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Empirically observed learning rates for concentrating solar power and their responses to regime change

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Concentrating solar power (CSP) capacity has expanded slower than other renewable technologies and its costs are still high. Until now, there have been too few CSP projects to derive robust conclusions about its cost development. Here we present an empirical study of the cost development of all operating CSP stations and those under construction, examining the roles of capacity growth, industry continuity, and policy support design. We identify distinct CSP expansion phases, each characterized by different cost pressure in the policy regime and different industry continuity. In 2008–2011, with low cost pressure and following industry discontinuity, costs increased. In the current phase (2011—present), with high cost pressure and continuous industry development, costs decreased rapidly. Data for projects under construction suggest that this trend is continuing and accelerating. If support policies and industrial structure are sustained, we see no near-term factors that would hinder further cost decreases.

Policies to promote relatively expensive renewable energy technologies are often justified on the basis of learning effects, which make these technologies less expensive and more competitive the more they are deployed[1–3]. The metric to describe this is the learning rate, which corresponds to the investment cost reduction for each doubling of installed capacity. Photovoltaic modules, for example, have had an average learning rate of 20% since 1990, comparing favourably to coal power (at 5–8%) over its first installed 1,000 GW (refs 4–6). Because of its ability to provide dispatchable renewable electricity, concentrating solar power (CSP) may be an attractive technology to policymakers. However, few CSP stations have been built to date, with three-quarters of them having been finished within the last six years, making it difficult until now to empirically estimate the CSP learning rate. Most policy analyses have assumed a learning rate of 5–15%, based on analysis of CSP stations built in the 1980s or on selections of a few stations[3,7–9], as well as extrapolation from other technologies[10–13].

The particular historical development of CSP also offers insights of relevance to the theory of technological learning. Current theory explains that growth improves costs because growth increases the likelihood of fundamental technological advances, incremental learning by doing, economies of scale in manufacturing, and standardization[6,14–18]. Nonetheless, theory has not yet established a clear link to two other potentially important factors: policy support design, and industry continuity. However, a learning curve analysis for CSP can shed light on this link because CSP has grown under a sequence of different policy regimes, rather than many regimes operating in parallel, and because the CSP industry has been marked by a long period of discontinuity, when new project development halted entirely.

Here, we present a comprehensive, global empirical study of the learning rate for CSP, based on observed costs for all CSP stations currently operating or under construction. Our findings suggest that the current learning rate for CSP is 18% or higher, making the prospects of this technology more attractive than previously assumed. We further suggest that the CSP technological learning rate has benefited substantially during periods of high cost pressure in policy support, and during periods of continuity in the component manufacturing industry.

CSP policy regimes and expansion phases

The global CSP generation capacity is currently 4.8 GW, with an additional 2 GW under construction (Fig. 1; see Supplementary Data 1 for all data and sources). This expansion happened in three phases, each driven by a specific policy regime: 1984–1990 in California; 2007–2013 in Spain; and, 2013–today in several countries. As there is only a slight overlap between the second and third phases, this phase-wise expansion enables us to consider the effects of the separate policy regimes in isolation, something not possible for wind power or photovoltaics, which benefited from multiple, parallel regimes.

The first phase began in 1984 as the company Luz built the first of nine Solar Electricity Generation Systems (SEGS), totalling 350 MW, in the Californian desert. The policy regime enabling the SEGS plants was the Public Utilities Regulatory Policy Act (PURPA), supplemented by Federal and State tax credits. PURPA required public utilities to purchase electricity through long-term power-purchase agreements (PPA) at rates equal to the avoided cost of covering peak demand by new fossil fuel power. In California, regulators included the avoided cost of environmental externalities. Under PURPA, all renewables projects, regardless of the technology, competed against each other, leading to high cost pressure. During the early 1980s, the expectation of high natural gas prices led to avoided cost estimates high enough to make construction of the SEGS financially viable. Gas prices then fell in the late 1980s, and the remuneration under PURPA became too low to support further CSP expansion. After failing to finance projects under development, Luz declared insolvency in 1991 and sold the SEGS units, which still operate today[19–23].

The second expansion phase commenced in 2007, resulting from a Spanish law increasing the feed-in tariff (FIT) for CSP facilities of up to 50 MW to US$0.43 kWh^{-1} (€$_{nominal}$0.27 kWh^{-1}). The government also offered a premium over the wholesale market price, but this option was abandoned in 2010. The government guaranteed the FIT for 25 years, followed by 15 additional years

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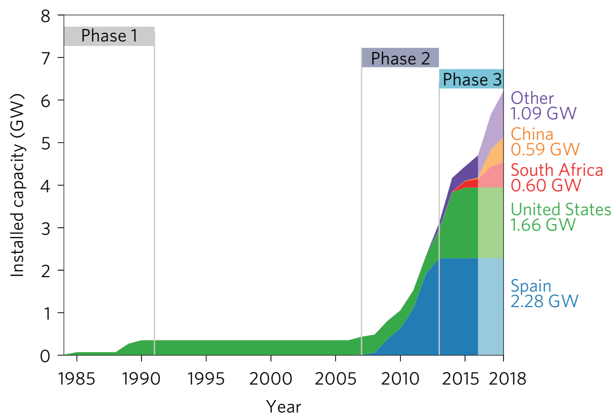

Figure 1 | Global expansion of CSP. The plot shows the expansion of CSP for stations built in 1984–2016 and stations currently under construction and scheduled for completion in 2016–2018. Solid colours describe existing CSP capacity; transparent colours show capacity under construction. Not shown: 5 stations of, in total, 322 MW capacity under construction in India (250 MW), China (60 MW) and Mexico (12 MW), as their completion dates are unknown. Hybrid stations are excluded. Source data can be found in Supplementary Data 1.

