COMPETITIVE SOLAR POWER TOWERS

How to efficiently involve CSP in a global energy transition

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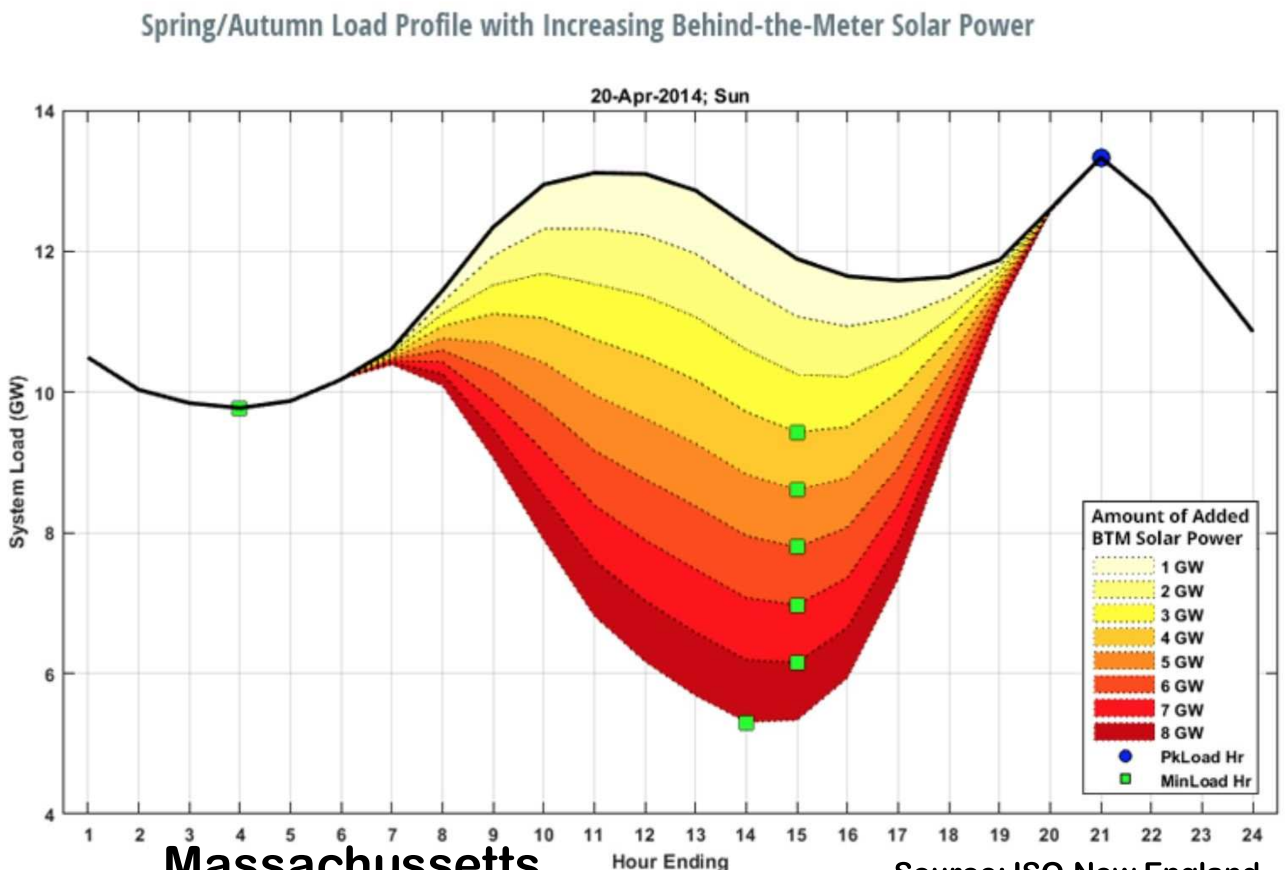
The fast-paced changes of electricity systems

Increasing shares of variable renewable power generation (mostly wind and PV):

- Decreasing net load (and market price) in the middle of the day
- Sharp ramp-up of net load in the early evening
- Even though demand-side management can be helpful, dispatchable (i.e. flexible) power generation is crucial



Massachussetts

Source: ISO New England

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Negative net load during many hours per year will be the rule

