Market Uptake of Solar Thermal Electricity through Cooperation

Deliverable 7.4: Pivotal decisions and key factors for robust CSP strategies

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Market Uptake of Solar Thermal Electricity

MUSTEC
Market Uptake of Solar Thermal Electricity

ABOUT THE PROJECT

In the light of the EU 2030 Climate and Energy framework, ***MUSTEC- Market uptake of Solar Thermal Electricity through Cooperation*** aims to explore and propose concrete solutions to overcome the various factors that hinder the ***deployment*** of concentrated solar power ***(CSP)*** projects in Southern Europe capable of supplying renewable electricity on demand to Central and Northern European countries. To do so, the project will analyse the ***drivers and barriers*** to CSP deployment and renewable energy (RE) cooperation in Europe, identify future CSP ***cooperation opportunities*** and will propose a set of concrete ***measures*** to ***unlock the existing potential***. To achieve these objectives, MUSTEC will build on the experience and knowledge generated around the cooperation mechanisms and CSP industry developments building on concrete CSP ***case studies***. Thereby we will consider the present and future European energy market design and policies as well as the value of CSP at electricity markets and related economic and environmental benefits. In this respect, MUSTEC combines a dedicated, comprehensive and multi-disciplinary analysis of past, present and future CSP cooperation opportunities with a constant ***engagement*** and ***consultation*** with ***policy makers*** and ***market participants***. This will be achieved through an intense and continuous ***stakeholder dialogue*** and by establishing a tailor-made ***knowledge sharing network***.

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EXECUTIVE SUMMARY

Concentrating Solar Power (CSP) offers flexible and decarbonised power generation and is - as a solar power-based balancing opportunity – able to contribute to the transition towards sustainable and stable future electricity systems. To have this technology available for the generation portfolio in Europe when it will be needed, certain conditions in the electricity systems have to be met. In this report, we shed a light on key factors and pivotal decisions for successful CSP deployment in Europe. From the wide range of factors that are relevant for CSP deployment in Europe's future electricity system, we elaborate in particular on the effect of cooperation, demand-side management, electricity grid expansion, decarbonisation ambition, technology cost developments of CSP and competing technologies, sector coupling, and increasing shares of fluctuating renewables and nuclear phase-out on CSP deployment. This assessment condenses many different outcomes of the MUSTEC project so far and is based on the policy pathway elaboration (WP7) and the core findings from the integrated model-based assessment (WP8). Compiled from these MUSTEC research activities, we present in this report the key drivers and policy decisions that are needed for effective CSP deployment in Europe in the coming years up to 2050.

- ***RES cooperation can act as important driver for CSP*** thanks to the increased demand for CSP, and the expectable ***decrease in financing cost driven by cooperation policies.*** This is (partly) confirmed by modelling where the CSP uptake is significantly stronger in scenarios assuming strong RES cooperation combined with strong electricity demand growth. In these cooperation scenarios, it makes long-term economic sense to invest in CSP.
- There are ***different niches for different flexibility options***. We showed that in the case of reduced flexibility (-50%) provided by decentral heat storage (linked to heat pumps) and e-mobility, the need for CSP is rarely impacted because it is needed in both cases due to its generation characteristics combined with (short-term) storage opportunities.
- If exporting countries decide to ***expand and diversify their transmission and interconnection capacities beyond what EU rules require***, they are able to better exploit the full capacity for deployment of dispatchable CSP.
- A ***full decarbonisation*** of the energy system in line with the Paris agreement as intended by the EU policy ***requires strong increases in sector-coupling*** and, consequently, ***in electricity demand***. This is a ***key driver for an enhanced uptake of CSP*** within Europe in future years.
- CSP needs ***effective price signals valuing dispatchable and CO2-free electricity generation***. If policies on market design ensure these price signals without allowing for CCS, CSP is able to play an important role.
- ***Technology cost reductions*** of all CSP components are necessary to keep this technology competitive and available for the transformation of our electricity systems. Since absolute CSP capacities installed are relatively small, policies for ***targeted support for CSP*** are needed and able to foster high learning rates.

- ***Thermal energy storage*** is a valuable and ***cost-effective flexibility option*** for future electricity systems. Under current cost assumptions, CSP becomes more competitive than PV + battery at around 4-5 hours storage duration. Support for the CSP enhances at the same time thermal storage technologies as flexibility options for the electricity system.
- ***CSP and PV can fulfil complementary tasks*** which have to be addressed by renewable policies. Competitive specific auctions can help to rate the system contribution of different technology options and value the dispatchability of CSP. Both, PV and CSP, are needed in the electricity system of 2050 according to our modelling.
- National or international policies causing ***nuclear (and/or coal) phase-out create a need for alternative dispatchable technologies, which can be covered by CSP***. National acceleration of the transition that aims for reaching fully renewable systems as early as possible increase these flexibility needs accordingly.

We show in detail how these factors can enhance the uptake of CSP in Europe and how they can be addressed in policy decisions. An important finding is also that many of the identified factors are closely linked to each other and significant synergies can be achieved by combinations of different key drivers (like e.g. strong decarbonisation ambition in the energy system and technology cost reductions of CSP) in policy decisions supporting the deployment of CSP.

1 INTRODUCTION

The European Union has set the target for 2030 to cut greenhouse gas emissions (GHG) by (at least) 40% compared to 1990 levels (European Commission, 2020a). Furthermore, the long-term vision is to become climate-neutral by 2050 (European Commission, 2020b). These targets will lead to a transformation of the energy infrastructure to a renewable energy based energy system (Jacobson et al., 2017). As wind and solar power generation are highly fluctuating, a higher amount of balancing technologies will be needed in the future power system (Joos & Staffell, 2018). CSP offers flexible and decarbonised power generation and is able to play a part in this transition as a solar power-based balancing opportunity. In order for this to happen, certain preconditions have to be met.

Within this report, we shed light on pivotal factors, strategies and policy decisions for the successful deployment of CSP. This report completes the analyses undertaken in the course of the MUSTEC project on policy pathways towards a decarbonized electricity system in the EU. The integrated modelling assessments conducted in WP8 then identified the role of CSP in these pathways. The qualitative and quantitative analyses that have been conducted in WP7 (*Policy Pathways for CSP*) and WP8 (*CSP integrated assessment*) build the basis of this report.

Central questions to be answered are: What are **pivotal factors** and **policy decisions** that **support or eliminate the need for CSP**? Are there **robust CSP expansion paths incorporating certain features** of the CSP fleet? This report summarizes in a concise manner the findings of the analyses that have been derived so far in the course of the MUSTEC project, complemented by insights gained from results and analyses conducted within former studies.

This report is structured as follows: In Section 2, we show how the policy pathways collected in WP7 are processed in the integrated modelling activities of MUSTEC. In Section 3, the key factors and policy decisions for CSP deployment are presented building on the modelling results of WP8 and compiling their most important findings. Section 4 puts these findings on the question of what CSP needs to take off in terms of market conditions in comparison to results from former research. Section 5 concludes the report.

2 Incorporation of the policy pathways (WP7) into the integrated modelling approach (WP 8)

Within the MUSTEC project, WP7 collected and processed comprehensively a broad range of policy pathways within the EU and in particular, in the countries Spain, Italy, France, and Germany. The identified policy pathways are classified into majority and minority pathways. Further, they are characterised by the different ideologies driving them: market-centred, State-centred, grassroots developments, and a fourth class outside of these classifications. These policy pathways form the basis of the modelling activities by defining central input parameters like electricity demand, renewable targets, decarbonisation levels and technology mix in future years (2030, 2050) in the different countries. Objective of this report is to show how policy decisions as part of the different pathways are able to create conditions in the electricity system that foster the need for CSP and ultimately CSP deployment.

Table 1 provides an overview on the identified policy pathways from WP7. Complementary to that, Table 2 informs on how they are taken up in the integrated model-based assessment in WP8. This report gives an overview of the most important findings concerning key factors and policy decisions that can foster CSP deployment. For a detailed description and full documentation of the scenarios and models, please see Resch et al. (2020).

Two ideological worlds are represented by the scenarios.

- On the one hand, there is the setting of enhanced **(RES) cooperation** across the EU. Here we take the assumption that all EU countries intensify cooperation in the field of renewables in forthcoming years. Specifically, we presume that a least-cost approach is followed, reflecting full competition across technologies and corresponding sites across the whole EU. Deployment of RES technologies will consequently take place in those countries where it is most cost-efficient from the power system perspective towards the 2030 (and 2050) (renewable) energy and climate target achievement.
- On the other hand, we model the four countries analysed in detail (i.e. France, Italy, Germany, and Spain) according to their own (majority) preferences as stated in the 2030 National Energy and Climate Plans (NECPs), cf. the majority pathways as listed in Table 1. This world is representing the **national preferences** which can differ to a large degree between the countries in terms of technology choices, RES ambition, etc…

These two policy worlds – i.e. cooperation and national preferences – are then compared and complemented by different sensitivity analyses, resulting in scenarios with low electricity demand levels, limited availability of competing demand-side flexibility options, limited grid extensions, and lower decarbonisation ambitions.

Table 1: Identified policy pathways for the EU, France, Germany, Italy, and Spain (WP7). Characteristics in terms of energy and climate targets and description of the uptake in the modelling (WP8).

Acronym	Characterisation	RES-E (RES) targets		ETS (overall) GHG reduction targets	In accordance with WP7 policy characterisation	Uptake in modelling
EU level		2030	2050	2050		
EU majority (market-centred)	Market-centred, aiming for full decarbonisation in a "least cost manner"	n.a. (>32%)	n.a. (n.a.)	100% (100%)	YES	YES
EU grassroots	Grass-root centred across the EU, with accelerated full decarbonisation (2040)	n.a. (>45%)	100% (100%)	100% (100%)	YES	Partly (infeasibility due to diffusion constraints demonstrated with Green-X)
FR						
FR majority (state-centred)	FR state-centred, aiming for full decarbonisation, done by maintaining its supply portfolio (nuclear and RES)	40% (34%)	50% (n.a.)	n.a.	YES	YES - in combination with majority paths of other countries and the (rest of) EU
FR rassemblement national	FR rassemblement national puts energy independency in focus, maintains the strong role of nuclear power and increases slightly the contribution of RES.	n.a.	n.a.	n.a.	YES	NO - no pendant identified in other MSs or at EU level
FR grassroots	FR grass-root centred, with mediocre decarbonisation (85%) by 2050 and a strong RES-E uptake (to 100% by 2050)	n.a.	100% (n.a.)	100% (ca. 85%)	Partly (limitations on early nuclear phase-out)	Partly (infeasibility due to diffusion constraints demonstrated with Green-X)
FR market-centred (with low decarb targets)	FR market centred, with low decarbonisation (75%) by 2050	40% (n.a.)	n.a. (n.a.)	n.a. (ca. 75%)	YES	YES - in combination with corresponding paths of other MSs
DE						