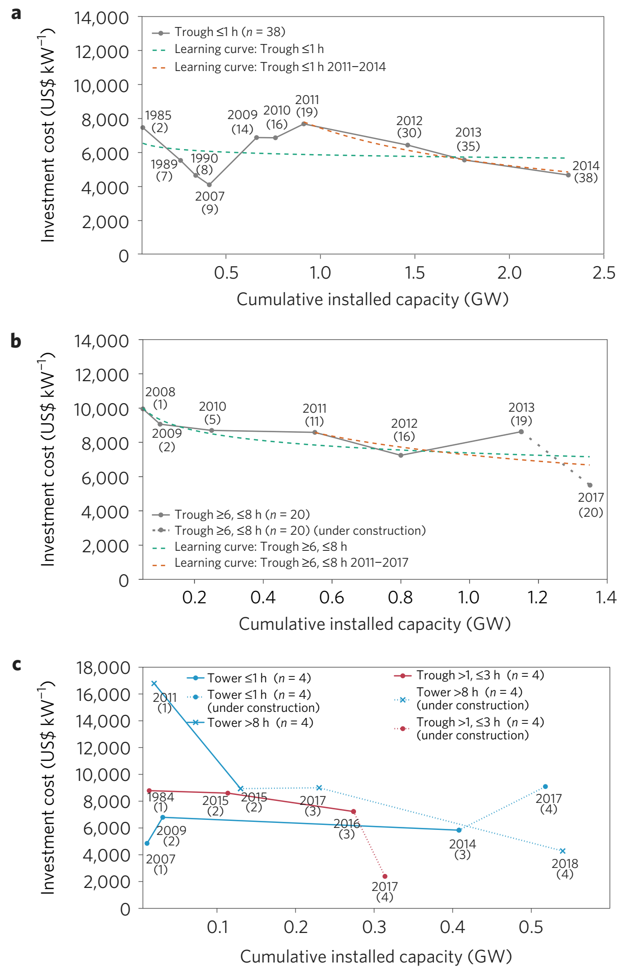

Figure 2 | Investment cost development and fitted learning curves for different types of CSP. a–c, The cost development curves and fitted learning curves (see Methods for details) for parabolic trough (PT) stations with <1 h thermal storage (2011–2014 learning rate = 0.297, R^2 = 0.972) (**a**), PT stations with 6–8 h of thermal storage (2008–2017 learning rate = 0.068, R^2 = 0.577; 2011–2017 learning rate = 0.175, R^2 = 0.337) (**b**), and for solar towers (ST) and PT with 1–3 h storage (no good learning curve fit) (**c**). Technology/storage configurations with 3 or fewer stations are not shown. The years written on each data point indicate when each installed capacity was reached; the numbers in brackets indicate the number of stations of each type installed by each year. The dashed lines are the fitted learning curves (see Methods for equation). Data points are yearly averages. See Supplementary Data 1 for source data.

at 80% of the initial tariff. All CSP stations were eligible and although the FIT was initially meant to decrease after the first 500 MW, no clear mechanism to decrease support over time was introduced and support remained constant, meaning that there was no downward pressure on costs. In 2007, developers applied for grid connection for 4 GW of new capacity, which rose to 15.6 GW by 2009[24], representing almost half of the Spanish peak load; in fact, the FIT was so attractive that the government delayed the operation date for new stations. The government stopped accepting new applications in 2012 and by 2013, 49 projects totalling 2.3 GW had been completed. In the wake of the financial crisis, the government then retroactively reduced the FIT for all existing stations, marking the end of the Spanish CSP expansion. A lingering effect is that Spanish companies, built up during the FIT regime in 2007–2012, remain dominant in the global CSP market today, although their domestic market has collapsed[24–27].

The third phase started in 2013 and is marked by expansion first in the United States (which subsequently halted, following uncertainty about future policy support[10]), and then in emerging countries including China, South Africa and Morocco. Across these countries, policy support shifted to tendering schemes, resulting in long-term PPAs. Each tender involved competition, and this led to rapidly decreasing remuneration, as we describe in the next section.

The last few years also saw market actors disappear or experience economic difficulties. The dominant CSP company, Abengoa, narrowly avoided insolvency in 2016, and is now changing its business model to focus on project development, abandoning the model of developing, owning and operating CSP stations[28,29]. Major component manufacturers (for example, Siemens) and project developers (for example, Solar Millennium) have exited the industry, and the two largest receiver manufacturers—Schott and Rioglass—merged in 2016[30–34]. The number of experienced industry players is today lower than five years ago, although new companies, especially Chinese manufacturers, are emerging.

Observed investment cost development and learning rates

Two types of CSP station—parabolic trough (PT) and solar tower (ST)—account for over 90% of the industry, with Fresnel stations adding a few per cent to global capacity. One can also differentiate CSP stations according to their thermal storage capacity, which influences plant design and operation. Because of the fundamental difference between the technologies and storage configurations, it is appropriate to develop separate learning rates[10,11] (see Methods).

Figure 2a shows the development of the yearly average investment cost of the most common CSP configuration: PT with little (≤1 h) or no-storage capacity. Following strong reductions during the SEGS era (pre-1990), average investment costs almost doubled during early Spanish era (2007–2011); about one-third of this increase is due to the weaker solar resource in Spain (see Supplementary Note 1). Since 2011, the investment costs steadily decreased, as technology improved; only one-sixth of the learning rate can be attributed to better solar resources for new projects (see Supplementary Note 1). The average investment costs for the latest no-storage PT stations were roughly the same as in 2007, but 40% lower than the 2011 peak. However, the cost difference between single stations is large, up to 20% of the yearly average (see Supplementary Note 2). Due to the cost increase in 2008–2011, fitting a learning curve over the entire time is of little value (R^2 = 0.04). For the time after 2011,

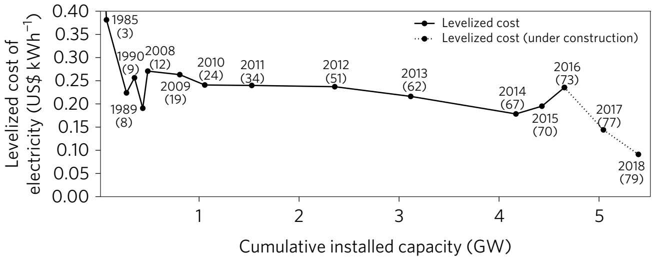

Figure 3 | Levelized cost of electricity for all CSP stations. Each point is the average of all stations entering into operation in that year. The years written on each data point indicate when each installed capacity was reached; the numbers in brackets indicate the number of stations of each configuration installed by each year. The LCOE for SEGS 1 lies above the plotted range. See Supplementary Data 1 for source data.

however, the function fits very well (R^2 = 0.97), with a learning rate of 30%; using alternative, not project-specific, data from the Spanish government, the learning rate is 21% (see Supplementary Note 3).

