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Potential for concentrating solar power to provide baseload and dispatchable power

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Previous studies have demonstrated the possibility of maintaining a reliable electric power system with high shares of renewables, but only assuming the deployment of specific technologies in precise ratios, careful demand-side management, or grid-scale storage technologies[1,2]. Any scalable renewable technology that could provide either baseload or dispatchable power would allow greater flexibility in planning a balanced system, and therefore would be especially valuable. Many analysts have suggested that concentrating solar power (CSP) could do just that[3–8]. Here we systematically test this proposition for the first time. We simulate the operation of CSP plant networks incorporating thermal storage in four world regions where CSP is already being deployed, and optimize their siting, operation and sizing to satisfy a set of realistic demand scenarios. In all four regions, we show that with an optimally designed and operated system, it is possible to guarantee up to half of peak capacity before CSP plant costs substantially increase.

Greenhouse gas emissions will need to fall substantially over the coming decades if the worst impacts of climate change are to be avoided, a conclusion reflected in mid-century emissions reduction targets of 80% in numerous political jurisdictions, including California and the European Union[9–12]. Given the suite of technologies now available, there is widespread belief that renewable sources of energy, and above all renewable sources of electricity, will have to play an important role in this decarbonization[13,14]. Wind and solar power offer an abundant supply potential, but both are intermittent, with their output determined by diurnal and annual cycles, as well as by local weather conditions[15–17].

Recent studies have used data with high spatial and temporal resolution to study the feasibility of integrating large amounts of wind and solar within a portfolio of renewable energy sources. They have found it to be possible, but that it requires optimizing the system design across several technologies[1,2], and incorporating excess solar and wind capacity of up to twice the peak power demand if the need for grid level storage is to be avoided[18,19]. These factors could make integration difficult in practice, first because of the complexity of optimizing across multiple technologies, and second because the land required for excess renewables capacity may be a binding constraint in densely populated regions, such as Europe or South Asia. Using technologies that either use less land or can be built in remote, sparsely inhabited regions would hence be beneficial[20], as would identifying whether there is a single technology that on its own could offer a high level of reliability, so as to give energy system planners and policy-makers greater flexibility with respect to balancing a decarbonized electricity system. We therefore study the reliability of CSP, which can best be deployed in deserts where land-use limitations do not appear to be a constraining factor, and which offers the promise of overcoming intermittency by making use of short-term thermal storage to bridge the day–night cycle and periods of cloudy weather. Some existing CSP plants can already operate at full capacity around the clock in summer[6,7]. In winter, or when cloudy conditions are prolonged, however, even these CSP plants need to cease power production.

Two well-known strategies can increase the availability of renewable power. First, for all wind and solar technologies, an interconnected fleet taking advantage of anticorrelation between weather at geographically dispersed sites can provide greater availability than a single plant[21–24]. Second, for CSP plants specifically, the size of an individual plant's solar field relative to its power block can be increased, allowing the plant to more rapidly fill its heat storage during sunny conditions. We illustrate the effects of both strategies in Fig. 1 for CSP plants operating in the Mediterranean countries (see Supplementary Fig. 1 for the results in the other regions, Supplementary Fig. 6 for the possible sites and Supplementary Table 2 for plant design parameters). Figure 1a shows hourly generation curves for a hypothetical network of 100 CSP plants in the Mediterranean basin, revealing that there are extended periods in winter when the fleet must operate at or near zero generation. Figure 1b illustrates the effect of including a reserve buffer by doubling the solar collection area of each plant, while maintaining the storage and turbine capacity. This allows individual plants with beneficial conditions at a given time to compensate for adverse weather elsewhere in the system, and improves fleet availability, although as shown in the figure still does not provide 100% reliability. Oversizing comes at a financial penalty because it discards much of the thermal energy collected: assuming 2010 technology costs, the levelized cost of electricity for the case in Fig. 1a is 0.15 USD/kWh, compared to 0.19 USD/kWh in Fig. 1b.