DE majority (state-centred)	DE state-centred, aiming for full decarbonisation, done by increasing the domestic RES-E portfolio to (above) 80%	65% (30%)	>80% (60%)	100% (80-95%)	YES	YES - in combination with majority paths of other countries and the (rest of) EU
DE grassroots	DE grass-root centred, with strong decarbonisation (100% in electricity) and a strong RES-E uptake (to 100%) by 2030	100% (n.a.)	100% (n.a.)	100% (>95%)	YES	Partly (infeasibility due to diffusion constraints demonstrated with Green-X)
DE market-centred (with low decarb targets)	DE market-centred, aiming for (comparatively low) decarbonisation in a "least cost manner"	n.a. (n.a.)	n.a. (n.a.)	n.a. (>80%)	YES	YES - in combination with corresponding paths of other MSs
IT						
IT majority (market-centred)	IT market-centred, aiming for full decarbonisation, done by strongly increasing the domestic RES-E portfolio	55.4% (>30%)	100% (implicitly due to decarbonisation needs) (n.a.)	100% (100%)	YES	YES - in combination with majority paths of other countries and the (rest of) EU
IT grassroots	IT grass-root centred, with strong decarbonisation (100% in electricity) and a strong RES-E uptake	n.a. (n.a.)	100% (n.a.)	n.a. (n.a.)	YES (to a large extent)	Partly (comparatively similar system impacts as in IT majority path)
ES						
ES majority (state-centred)	ES state-centred, aiming for full decarbonisation, done by strongly increasing the domestic RES-E portfolio	>74% (42%)	100% (100%)	100% (>90%)	YES	YES - in combination with majority paths of other countries and the (rest of) EU
ES grassroots	ES grass-root centred, with strong decarbonisation (100% in electricity) and a strong RES-E uptake (100% by 2045)	80% (45%)	100% (100%)	100% (95%)	YES	Partly (infeasibility due to diffusion constraints demonstrated with Green-X)
ES market-centred (with low decarb targets)	ES market centred, aiming for (comparatively low) decarbonisation in a "least cost manner"	n.a. (n.a.)	n.a. (n.a.)	n.a. (80%)	YES	YES - in combination with corresponding paths of other MSs

Table 2: Overview of modelled scenarios. For each scenario and country, a policy pathway was selected and combined.

Acronym	Characterisation	Policy pathway selection				
		Rest of EU	DE	FR	IT	ES
EU level						
Cooperation	Market-centred, aiming for full decarbonisation in a "least cost manner"	EU majority	EU majority	EU majority	EU majority	EU majority
Grassroots	Grass-root centred across the EU, with accelerated full decarbonisation (2040), and with consideration of national preferences (DE, FR, IT, ES)	EU grassroots	DE grassroots	FR grassroots	IT grassroots	ES grassroots
National preferences	State-centred in DE, FR and ES - whereas in the remainder of the EU a market-centred approach is followed, aiming for full decarbonisation in a "least cost manner"	EU majority	DE majority (state-centred)	FR majority (state-centred)	IT majority (market-centred)	ES majority (state-centred)
National preferences, low demand	Market-centred, aiming for full decarbonisation in a "least cost manner" - but thanks to strong energy efficiency and/or less emphasis on sector-coupling electricity demand growth is moderate (i.e. comparatively low) at least in the "big 4" (DE, FR, IT, ES)	EU majority	DE majority (state-centred)	FR majority (state-centred)	IT majority (market-centred)	ES majority (state-centred)
National preferences, with low flexibility from sector coupling	Market-centred, aiming for full decarbonisation in a "least cost manner" - and low flexibility provision from sector coupling (due to incentivisation and corresponding regulation)	EU majority	DE majority (state-centred)	FR majority (state-centred)	IT majority (market-centred)	ES majority (state-centred)
National preferences, with grid expansion restrictions	Market-centred, aiming for full decarbonisation in a "least cost manner". Grid expansion faces difficulties across the EU due to low public acceptance	EU majority	DE majority (state-centred)	FR majority (state-centred)	IT majority (market-centred)	ES majority (state-centred)

Cooperation, low demand	Market-centred, aiming for full decarbonisation in a "least cost manner" - but thanks to strong energy efficiency and/or less emphasis on sector-coupling electricity demand growth is moderate (i.e. comparatively low) at least in the "big 4" (DE, FR, IT, ES)	EU majority	EU majority	EU majority	EU majority	EU majority
Cooperation, deep but not full decarbonisation	Market-centred, aiming for a deep but not full decarbonisation, done in a "least cost manner" (implies less emphasis on RES-E)	EU majority	DE market-centred (with low decarb targets)	FR market-centred (with low decarb targets)	EU majority	ES market-centred (with low decarb targets)
Cooperation, with low flexibility from sector coupling	Market-centred, aiming for full decarbonisation in a "least cost manner" - and low flexibility provision from sector coupling (due to incentivisation and corresponding regulation)	EU majority	EU majority	EU majority	EU majority	EU majority
Cooperation, with grid expansion restrictions	Market-centred, aiming for full decarbonisation in a "least cost manner". Grid expansion faces difficulties across the EU due to low public acceptance	EU majority	EU majority	EU majority	EU majority	EU majority

3 KEY FACTORS AND PIVOTAL DECISIONS FOR THE DEPLOYMENT OF CSP

There is a range of factors that are relevant for CSP deployment in Europe's future electricity system. In the following, we elaborate on some of them, in particular on the effect of cooperation, demand-side management, electricity grid expansion, decarbonisation ambition, technology cost developments of CSP and competing technologies, increasing shares of fluctuating renewables and nuclear phase-out on CSP deployment.

This section informs on key drivers and pivotal policy decisions for CSP deployment according to our own analyses, specifically derived from the modelling works undertaken in the course of the MUSTEC project. The focus is laid on the presentation of spotlights of the most important findings and their policy implications concerning policy decisions and pathways. A detailed description of the modelling activities, assumptions and findings, can be found in the corresponding reports of WP8 (Schöniger & Resch (2019) and Resch et al. (2020)).

3.1 Brief overview on the modelling framework

The MUSTEC modelling system

To summarise briefly, the modelling works within MUSTEC have been conducted using three distinct energy system models in an integrated manner whereby all models complementing each other in the analysed aspects of the energy system[1]:

- **Green-X:** the (renewable) energy policy assessment model; used for analysing policy-driven renewable investments, renewable developments and related impacts on costs, expenditures and benefits
- **Enertile & Balmorel:** two energy system models; serving to shed light on the interplay between electricity supply, storage and demand in the EU electricity market.

Scenarios and key assumptions

<u>Cooperation vs. National Preferences:</u> As outlined in chapter 2 of this report, building on the policy pathway elaboration conducted within WP7, all subsequently presented scenarios are based on one of the two distinct ideological (renewable) energy policy settings: **(RES) cooperation** or **national preferences**. While in the *cooperation* setting, all countries follow a least-cost approach to reach the overall EU renewable energy targets, deploying the renewable technologies in the countries where it is most efficient, the scenario setting named *national preferences* represents the majority

[1] For detailed model descriptions and their interactions, see Schöniger & Resch (2019) for Balmorel and Resch et al. (2020) for Green-X and Enertile or Section 6 in the Appendix of this report.

policy paths (as described in the corresponding NECPs) of the four dominating EU member states France, Italy, Germany, and Spain, and adapted strategies in the rest of the EU.

Electricity demand (growth): There are sensitivity analyses covering the effect of overall electricity demand levels (*High Demand* vs. *Low Demand*). In the scenarios with high demand, sector coupling is more prominent and strong electrification of heating and transport acts as a driver for increased electricity demand.

Climate ambition: As default we take the assumption that a full decarbonisation of the energy system, and in particular of the power system is achieved until 2050 at EU level. In general terms, this has strong implication on future technology choices (e.g. fossil CCS is no viable generation option in the power sector) and on energy market developments. To achieve the full decarbonisation within our stylised energy system representation, a strong increase in carbon prices is assumed in modelling. Complementary to that, in a sensitivity analysis we assess the impact of a lower climate ambition *(Low CO_2 Price)* – here we assume instead of a full decarbonisation only a GHG reduction of 91% in the electricity sector until 2050 compared to 1990 levels.

Grid expansion: As default we presume a strong expansion of the power system infrastructure in future years, specifically of the transmission grid. As part of the sensitivity analyses, we analyse the impact of limits to that. In this context, the *GridLim-Offsh*[2] scenario assumes limitations in transmission grid expansion in order to evaluate this effect on CSP deployment.

Cost assumptions

For the CSP plants, an 11 hours thermal storage system and a site specific ratio between field and generator is assumed.

Table 3: Cost assumptions for CSP in Enertile in the MUSTEC project

Year	Lifetime [a]	Specific investment [€2010/kW]	Fix O&M cost [€2010/(kW a)]	Var. O&M cost [€2010/MWh]	Efficiency
2030	30	3525	66.7	0.046	44%
2040	30	3078	53.3	0.046	49%
2050	30	2554	40.0	0.046	52%

[2] *Offs*: $Wind_{Offshore}$ is allowed as additional investment option in this scenario to allow for the required power system flexibility, specifically in Northern European countries.

3.2 Key results from the integrated model-based assessment of the future EU electricity system

Below we provide a brief overview on key results from the integrated model-based assessment of the future EU electricity system, shedding light on the possible niche for CSP within that. For a detailed description of all results and scenarios, please refer to Resch et al. (2020).

As a starting point, Figure 1 and Table 4 provide a technology breakdown of electricity generation by 2050 for the analysed scenarios. In general, one can observe that variable RES like wind and solar PV dominate future electricity supply. Additionally, thanks to the strong climate ambition underlying the model calculations, fossil fuels are by then (2050) no longer part of the supply portfolio.

An important difference between the scenarios is the share of nuclear generation. If France follows its NECP in the national preferences setting, nuclear power plays a bigger role which reduces the niche of CSP in the system.