Figure 2b shows the cost development for PT with 6–8 h of thermal storage. This curve follows a different pattern, as no such stations were built before 2008. After a rapid cost decrease in 2008–09 (between Andasol 1 & 2; mainly driven by exchange rate changes, see Supplementary Note 4), costs remained stable until 2011 and decreased weakly since. The most recent station (Noor II, under construction) is 40% cheaper than the first, Andasol 1, while two particularly expensive Spanish stations completed in 2013 were major outliers. For the entire period 2008–2017, the learning function fits acceptably (R^2 = 0.58) with a learning rate of 7%, whereas it is considerably higher (18%) but with a worse fit (R^2 = 0.34) for the same subperiod (2011—present) as in Fig. 2a.

Figure 2c shows the cost development for ST, and for other PT configurations. Costs follow no clear trend, primarily since there are very few stations of each configuration.

Observed development of levelized costs of electricity

Figure 3 shows that the generation-weighted average levelized cost of electricity (LCOE) of CSP has been volatile over time. It decreased sharply during the SEGS era, then increased by 40% in 2008 with the shift to Spain, decreased by about 40% again by 2014, and then increased by 30% in 2015–16. The average LCOE of existing stations in 2015–16 is US$0.22 kWh^{-1}, slightly higher than for Nevada Solar One (2007), and up from US$0.18 kWh^{-1} in 2014, following a shift in expansion to new technologies (more towers; larger storage) and new countries (South Africa, Morocco); individual stations deviate strongly from the average (see Supplementary Note 2). Except for the period 2012–14, when the LCOE decrease was driven by a shift to better solar resources, changes in technology cost are the main driver of LCOE changes (see Supplementary Note 1). The average capacity factor has increased from 30% in 2007–09 to 50% in the newest stations (see Supplementary Note 6), indicating that CSP developers seek not only to reduce costs but increasingly also to leverage the dispatchability of CSP.

The decreasing LCOE trend of 2009–2014 accelerates for new stations under construction, decreasing LCOE by 33% over the period 2016–18. The Chinese stations drive this trend, claiming 35–60% lower LCOE than recent stations in South Africa, as low as US$0.07 kWh^{-1}, despite a much worse solar resource. Although the high (US$0.18 kWh^{-1}) Chinese FIT indicates that these LCOE statements may be exaggeratedly low, the long-term decreasing LCOE trend appears to continue and even accelerate.

Observed remuneration for CSP stations

Whereas the Spanish phase (2007–13) was characterized by constant FIT remuneration in local currency, Fig. 4 shows that the shift to PPAs and expansion in other countries caused a sharp remuneration

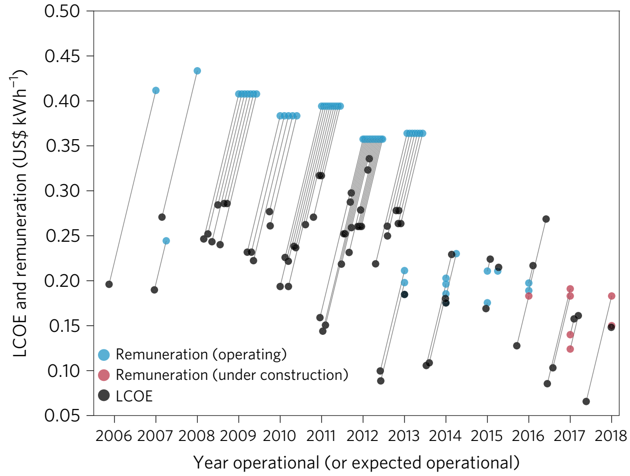

Figure 4 | LCOE and remuneration of each individual CSP station with both data points available. The first phase (1984–1990) is not shown, as we have no remuneration data for SEGS. See Supplementary Data 1 for source data.

decrease in 2013, from US$0.36 kWh^{-1} to US$0.14–0.21 kWh^{-1} within one year, followed by a weak decrease since. The South African stations have higher LCOE than remuneration, as the time-of-day bonus is not included in Fig. 4. The Moroccan stations Noor I and II also have higher LCOE than remuneration, probably because our weighted average cost of capital (WACC) assumption of 5% is too high given the large amount of concessional finance for these plants, which typically depresses the WACC (see Methods for details on the WACC assumptions).

We can say that cost pressure has increased markedly since 2013, because while the LCOE has decreased, remuneration has decreased more. During the Spanish phase, the average difference between remuneration and LCOE is US$0.12 kWh^{-1}, whereas it is US$0.03 kWh^{-1} for the post-Spanish stations (see Supplementary Note 5). Note that these numbers include the 30% investment tax credit for the US stations Solana, Genesis, Ivanpah, Mojave, and Crescent Dunes, represented as a 30% increase in the PPA price (also in Fig. 4), but not the 270% time-of-day bonus for the South African stations during 5 peak hours in the afternoon: assuming 17 h baseload (from 5 h storage), this would roughly equal a 50% support increase for these stations.

Today, the South African policy support in particular drives the reduction in remuneration, with tender outcomes in 2016 40% lower than in 2014. In 2016, the Chinese government introduced a FIT of US$0.18 kWh^{-1} (ref. 35), breaking with the general trend of decreasing remuneration. Recent tender bids elsewhere are low: SolarReserve set a record in 2016 bidding for a 240 MW tower in Chile at US$0.06 kWh^{-1}, a price that could compete with fossil fuels for dispatchable electricity[36]. For this trend to persist, continued cost pressure is necessary, requiring project developers to continue reducing LCOE.

