The potential until 2030 of Concentrating Solar Power in Portugal using Inductive Projection Planning

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Asociación Española para la Promoción de la Industria Termosolar (PROTERMOSOLAR)

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Acronyms

c€/kWh	cent of euro per kilowatt-hours
Ciemat	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CSP	Concentrating Solar Power
DGEG	Direção Geral de Energia e Geologia
EC	European Commission
Estela	European Solar Thermal Electricity Association
GWh	Gigawatt-hours
IPP	Inductive Projection Planning
LCCE	Least Cost Capacity Expansion
LNEG	Laboratório Nacional de Energia e Geologia
NECP	National Energy Climate Plan
NGCC	Natural Gas Combined Cycle
PSA	Plataforma Solar de Almería
Protermosolar	Asociación Española para la Promoción de la Industria Termosolar
PV	Photovoltaics
TSO	Transmission System Operator
TWh	Terawatt-hours

Executive summary

Portugal National Climate and Energy Plan presents an ambitious roadmap to decrease CO2 emissions in 2030 by 55% compared to 2005 levels thanks, among other measures, to an 80% of electricity coming from renewable sources. This presents an opportunity to analyse how the future electrical mix would work depending on the penetration rate of both non- and dispatchable sources.

The main problem of traditional energy planning models relies on the lack of consideration towards curtailments (and associated system dysfunctionalities) and hidden costs. However, Inductive Projection Planning considers not the sum of the technologies, but the behaviour of the system hour by hour, forcing rational dispatch to CSP and Hydro, and maximizing the contribution of PV and Wind when the primary source is available.

The installation of a large share of intermittent renewables implies curtailments are unavoidable. However, the key is to maintain curtailments under manageable levels to avoid (i) the market becomes non attractive for new project at merchant prices – and therefore regulated tariff are needed to keep with the decarbonization- and (ii) additional, very expensive, measures are needed as back-up, such as the use of natural gas combined cycles in stand-by most of the year only generating when PV and Wind are not enough to meet the demand.

The use of Inductive Projection Planning provides policy makers a very powerful tool to further understand how a specific electricity mix would work using actual generation curves and demand profiles from previous years to simulate, hour by hour in year 2030 the contribution of each source (renewable or fossil). The result is a graph with hundreds of valid solutions – all of them meet demand and are below the CO2 target- with the cost on the vertical axis and the level of curtailments on the horizontal axis. The optimal set of solutions are in the so-called Pareto-front in which none can be improved by either cost or curtailment without jeopardizing the other variable.

This report recommends a range of CSP between 1.2 and 2 GW of installed capacity until 2030 -over the actual 0.3 GW. These solutions reduce curtailments between 50% and 80% compared to the NECP, increase the amount of synchronous power into the grid and keep the overall system cost into virtually the same values.

Further advantages are a lesser need of additional equipment to maintain grid stability, not cannibalization of PV prices during the day, allowing a normal development at merchant prices facilitating its deployment and a very robust complement to hydro to displace natural gas both in wet and also in dry years.

Finally, the storage system of CSP plants could work – to a large extent – as an independent infrastructure and be always prepared to deliver full nominal power at the peaking demand times, independently on whether the previous days would have been sunny or not, even in wintertime. The value of such kind of services – strategic reserve, curtailment collection, price arbitration. balancing, etc, – that can be provided by the storage system of the CSP plants – with zero or much lower investments as compared with batteries or new pumping stations – were not considered in this study. These contributions should provide additional reasons to increase the planned share of CSP by 2030 in line with the above-mentioned recommendations of this study.

1. Introduction

The history that brought us here.

Last November 2020, during a webinar organized by the University of Evora, Protermosolar had the opportunity to explain the advantages of using a well-balance mix of photovoltaics ("**PV**") and concentrating solar power ("**CSP**") into the Portuguese energy mix for 2030. CSP is the perfect complement to PV when the sun sets as a night back-up to cover the night-time demand. Moreover, CSP keeps curtailments under a manageable control, provides reliable synchronous power, and its storage system is designed to deliver full nominal power at any time.

Protermosolar had previously issued a report in Spain using Inductive Projection Planning ("**IPP**") to prove that a well-balanced of non- and dispatchable renewable sources not only meet demand avoiding at a large extent the need fossil backup but that it can be done at similar or even lower costs than the resulting – so called – optimum fleets using the business-as-usual Least Cost Capacity Expansion ("**LCCE**") models. That report was based on real generation based on previous years and hourly demand data and pointed out the complementarity among different renewable technologies, which is often forgotten when the cost is the only planning criteria. The Spanish authorities welcomed such report and announced 5 GW of CSP in their National Energy and Climate Plan ("**NECP**").

Protermosolar offered to the Direção Geral de Energia e Geologia ("**DGEG**") a similar study tailored for the Portuguese context which was accepted and even the DGEG offered to collaborate into this research. Prior to the present report, there was a meeting between Protermosolar, the European Solar Thermal Electricity Association ("**Estela**"), the DGEG and the Laboratório Nacional de Energia e Geologia ("**LNEG**") to exchange impressions and comments on the preliminary results. This document includes all the recommendations made by DGEG and LNEG.

Figure 1. Aerial view of Plataforma Solar de Almería (PSA)

Estela coordinates HORIZON-STE a Horizon 2020 funded project with the aim of launching CSP industry in Europe. Estela agreed to include the results of this study into the project to show the hidden issues with LCCE models and the real contribution of CSP to the Portuguese energy mix.

Estela hired Protermosolar to undertake the study. Then, Protermosolar contacted the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas ("**Ciemat**"), and the Plataforma Solar de Almería ("**PSA**"), which belongs to Ciemat. PSA has developed a powerful tool to carry out Inductive Projection Planning analysis as the one used in this study.

The Portuguese NECP presents an opportunity for the energy transition.

The **NECP** [1] presents ambitious goals for a full decarbonization of the energy system in 2050 with the following targets for the year 2030:

CO_2 reduction: 45-55% compared to 2005
Renewables in the electricity mix: 80%

The assessment of the European Commission ("**EC**") [2] was positive, encouraging the ambitious value of 80% of renewable sources into the electricity mix and pointing out the priority on the security of supply given this percentage of renewable sources, highlighting the need of energy storage. The assessment also highlighted the Portuguese NECP will help to reduce energy dependence. Accordingly, this study will present hundreds of combinations to help policy makers to define an ad-hoc energy mix according to their particular goals. Particularly, this report analyses the dependence of natural gas and imports and applies storage and hydro to complement PV and Wind minimizing curtailments and ensuring energy supply.

Some (wrong) beliefs about renewable energies into the electricity mix.