Table 4: Technology breakdown of electricity generation in the year 2050 for the EU28 (plus Norway and Switzerland) according to assessed scenarios [TWh]

Technology	Coop-High Demand	Coop-High Demand-Low Flex	Coop-High Demand-Low CO2-Price	NatPre-High Demand	Coop-Low Demand	NatPre-Low Demand	NatPre-HD-Grid Lim-Offsh-it1
Gas/biogas	67.2	66.4	137.4	26.0	40.1	19.7	131.7
Hard coal	0.5	0.5	4.2	0.3	0.2	0.6	1.2
Lignite	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nuclear	28.6	28.6	470.4	474.1	28.0	233.4	469.1
Oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.0	0.0	0.2	0.0	0.0	0.0	0.0
Biomass	36.0	36.0	36.0	36.0	36.0	36.0	36.0
Hydro	549.6	549.5	541.5	545.3	540.9	540.7	545.3
Other (Geoth.)	34.9	34.9	24.3	34.1	23.3	25.9	34.1
CSP	298.3	303.7	214.1	253.5	102.5	126.2	125.4
PVr	744.1	744.1	742.1	733.1	734.9	627.6	733.1
soPV	641.7	642.2	629.9	602.9	599.9	462.1	602.9
$Wind_{offshore}$	1381.2	1383.5	828.8	1109.1	610.5	840.0	1380.2
$Wind_{onshore}$	2412.0	2412.3	2367.9	2387.0	2332.6	2098.1	2387.0

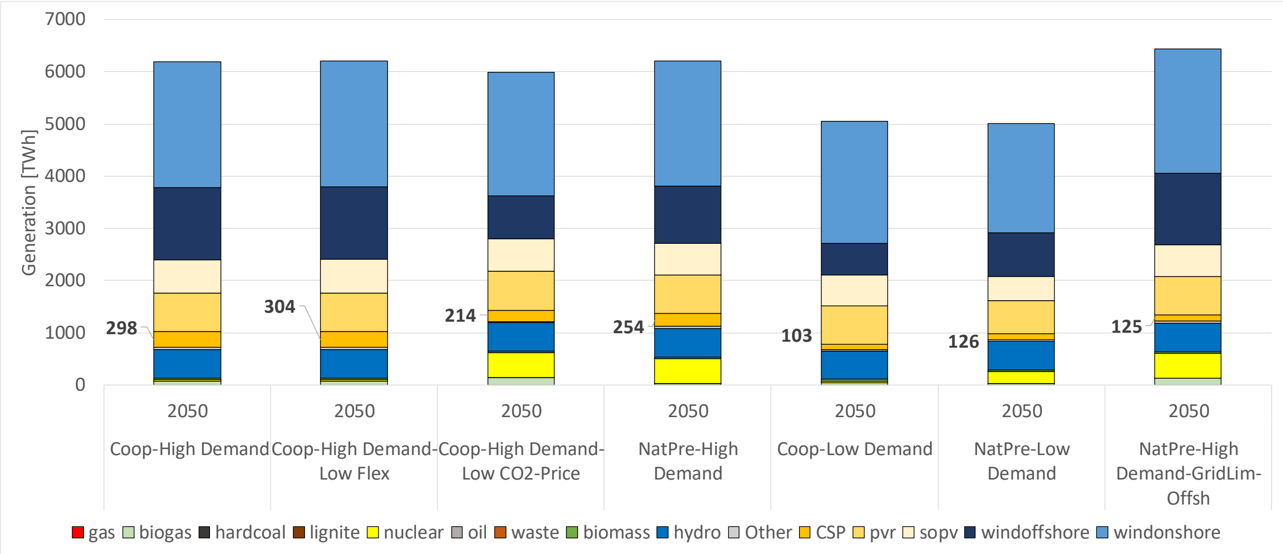

Figure 1: Technology breakdown of electricity generation in the year 2050 for the EU28 (plus Norway and Switzerland) according to assessed scenarios

Figure 2 gives an overview of the installed capacities in the different scenarios for the year 2050. CSP capacities installed by then range from 26 GW in the *Coop-Low Demand* scenario to 81 GW in the *Coop-High Demand-Low Flex* scenario.

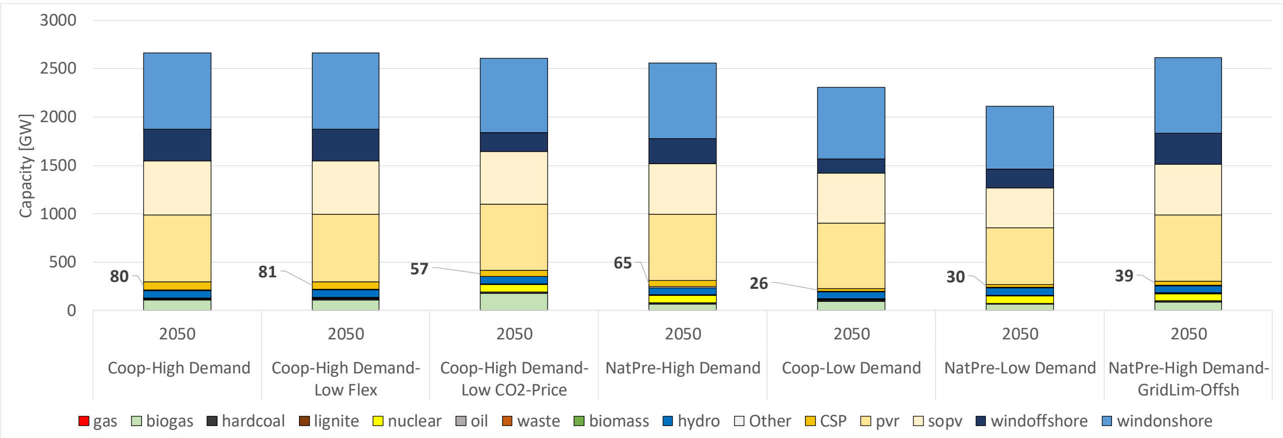

Figure 2: Technology breakdown of installed electricity capacities for the year 2050 at EU level according to assessed scenarios

3.3 Cooperation – a driver for CSP

The policy choice (**national preferences vs. cooperation**) has an **ambiguous impact on CSP use according to our modelling**:

- On the one hand, in the case of *high demand growth*, comparing the electricity generation from CSP (cf. Figure 3) in the two settings ***cooperation vs. national preferences***, we find that in the high demand case, CSP produces around 45 TWh more electricity when there is full RES cooperation across the EU (*Coop-High Demand* vs. *NatPre-High Demand*) compared to the national preferences setting.

- In *low demand* scenarios we see however the opposite trend: CSP generation ranges then from 103 TWh (Cooperation) to 126 TWh (National Preferences), and is, in contrast to above, by 23 TWh lower in the cooperation compared to the national preference scenario. A closer look at the regional and country level indicates that this increase is driven by developments in the Iberian Peninsula where Spain and Portugal give higher preferences on CSP in the national preference setting compared to the cooperation world, partly driven by changes in the supply mix of France (i.e. more nuclear power in the national preferences setting). Thus, that increase in the demand for CSP within these countries is driven by changes in local supply and demand patterns rather than the "big policy picture" at EU level.

Apart from the power system modelling, we can however conclude that RES cooperation can act as important driver for CSP. One element in that is the expectable decrease in financing cost driven by cooperation – since financing conditions are from today's perspective worse in Southern European host countries compared to the EU average.

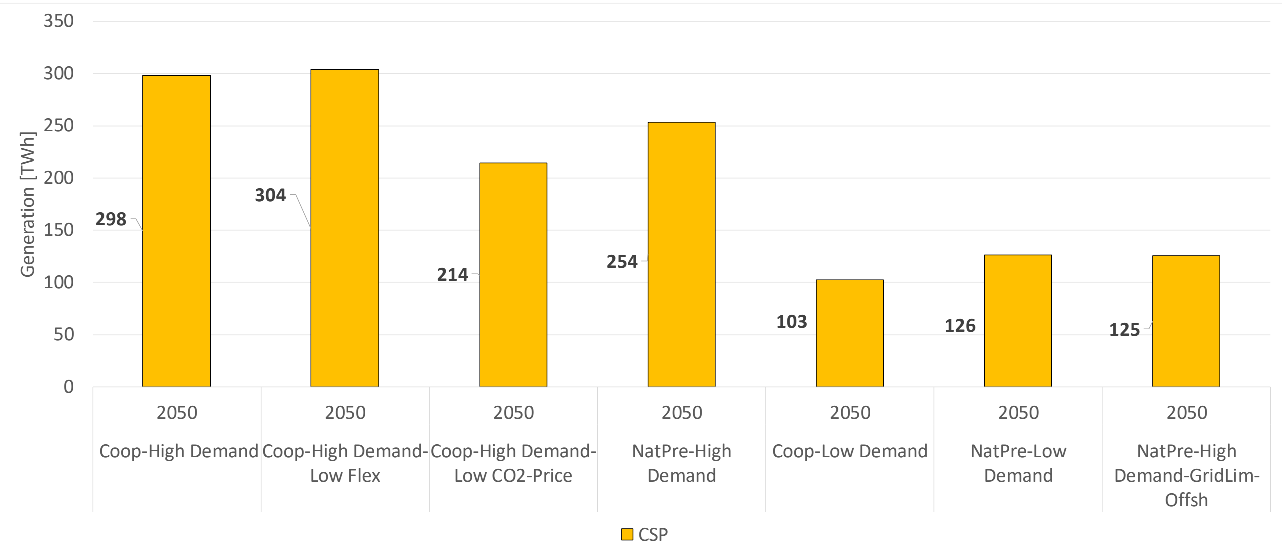

Figure 3: Comparison of CSP generation for the year 2050 for EU28 (plus Norway and Switzerland) for assessed scenarios

In the case of cooperation, southern countries (especially Spain and Portugal) can benefit from their solar resources and export a high share of their CSP generation to northern countries in order to reach the overall energy and climate targets in the EU. Spain, Italy and Portugal are the main countries for CSP taking place (cf. Figure 4).

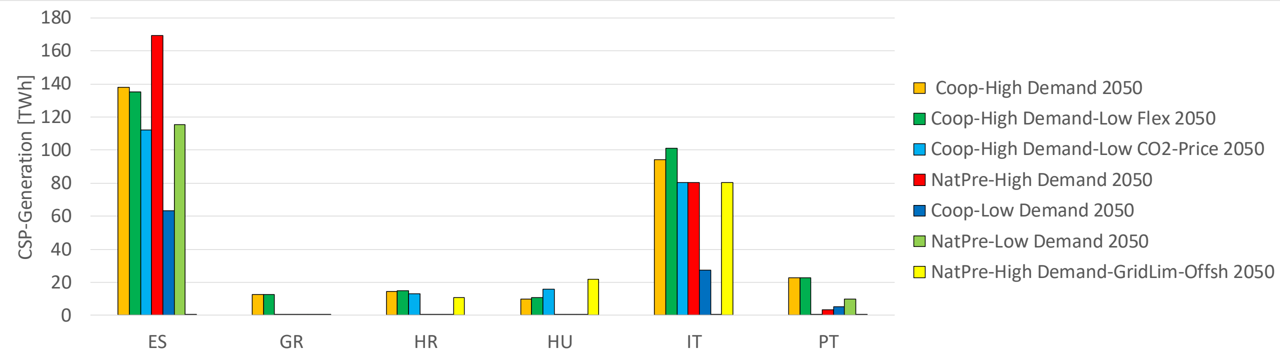

Figure 4: Comparison of country-specific CSP generation for the year 2050 for assessed scenarios

Policy implication I

RES cooperation can act as important driver for CSP thanks to the increased demand for CSP, and the expectable decrease in financing cost driven by cooperation. This is (partly) confirmed by modelling where the CSP uptake is stronger in scenarios assuming strong RES cooperation combined with strong electricity demand growth. In these cooperation scenarios, it makes long-term economic sense to invest in CSP.

3.4 Competition with demand-side flexibilities

The most valuable feature of CSP from a system perspective is its dispatchability due to the thermal storage system. Therefore, CSP is a flexibility option which is competing against other technologies able to provide flexibility to the electricity system. These options include dispatchable generation technologies like e.g. biogas power plants, storage facilities like pumped hydro storages or battery systems, the electricity grid that balances supply and demand by importing and exporting electricity, or demand-side management measures. There is a wide range of demand-side applications offering flexibility to the electricity system by shifting demand over different time periods. The effect of two of these options is analysed in a more detailed manner in D8.2: flexibility by e-mobility charging in a smart, electricity system-friendly way and decentral heat-pumps providing demand-side flexibility due to their heat storage capacities. The flexibility offered by these two options was reduced to evaluate the effect on CSP deployment.