- Let us consider an electric system in which: 1/ PV can generate power during 2000 equivalent peak power hours per year; 2/ PV capacity is growing.
- When the installed PV capacity reaches a certain threshold, curtailment of PV begins during the sunniest hours; therefore, the "marginal added PV panel" begins to produce less than 2000 hours per year.
- If PV farms keep being built, at a certain stage the "marginal panel" will produce e.g. 1500 hours per year (i.e. it will be curtailed 500 hours per year).
- Consequently, its LCOE will mechanically be 33% higher.
- However, the cost of PV is getting so low that even under such unfavorable conditions it makes economic sense to build these extra farms.
- The same reasoning applies to wind turbines, although their behavior is not so massively synchronous as that of PV panels.
- Bottom line: because of the ever-increasing share of variable renewables, zero net load (i.e. power curtailment) during several hours of the day will be commonplace in the mid-term future.

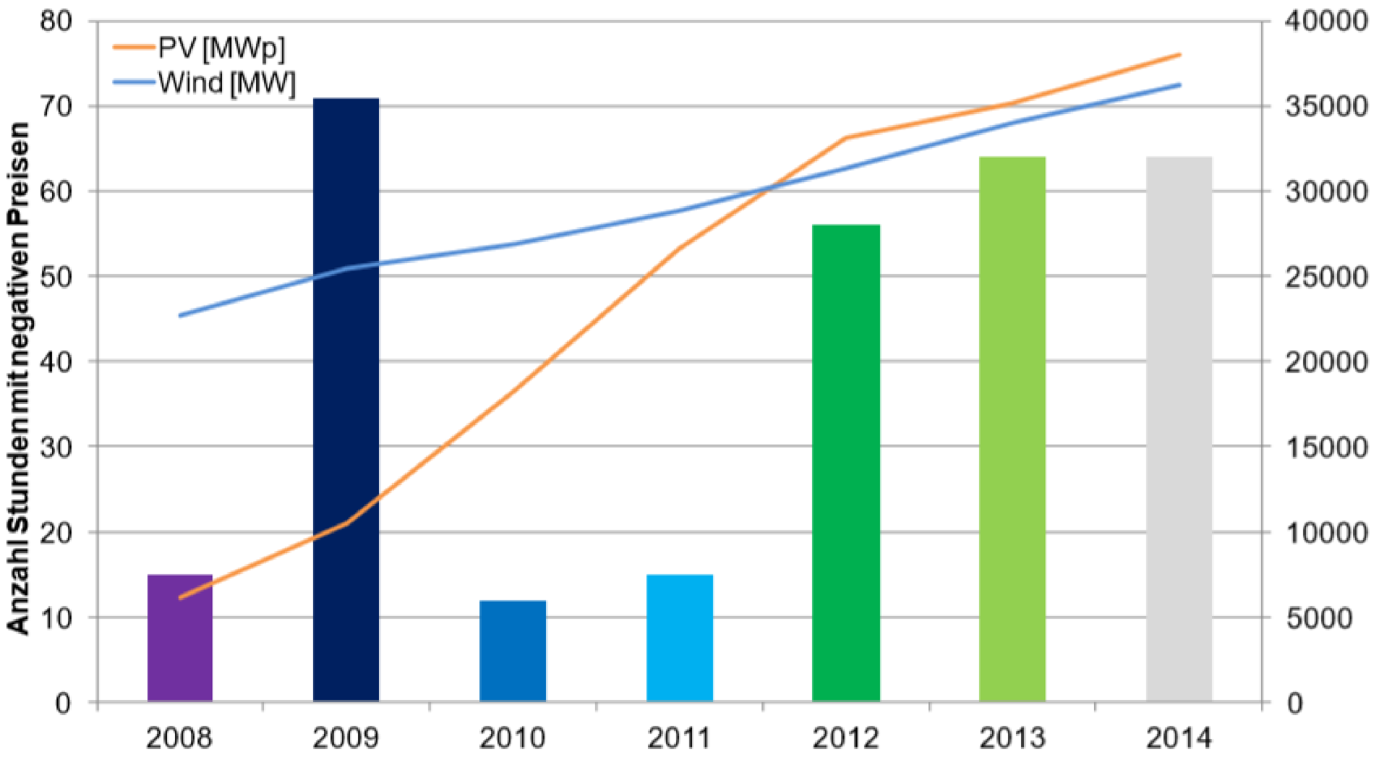
Supply side: plenty of power in excess

- Curtailed power generation has no commercial value, but… Waste does not either.
- Both can be considered as primary energy to be converted later into power during peak hours.
- Good conversion efficiency is always better but may not be crucial when the primary energy source is free (power that would otherwise be curtailed) or much cheaper than peak power.