There is a trend to think that PV and Wind will be enough for a complete energy transition. However, the serious dysfunctionalities induced by high shares of non-dispatchable renewables are neglected:

- Curtailments will not be an issue as batteries and hydrogen will absorb them all.
- Natural gas combined cycles ("**NGCC**") will respond when PV or Wind are not producing

Green Hydrogen electrolysers will be present not only in the Portuguese market, but across Europe. However, it does not seem sensible, at this point of time, to think those electrolysers will work mainly on intermittent renewables electricity, as there would require an overdesign of the installed power increasing the curtailments even more. A hybrid plant of PV+CSP would present a large capacity factor reducing curtailments and facilitating green hydrogen production; but the electrolysers are not expected to be largely deployed by 2030. Please bear in mind the benefits of PV+CSP (24h renewable electricity with very low prices during the day and affordable prices during the night) can be achieved either at plant level or a system level by properly combining the installation of both technologies.

NGCC cannot be the main back-up system because (i) given the reduced number of hours that they would operate and the increase of daily start-ups and shutdowns, costs and CO_2 emissions will be significantly increased, and it would be necessary to consider the remuneration model under which they could provide their indispensable service to the system with a reasonable return for their owners; (ii) there is no energy independence as Portugal has no natural gas of its own; and (iii) the current fleet of NGCC will not be enough to cover the PV installed capacity every day after the sunset nor to act as back up if PV and Wind are not producing – considering the actual 3.8 GW of NGCC and the foreseen 18+ GW of PV and Wind in 2030.

There is no doubt curtailments are unavoidable, however the key is to keep them under a manageable level, not only from a technical point of view (maintaining the stability of the grid) but also from a commercial perspective. Any marginal increase on the curtailments has strong consequences on system's dysfunctionalities, which will result in large additional investments to assure the reliability of the system and will prevent the deployment of new intermittent renewable sources that would be at merchant prices. Excessive curtailments will result into a non-attractive market for PV and wind given the large number of hours per year with zero or very low prices and therefore it may imply the need of auctions or any other regulated retribution scheme to keep Portugal attractive for renewable developers.

A well-balanced fleet of non- and dispatchable renewable energy sources will reduce the need of fossil fuels without further investments and keeping the grid stability.

LCCE Models do not lead neither to more reliable nor cheaper systems.

Some disadvantages of using LCCE models are the following:

- Not analyses the feasibility of business plans as they do not consider neither the curtailments nor the low captured prices of non-dispatchable (*unrealistic business plan*).
- Not include the system's requirements to keep grid stability on their cost hypothesis (*hidden cost*).
- Not consider the real demand-profile and ramps on hourly bases nor the actual weather data on real years (*generation-demand mismatch*).
- Ends up in more expensive solutions once all the back-up sources (*endless fossil fuel back-up*) and (high) curtailments are jointly analysed.

LCCE Models could include CO_2 caps, updated auction prices instead of capex, CSP specific dispatch profile, ramp-up constraints, hourly simulation, etc., but they usually do not do it. Furthermore, they can be referred as "short-sighted" as they do not consider the impact of high non dispatchable renewable sources at market prices, which would prevent further investment decisions. Therefore, the results are unrealistic.

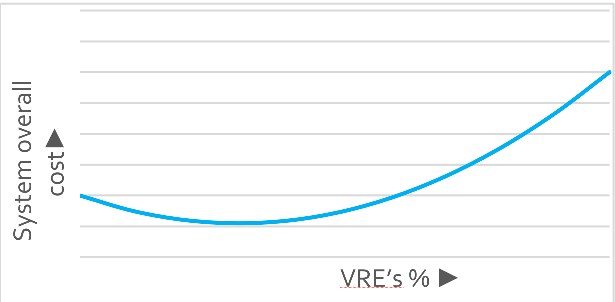


Figure 2. System overall cost as Variable Renewable Energy share increases

In any electricity system, generation and demand must always be balanced. The alternative proposed in this report is to explore the natural complementarity of renewables together with the possibilities of generation profiles adapted to the needs of the system that dispatchable technologies such as solar thermal can provide for their optimisation. **The result is** that not only can the necessary back-up capacity be reduced by understanding the versatility of operation of certain technologies, but **a cheaper** (considering hidden costs) **generation mix can also be achieved, responding to the objectives of a true energy transition**.

IPP seeks the optimum combinations of all renewable electricity mix.

IPP considers any potential combination of renewable sources and seeks the optimum combination that meet all the requirements (demand and CO_2 target) by **imposing rational dispatch** profiles to the dispatchable technologies and presents the set of optimum solutions in terms of cost and curtailments.

One of the key aspects of IPP is the use of a real year as a refence case, to fully integrate the actual profiles of demand and generation – therefore this report will use two separate reference years, one dry and one wet, to account for the weather conditions.

The model, contrary to LCCE, considers a complementing dispatch profile between PV and CSP as a basic point of the inductive approach. Then, **CSP does not cannibalize prices to PV, helping its development**, **whereas introduces long-duration renewable storage to the system**, complementing the existing capacity of hydro. Batteries do not provide this long-term storage, but a quick response of short duration mainly for technical aspects of the grid.

Figure 3. Aerial view of a Concentrating Solar Power plant

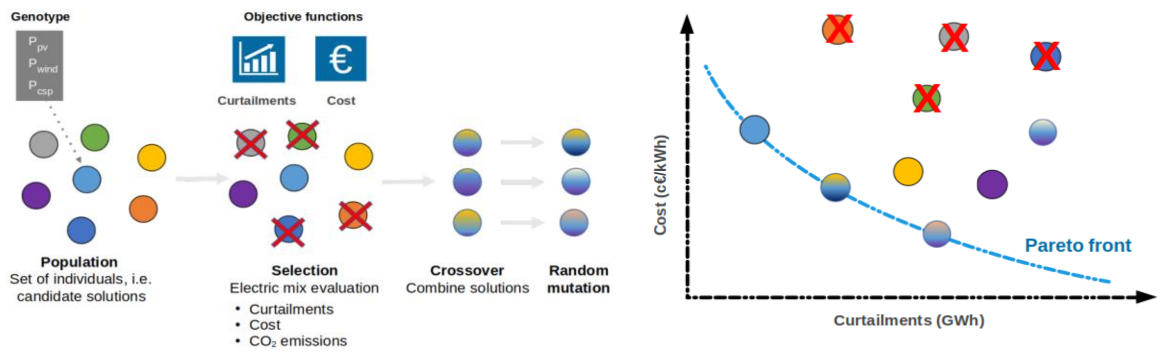
2. Methodology and inputs

Methodology

All these simulations are thanks to the intensive research undertaken by Ciemat, a Spanish R&D institution which has been involved, thanks to their solar facilities in southern Spain known as Plataforma Solar de Almería ("**PSA**"), in the development of solar technologies for more than 30 years. PSA designed and tested the tool use for all the simulations and results described in this report.

This tool [3] relies on demand and electricity generation historical data as a starting base case. The optimization process is performed by applying artificial intelligence using a genetic algorithm. The optimization estimates the optimum new power to be installed for PV, Wind, and CSP power plants that at least satisfy the demand, minimize the curtailments at the lowest possible cost while at the same time the maximum CO2 equivalent emissions are not surpassed.