Policy regime impacts on cost development

In the analysis below, we observe changes in policy regimes to have had a major influence on the cost development of CSP, controlling for other factors that have also changed. One such factor is a general shift towards lower solar resources at the station sites. The shift from North American deserts to Spain meant a reduction of the solar resource but this explains only about one-third of the 90% price increase of no-storage PT CSP from 2007–2011 and about half of the 40% LCOE increase in 2008 (see Supplementary Data 1 and Supplementary Note 1). Another potential factor is changes in commodity prices, which have affected the learning rates of wind power in particular[9], but there appears to be little relationship between CSP costs and commodity prices (see Supplementary Note 7).

Instead, the most striking development underlying both the LCOE development and PT learning curves is a shift in expansion across a sequence of regions and the accompanying shift in policy regimes. Three causal pathways appear to play a role.

First, there seems to be a first-mover disadvantage, making the first stations in any given country more expensive than those that follow. The two exceptions to this are China and India, where all stations are major downwards outliers in our data; possibly, lower labour costs can be a contributing factor to the very low—possibly exceedingly low—stated LCOEs in these countries. This can cause price jumps when the locus of CSP development shifts from one country to another. For example, the Spanish stations in 2009 were 70% more expensive than the last SEGS stations. Similarly, first stations built in the United Arab Emirates (Shams) and South Africa (KaXu) cost the same or more than the last Spanish plants, despite being twice the size and having better solar resources. In other words, continuous expansion driven by a stable policy regime within a single country stimulates learning.

Second, it appears that discontinuities in the industry lead to rising prices, as later engineers need to 'reinvent the wheel'. In 1991 Luz, the only active CSP company at the time, went bankrupt, and while the SEGS are still operational today[21], most engineers involved in construction moved on to other jobs. Interestingly, some of the engineers involved in operating the SEGS stations contributed to planning Nevada Solar One (2007), and it is striking that this station fits well on the SEGS cost curve. These American engineers played no role in the Spanish expansion, despite it involving no-storage PT CSP similar to SEGS. None of the Spanish and German companies in Spain had previous CSP experience, and this also helps explain the particularly sharp rise in costs. By 2011, the market had become more diversified with several companies experienced in development and manufacturing, and costs started decreasing. During the Spanish expansion, we observe a smooth cost reduction trajectory for large-storage plants but not for small-storage ones (see Fig. 2a,b). Almost all of the large storage plants were built by a single company (Cobra), which could accumulate experience quickly, whereas the market for plants without storage included several different companies, each gaining experience more slowly before costs started to decrease. Hence, accumulation of experience within companies—rather than at the global level—appears to drive learning rates: when policy support becomes inadequate and firms exit the market, learning suffers.

Third, the degree of competitive cost pressure that a given policy regime generates appears to play a role. Such cost pressures differed strongly across the three regimes. In the Spanish regime, there was no competition and low cost pressure, as all CSP stations were eligible to receive the high and constant tariff[25]. It is in Spain where the lowest, or even negative, learning rates can be observed. Before and after the Spanish CSP expansion phase, first under PURPA in California and later with separate national tendering schemes, cost pressures were substantially higher; each project developer has had to compete with other bidders, and in the case of PURPA these included other renewable energy technologies. Cost pressure of the support scheme correlates with the cost reductions seen in each expansion phase.

Conclusions

We have shown that investment costs, LCOE and remuneration of CSP have decreased rapidly over the last five years, after a marked increase in 2008–11. They are likely to continue decreasing into the near future, despite a short-term LCOE increase in 2015–16 caused by a shift to new countries and less mature technology configurations. Concentrating solar power is still more expensive than wind and photovoltaics, but the observed recent (2011—present) trend of decreasing costs is strong, on par with photovoltaics and substantially higher than previous estimates and expectations for CSP.

We identified three expansion phases for CSP, each with a distinct policy regime and industry development, and each with different cost development trends. Industry discontinuity in the 1990s had a strong negative impact on CSP cost development. We also observed that costs tend to be higher for first projects in each new country. In contrast, during times of continuous expansion and continuity and diversity among suppliers and developers, costs decreased. Our results indicate that continuity both in policy support and in the project developer and component manufacturing industries are important for cost reduction.

In this sense, the recent financial problems of the dominant CSP actor—Abengoa—may be a threat not only to that company, but also to global CSP development. Further, the fact that markets for solar-specific components are thin raises concerns about continued cost reductions. If CSP is to expand and continue experiencing decreasing costs, ensuring and increasing industry diversity could be a key policy task in the coming years.

Finally, we show that learning effects are strongest in policy regimes with high cost pressure. During the Spanish regime, where the absence of decreasing support over time resulted in low cost pressure, the observed cost reductions were miniscule. Hence, our results suggest that policy support design matters not only for the pace of expansion, but also for technology cost development: without cost pressure, CSP did not get cheaper. Although the recently announced Chinese FIT appears to have low cost pressure, the tender schemes elsewhere are highly competitive, giving reason to expect that CSP costs will stay on their rapidly decreasing trend, if the industry is diverse and strong enough to support further CSP expansion.

Methods

Data. All of our results are based on a global data set of all operational CSP stations with a capacity of 10 MW or more, including plants verified as currently under construction. All data used for this article can be found in Supplementary Data 1. Our CSP data are also made available and periodically updated on www.csp.guru.

We based our data set on data from SolarPACES, which provides the largest publicly available CSP database[37], and complemented this data with additional sources. First, we filled gaps with data from two industry publications, *CSP World*[38] and *CSP Today*[39]. We then searched for data to fill remaining gaps directly from power station operators or developers, and from funding agencies for the specific projects. Where the data set was still incomplete, we also relied on government reports, and on releases from news portals, such as Bloomberg or Reuters. As a last step, in a few cases we obtained data for particular stations from academic articles. We include data for CSP stations under construction, but not for stations 'under development' or 'announced', as it is uncertain whether such projects will be realized. Even data for projects under construction are uncertain and may be incomplete. Thus, we use and publish data only for stations that we could verify as under construction using satellite pictures, or for which we found multiple, seemingly independent, sources stating that construction had begun (see below for detail on verification of projects under construction).