In the scenario *Coop-High Demand-Low Flex*, the flexibility provided by e-mobility and decentral heat pumps was reduced by 50%. This means that only 50% of the charging in e-mobility is conducted in a smart way (compared to 100% in the *Coop-High Demand* scenario) and heat storage capacity connected to decentral heat pumps is halved compared to the *Coop-High Demand* scenario. For the years 2030/2040/2050, this translates into 14/71/185 TWh (e-mobility) and 228/256/304 TWh (decentral heat pumps + storage) of electricity demand being inflexible in the *Coop-High Demand-Low Flex* compared to the *Coop-High Demand* scenario.

Reduction in flexible load [TWh]	2030	2040	2050
E-mobility	14	71	185
Decentral heat storage linked to heat pumps	228	256	304

The results show that decreased flexibility provided by the competing flexibility options – decentral heat pump storage and smart charging of e-vehicles - does not significantly increase electricity generation (cf. Figure 5) and installed capacities (cf. Figure 6) of CSP.

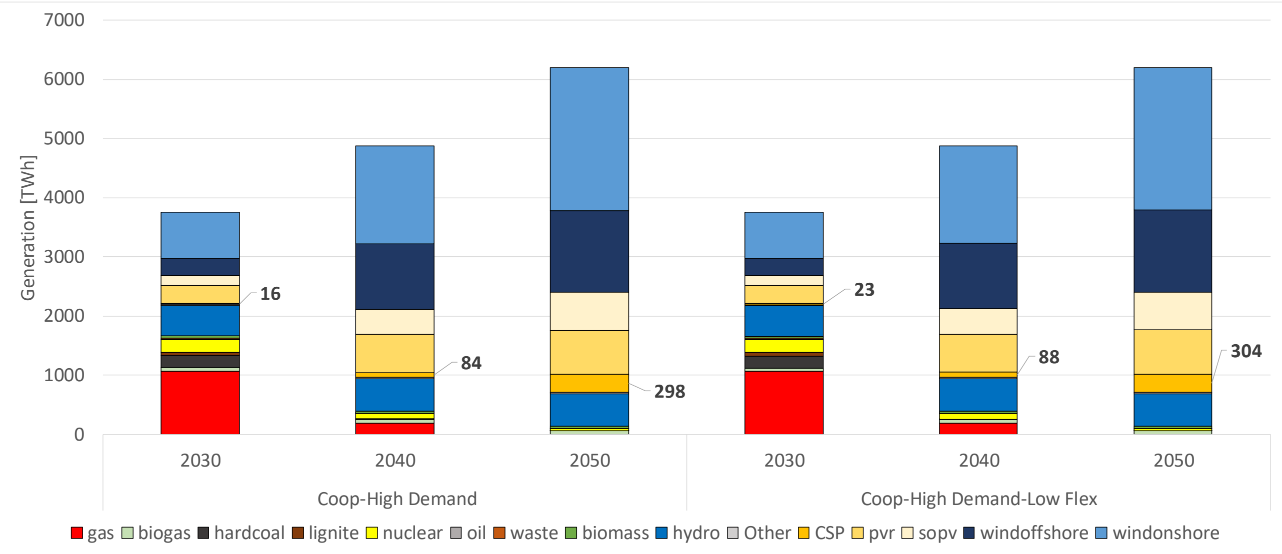

Figure 5: Electricity generation in EU28 + Norway + Switzerland for the Coop-High Demand scenario without flexibility limitations (left) and -50% flexibility in e-mobility and decentral heat pump storage capacities (right)

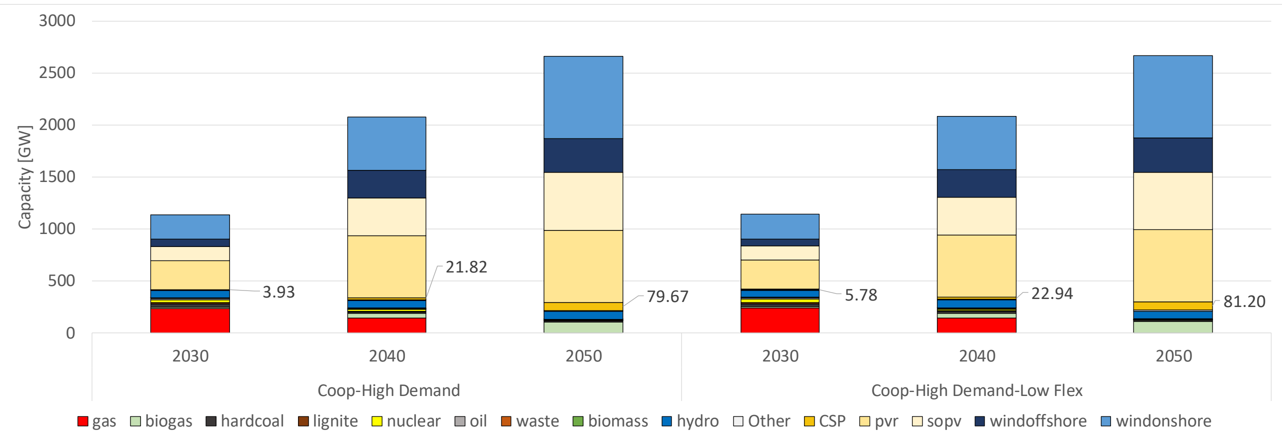

Figure 6: Installed generation capacities in EU28 + Norway + Switzerland for the Coop-High Demand scenario without flexibility limitations (left) and -50% flexibility in e-mobility and decentral heat pump storage capacities (right)

The results show that flexibility provided by CSP is competitive against other flexibility options and increased flexibility by decentral heat storage and e-mobility does not eliminate the need for CSP in the electricity system. However, it has to be kept in mind that there are several more flexibility options available in the system which are not touched upon in this scenario. That is e.g. the production of hydrogen and flexibility provided by a well-established electricity grid.

> ***Policy implication II***
>
> ***There are different niches for different flexibility options. CSP is also needed in systems with high shares of decentral heat storage (linked to heat pumps) and flexible charging of e-vehicles because of its generation characteristics.***

3.5 Expansion of the transmission grid – an ambivalent factor

Another key factor for the deployment of CSP is the available transmission capacity. The effect of this factor is ambivalent. EU policies are clearly targeted at increased cooperation and grid integration (cf. e.g. Directive 2009/28/EC). **Electricity grid extensions** have different effects on CSP deployment. On the one hand, a lack of export opportunities hinders CSP and it benefits from transmission capacities from Southern countries to central Europe. But on the other hand, increased transmission capacities are a flexibility option own their own and, consequently, competing against CSP.

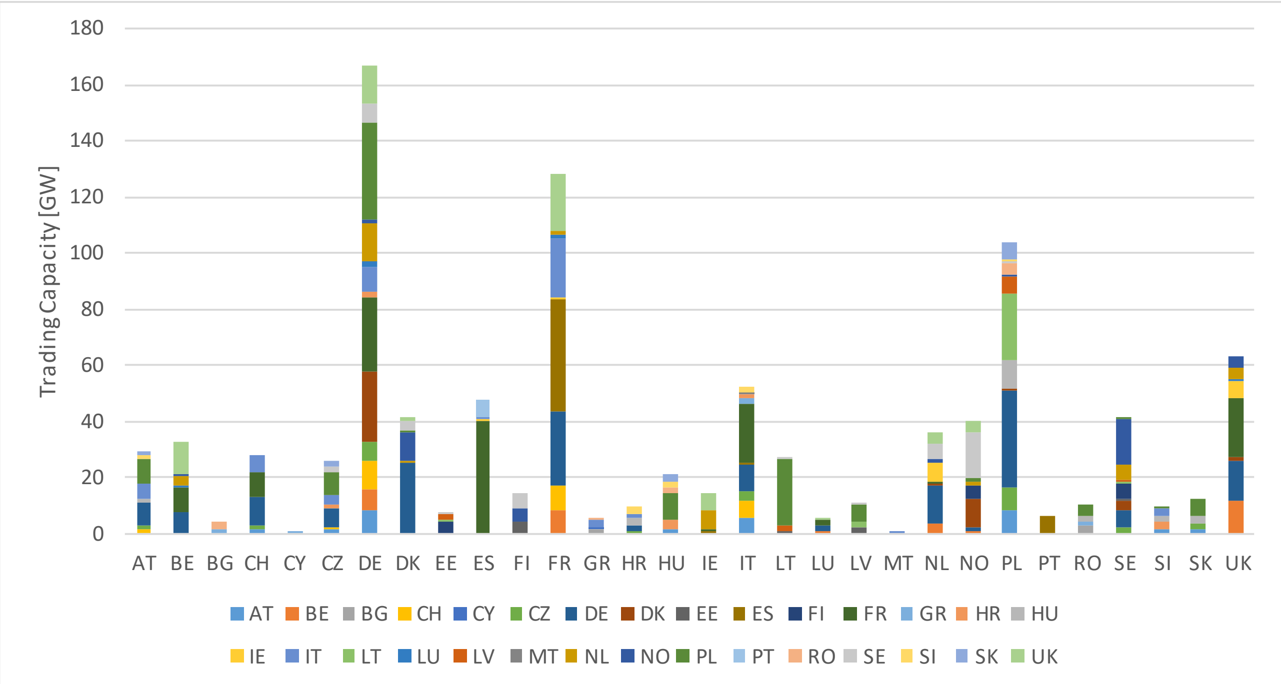

Figure 7: Cross-border transmission capacities [GW] assumed in the MUSTEC scenarios for 2050 (derived from the Diversification scenario in SET-Nav, 2019)

To elaborate on the issues raised above, we conducted a sensitivity analysis with reduced transmission capacities. The standard assumption on electricity grid development was derived from the Diversification scenario of the SET-Nav project (SET-Nav, 2019), cf. Figure 7. This is a setting with strong expansion of transmission capacities throughout Europe.

In the scenario *National Preferences-High Demand-Grid Limitation-Offshore*, a lmited grid expansion is assumed, see Figure 8. The cross-border transmission capacities are here limited to the capacities planned according to the TYNDP 2018 (ENTSO-E, 2019) for the year 2030 and with a maximum of 15% capacity increase per decade after 2030.