To examine this tradeoff between cost and availability in detail, we next consider actual load curves that the operator of a network of CSP plants might design and operate a system to satisfy. Such load curves would mainly depend on the power demand, but also very much on the power mix; whether, for example, supply contained a great deal of day-only photovoltaic power, volatile wind power, seasonally determined hydro power or flexible gas power. As we cannot predict what the electricity mix might look like at a time when CSP is needed to offer high availability, we consider three extreme cases, which together can provide an indication of possible needs. The first is a flat load curve, meaning that CSP would be required to provide baseload, much like nuclear power does today

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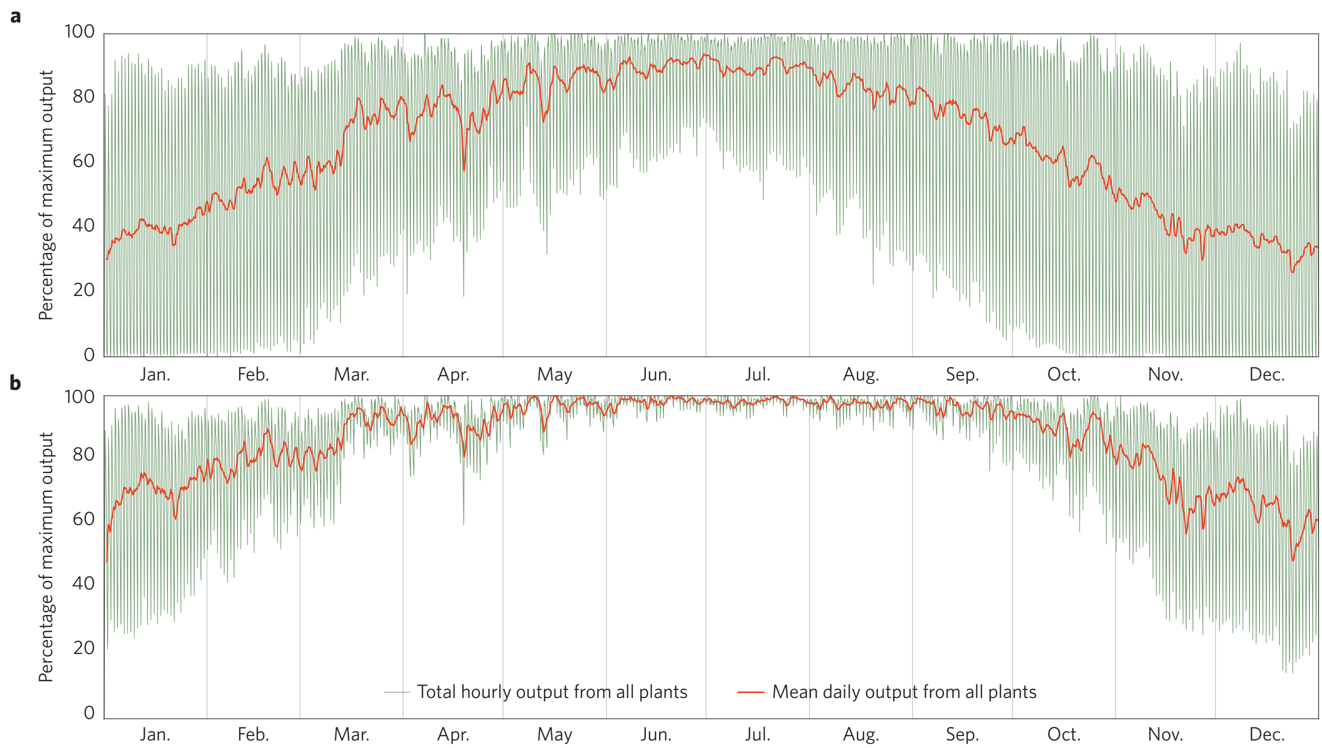

Figure 1 | Total output for the year 2005 from 100 plants spread across locations in the Mediterranean basin. a, The plants are operated without concern for demand or coordination: in each hour, each plant produces as much power as possible. See text for plant dimensions. **b**, The size of the solar field is doubled, while the power block and storage size is kept constant.

in many countries. The second is the load curve for the European Union, meaning that CSP would be required to follow the load of a region that experiences peak demand in winter, and during evening hours after sundown ('winter peak demand'). The third is the load curve for California, a warm industrialized region where peak demand is dictated by air conditioning needs, with the highest demand during summer afternoons ('summer peak demand').