All data were collected between February and August 2016. Later developments are not included in our analysis, with one exception: we include the Chinese FIT, released in September 2016, for the stations already under construction in August 2016 that are eligible for that support. In addition to the name, location, solar resource, dates for construction start and start of operations for each station, our data describe the technical features (capacity; technology; storage size; solar field size; cooling type; expected generation) and economic and financial aspects (total investment cost; solar-specific component manufacturer; remuneration scheme, duration and level; concessional funding or other financial support). The resulting data set is complete with respect to the technology used, capacity, operational status and project developer for all non-hybrid CSP stations, and it is almost complete (>94%) for location, solar resource, year operational and storage capacity. Our data concerning expected generation cover 88% of all non-hybrid stations operational or under construction, we have data for investment costs for 86%, and for remuneration type and level for 80% of all stations.

Our cost data refer to the total station cost: it was not possible to disaggregate cost for station subsystems using project-specific data. We convert all costs to US dollars (US$) using the average exchange rate of the year when each project became operational[40], and then deflate the costs to US$$_{2015}$ (ref. 41). All costs are in US$$_{2015}$, unless stated otherwise (for example, €$_{nominal}$).

Except for the adjustments described below, the data are included unmodified from the stated references. For six Spanish stations (La Dehesa, La Florida, Solabén 2&3, Solacor 1&2), we found no cost data, and filled these gaps with investment costs from the Spanish government[42]. In some Spanish cases (Solabén 1&6; Palma del Río 1&2 and Madajas; Termosol 1&2) we found investment costs only for 2–3 stations together, and hence split the total costs proportionally. For Genesis (US), we found no investment cost data, but only a statement that the granted loan covers 80% of the investment, and scaled the total cost accordingly. We base the data for Supcon phase 1 (China) on data from SolarPACES, and divide the numbers by 5 as only 10 of the total 50 MW are operational, while allocating the remaining 40 MW as under construction. Cost and generation data for the SEGS stations are not available from the databases described above or from the station operator or developer, and for these stations we had to rely on academic publications. The cost data we use are from ref. 43, whereas the generation data are not the expected generation, as for all other stations, but the actual average generation in 1998–2002[21].

For the stations under construction, all stations for which we identified coordinates are visible as construction sites on Google Maps satellite pictures, except Abijheet, Gujarat and KVK (India). The South African stations Redstone and Kathu are not visible on satellite pictures, but are verified as started (Kathu) or about to break ground (Redstone) in September 2016. In some cases, especially in China, the satellite pictures show construction sites of some unidentifiable sort, and in one case (Dacheng), updated satellite images showed that the construction site was for a photovoltaic station. When we found statements that a CSP station is under construction, and could see that some construction is going on at the specified place and/or have found press releases supporting that construction has begun, we included the station in the data set.

For the remaining non-verified stations, either the coordinates are inaccurate, or construction had not started at the time the satellite photo was made (which can be several years ago), or the project has been delayed or cancelled. For the Indian projects, we were not able to confirm the SolarPACES data, so that these projects remain uncertain, but we did find several seemingly independent reports about construction progress of these projects. It is possible, but as we judge it improbable, that the numbers for the Indian projects under construction are an overestimate.

There is no comprehensive overview of the Chinese projects, and there is considerable confusion about project names, sizes, technology and status. Hence, we have listed and verified them as well as we could. Four Chinese stations from SolarPACES are not visible on satellite images, but multiple sources, including the FIT programme[35], report their existence. The list of Chinese projects under construction is to the best of our knowledge correct, and it covers about half of the capacity of the FIT programme; in the remaining cases, construction has probably not yet started (October 2016).

Hence, the 23 stations listed as under construction in our database are verified stations (by satellite picture), or projects we have no reason to question. Our list is shorter than published by others. For example, Greenpeace and ESTELA[44] report 30 CSP projects (2.2 GW) larger than 10 MW under construction, of which we confirm 21; of the 8 Chinese projects in that study, we confirm 2. However, their project list is outdated—most projects are listed as scheduled to finish in 2014–2016—and several projects reported as 'under construction' were already operational when the report was published.

Investment cost functions for learning curves. Learning curves describe how costs develop as a function of cumulated production. Typically, learning rates are positive, meaning that costs decrease over time, for example via efficiency improvements in manufacturing and at power plant level, and/or scale effects. The learning curve is expressed as

$$C_{cum} = C_0 n^b \quad (1)$$

where C_{cum} is the cost per unit as a function of cumulative output, C_0 is the cost of the first unit, n is the cumulative output and b is the experience index; for each doubling of cumulative capacity, the costs decrease by the learning rate LR = $1-2^b$ (ref. 45).

The three types of CSP station—PT, ST and Fresnel—collect solar energy in different ways, onto a linear absorber tube using curved (parabolic trough) or many flat mirrors (Fresnel) or onto a central receiver using a multitude of individually controlled flat mirrors (tower). As the technology used for each type of station is different, it is not appropriate to derive one learning rate for CSP, but separate ones for each technology. Further, each station subsystem (for example, solar field, storage, power block) has its own learning rate and weight in the total cost of different CSP configurations, especially depending on the storage size. Hence, in addition to splitting along technologies, we here create separate learning curves for each technology, and for different amounts of thermal storage.

We do not include hybrid CSP stations in any of our analyses, as these are technically different from solar-only stations (or solar-mainly, as many existing stations use small amounts of natural gas).