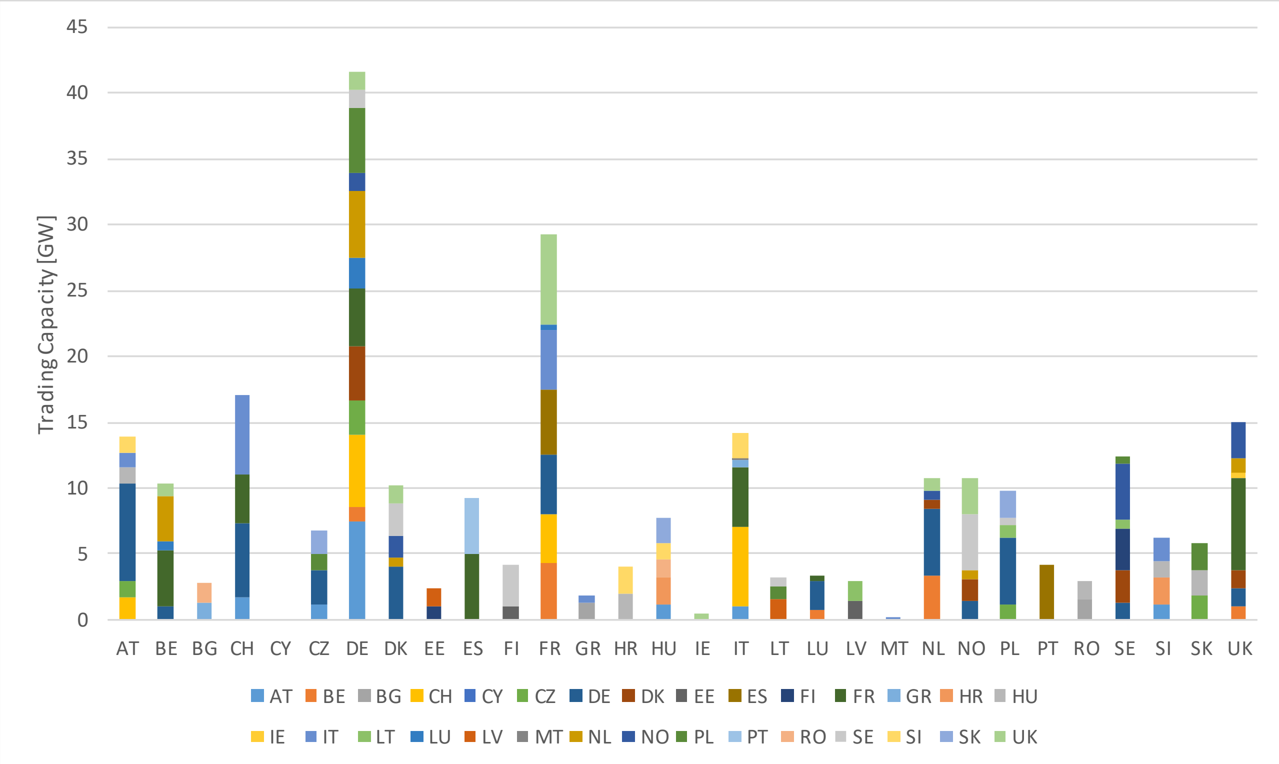

Figure 8: Cross-border transmission capacities [GW] assumed in the sensitivity analysis National Preferences-High Demand-Grid Limitation-Offshore for 2050. Values for the year 2030 are derived from the TYNDP 2018 (ENTSO-E, 2019)*, afterwards a capacity increase of 15% per decade is allowed.*

The results show that expansion of transmission capacities is especially important for southern countries which are connected to northern countries via a small number of connections and export a high share of their CSP generation.

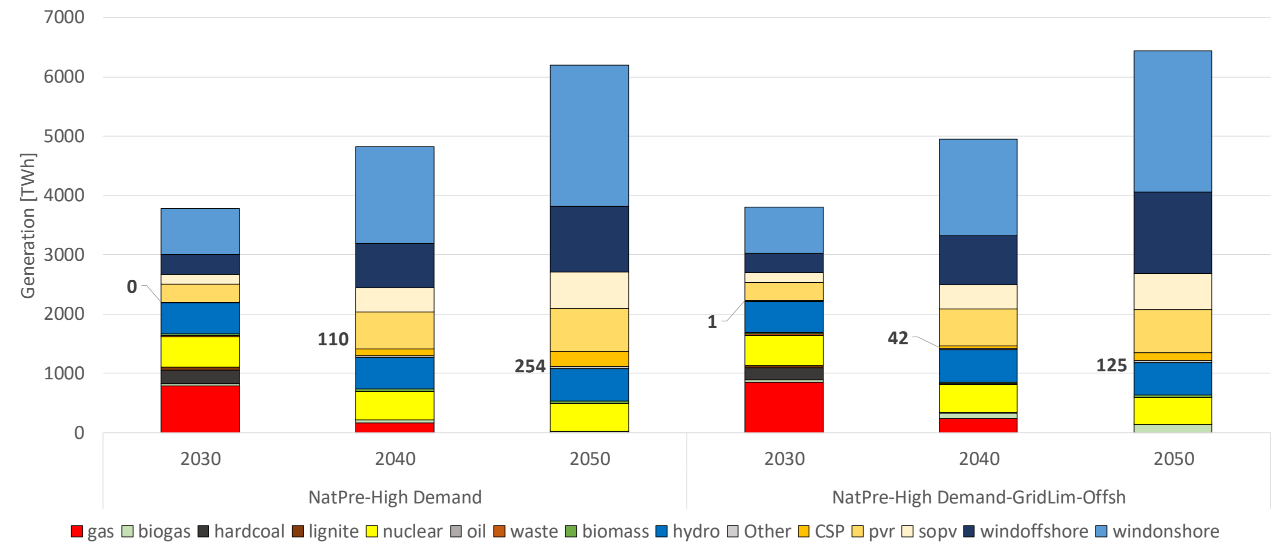

Figure 9: Generation mix by technology (2030-2050) in the scenario NatPre-High Demand (left) and the sensitivity analysis with limited grid expansion (NatPre-High Demand-GridLim-Offs, right)

In the scenario NatPre-High Demand, reduced transmission capacities lead to a significant decrease of CSP capacities installed for Spain and Portugal (cf. Figure 10) because these countries are especially dependant on their cross-border connection to France. Italy on the other side is rarely impacted by the grid limitations because Italy consumes a larger share of the CSP generation in the country and is able to expand transmission lines to several countries. On the other side, inland countries like Hungary with limited renewable potentials and no option for $Wind_{Offshore}$ build CSP capacities in the scenario with limited grid expansion.

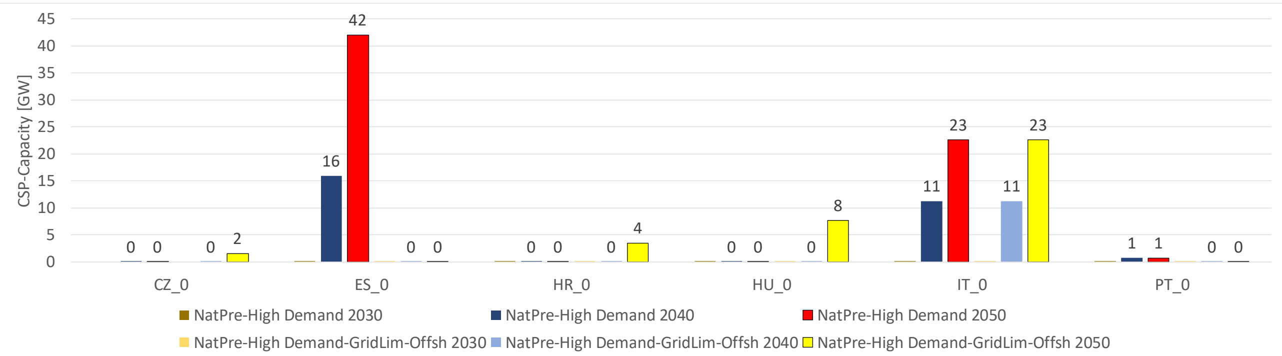

Figure 10: CSP capacities installed (2030-2050) in the scenario NatPre-High Demand (left) and the sensitivity analysis with limited grid expansion (NatPre-High Demand-GridLim-Offs, right)

Policy implication III

If exporting countries decide to expand and diversify their transmission and interconnection capacities beyond what EU rules require, they are able to better exploit the full capacity for deployment of dispatchable CSP.

3.6 Strong decarbonisation as key driver for CSP

The integrated model-based analysis points out that there is **a strong indirect impact of decarbonisation on the demand for CSP**. Our aim to fully decarbonise the energy system by 2050 acts as key driver for an enhanced sector-coupling – since the range of cost-effective and ready to use decarbonisation options is much broader in the electricity sector than in transport or in heating and cooling. This, in turn, leads to an expectably strong growth of electricity demand in future years. Building on above, our model-based assessment clearly indicates that all scenarios assuming a higher electricity demand (driven by sector-coupling) leads to a strong increase of the demand for CSP: e.g. 103 TWh (low demand) vs. 298 TWh (high demand) in the Cooperation scenarios, cf. Figure 3.

Policy implication IV

A full decarbonisation of the energy system in line with the Paris agreement as intended by the EU policy requires strong increases in sector-coupling and, consequently, in electricity demand. This is a key driver for an enhanced uptake of CSP.

Decarbonisation policies are highly important for shaping the energy system in a way that CSP can play a role in it. However, it is crucial how decarbonisation is achieved and policies decide to a large extent on the technology mix of CO_2-free electricity generation. On the one hand, studies show that the availability of fossil power plants with CCS is hindering the deployment of dispatchable, renewable technologies like CSP (cf. also Section 4). On the other hand, carbon pricing in the form of CO_2 prices is creating a market environment where CSP can play out its advantages and gain competitiveness. Where explicitly CO_2-free and dispatchable generation is requested, CSP can compete against natural gas for example (cf. DEWA IV project in Dubai). The deployment additionally depends on the cost developments of CSP components as well as other flexibility options and competing technologies, e.g. wind and PV in combination with storage technologies.

Price signals that value dispatchable and decarbonised electricity are a **precondition but not a guarantee for increased CSP deployment**. The pricing design must reward dispatchable and carbon-neutral generation, e.g. in the form of a predictable CO_2 price combined with an electricity price pattern that is beneficial for flexible generators in the power market. Another possibility is targeted auction design requiring a zero-carbon emission standard in combination with guaranteed production times (after sunset) like this was the case in the DEWA IV project in Dubai. These price signals are often modelled in electricity systems in the form of carbon prices. However, they could also take another form e.g. targeted support payments. We analyse in the following the effect of CO_2 prices – keeping in mind that any price signal received by CSP could have the same effect on CSP deployment.

In order to visualize the effect of the two factors – CO_2 prices and technology cost developments – on CSP deployment, we present a concise case study done in Balmorel[3]. We model a closed system whose demand can be covered by three technology options: CSP, PV, and a condensing natural gas turbine. The model optimizes the investment in a combination of the technologies in Table 5 and their dispatch to cover the demand[4].

Table 5: Technology options for investment in the optimization model run. Cost assumptions as in Deliverable 8.1 (for detailed description see Schöniger & Resch (2019)).