Genetic algorithms are inspired by biological operators such as crossover, selection, and mutation, based on the concepts developed in Darwin's theory of evolution. In a genetic algorithm, a population of candidate solutions is evolved toward better solutions. Each candidate solution has a set of properties knows as genotype (new power to be installed for PV, Wind, and CSP power plants) – please refer to Figure 4. The evolution is an iterative process and usually starts from a population of randomly generated candidate solutions. The fitness of every candidate solution in the population is evaluated at each generation and determined by the objective functions (curtailments and cost). Multi-objective optimization problems deal with conflicting objectives; while one objective increases, the other decreases and vice-versa. There is not a unique global solution but a set of solutions. Some candidate solutions may be unfeasible due to restrictions (satisfy demand and allowed maximum CO2 emissions). A solution dominates another solution when it is better with respect to every objective. The non-dominated set of solutions are those that are not dominated by any member of the population. The non-dominated set of feasible solutions are the optimal set of solutions and they are arranged in the Pareto front Figure 4 (b) optimum solutions that do not have lower cost for the same curtailments or less curtailments for the same cost.



(a) One iteration of the genetic algorithm (b) Pareto front

Figure 4. Genetic algorithm principle.

Each candidate solution in the population represents an electric mix configuration and must be evaluated to determine its feasibility (satisfy demand and maximum CO2 emissions) and its fitness through the evaluation of the objective functions (curtailments and cost). The electricity demand for a whole year is elaborated using hourly historical data and the predicted yearly increment. The generation profile of each energy source is also given by historical data and it is proportional to the installed power. Figure 5 summarizes the evaluation process.

The annual average electricity cost is calculated considering the hourly electricity generation. If there are not curtailments and the minimum number of equivalents hours is reached, this nominal electricity cost is used.

An equivalent hour for any energy source is defined as an hour where the energy source produced electricity at its maximum power, ie. its installed power. If the minimum number of equivalent hours is not reached, Equation 1 is used to calculate the adjusted electricity cost, where power is the installed power (MW), h_{min} is the minimum number of equivalent hours (h), cost is the nominal cost (€/MWh) and energy is the electricity produced (MWh). Note that h_{min} is given by Equation 2, where $energy_{nominal}$ is the nominal electricity to reach the minimum number of equivalent hours. If the energy source generates curtailments, the previous cost is adjusted considering Equation 3.

$$\frac{power \cdot h_{min} \cdot cost}{energy}$$

Equation 1. Adjusted electricity cost as a function of equivalent

$$\frac{energy_{nominal}}{power}$$

Equation 2. Minimum number of equivalent hours

$$\frac{(energy + curtailments) \cdot cost}{energy}$$

Equation 3. Adjusted electricity cost as a function of curtailments

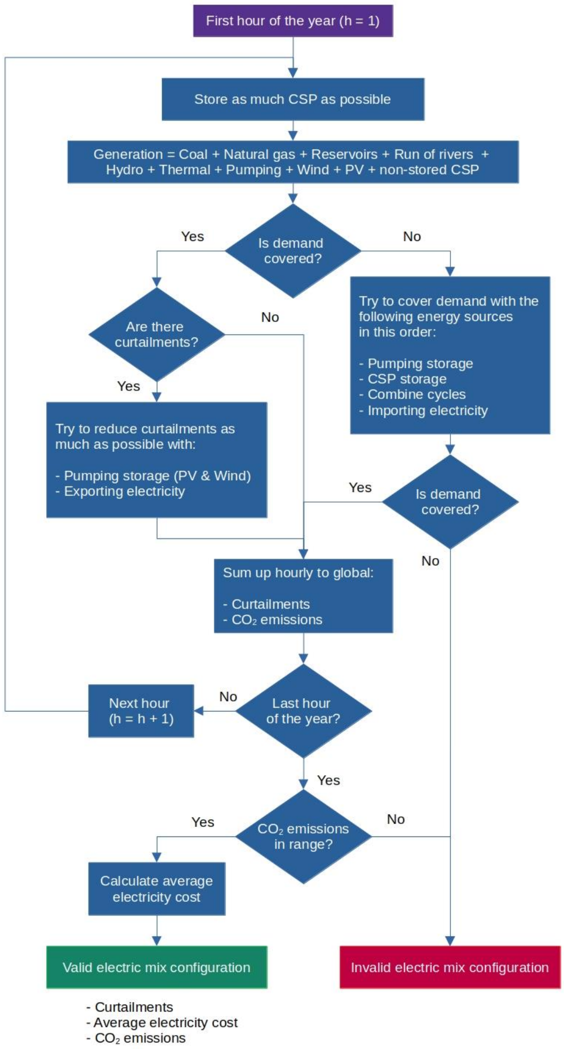


Figure 5. Electricity mix evaluation

Objectives

It is important to consider what will be the main drivers of the model. On one hand side, it is clear the variable **cost** must be considered as a primary objective. But to completely define a functional system, besides the cost, it is necessary to understand other variables. Figure 7 represents a potential policymaker concerned about many potential dysfunctionalities into an electrical system, which, directly or indirectly, are all related to the level of **curtailment**:

- Will the synchronous power requirements be met at any time?
- Will the fleet of combined cycle be enough to back up PV after the sunset?

- What would be the dependence on imports to meet demand?
- Would it be necessary to make important further investments or to subsidize batteries to keep the system stable?
- Will the exports be available when most needed?
- What will be the impact of curtailments into new developments?
- …

As curtailments increase, would the **market be attractive for new merchant projects**? If not, it would be necessary new regulated schemes for new projects – increasing the overall system cost.

Could c. 3 GW of NGCC provide the necessary back-up to 9 GW of PV after the sunset? In other words, is there enough power to face the **duck curve** every day? How reliable are the **imports** under severe circumstances? Are **exports** always available even in the excess of Sun radiation?

Reducing curtailments by increasing the share of dispatchable technologies would facilitate the deployment of renewables and would prevent from system's dysfunctionalities

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Figure 6. Upcoming policy-maker tribulations

The level of curtailments is precisely the variable that is - directly or indirectly - behind all these system's dysfunctionalities. That is why the results of this study are presented in terms of systems generation cost and curtailments level to help policy makers to make the best choice.

Inputs

This section describes in detail the inputs used for the simulations.