Levelized costs of electricity. For the LCOE calculations, we assume an economic lifetime of 25 years, which corresponds to the duration of most PPAs, but is shorter than the 25 + 15 year duration of the FIT payments in Spain. We assume yearly operation and maintenance (O&M) costs of 1.5% of the investment cost. Actual O&M costs are usually lower for larger projects, so that our method may slightly overestimate the O&M costs of large stations, by a few per cent; as the O&M costs are only a small fraction of the LCOE, this assumption has miniscule effects on the final LCOE[46]. The yearly generation is the expected generation as stated by the project developer or another entity involved in construction or operation of each station. Hence, important and project-specific factors such as the solar resource at the site of each station and other station design and operation choices are implicitly included in our assessment, as integral parts of the expected generation.

We assume a uniform weighted average cost of capital (WACC) of 5%, which is similar to the SunShot studies, which use 5.5%[47] and 4.4%[10].

The baseline assumption of a WACC of 5%, which is relatively low by global standards, reflects our judgement that all stations were built in relatively low-risk economic schemes (long-term FITs or PPAs, both of which reduce or eliminate the price risk). This both reduces the overall risk level for all CSP stations and makes the investment risk—and hence the WACC—more similar across stations, including across stations in different countries. Further, many stations—although we do not have complete data for this—are backed with concessional loans or state guarantees, which further reduces the investment risk. Still, the 5% WACC may in some cases be an underestimation of actual costs of capital, especially as CSP investment has shifted from low-risk (Spain, US) industrial countries to higher-risk emerging countries (South Africa, Morocco, India, China). As previous studies have shown, the investment risk, as expressed by the WACC, strongly affects the LCOE of renewables and CSP[48–50]: hence, any assumption on this must be well considered. Therefore, we also present LCOE results using 10% WACC (see Supplementary Note 5).

Data availability. The data and the data sources can be found in Supplementary Data 1 and in a periodically updated database found on www.csp.guru.

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Author contributions

J.L. designed the study and drafted the article; J.L. and M.L. gathered the data; J.L. and S.P. analysed the data; S.P. generated the figures; all authors worked with the final manuscript; A.P. supervised the grant.

Additional information

Supplementary information is available for this paper.

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Competing interests

The authors declare no competing financial interests.

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AMENDMENTS

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Author Correction: Empirically observed learning rates for concentrating solar power and their responses to regime change

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In the version of this Analysis originally published, the total learning rate for parabolic trough stations with 6–8 hours of thermal storage (Fig. 2b) was calculated to be 25%. After publication, the authors found a code error that caused the learning curve fit function to believe that the first station in the dataset was marked as 1 GW and not 0 GW. As a result, the estimated learning rates for the complete timespan were too high. The correct learning rates should be 2.7% for Fig. 2a and 6.8% for Fig. 2b (instead of 5.2% and 25.2%, respectively). These learning rate fit curves have been updated and the captions have been corrected. In Fig. 2a, the fit for 2011–2014 was unaffected. For consistency with Fig. 2a, a fit for 2011–2017 has been added to Fig. 2b, showing a learning rate of 17.5% ($R^2 = 0.337$). The text has been modified in the abstract and the sections 'Observed investment cost development and learning rates', 'Policy regime impacts on cost development' and 'Conclusions' to reflect the quantitative changes to the learning rates. Supplementary Notes 1, 3 and 4 and Supplementary Figs. 2, 6 and 7 and their captions have also been updated to reflect the new learning rates. In the caption of Supplementary Fig. 2b, "(2008–2017 learning rate=0.21, R2=0.468)" has been changed to "(2008–2017 learning rate=0.06, R2=0.513; 2011–2017 learning rate=0.079, R2=0.072)". In the caption of Supplementary Fig. 6b, "(2008–2017 learning rate=0.289, R2=0.715)" has been changed to "(2008–2017 learning rate=0.077, R2=0.631; 2011–2017 learning rate=0.225, R2=0.498)". In the caption of Supplementary Fig. 7, "(a) parabolic trough (PT) stations with <1 hour thermal storage (2011–2014 learning rate=0.297, R2=0.972 (US$) and learning rate=0.27, R2=0.909 (€)); and (b) PT stations with 6–8 hours of thermal storage (2008–2017 learning rate=0.252, R2=0.621 (US$) and learning rate=0.138, R2=0.502 (€))" has been changed to "(a) parabolic trough (PT) stations with <1 hour thermal storage (2011–2014 learning rate=0.297, R2=0.972 (US$) and 2011–2014 learning rate=0.27, R2=0.909 (€)); and (b) PT stations with 6-8 hours of thermal storage (2011–2017 learning rate=0.175, R2=0.337 (US$) and 2011–2017 learning rate=0.072, R2=0.149 (€))". The underlying data were correct as originally published and remain unchanged. The corrected figures are shown below.