Technology	Efficiency	Investment costs	Fix O&M costs	Variable O&M costs
Solar field[5]	1	1 391 $€_{2018}/kW_{th}$	15.88 $€_{2018}/kW_{th}$	-
Power block	0.42	1 195 $€_{2018}/kW_{el}$	13.64 $€_{2018}/kW_{el}$	0.15 $€_{2018}/MWh_{el}$
Thermal storage	0.99	8.4 $€_{2018}/kWh_{th}$	0.958 $€_{2018}/kW_{th}$	-
Gas turbine condensing	0.35	939 $€_{2018}/kW_{el}$	23.5 $€_{2018}/kW_{el}$	0.71 $€_{2018}/MWh_{el}$
PV[6]	1	953 $€_{2018}/kW_{el}$	25.5 $€_{2018}/kW_{el}$	0.10 $€_{2018}/MWh_{el}$

The CO_2 price is varied between 30 and 300 $€_{2018}/t$ and the cost reduction of CSP between 0 (current cost), -25%, and -50% (ceteris paribus). Cost reductions are distributed equally to the three components CSP solar field & receiver, TES, and power block.

Figure 11 shows the impact of CSP cost reductions (y-axis) and price signals in the form of CO_2 prices (x-axis) on the share of CSP generation (z-axis) in the modelled, closed system. In general, the higher the CO_2 price and the lower the CSP technology cost, the higher the share of CSP in the system (up to 52.9% of demand is covered by CSP in our analysis). The rest of the demand is covered by PV and natural gas.

[3] For a detailed model description, please see the Appendix of this report.

[4] 1203 GWh following the Spanish load profile are modelled in this isolated system

[5] 2118 FLH

[6] 1401 FLH

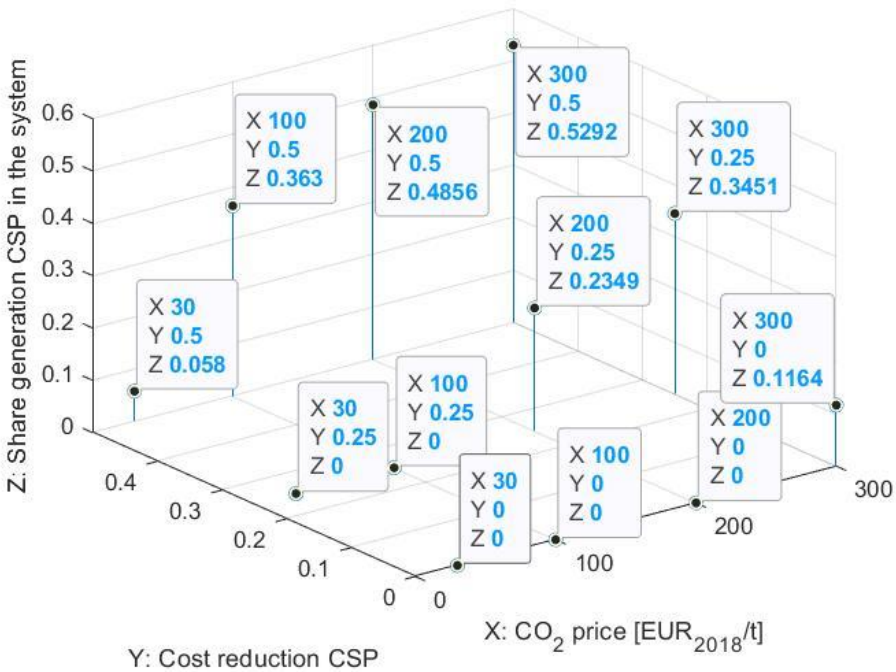

Figure 11: Impact of CSP technology cost reductions and CO_2 price on the share of CSP generation in a closed system following the demand patterns of Spain. Demand is covered by the three technology options CSP, PV, and natural gas.

In this model setting where CSP competes with natural gas, the higher the CO_2 price, the higher the share of CSP in the system. However, under current cost assumptions, CSP is not deployed even with a CO_2 price of 200 €/t. If technology cost reductions are achieved, the share of CSP increases in a similar way. However, high cost reductions or a high CO_2 price alone are not enough and result in a CSP share of below 10% in the system. It needs the two factors in combination for CSP to play a bigger role in the system. In the case of 50% cost reductions and a CO_2 price of 100 €/t, the CSP share is 36% - about the same at a price reduction of 25% but a CO_2 price of 300.

Policy implication V

CSP needs effective price signals valuing dispatchable and CO_2-free electricity generation. If policies on market design ensure these price signals without allowing for CCS, CSP is able to play an important role.

3.7 CSP cost reductions: An outlook to 2030 - what does CSP need in order to be installed?

As we saw in Section 3.6, effective price signals are key to increased deployment of CSP. However, we also saw that an important factor is technology cost reduction through technological learning. Competitiveness of CSP is dependent on the cost developments and deployment levels of other technologies as well.

In WP7, different policy pathways for several countries have been developed. The majority pathway is the state-centred version and corresponds to the National Energy and Climate Plans (NECPs)[7] developed by the EU Member States in order to assure and align ambitions towards the achievement of the Union's common 2030 targets. Spain states in its NECP that it plans to have installed 7.3 GW of CSP in 2030. The question is what does it need for these capacities to be installed?

Table 6: Spain's planned installed CSP capacity by 2030 according to the Draft National Energy and Climate Plan (NECP, 2019)

Technology	GW_{el}
CSP	7.3

In order to answer this question, we use the planned capacities of non-dispatchable renewable energies for Spain in 2030 as exogenous input parameters for the model.

Table 7: Spain's planned installed capacities by 2030 according to the Draft National Energy and Climate Plan (NECP, 2019) *given as exogenous input parameters to Balmorel*

	Technology	GW_{el}
Exogenously given input paramters to Balmorel	Wind	50.3
	Hydro Run-of-river	1.2
	Hydro water reservoir	13.4
	PV central	15.0
	PV decentral	21.9

The missing generation capacities in order to cover the remaining demand are calculated by an investment optimization run done in Balmorel. That means the model chooses the most cost-effective means to provide flexible generation to be able to cover demand in this system at all times. The technology options available and their characteristics are displayed in Table 8.

Table 8: Technology characteristics. Cost assumptions as in Deliverable 8.1 (for detailed description see Schöniger & Resch (2019)*).*[8]

Technology	Efficiency	Investment costs	Fix O&M costs	Variable O&M costs
Solar field[9]	1	1391 $€_{2018}/kW_{th}$	15.88 $€_{2018}/kW_{th}$	-

[7] https://ec.europa.eu/energy/en/topics/energy-strategy/national-energy-climate-plans#national-long-term-strategies

[8] Cost assumptions for utility-scale Li-Ion battery and electric boiler taken from (Schöniger et al., 2019)

[9] 2118 FLH

Power block	0.42	1195 €$_{2018}$/kW$_{el}$	13.64 €$_{2018}$/kW$_{el}$	0.15 €$_{2018}$/MWh$_{el}$
Thermal storage	0.99	8.4 €$_{2018}$/kWh$_{th}$	0.958 €$_{2018}$/kW$_{th}$	-
Gas turbine condensing	0.35	939 €$_{2018}$/kW$_{el}$	23.5 €$_{2018}$/kW$_{el}$	0.71 €$_{2018}$/MWh$_{el}$
PV[10]	1	953 €$_{2018}$/kW$_{el}$	25.5 €$_{2018}$/kW$_{el}$	0.10 €$_{2018}$/MWh$_{el}$
Utility-scale Li-Ion battery	0.85	500 €$_{2018}$/kWh$_{el}$	13 €$_{2018}$/kWh$_{el}$	-
Electric boiler	1	347€$_{2018}$/kW$_{th}$	5.2€$_{2018}$/kW$_{th}$	1.0 €$_{2018}$/MWh$_{th}$

Electric as well as thermal storage options are included as investment options. The thermal storage can be used in combination with CSP as well as together with an electric boiler which allows for the transformation of electricity (e.g. produced by wind or PV) to thermal energy and back.

Three scenarios are modelled: the CO_2 price is varied between 77€/t, 200 €/t and 300 €/t. The starting value of 77 €/t$_{CO2}$, as well as the assumed natural gas price (which is rather low), is taken from the Sustainable Development Scenario of the World Energy Outlook 2018.

Table 9: CO_2 prices from the World Energy Outlook 2018, Sustainable Development Scenario (International Energy Agency, 2018)*. Years 2030 and 2050 are linear interpolations.*

CO_2 price (€$_{2018}$/t)		2025	2030	2040
Advanced economies	Power, industry, aviation	54	**77**	121

Natural gas price (€$_{2018}$/GJ)	2025	2030	2040
European Union	6.4	**6.45**	6.57

The results as shown in Figure 12 indicate that the higher the cost reductions and the higher the CO_2 price, the higher the share of CSP in the system. When the CO_2 price increases to 200 or 300 €/t, the share of installed natural gas capacities decreases and is replaced by CO_2-free flexible generation technologies. Under current cost assumptions, this is achieved mainly by PV in combination with electric and thermal storage. The higher the cost reductions for CSP, the more the installed generation shifts from PV with storage towards CSP and TES.

Policy implication VI

Technology cost reductions of all CSP components are necessary to keep this technology competitive and available for the transformation of our electricity

[10] 1401 FLH

systems. Since absolute CSP capacities installed are relatively small, policies for targeted support for CSP are necessary and able to foster high learning rates.

CO_2 prices alone do not reward dispatchability but they make CSP more competitive compared to non-renewable flexible alternatives like natural gas and increase the share of fluctuating renewables. Increased PV shares in the system cause lower electricity prices at times when the sun is shining. These price signals make it more profitable for CSP to shift its generation and increase its competitiveness and value to the electricity system. At a CO_2 price of 77 €/t and a 50% cost reduction of CSP, 10 GW of CSP are installed in the model optimisation (cf. Table 10). This is more than the planned 7.3 GW in Spain's NECP for 2030.