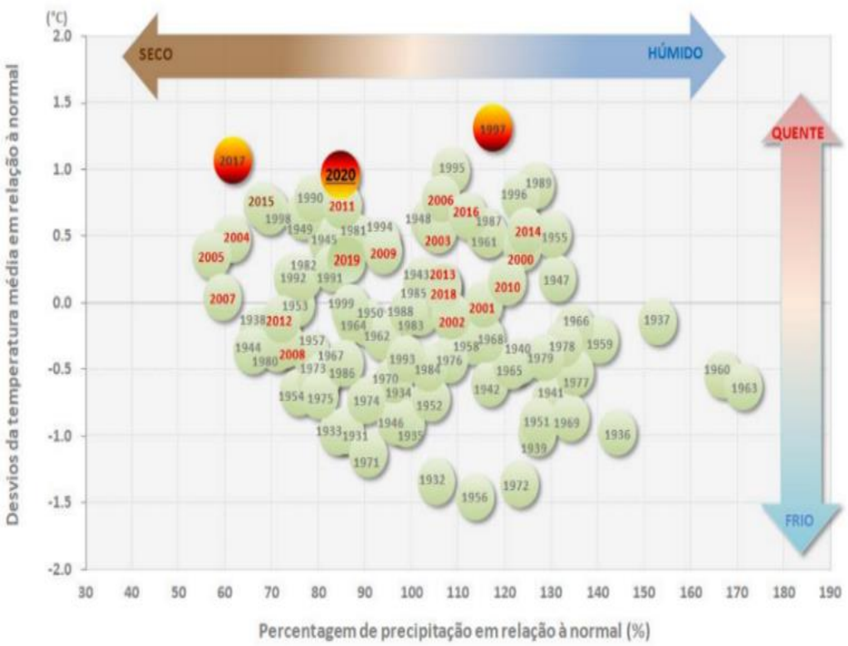


Figure 7. Average temperature and precipitations in continental Portugal between 1931 and 2020

The selection of the **reference year** considering the average precipitations (*wet* and *dry*) according to [4] and being recent years so that the energy mis and the demand are representative. Then, **2018** has been chosen as **wet** year whereas **2019** as **dry** one.

The **demand** has used the actual one from years 2018 and 2019 [5] with an annual increase of **1.5%** as per [6].

The **actual generation** is taken from [5] but, as there is no CSP installed in Portugal, this report uses the CSP actual generation from a neighbouring area in Spain [7]. The actual CSP data correspond to parabolic trough actual plants. In order to account also for a deployment of tower technology, an improvement factor is included representing the cosine factor.

Table 1 shows the **technology cost expected in 2030** considering a variety of sources, both reports and results from recent auctions in Spain and Portugal [8] [9] [10] [11] [12]

Electric source	Installed Power (MW)	Cost (c€/kWh)
Coal	0	-
Natural gas	3,200	7.6
Reservoirs	2,374.8	2
Run of rivers	1,206.6	2
Hydro	1,319 (1)	2
Thermal	460 (2)	6.5
Pumping	3,600	4.5
Wind	**TO OPTIMIZE**	2.7
Photovoltaic	**TO OPTIMIZE**	2
Solar thermal (CSP)	**TO OPTIMIZE**	6
Import	4,200	6
Export	0	-

Table 1. Technology cost for 2030 used in the simulation

Finally, the last input is the **CO_2 emission factor per source** applying [13] but adjusting the natural gas by [14] to account for the higher penetration rate of intermittent renewable sources and therefore the lower efficiency of the NGCC.

Energy source	Factor (ton CO_2/GWh)
Coal	933
Natural gas	650 (1)
Fossil cogeneration	327 (2)

(1) https://euanmearns.com/co2-emissions-variations-in-ccgts-used-to-balance-wind-in-ireland/
(2) It applies to Biomass w/ cogeneration and Fossil cogeneration. It is approximately 2/3 of Thermal power.

Table 2. CO_2 emission factor per source

3. Results

This IPP model analyses thousands of energy mix combinations, for different shares of installed capacity of PV, Wind and CSP. Most of these solutions are discarded when they do not meet either the CO_2 target or the demand every single hour in year 2030. For the remaining hundreds of valid combinations, the model plots all of them in a graph defined by the overall system cost [c€/kWh] (vertical axis) and the curtailments [GWh] (horizontal axis). The focus for planning purposes should be put on those solutions along the Pareto front, which provides the choices in terms of cost and curtailments.

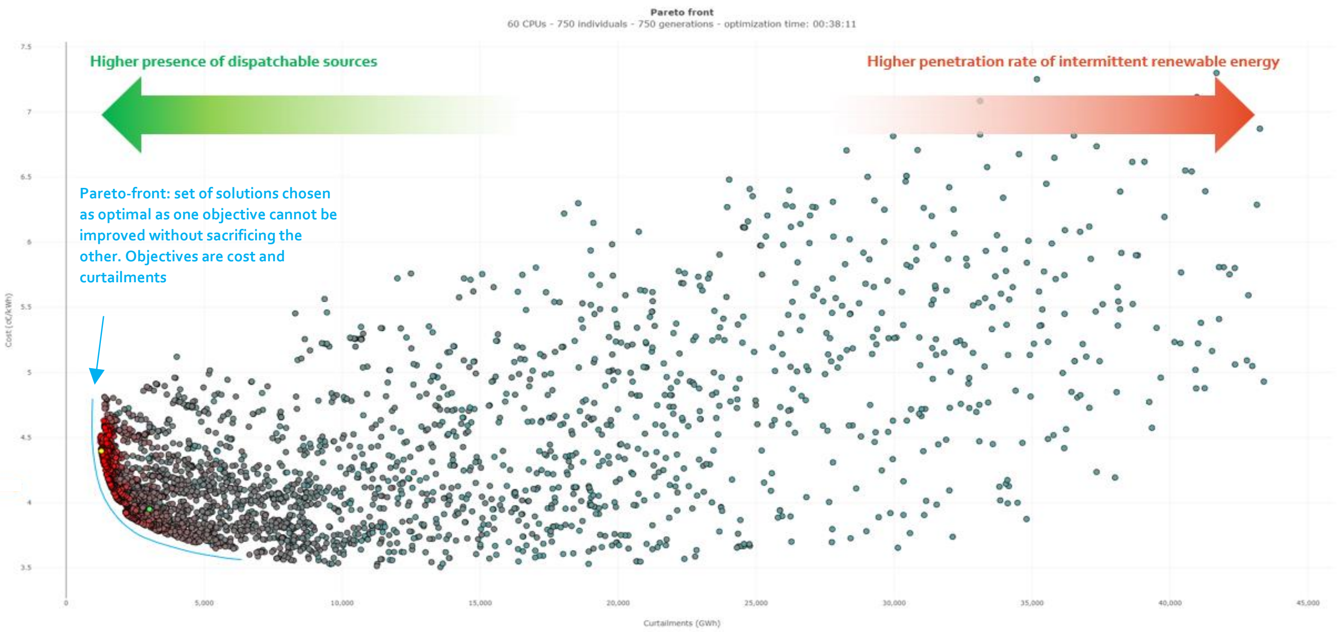


Figure 8. Example of the IPP results with the Pareto-front definition

As explained into the previous section, it is important to consider both wet and dry years [4] as Portugal presents a significant fraction of hydro power; therefore, all the results are split into two reference years with relevant differences between them.