Demand side: frequent shortages of power

- In a highly renewable electric mix, two types of supply vs. demand mismatches must be addressed:
  - Inter-season mismatch; for example, in a sunny area with a continental climate, heating may be required during winter when PV production is lowest;
  - Intraday or sometimes intra-week mismatch, as already shown in the Duck Curve.
- Inter-season and intraday storage are very different issues; the appropriate answers are quite different.

Increasing curtailment and negative prices in Germany



Left scale:
Number of yearly hours with negative price of electricity

Right scale:
Installed power of PV and Wind in MWe

Yearly occurrence of negative prices on the electricity wholesale day-ahead market in Germany & Austria
https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/Gutachten/negative-preise-stromgrosshandelsmarkt.pdf?__blob=publicationFile&v=2

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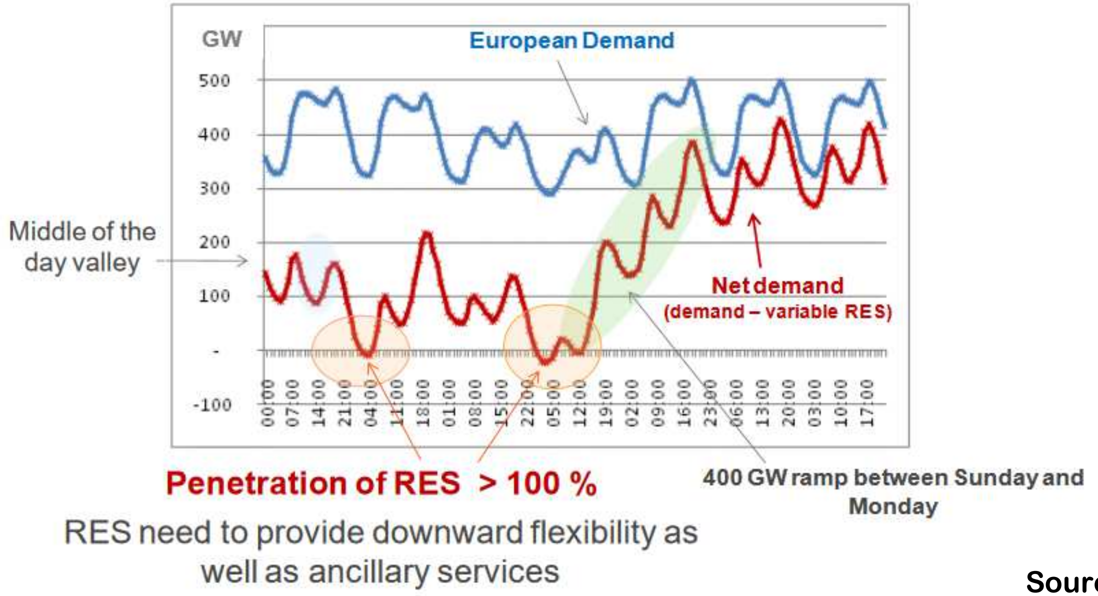
60% RE Study performed by EDF

FIGURE 10 : **LOAD-GENERATION BALANCING BECOMES QUITE COMPLEX FOR PERIODS WITH HIGH NET DEMAND VARIABILITY**



Source: EDF

☛ The solicitation of the **manoeuvrability of conventional generation plants** is higher with an increase exposure to higher and less predictable ramps.

☛ **Above a certain instantaneous penetration,** the ability to **dispatch variable RES becomes crucial to maintain the load-generation balance**. During these periods, **system security can be maintained only if variable RES contribute to ancillary services and reserves.**

Synthetic fuels are appropriate for inter-season storage

- Inter-season storage cycles once or twice a year only. Therefore:
  - → The discounted number of cycles during the lifespan of the storage system is extremely low;
  - → Poor Capex amortization of the storage itself (i.e. tanks only);
  - → The Capex of the storage itself must therefore be very low.
- With thermal storage, this Capex is too high because of the low storage density (sensible heat) and material issues caused by high temperatures.