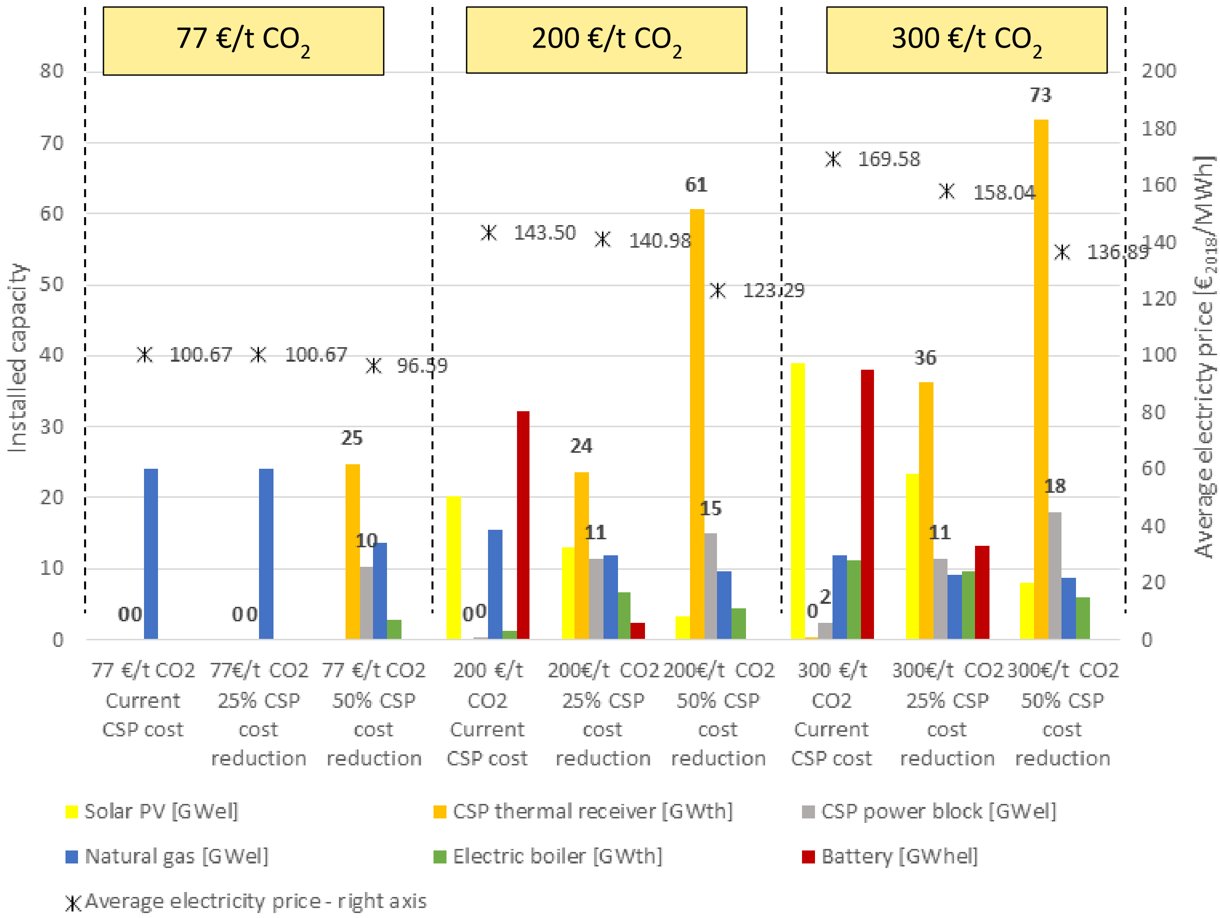

Figure 12: Results of the investment and dispatch optimisation for Spain 2030. The planned fluctuating renewable generation capacities hydro power, PV, and wind were given as exogenous input parameters.

Thermal storage capacities play an important role in order to provide flexibility to the energy system. As soon as other options than natural gas are installed, thermal storage capacities are deployed in the model and is the preferred storage option (see Table 10). In the cases, when a TES is installed, the optimised thermal storage size varies between 5.9 and 14.5 hours in the model. That shows that in the future, a promising and important part of CSP will be its thermal storage capacity. This finding is also supported by the fact that CSP stations currently under construction (September 2019) have, on average, 9.5 hours of storage (CSP.guru, 2019).

Table 10: Results for the sensitivity analysis in Spain for the year 2030

	Solar PV [GWel]	CSP thermal receiver [GWth]	CSP steam turbine [GWel]	CSP thermal storage [GWhth]	Natural gas [GWel]	Electric boiler [GWth]	Battery [GWhel]	Average electricity price [EUR2018/ MWh]
77 €/t CO2 Current CSP cost	0.0	0.0	0.0	0.0	24.0	0.0	0.0	100.67
77€/t CO2 25% CSP cost reduction	0.0	0.0	0.0	0.0	24.0	0.0	0.0	100.67
77 €/t CO2 50% CSP cost reduction	0.0	24.8	10.3	144.2	13.7	2.8	0.0	96.59
200 €/t CO2 Current CSP cost	20.3	0.0	0.3	8.9	15.6	1.3	32.2	143.50
200€/t CO2 25% CSP cost reduction	13.1	23.6	11.4	194.9	12.0	6.7	2.4	140.98
200€/t CO2 50% CSP cost reduction	3.3	60.6	15.0	409.8	9.7	4.4	0.0	123.29
300 €/t CO2 Current CSP cost	38.9	0.3	2.5	85.9	11.9	11.3	38.0	169.58
300€/t CO2 25% CSP cost reduction	23.3	36.2	11.4	330.1	9.2	9.5	13.3	158.04
300€/t CO2 50% CSP cost reduction	7.9	73.2	18.0	482.0	8.6	5.9	0.0	136.89

When looking at these numbers, it has to be kept in mind that existing, dispatchable units are not taken into account in this modelling exercise. These assets might make it harder for new CSP capacities to be invested in. On the other hand, we do not consider any policy measures or targeted support for CSP and compare the technology options simply based on their economics.

Policy implication VII

Thermal storage is a valuable and cost-effective flexibility option for future electricity systems. Policies supporting CSP make thermal storage technologies available as an electricity storage option.

The installed capacities are highly dependent on the price development of all available technology options. We can see, that at high decarbonisation levels, CSP with TES and PV with batteries are installed alongside because they can cover different needs of the electricity system. This interplay is also dependent on the required storage hours which is explained in the section below.

3.8 Increasing shares of fluctuating renewables: CSP and PV as complementary players

In order to reach the 32% share for renewable energy within the EU until 2030 (European Commission, 2020a), significant capacities of wind and PV generation will be installed.

CSP can play an important role in the integration of significant shares of PV and wind generation in future electricity systems. This was also shown in case study analysis of prospects for different CSP technology concepts in D8.1 (Schöniger & Resch, 2019): CSP achieves the highest market values in systems with high shares of fluctuating renewable generation by PV and wind. In the scenario with the highest PV shares, CSP's market value was 144% of the average electricity price in the system (cf. Figure 13).

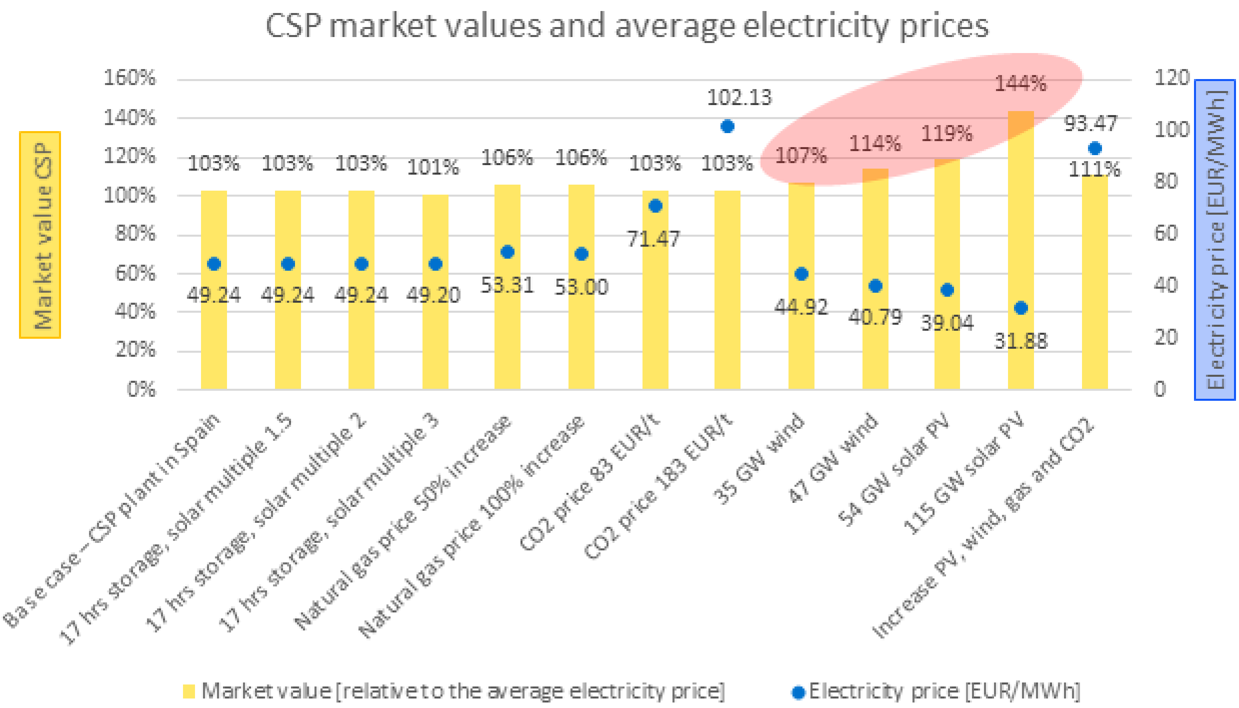

Figure 13: Summary of the results of case study 1 in D8.1 – CSP plant as system contributor in Spain (Schöniger & Resch, 2019)

In Section 2, a finding from the Diversification Scenario was also that – in addition to the vast exploitation of the PV potential in Europe – CSP is necessary in order to cover demand in 2050.

The phenomenon of low levels of residual load during noon can be observed in high PV penetration electricity systems. The resulting net load curve shows a high peak in the hours after sunset when the demand is still high but the sun is not available any longer ("duck curve").

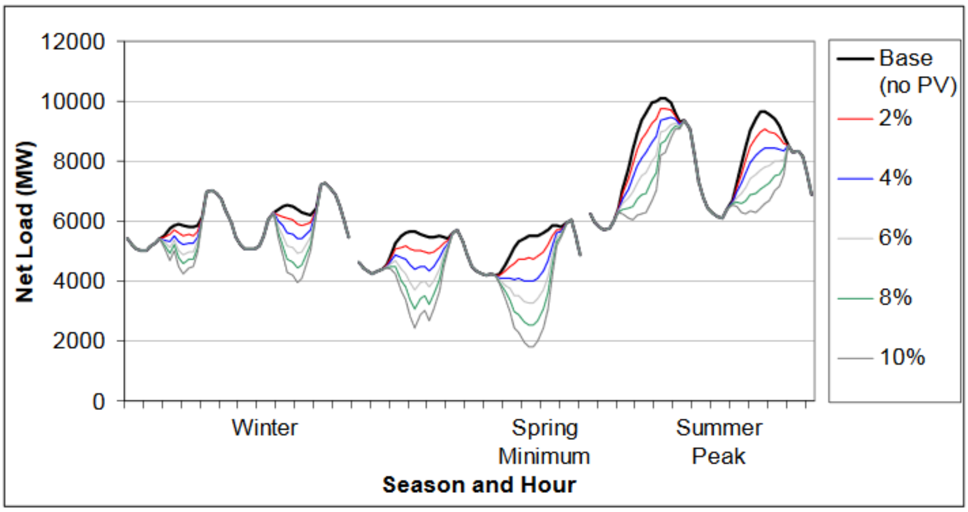

Figure 14: Load Shapes in Colorado with various WECC PV Penetration Scenarios (Denholm, Margolis, & Milford, 2008)

This means that in these energy systems, dispatchable solar power like CSP with TES can use competitive advantages by being able to sell the generated (and stored) electricity at (night) times of higher price levels.

One factor which is of importance when producing night time solar power is the required storage duration (as elaborated on in Schöniger, Thonig, Resch, & Lilliestam (2019), in review). CSP has a competitive advantage for longer storage durations (starting at around 4-5 hours) and PV + Li-Ion battery for shorter storage durations (cf. Figure 15).

