competitive current system prices combined with a higher learning rate puts CPV in a good position relative to PV and CSP for the rest of this decade.

The learning rate approach is robust for evaluating future prices, as long as the sources of uncertainty are quantified:

- The variability in past data is reflected in the present paper in 90% CIs on the estimates.
- The variability in future projections of CPV deployment volume was reflected in the analysis of multiple scenarios.

The learning rate is also employed to assess the deployment volume required in order to achieve future price targets. To achieve a price of 1 $/W in 2020, the cumulative deployment needs to increase at a CAGR of 67% (which is lower than the historical CAGR for CPV systems) and grow to 7,900 MW. A judgement is then needed as to whether the rapid CPV deployment during its initial commercialization can be sustained over the remainder of the current decade.

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