  Besides, thermal losses during periods of several weeks or months would be excessive.
- Synthetic fuels (e.g. liquid, H_2) are the right answer for inter-season storage:
  - The storage density is based on fuel heating value >> specific sensible heat → Cheaper tanks.
  - The expensive part of the system is the plant that converts power into fuel; it is decently amortized since it should operate several hundred hours per year.
  - Synthetic fuels can also be used for transport.

Thermal storage is appropriate for intraday* storage

* or intra-week sometimes

- Example: 300 cycles/year, lifespan = 25 years, discount rate = 5%
  → Discounted lifespan ~15 years → Discounted number of cycles during lifespan ~4500.
- The Capex structure of a thermal storage system is properly amortized in such operating conditions.
- Consequently, the Capex of a typical molten salt thermal storage system ($NaNO_3$-KNO_3 eutectic, range = 290°C-565°C) is low: about 25 €/kWh, heat-to-heat.
  This figure does not account for salt heating and conversion of heat into power.
- Considering that the salt is heated with electric heaters (Joule effect), the round-trip efficiency is that of the power cycle: 40-45%.
  This is not a great value (batteries and hydro are above 80%).
- Considering the above, the Capex of the sole storage system (i.e. without the cost of salt heating and conversion of heat into power) is about 60 €/kWh, electricity-to-electricity (reminder: it is about 300 €/kWh for a storage system using batteries).

Two applications of thermal storage make sense

(as regards electricity)

To summarize:

i. Thermal storage has a low round-trip electricity-to-electricity efficiency: 40% to 45%;

ii. But its Capex per kWh_{elec} is about 5x lower than that of batteries, provided one does not have to pay (or has little to pay) for the salt heating and the heat-to-power conversion.

- i. above is acceptable for some electric systems (free or very cheap power during off-peak hours, as previously explained), but only if ii. is true.
- In other words: thermal storage can be a good solution only if one does not have to pay for the power cycle (heating the salt with electric heaters is rather cheap).
- Only two possibilities meet these requirements:
  - Refurbishment of a coal plant as a heat pumping unit that stores electricity: the thermal storage system equipped with electric heaters replaces the boiler;
  - Integration of a thermal storage in a CSP Power Plant.

CSP needs thermal storage…

Without storage, it competes with PV that is ~2,5x cheaper;

But thermal storage does not always need CSP:

It can be integrated in a coal plant refurbished into a heat pumping unit that stores electricity.

CSP is and will remain competitive…

… at least as a niche market

- **When conditions are favorable (main criterion: Direct Normal Irradiation; above, say, 2200 kWh/m^2.year), CSP makes sense.**

- **In other words: if the DNI is good, the best way to charge a thermal storage system is to use a concentrating solar field using mirrors. We should not let this opportunity go by.**
  Remark: Hybrid systems with mid-temperature (i.e. parabolic trough) CSP supplemented with high-temperature heaters fed by PV are also competitive.