Figure 2 shows the projected levelized costs of satisfying varying levels of availability with a CSP fleet in the ten best sites in the southern and eastern Mediterranean countries, and considering steps taken to optimize the system design around three demand profiles. The curves show the effects on cost of varying availability, expressed as the requirement for dispatchable, non-CSP backup capacity as a fraction of peak load. For the top curve, as in Fig. 1, we do not assume any effort to optimize the siting or operation of plants towards a particular demand curve, and the only control variable is the oversizing of the solar fields across the whole system. The middle set of curves shows the results when one assumes that the entire plant fleet is coordinated, to satisfy a given share of each of the demand curves at the lowest possible cost. Such optimization could include using storage to delay output at one plant, to maintain availability above a particular threshold when another plant in the system is forced to go offline because of poor weather. The relative sizing of individual plants is still not optimized in this case. Finally, the lowest set of curves shows results when adding efforts to optimize the planning of each individual plant by also allowing the optimization to choose the size of each plant's generator, solar field and thermal storage system independent of each other. This allows the model to increase overall system reliability and further reduce costs by optimizing the utilization of each individual plant and the dimensioning of its components (see Supplementary Information for full assumptions in the model, results for other world regions in Supplementary Fig. 2, and comparisons using projected 2030 costs in Supplementary Fig. 7).

The results in Fig. 2 illustrate that it is possible to improve the cost/availability frontier substantially by coordinating and optimizing the design and operation of plants within a system. In the optimized cases, high levels of reliability, 70–80%, can be achieved with practically no cost penalty, and very high levels of reliability with cost penalties of less than 50%, which may be considered modest or affordable. Unsurprisingly, the cost penalty is lowest when the need is to satisfy peak summer demand, and greatest when the need is to satisfy peak winter demand.

A final question concerns whether these qualitative insights gained from Fig. 2 can be generalized to other world regions. Figure 3 shows results for the fully optimized case, illustrating differences across four world regions. It is possible to achieve quite similar levelized costs, across all regions and demand scenarios, when the availability of backup generation is high and the needs for CSP availability correspondingly low. However, the costs for power from CSP generation in the absence of substantial backup capacity vary widely across regions and scenarios. In countries with well-developed power sectors the required dispatchable backup capacity already exists, primarily in the form of fossil-fired plants with fast start-up times. Thus, for an initial deployment of CSP the most sensible cost figures to draw from are well above 50% available backup capacity. However, if the ultimate goal is the decarbonization of power generation with reliable CSP generation, existing backup capacity will need to be relied on less and less. The cost penalties for achieving high CSP reliability are much higher for the United States and India, reflecting less favourable climatic conditions in terms of greater spatial correlation of cloud cover.

Baseload capability or full load-following capability may be an illusive, and unnecessary, goal for any single technology. Nuclear power stations, for example, have an average availability of around 80%, mainly because of maintenance and unforeseen stoppages[25]. Droughts and heat waves can at present force existing wet-cooled thermal power stations to reduce or stop production

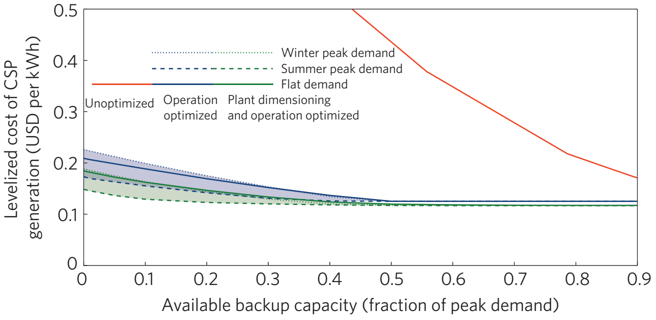

Figure 2 | Costs of guaranteeing to meet various fractions of the load in the three load profiles by CSP plants, for the worst (costliest) year out of the four simulated in the Mediterranean basin.

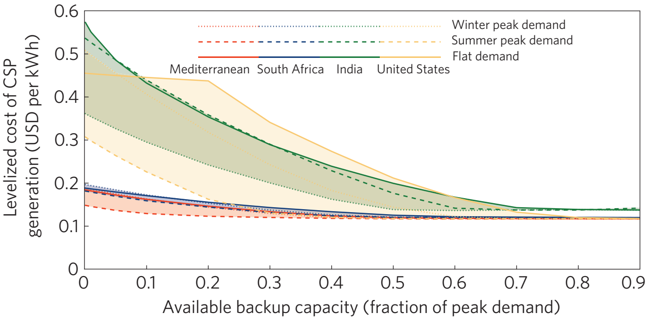

Figure 3 | Costs of guaranteeing to meet various fractions of the load for fully optimized plants (design, location and operation) in the four regions, for the worst (costliest) year out of the four simulated years. The shaded area shows the range of costs resulting from the three different load profiles.

during sustained periods owing to cooling water temperature restrictions, and climate change is likely to reduce water availability and increase surface water temperatures further[26,27]. Our results suggest that a geographically dispersed CSP network, using current thermal storage technology, could be a comparably dispatchable or baseload-capable technology in some parts of the world. This could overcome one of the key perceived barriers to an energy system based primarily on renewables, which may be crucial for successful decarbonization and thus for avoiding severe unmitigated climate change.