For any solution, besides the cost and the curtailments, it is necessary to pay attention to the following parameters:

Synchronous power

Any TSO worldwide needs a minimum level of synchronous power to handle the grid. Although, thanks to the development of power electronics, the asynchronous sources could present some virtual inertia in practical terms this would be an additional hidden cost of the intermittent renewable sources. Our study analyses the number of hours below a synchronous power threshold so that the Portuguese authorities can determine any limit they want to impose to the system.

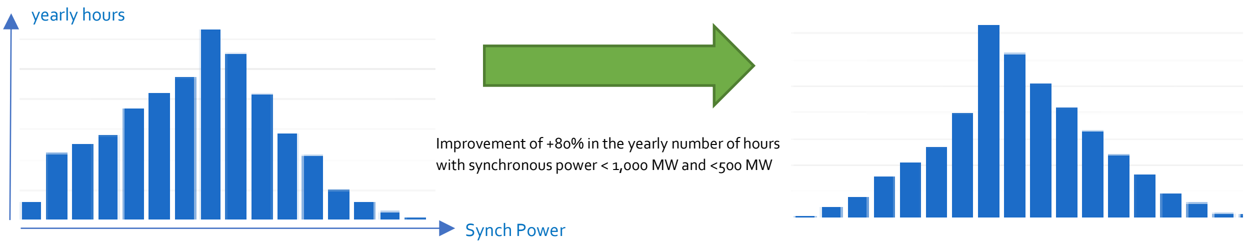


Figure 9. Improvement in synchronous power from the NECP to a scenario with >2 GW of CSP

This parameter is essential to quantify additional hidden costs. A low synchronous-power mix presents more curtailments, and the need of additional equipment such as grid forming devices and more batteries for technical purposes. Then, the overall system cost would not be just the sum of PV and Wind but also this equipment.

Natural gas combined cycles ramps

The presence of natural gas combined cycles in Portugal in the year 2030 considered in the NECP is in a range between 2.8 and 3.8 GW. Regardless of the existing operating capacity in 2030, it is assumed the main role of the natural gas will be the back-up of PV while the Sun is not shinning (in winter/cloudy days and during the night), meaning combined cycles will not provide baseload of the Portuguese energy system, but a back-up role with plenty of shutdowns per year.

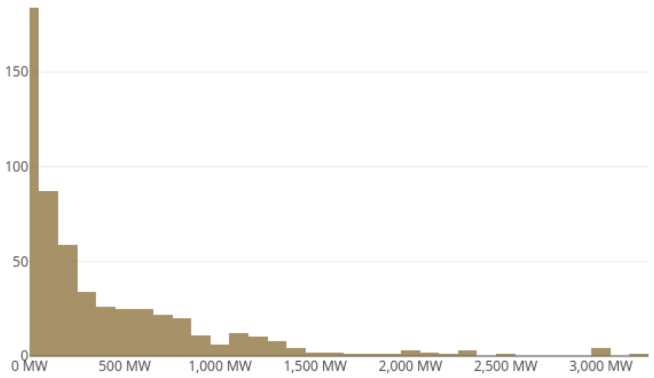


Figure 10. Histogram with the number of hours in 2030 for each ramp increase

Thus, this study pays special attention to the needed ramps (defined as the difference in power provided by combined cycles from one hour to the next, every single hour during year 2030) to assess their feasibility. The Portuguese authorities or TSO may impose any threshold they consider it is not feasible to reach by the fleet of natural gas plants. The results provide the number of hours the system might be at risk (ie. above the required threshold).

Results

Prior to the recommended range of CSP in Portugal for year 2030 that will be detailed in the next paragraphs, the first step is to assess whether the NECP is located into the Pareto-front. In case it is not, there would be a better-off scenario by drawing a horizontal line and choose any point towards the left, as they will keep the same cost but reducing curtailments.

Figure 11 shows a simulation by which choosing a scenario with 0.56 GW instead of 0.3 GW reduces curtailments by 35% while keeping the same system cost.

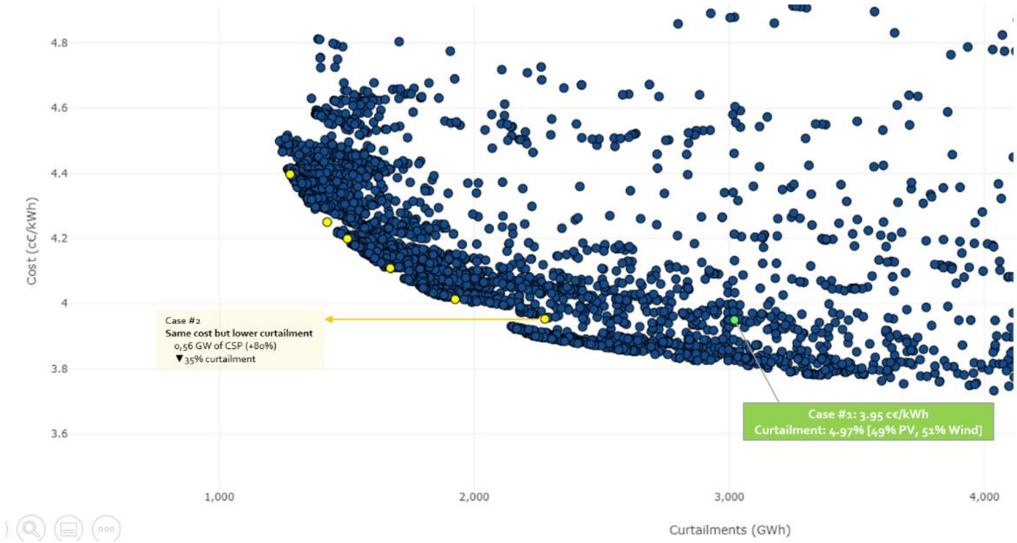


Figure 11. Example of simulation with a better off solution: same cost, lower curtailments

Table 3 and Table 4 summarize the results of a gradual CSP increase in installed capacity from the actual NECP up to a value by which the overall system cost increment does not exceed 10% - for both wet and dry years.

Our results show that sensible increments of CSP into the overall mix will strongly benefit the electrical system:

- ▲ Facilitates a higher penetration rate of PV and Wind by improving dysfunctionalities but also keeping an attractive market for intermittent renewable sources.
- = Maintains a very similar overall system cost – fewer hidden costs.
- ▼ Curtailments – and all associated dysfunctionalities- would be lower, and therefore, manageable.

The following tables details, as the CSP installed capacity increases, the overall system cost of the NECP and the correspondent increments, the initial curtailments and their reductions, the percentage, over the total demand, of imported energy, a histogram with the number of hours below a certain synchronous power and the resulting mix in terms of installed capacity.

Figure 12 and Figure 13 plot the curtailment reductions and synchronous power improvement (measured as the number of hours below a certain synchronous power during year 2030) as a function of the installed CSP capacity helping to determine which is the maximum contribution per new MW of CSP installed capacity.