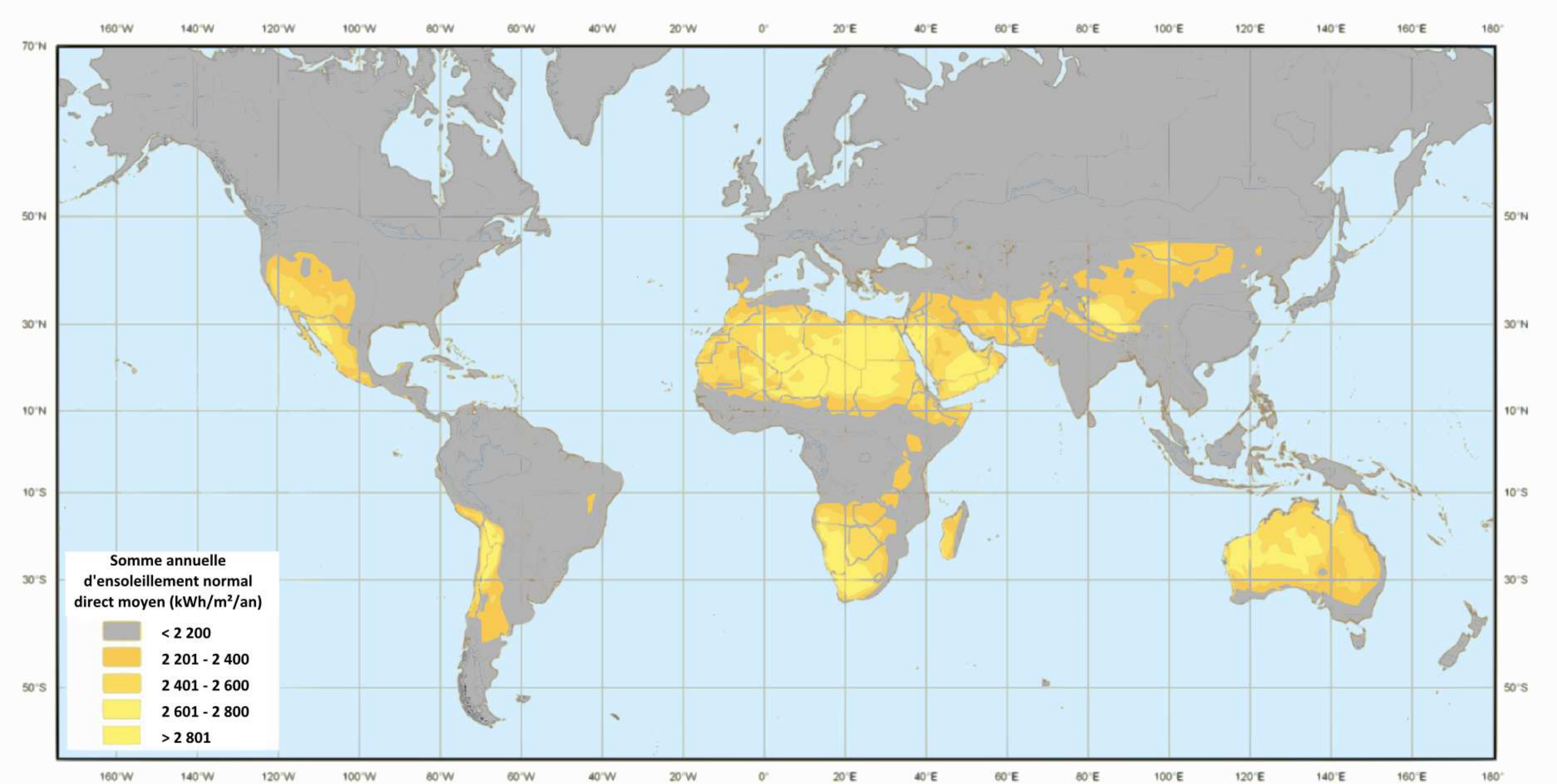
- **Today, CSP beats [PV + electrochemical batteries] whenever the storage capacity exceeds 2-3 hours of full power output. This number will increase because the cost of batteries decreases faster than that of CSP plants, but slowly.**

In conclusion:

- **There is a significant "niche market" of electric systems located in areas with high DNI that need massive storage (5 hours or more) in order to become highly renewable (>60%).**

- **Therefore, we think that there is a mid/long-term future for CSP.**

Suitable areas for CSP (DNI-wise)



Source: DLR, modified by EDF

The viewpoint of a global citizen…

Policies to boost CSP in the global energy mix:

Some recommendations

Public subsidies are required to boost storage…

…including CSP!

- Today, most electric systems have a moderate share of variable renewables and a generally carbonized mix. Their need for massive storage is therefore limited.
  Consequently, the short-term value of storage is not obvious.
- However, we know that storage will be mandatory over a medium-term horizon.
  → The market value of storage will justify its large-scale deployment.
- To fulfill this requirement by then, R&D must be performed right now. However, the time horizon is too distant to raise the interest of private companies.
- In order to anticipate the medium-term needs that we foresee, publicly-funded mechanisms are needed to facilitate the future deployment of massive storage.
- This applies to CSP that is technologically ready but needs further improvements to significantly lower its costs.

The viewpoint of a global citizen…

- **Being "technologically agnostic", some countries or authorities are more catholic than the pope. In this case, unless environmental externalities are seriously accounted for (e.g. through a significant pricing of the ton of Carbon), it will be difficult to beat a gas-fired Combined Cycle Gas Turbine.**

  Example: a bid to build a CSP plant in the Atacama desert in Chile to supply electricity to mining plants 24/7 (i.e. ideal conditions for CSP with the best DNI in the world) lost by a slim margin against a CCGT.