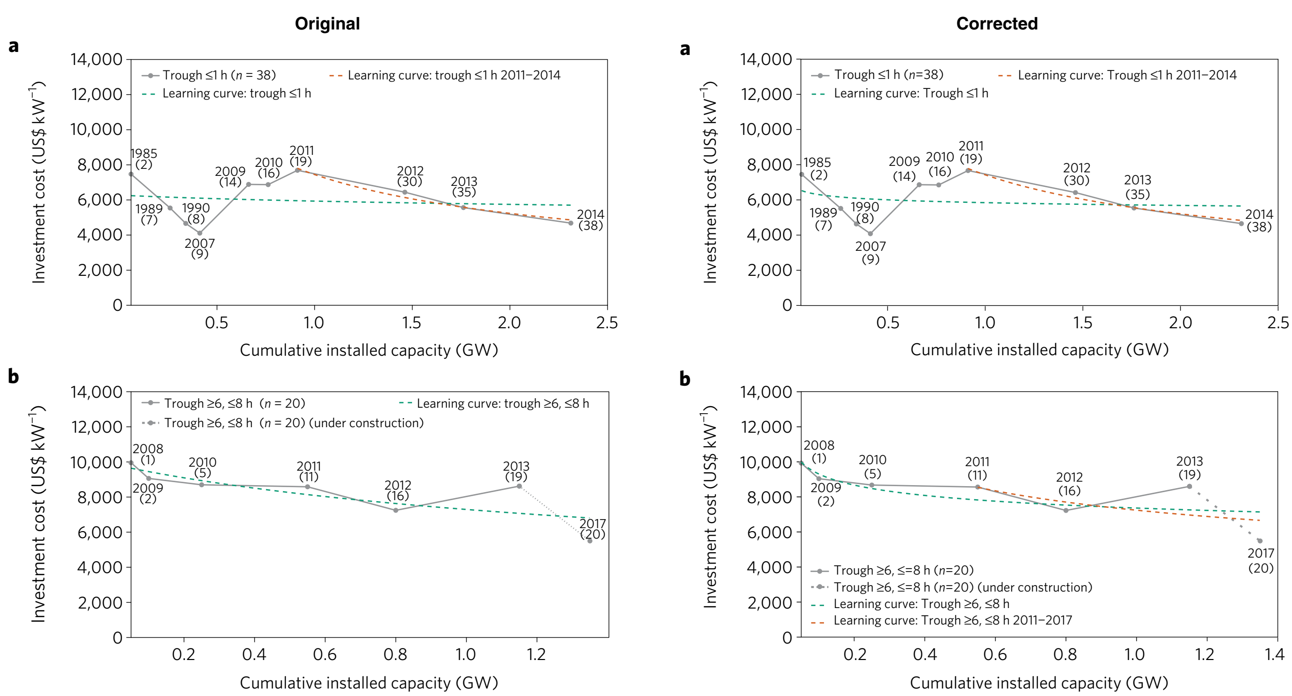
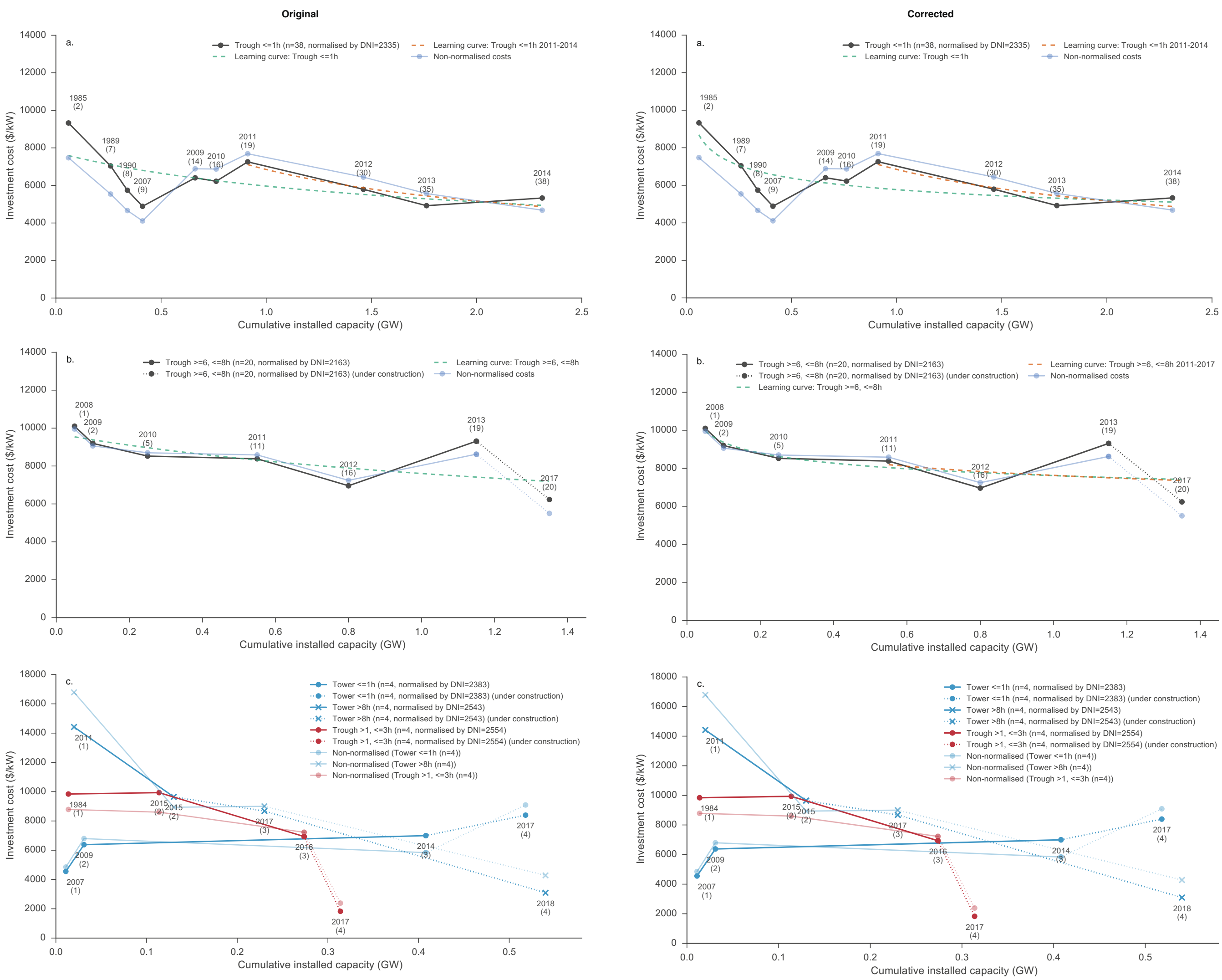
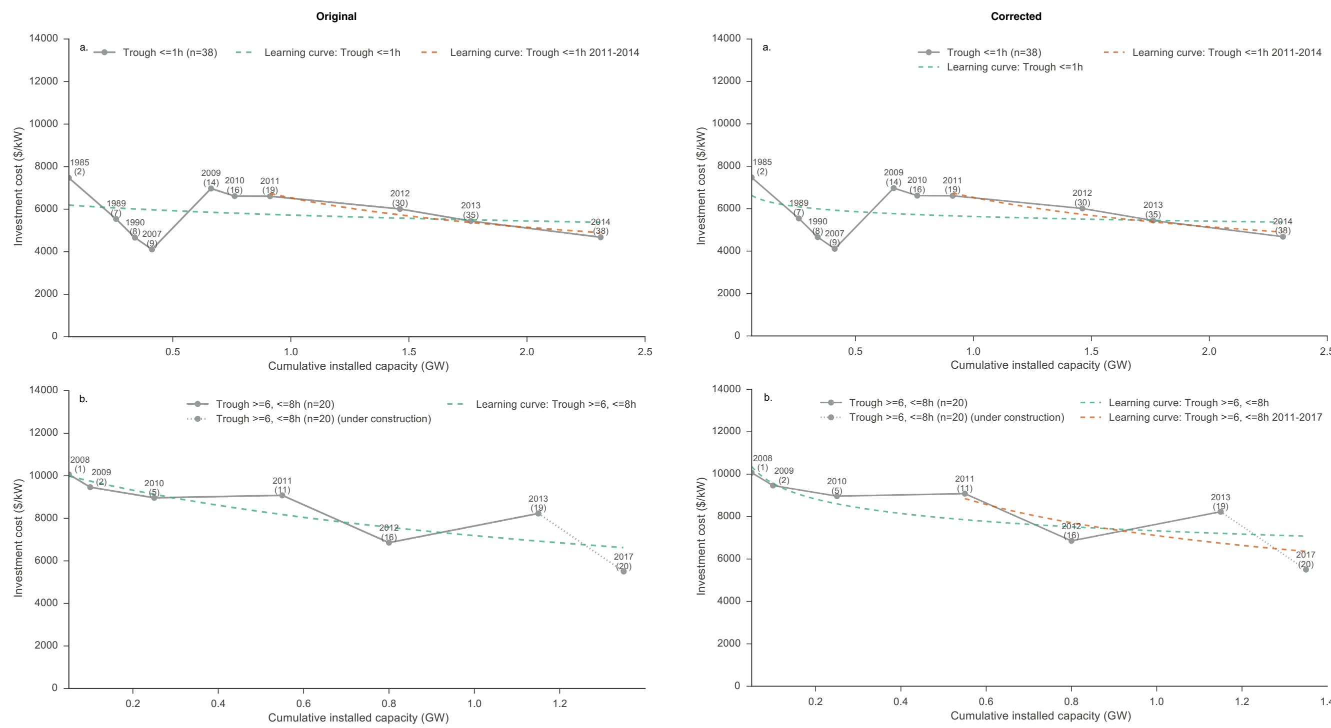