Considering the information of the tables and figures on the next pages, the **recommended range is between 1.2 and 2 GW** of CSP. Above 2 GW, the improvement in curtailments and synchronous power is not that relevant while there is an overall cost increase close or above 10%. Below 1.2 GW, there is still plenty of room to improve the system with at a very limited cost increase.

Recommended range (#3 – #4)

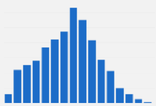
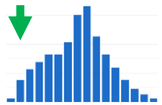
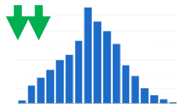
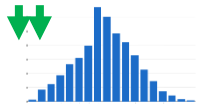
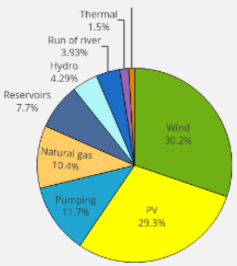
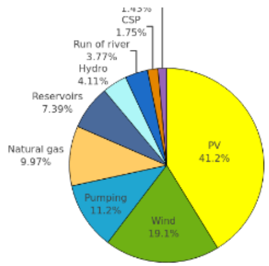
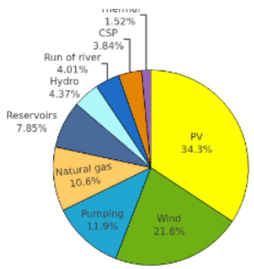
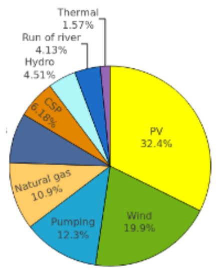
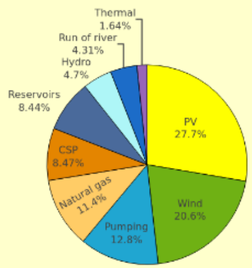
	#1 NECP	#2	#3	#4	#5
Installed CSP [GW]	0.3	0.56	1.16	1.81	2.38
Energy cost [c€/kWh]	3.95	=	▲4%	▲7%	▲10%
Curtailments NECP: [% over demand] Others: [€ reduction over NECP]	4.97%	▼35%	▼50%	▼56%	▼60%
Imported energy [%]	2.7%	3.5%	2.9%	3.1%	3.3%
Synchronous power Time: <1,000 MW [h] < 500 MW [h]	566 h / 124 h 	354 h / 48 h 	281 h / 38 h 	192 h / 26 h 	99 h / 16 h 
Installed capacity					

Table 3. Results for CSP between 0.3 GW (NECP) and 2.38 GW on a wet year

Recommended range (#8 – #9)

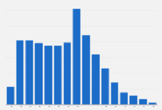
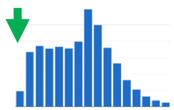
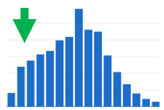
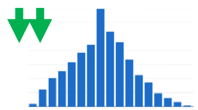
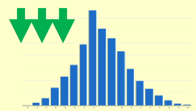
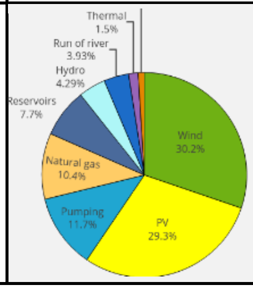
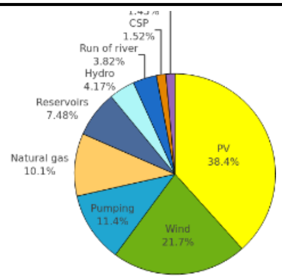
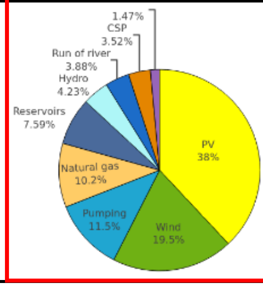
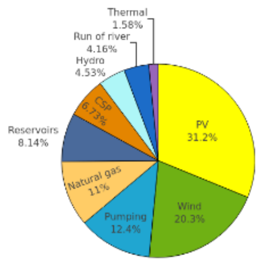
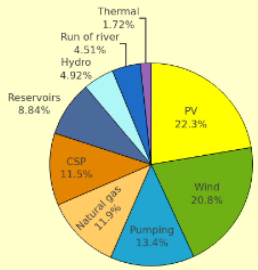
	#6 NECP	#7	#8	#9	#10
Installed CSP [GW]	0.3	0.48	1.10	1.96	3.09
Energy cost [c€/kWh]	4.02	=	▲3%	▲9%	▲16%
Curtailments NECP: [% over demand] Others: [€ reduction over NECP]	3.85%	▼60%	▼70%	▼80%	▼85%
Imported energy [%]	2.4%	2.7%	2.5%	2.6%	3.2%
Synchronous power Time: <1,000 MW [h] < 500 MW [h]	1,044 h / 226 h 	856 h / 189 h 	646 h / 166 h 	283 h / 39 h 	47 h / 6 h 
Installed capacity					

Table 4. Results for CSP between 0.3 GW (NECP) and 3.09 GW on a dry year

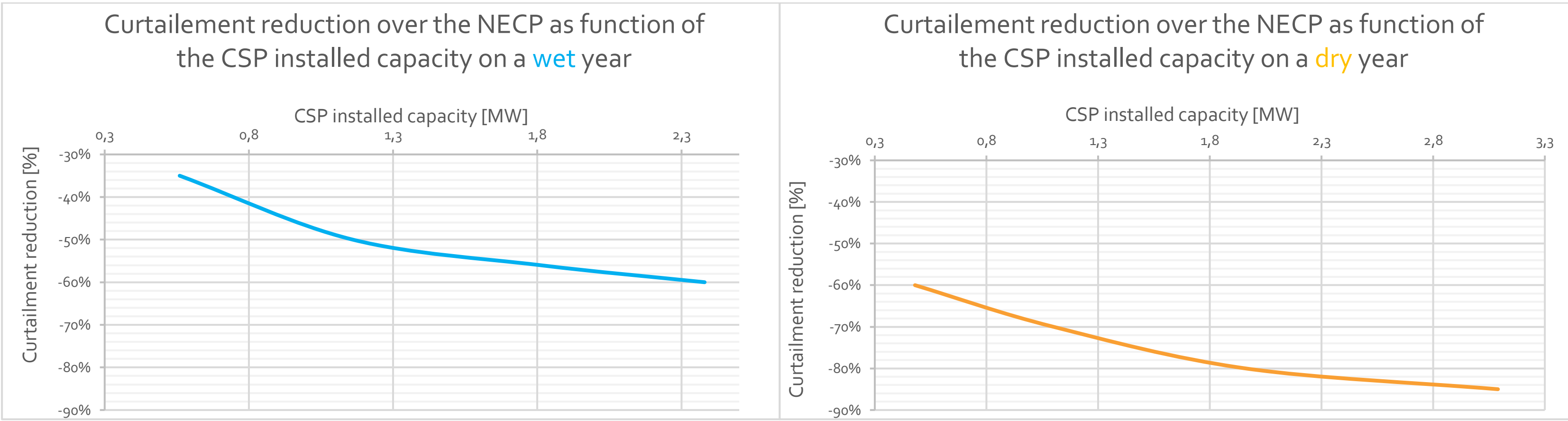


Figure 12. Curtailment reduction over the NECP as function of the CSP installed capacity on both wet and dry years

