

## The duck curve predicted limits of solar energy

There is a crisis among investors and developers in the solar energy industry in Denmark. The declining commercial value of solar energy seems to have caught them by surprise. In California, the problems were recognized long ago, so that the necessary preparations could be made.

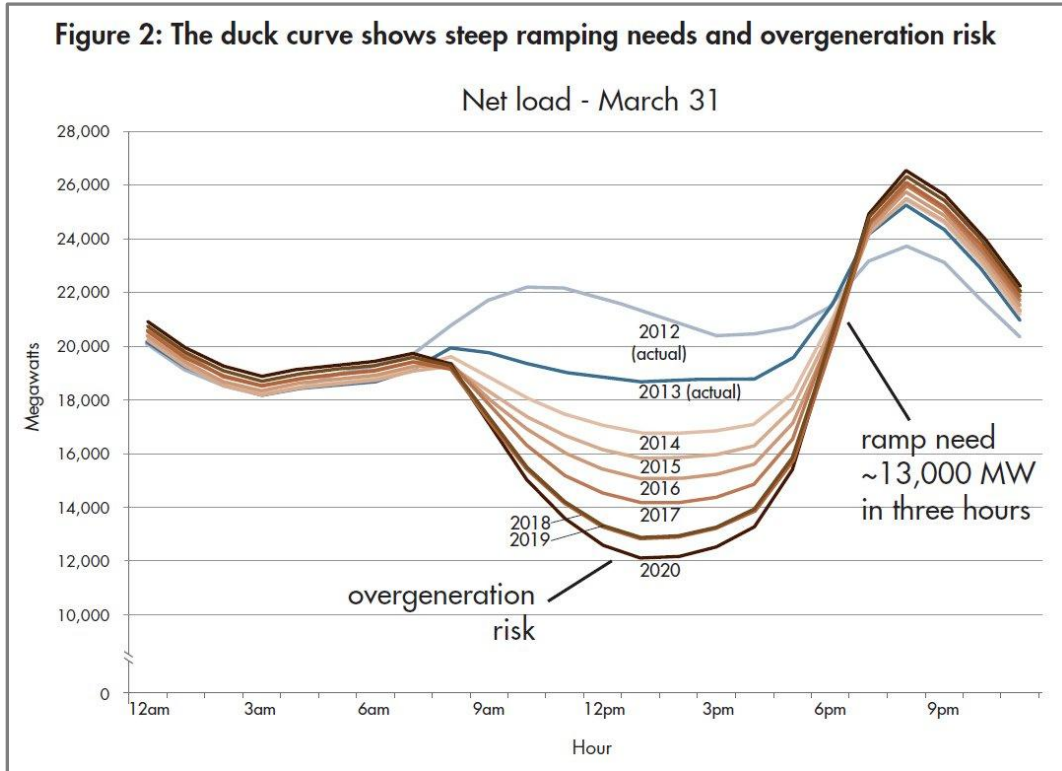


Fig. 1 - Growing solar power will cause dispatchable generation to plunge in the middle of the day.

The California Independent System Operator (CalISO) presented the famous duck curve in 2013, which made it clear that the growth of solar energy would sooner or later lead to operational problems.

The biggest problems occur at the times of year when the sun sets at the same time as electricity consumption increases towards the evening peak. That is why they have chosen to show the duck curve for March 31.

The ramp could become so steep that dispatchable production could not keep up. CalISO had to limit the ramp by curtailing solar power. In addition, a system service of quickly regulating production was developed.

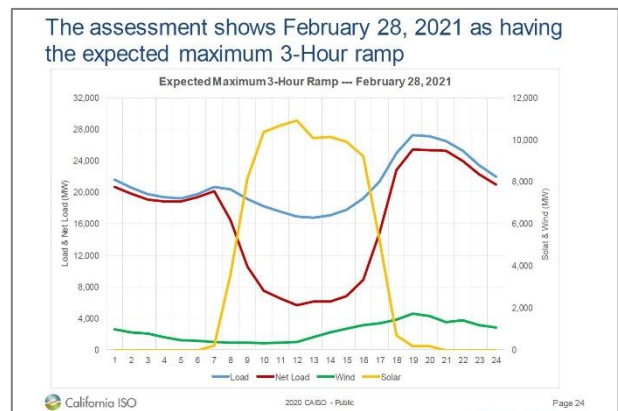


Fig. 2 - The solar energy figure fits the body of the duck.

A CaISO statement from 2020 on the need for flexible capacity shows an expected duck curve for February 2021 (Fig.2).

### Curtailments in California in 2023

CaISO has published data for electricity supply and curtailment for the year 2023. Gross consumption was 219,161 GWh distributed as in Fig. 3.

It was necessary to disconnect 2,509 GWh of solar energy. The maximum disconnection was 8,830 MW.

Without disconnection, the solar cells could have delivered 42,315 GWh with a maximum value of 16,268 MW. This gives a theoretical load factor of 29.7%. The utilized solar energy had a load factor of 28.3%.