- **Conversely, other countries/authorities subsidize(d) renewables quite heavily. For example, they organize tenders to specifically build a CSP power plant, knowing that the chosen bid will be much costlier than a non-renewable power plant.**

  Many examples, e.g. fat feed-in tariffs in Spain (maximum DNI is ~2100 kWh/m^2.year).

- **From a global standpoint, this is a very suboptimal way of spending taxpayers' money to boost CSP.**

… can match the viewpoint of a European citizen

- The bulk of CSP will not be built in Europe anyway (the DNI is too low). We (European research entities, technology providers, utilities, etc.) want to develop CSP mostly as a technology to be exported outside Europe .
- If we decide to spend e.g. 100 M€ to enable the design, construction and operation of CSP plants, we think it is more appropriate to use this amount to help build 300 MWe in Chile than 150 MWe in Morocco or 80 MWe in Spain.
- Subsidizing European technology as a future export activity does not necessarily mean subsidizing plants located in Europe.
- **We must accept the idea of subsidizing projects that are built outside Europe.**

  Pending issue: is it theoretically/practically possible as regards local competition laws?

To summarize (and temper a bit):

- **Direct incentives where they have the largest impact on fighting climate change**
  - Government funds tend to target domestic realizations.
  - However, 1€ of subsidies (esp. investment financing) is more efficient in areas with higher potential, i.e. solar resource in the case of CSP.

- **Nevertheless, some level of support to European projects remains relevant in order to create references that would help:**
  - Reduce the perceived technological risk,
  - Showcase the European know-how.

Favor technology-neutral calls for tenders

CSP may or may not be explicitly required

- Choosing a site with high DNI and requiring (either explicitly or implicitly) a massive (e.g. 10 hour) storage narrows the choice down to CSP.
- If the area is suitable for other flexible renewables, why not letting the call open? Let us be open-minded! This will be exceptional anyway.

Within the CSP scope, technological neutrality is advisable

- Requiring expected services rather than a given technology: generation profile according to time of day, ramp-up rate (MWe/minute), water consumption, etc.
- An example: so far, most experts (including EDF's experts) believed that the molten salt tower was the unbeatable benchmark.
  However, due to the ever-decreasing cost of PV, parabolic troughs enhanced with electric heaters fed by a PV farm appeared to be more competitive.

Open-mindedness is key!

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How to meet these contradictory requirements?

- **Laying down a level playing field for all competing companies, technologies, etc.**
  - Assessing technologies based on their levelized costs only conceals all market signals (notably price variation depending of time of day).
  - Using system-level indicators allows consistent and efficient decision-making at a greater scale.
- **Properly valuing the service provided to the grid**
  - All power production technologies do not provide the same service to the grid: dispatchability, ramping capability, spinning reserve, etc.
- **If possible, taking environmental (and others) externalities into account**
  - Water consumption, carbon content of the production, etc.
- **Subsidizing the electricity generated with CSP**
  - Whilst upholding the abovementioned level playing field.

Call for tenders: PPA or market price + premium?

- Market price + premium is a powerful tool that exposes any power plant to market needs
- But PPAs are useful to reduce the perceived financial risk for less mature technologies
  - Thereby reducing the risk premium affecting the IRR and eventually the LCOE.
- Innovative financing schemes are combining different types and sources of revenues (e.g. the Aurora project in Australia)
  - However, such combined mechanisms may increase the uncertainty on long-term revenues.
- Overall, we tend to prefer a well thought-out PPA
  - South Africa: nominal price during the day, zero during the night, x2,7 during the evening (peak hours).

What about hybridized fossil-fired power plants?

- Most electric systems will keep a significant share of fossil-fired power plants (hopefully CCGTs) during several decades from now.

- Taking this reality into account, adding CSP generation to an electric system through solar hybridization of existing fossil-fired power plants can be significantly cheaper (per MWe installed) than building Greenfield stand-alone CSP plants.
  - The candidates for solar hybridization: plants located in areas with good DNI and available land for the solar field. Other criteria also apply.
  - Some realizations (IGCCs) and aborted projects.