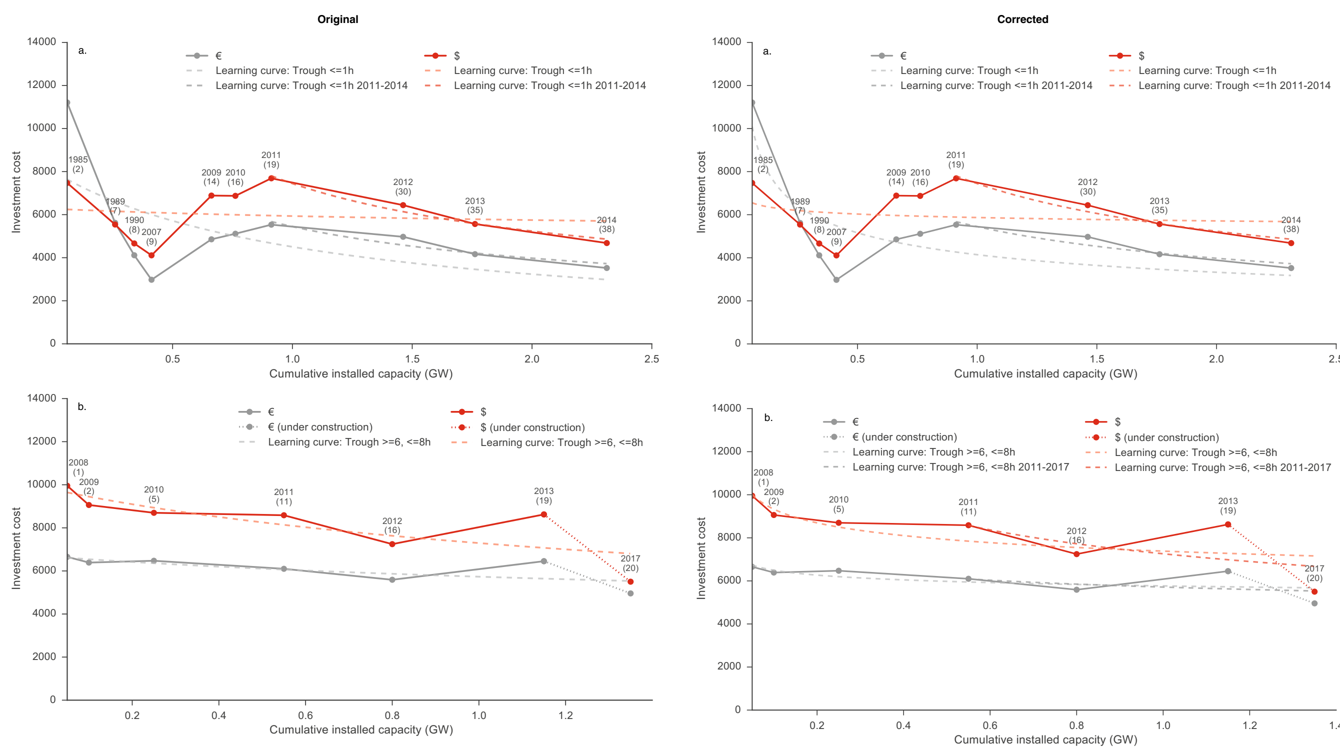
Fig. 2 | Original and Corrected.



Supplementary Fig. 2 | Original and Corrected.



Supplementary Fig. 6 | Original and Corrected.



Supplementary Fig. 7 | Original and Corrected.

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