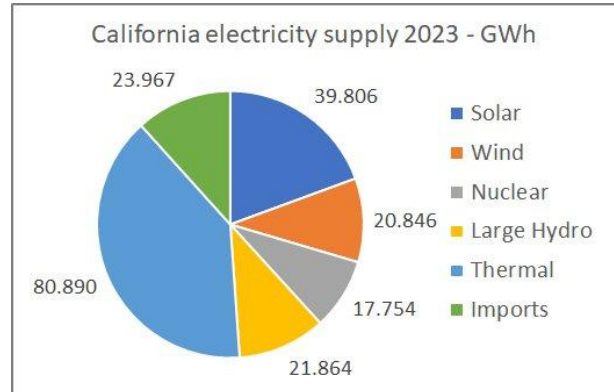


Fig. 3 - Solar energy accounted for 18.2% of consumption in 2023.

Only 151 GWh of wind energy were disconnected in California in 2023. The largest disconnection was 1,164 MW. The load factor for the utilized wind energy was 38.1%.

California and Denmark:

### Different conditions and different solutions

A comparison between California and Denmark shows interesting differences between the two areas' capabilities to use renewable energy sources for electricity supply.

California is a large country that can only count on limited support from electricity systems in neighboring states. Therefore, it is necessary for California to be able to cope with the steep regulations that result from unfortunate coincidences between variations in solar power and consumption.

For Denmark, the support of neighboring countries is absolutely crucial for the variations in solar and wind power to be offset. This has made possible the large share of wind power in the Danish electricity system.

Offshore wind farms have not yet been established in California. This is due to the great water depths in the Pacific Ocean very close to the coast. There is considerable interest in establishing floating wind turbines on pontoons that are anchored to the seabed.

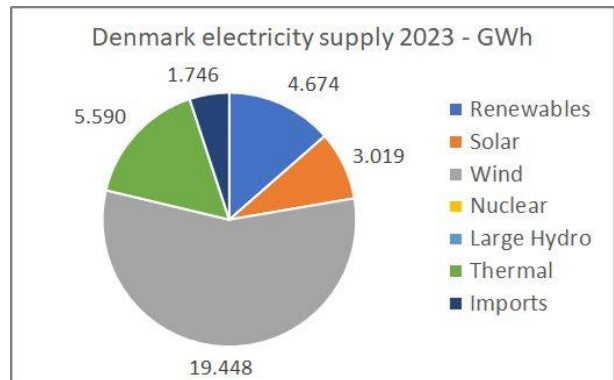


Fig. 4 - In Denmark, solar energy accounted for 8.8% of electricity consumption in 2023

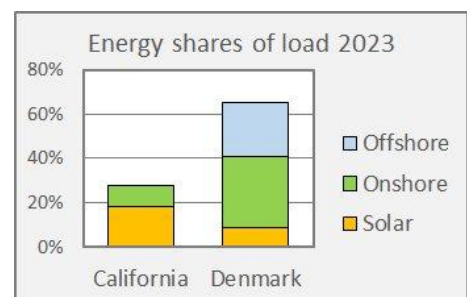


Fig. 5 - California does not yet have any offshore wind power

It is particularly interesting to compare capacity factors for solar and wind in California and Denmark. While 1 MW of solar cells in Denmark can deliver 1208 MWh of electricity annually, in California it can deliver 2507 MWh or more than twice as much.

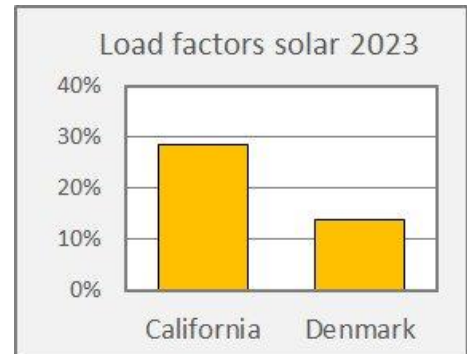
The infrastructure required to operate the solar parks depends more on the installed capacity in MW than on the energy output in MWh. This means that in Denmark more grid and other infrastructure must be installed to produce the same amount of energy. Therefore, it is particularly expensive to adapt the electricity system to solar energy in Denmark.

As a general rule, curtailments in Denmark are activated by producers who respond to price signals and regulate production down. This is clearly seen on the production curves, but has not been systematically recorded..

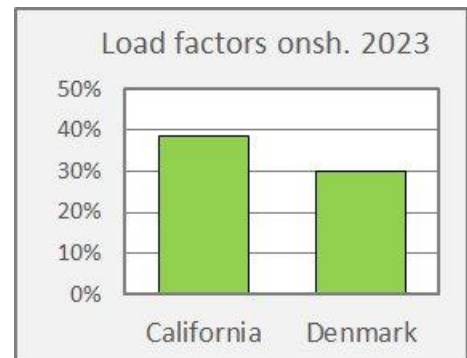
It is perhaps more surprising that onshore wind power also provides more in California than in Denmark (fig. 7).

While 1 MW of onshore wind power in Denmark can deliver 2624 MWh of electricity annually, in California it can deliver 3365 MWh or 28% more than in Denmark.

Together with the current problems with establishing infrastructure for new wind and solar power in Denmark, these results speak for a better optimization of the composition of renewable energy production in Denmark.



*Fig. 6 - One MW of solar power provides twice as much energy in California as in Denmark*



*Fig. 7 - One MW of onshore wind power provides 28% more energy in California than in Denmark*