- How to subsidize solar hybridization whilst respecting the previously mentioned criteria?
  - The marginal solar generation must be subsidized as if it were produced by a stand-alone CSP plant.
  - This can be easily performed using only a few measurements on the power cycle.

Other (and more technological) suggestions

Some widely used criteria should be streamlined

Focus on the parameters that characterize the solar irradiation :

- **Annual DNI: is it good enough to sum the 8760 hourly (or any other time interval) DNIs ?**
- **Latitude: shouldn't it be taken into account (beside its implicit influence on DNI)?**

The irradiation is the most decisive criterion to build a CSP plant, and it may impact the choice of the most appropriate architecture (parabolic trough / solar tower, etc.)

Determining a more relevant criterion than the annual DNI should help countries/authorities (to chose the best site) as well as developers (to choose the best architecture).

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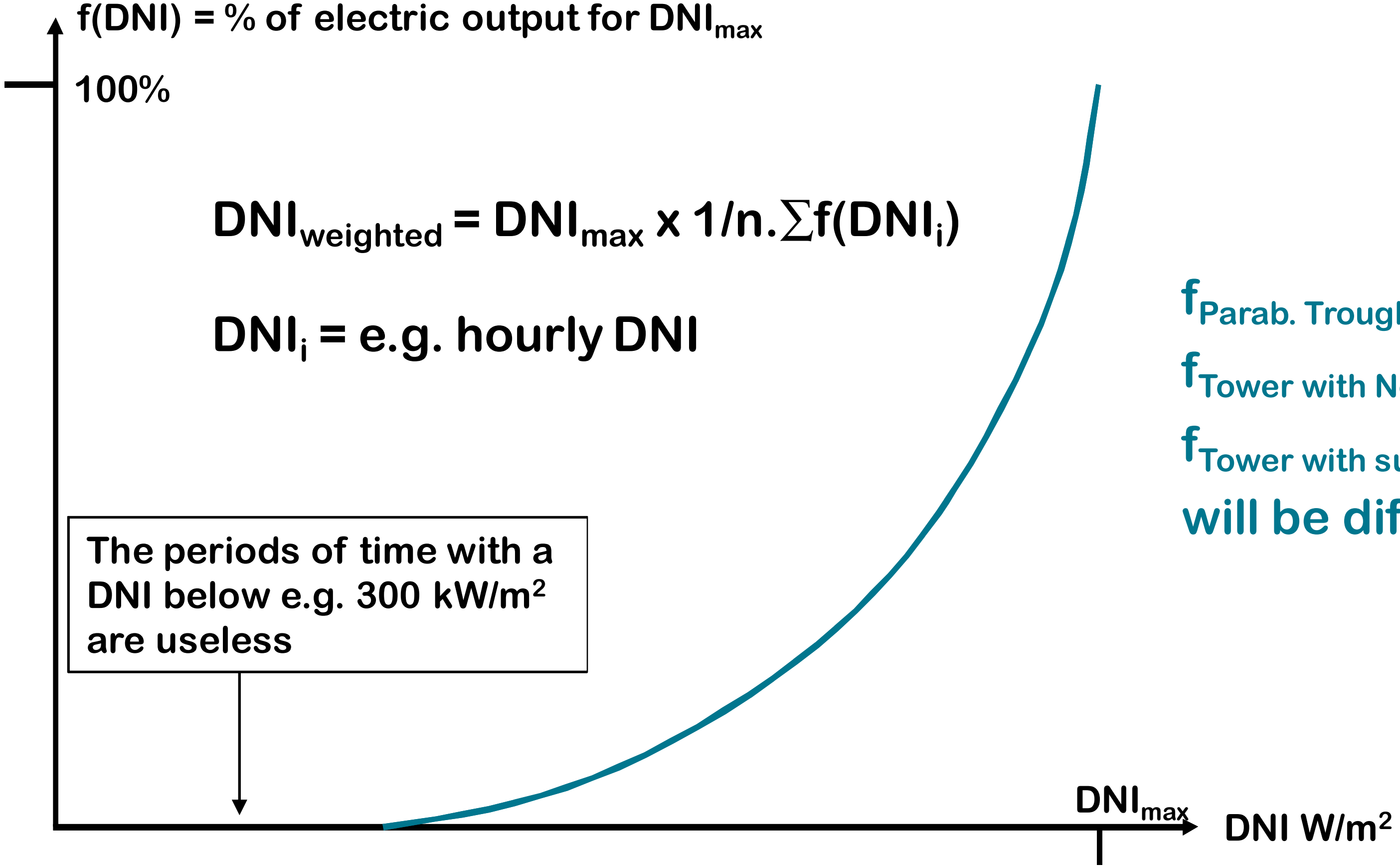
Annual DNI does not tell the whole story