OFF *As CSP grows, there is a significant reduction in curtailments and strong improvement in synchronous power*

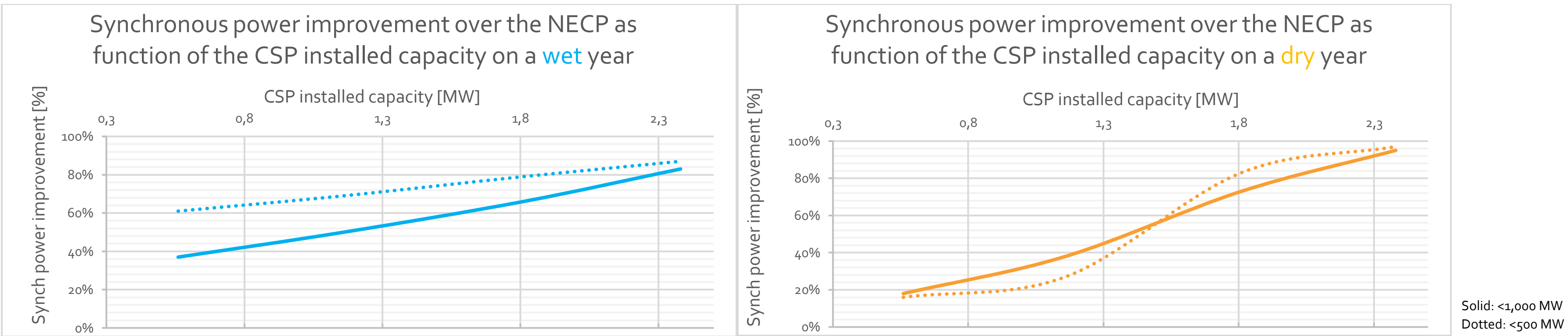


Figure 13. Synchronous power improvement over the NECP, measured as number of hours below a threshold, as function of the CSP installed capacity on both wet and dry years

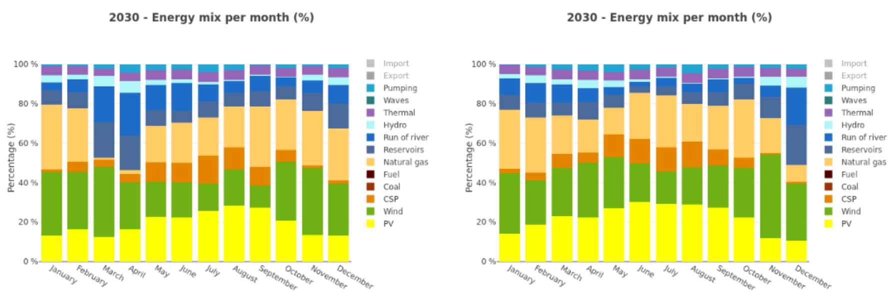
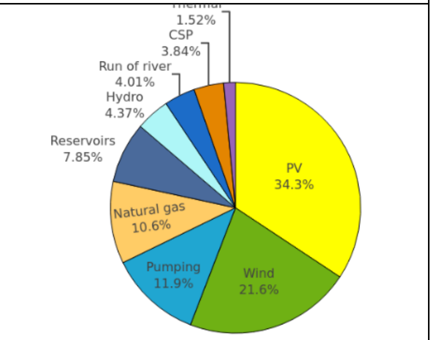
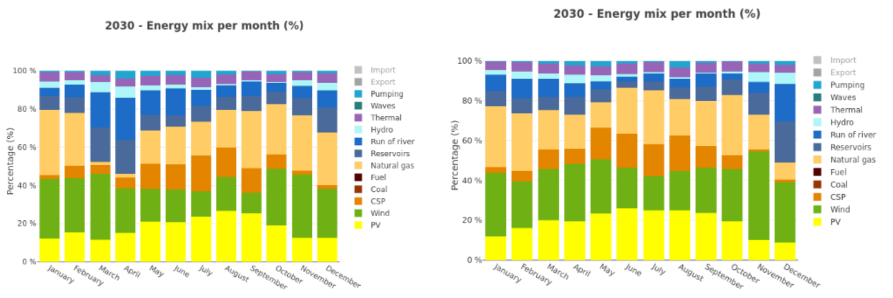
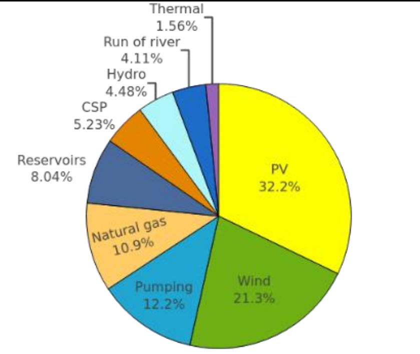
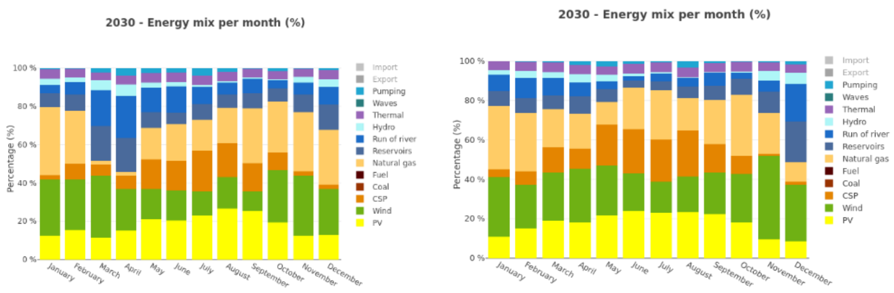
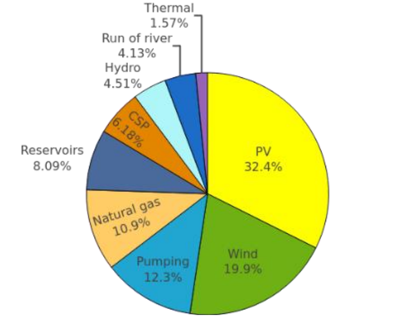
CSP [GW]	Cost (▲ NECP)	Imported Energy [TWh] NECP: 1.40-1.67	Energy generation per month in year 2030 wet (left) and dry (right) years	Energy mix [%] of the installed capacity
1 GW (1,16 – 1,10)	**3-4%**	**1.50-1.81**		
1,5 GW (1,54 – 1,50)	**6 %**	**1.50 – 1.84**		
2 GW (1, 81 – 1,96)	**7-9%**	**1.59 – 1.91**		

Table 5. Recommended range of Protermosolar for CSP installed capacity detailing the system cost, the annual imported energy, the generation per source and the installed capacity in 2030.