This result comes with one condition and two caveats. The condition is that the plants in that system be designed and operated in a coordinated fashion, rather than in a manner where each is as large as possible or is operated without consideration of regional weather conditions and the total fleet output. We have not considered whether the coordination takes place through the actions of a central planner, an appropriately designed power market, or some other mechanism, nor do we make statements concerning how likely such coordination is. We do, however, show that as few as ten geographically dispersed locations are, with coordination, sufficient.

The first caveat is that very high availability of CSP, namely without any need for dispatchable backup capacity, may be economically practical only in some world regions. Of the four regions we examined, the Mediterranean and South Africa offer the promise of very high availability without a substantial cost penalty, whereas the United States and India do not. Progress on high-resolution solar resource modelling will allow future work to investigate these disparities further. In these latter two regions, CSP might still be able to provide a large share of reliable power, but the exact extent would be contingent on specific demand curves and the features of the other technologies in the power mix. This becomes important when deep emissions reductions require that existing dispatchable backup capacity provided by fossil-fired power stations is decommissioned and replaced with emissions-free alternatives.

The second caveat is that CSP is at present more expensive than other technologies. It has yet to experience deployment at a scale comparable to wind or photovoltaics, yet there is reason to believe that should it do so, perhaps driven by its greater degree of reliability, its costs could quickly fall. To assess the implications of this possibility, we ran the fully optimized scenario with estimated 2030 costs (Supplementary Fig. 7). These costs were derived by extrapolating estimated 2020 component costs using IEA estimates for overall CSP plant costs in 2030 (Supplementary Table 3). The results show levelized electricity costs cut by more than half and a narrower range of costs to supply the different demand curves. Because the future costs of CSP, not to mention future options for electrochemical storage, are difficult to estimate, we have not engaged in any detailed analysis comparing dispatchable CSP systems with other systems integrating intermittent generation with grid-level storage. Our results suggest, however, that CSP may be an attractive option, and it is thus possible to consider CSP satisfying a large fraction of a future decarbonized, affordable, and reliable electricity system.

Methods

We conducted our analysis using an existing CSP plant model as described in ref. 28, and extended it by adding an optimization component to consider coordinated plant siting, design and operation. This is a linear programming model specifically designed to run on high-performance clusters to examine a large number of optimization scenarios. The structure and equations of the model are described in greater detail in the Supplementary Information.

The primary input data to run the model comprises hourly data on solar radiation, surface temperature and wind, the latter two to calculate thermal-to-electric conversion efficiency. Radiation data were supplied by satellite observation, whereas temperature and wind were derived from climate model reanalyses. We ran the model based on these data from four world regions: the Mediterranean region (Northern Africa, the Middle East and Southern Europe), South Africa, the United States and India. We selected the regions based on two criteria: there is planned or ongoing use of CSP in the region, and both solar irradiance and weather data were available.

For each region, we performed three sets of model runs. The first set of model runs simulated plants running at their maximum output for as long as possible, and was performed for all sites in the respective region. The second and third sets of model runs expanded this to perform an optimization of plant operation and of plant design and operation, respectively, and were performed for ten sites selected from the initial set of sites in each region, by choosing those ten sites with the highest annual Direct Normal Irradiance (DNI). In these latter two runs we made the model more tractable by resampling the data in three-hour timesteps.

The optimization runs required the specification of demand curves. We selected three alternatives—a typical winter peak demand, a typical summer peak demand and a constant demand—to simulate the widest range of realistic scenarios.

Details on all of our data, including satellite and reanalysis irradiance and weather data, electricity demand data and cost data, are available in the Supplementary Information.

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Author contributions
S.P., J.L. and A.P. designed the study and drafted the manuscript. S.P. implemented the models and performed all analyses. P.G. contributed the CSP plant model and solar resource data. K.D. performed the site selection and obtained demand data. F.W. contributed to model development and implementation. All authors contributed to editing and discussing the manuscript.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to S.P.

Competing financial interests
The authors declare no competing financial interests.