- In order to make the right choices at the early stages of a project, defining relevant basic criteria should be useful. One example: the DNI.
- Annual cumulative irradiation may not be fully relevant:
  With half the nominal DNI, a CSP plant will produce much less than half the nominal output.
  → For a given amount of kWh/m^2.year, an area with some very cloudy days (most remaining days being excellent) is more appropriate than an area with a majority of fair days.
- The various available technologies of solar fields react differently to the sun elevation (latitude and season):
  Parabolic troughs, solar tower with surrounding field, solar tower with north/south field… are not equally sensitive to cosine effect, shading, etc.
  The latter is less sensitive to high latitudes (meaning lower sun elevation)
  → The best technology may not be the same in e.g. Spain and in Mexico.

Proposal: defining a set of “weighted” DNIs



$$DNI_{weighted} = DNI_{max} \times 1/n.\sum f(DNI_i)$$

DNI_i = e.g. hourly DNI

$f_{Parab.\ Trough}$

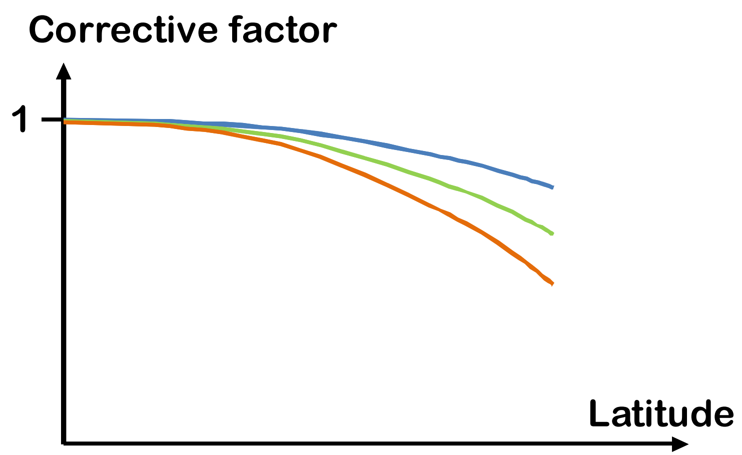
$f_{Tower\ with\ North/South\ field}$

$f_{Tower\ with\ surrounding\ field}$

will be different

Proposal: correcting the annual DNI with latitude

- **One correcting function for each solar field technology:**
  - CADNI = Corrected Annual DNI
  - CADNI = [Weighted DNI (see previous page)] x f_i(latitude)
  - $f_1 = f_{\text{Parabolic trough}}$ (green)
  - $f_2 = f_{\text{Tower with surrounding field}}$
  - $f_3 = f_{\text{Tower with north or south field}}$ (blue)
  - $f_4 = f_{\text{Linear Fresnel Reflectors}}$ (orange)



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Key takeaways

- In order to anticipate medium-term needs, publicly-funded mechanisms are needed to enable the future deployment of massive storage.
- This applies to CSP with its built-in thermal storage; it must lower its current cost. Worldwide, there is a significant potential "niche market" for CSP.
- We must accept the idea of subsidizing projects that are built outside Europe in order to develop CSP as an exporting industry. Subsidies must be directed towards areas with high solar resource.
- When subsidizing CSP, technological neutrality is advisable to lay down a level playing field.
- PPA or market price + premium? Both have their respective merits. We prefer PPAs because they lower the perceived risk, hence the required IRR and eventually the LCOE.
- Hybridizing existing fossil-fired plants is a cheap way of adding CSP to a grid. The "marginal solar generation" must be subsidized as if it were produced by a stand-alone CSP plant.
- Some widely used criteria (such as the annual DNI) should be streamlined in order to ensure a fair comparison between sites and plant architectures.

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Thank you for your attention!

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