For the recommended range of 1.2-2GW, Table 5 further analyses the scenarios also indicating the monthly electricity generation per source. A very interesting insight is that, as CSP installed capacity increases, the energy generated by CSP displaces the natural gas contribution, being more evident on dry years as during wet ones the contribution of hydro is very significant.

CSP displaces natural gas contribution, complementing hydro on dry years

For Portugal, hydro and CSP can play a significant role as being the most attractive dispatchable energy sources to complement PV and wind. Hydro needs a complement for dry years (the last 4 out of 6 since 2015).

Discussion

This study is based on certain assumptions that are challenged in the following paragraphs:

Sensitivity to CSP costs

An increase of the CSP cost would not substantially change the results – rather than an increase in the overall system cost- as natural gas' contribution is limited to the CO_2 emissions and hydro to the expected growth into the NECP (there is no optimization on this technology). Therefore, CSP has no competitor for the night supply and to reduce curtailments. Figure 14 shows an increase between 0.18 and 0.02 of c€/kWh in the overall system cost per one c€/kWh of increase in the CSP cost – depending on its share of the energy mix.

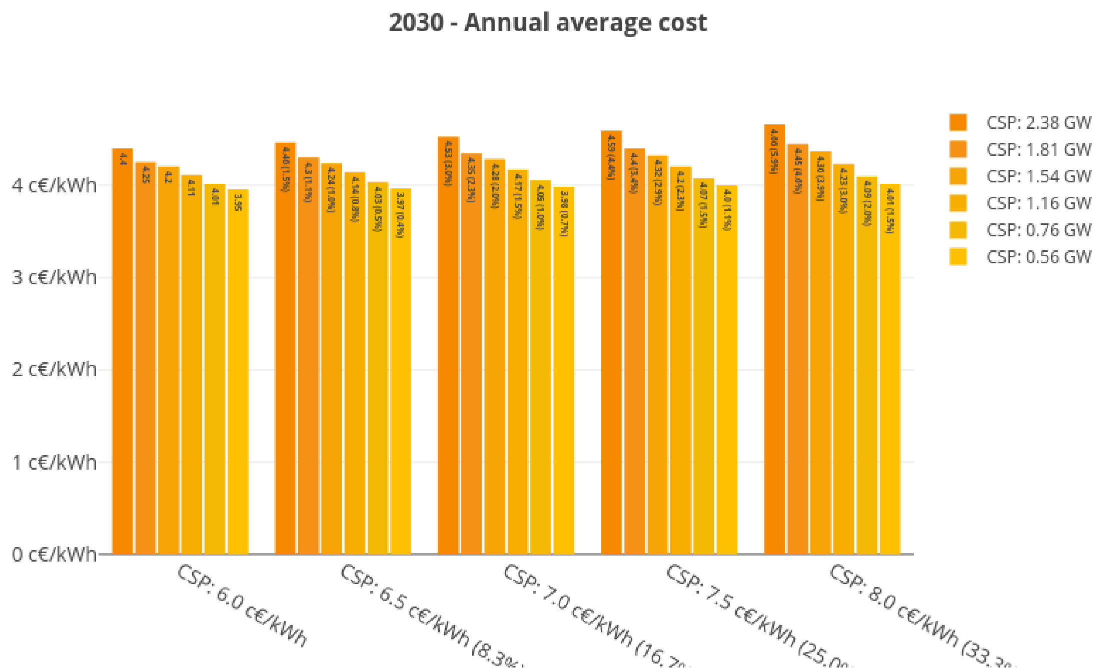


Figure 14. Sensitivity analysis of the CSP cost

Sensitivity to PV and wind costs

Similar to the above, the main impact would be limited to the overall system cost but maintaining the same energy mix as PV and Wind costs are far below any other technology as Table 1 indicates.

Sensitivity to the CO2 target

This factor, contrary to the previous ones, has a significant impact on the energy mix. A less demanding target would allow natural gas to contribute as much as possible - the model considers the actual contribution in years 2018 and 2019 when it was quite relevant. Natural gas growth would supply night demand - mostly in winter of dry years when there is no alternative if CSP is not deployed.

On the contrary, a more demanding target would virtually eliminate the natural gas into the energy mix (depending on how aggressive is the target), being replaced mostly by CSP.

This study has not quantified any other CO2 target as 55% seems reasonable, in the high range of the goal, aligned with similar member states. If there were strong reasons to simulate a different target, the optimization can be easily adapted.

Portuguese NECP

The goal of this study is not to challenge or evaluate the actual Portuguese NECP as there might be some parameters to be further adjusted – such as the increase in demand, the demand or generation profiles, the costs or CO2 emission factor, etc. Therefore, this report cannot conclude whether the NECP is "good" or "bad".

The purpose of this report is to create awareness of some potential dysfunctionalities to the system, namely curtailments and directly related impacts on system's dysfunctionalities such as unrealistic business plans for PV and Wind developers, synchronous power w/o any additional investment on power electronics, feasibility of the natural gas back-up, etc.; to provide a powerful planning tool to the Portuguese authorities into their design of the future electricity mix.

4. Conclusions

The main conclusion from this report is the **recommended range for CSP installed capacity until 2030 in the range of 1.2 – 2 GW**, an increase of 4x – 6x over the existing 300 MW of the Portuguese NECP.

The recommended CSP range for Portugal is between 1.2 and 2 GW

Adding CSP will help to increase the presence of other renewable energies as merchant prices will remain attractive since curtailments are under control. Furthermore, adding more CSP will enable the deployment of intermittent renewable energies such as wind and PV without any support from the State, as lower curtailments would motivate investments on merchant projects reducing future auction prices.

In addition to the above, a high penetration rate of CSP avoids further investments on grid stability equipment given the fact that CSP provides a reliable synchronous power additional to the existing sources, namely hydro power and natural gas combined cycles that would be displaced by CSP in the future. **The complementarity of hydro for wet years and CSP for dry and sunny ones is the best renewable strategy to replace the use of fossil fuels in Portugal**.

Finally, the storage system of CSP plants could work – to a large extent – as an independent infrastructure and be always prepared to deliver full nominal power at the peaking demand times, independently on whether the previous days would have been sunny or not, even in wintertime. The value of such kind of services – strategic reserve, curtailment collection, price arbitration. balancing, etc, – that can be provided by the storage system of the CSP plants – with zero or much lower investments as compared with batteries or new pumping stations – were not considered in this study. These contributions should provide additional reasons to increase the planned share of CSP by 2030 in line with the above-mentioned recommendations of this study.

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