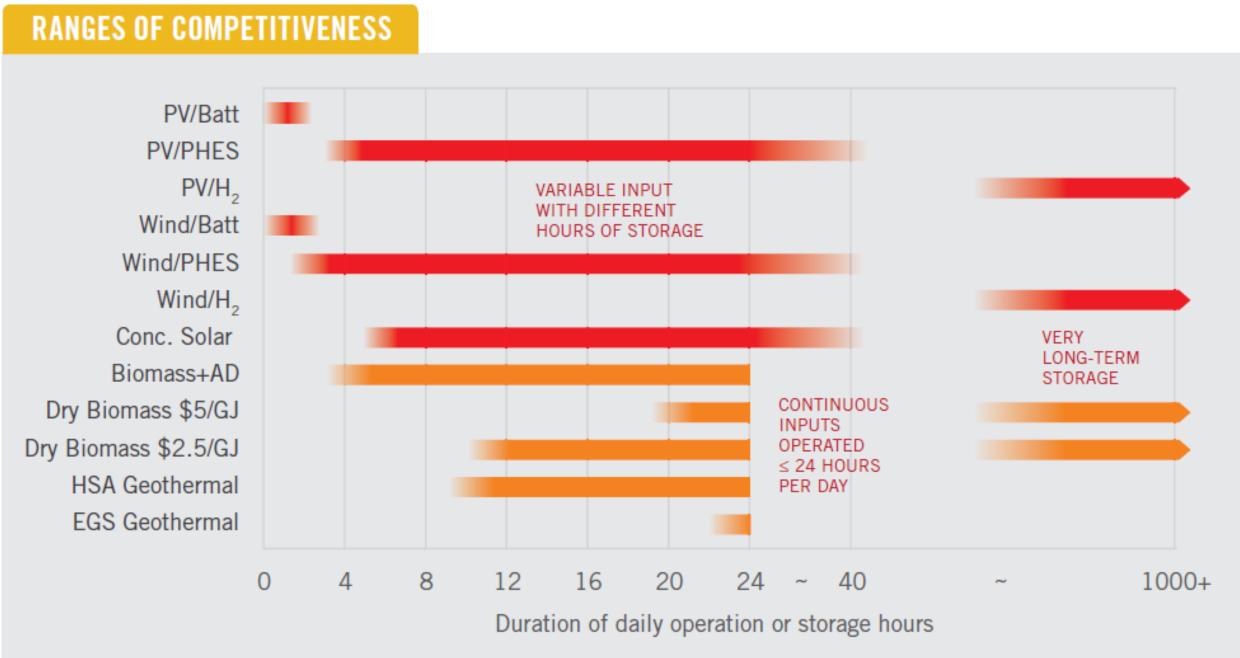

Figure 15: Comparison of dispatchable renewable electricity options (Lovegrove et al., 2018)

This is due to the fact that the specific power block costs for CSP decrease with the storage time. The storage duration when CSP becomes more competitive highly depends on the technology costs (compare Figure 16). Depending on the cost assumptions, this point ranges between 3 and 10 hours.

The setting for this modelling exercise looked the following: CSP + TES and PV + Li-Ion battery (and PV + TES + elect. boiler) were modelled for a specific location in Spain and different cost assumptions up to 2050. In an investment and dispatch optimisation, a certain amount of night-time power (100 MW) have to be covered from storage (1-24 hours).

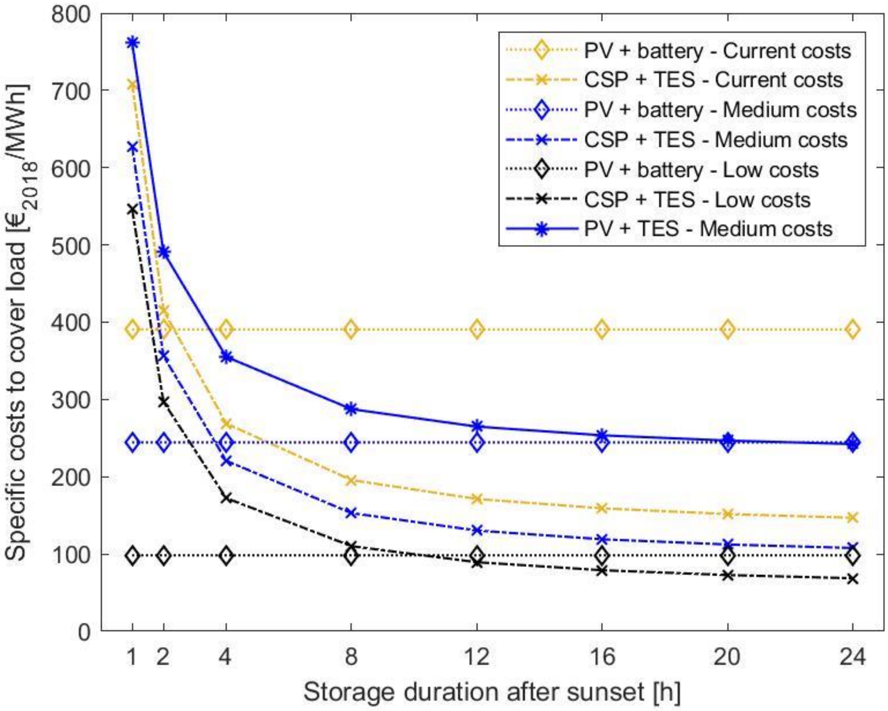

Figure 16: Specific costs for different hours of continuous generation (100 MW) from storage (Schöniger et al., 2019, in review)

A good example of the complimentary use case of CSP and PV is the DEWA IV (fourth phase of the development) project. It is the largest single-site solar park in the world, with a planned capacity of 1 GW by 2020, and 5 GW by 2030. It will be comprised of three Parabolic Trough units of 200 MW with 11 hours TES and a Power Tower unit of 100 MW with 15 hours TES. The DEWA IV project has been realized because targeted auctions giving value to the dispatchability of the solar plant were conducted. The project is described in detail in the selection of representative and strategic CSP/STE projects potentially suitable for cooperation conducted within D5.1 (Souza, 2018). This project visualizes the vision of solar thermal and photovoltaic energy working in a complementary manner which may constitute the most rational approach to move towards a CO_2-free electricity generation in the countries of the solar belt. This example shows how policies that explicitly aim for **CO_2 free and flexible generation also during times when no sun is available** can create a market setting where CSP can play out its competitive advantages.

In this project, CSP was able to offer at lower prices than new combined-cycle gas turbines covering the required operational/dispatch profile at a reduced number of hours per year. The most important feature of this project is its operational profile: it collects solar heat during the day and concentrates its electricity production between 4 pm and 10 am, which means that the operator can make the most of PV during the day and then switch to electricity generation from CSP to supply demand after sunset. On the downside, that means that cheap PV and storage can eliminate the need for CSP.

The complementarity of CSP generation and the generation of other fluctuating renewables is not the same for all technologies. Since the generation profile of wind and PV is different (cf. Figure 17), the role of CSP to complement them is also not the same. We showed that the relative market value of CSP is higher in high PV penetration scenarios than in high PV penetration scenarios (cf. Figure 13). That means that the value of dispatchable CSP generation is higher in high PV penetration systems.

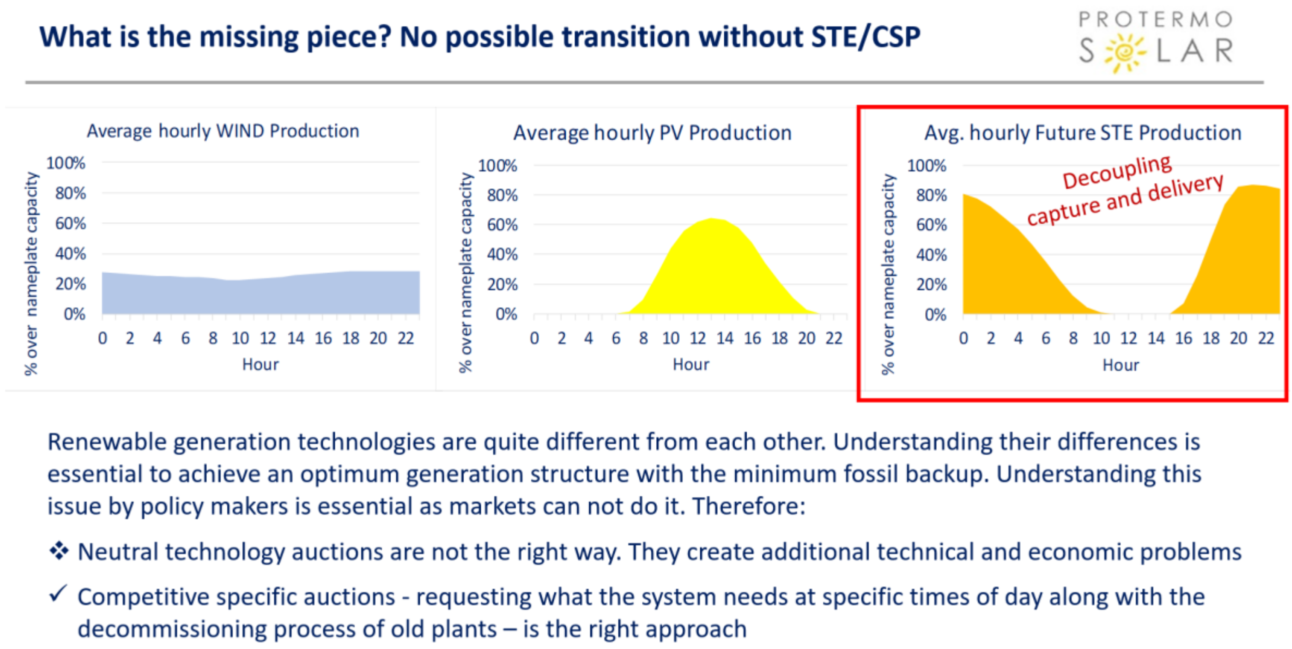

Figure 17: Complementary technology concepts PV and CSP (Souza, 2018)

The availability of PV power is also more predictable than the one of wind power since there is no generation during the night and a typical profile during the day. Countries with a high share of PV in the electricity system are likely to have high solar potentials in general, and are therefore convenient locations for CSP as well. However, CSP is able to produce its electricity flexibly, so it is also able to adapt its generation to other fluctuating renewables like wind as long as there are the appropriate price signals and high-quality forecasts available.

Policy implication VIII
There will be different niches for both, CSP and PV with storage, in the future electricity system. In order to have both technologies ready and competitive, it is necessary to design targeted support, e.g. through competitive specific auctions.

4 LESSONS LEARNED FROM FORMER STUDIES: WHAT DOES IT NEED FOR CSP TO TAKE OFF?

4.1 CSP in SET-Nav

The role of CSP in transitioning energy systems has been analysed in several studies before. In this section, we take a look at a former study which analyzed the role of CSP in future energy systems in Europe. We compile the findings of the project SET-Nav (SET-Nav, 2019) with a focus on CSP in order to identify factors which are decisive for CSP deployment. This analysis was conducted in Enertile[11].

The storage size of the modelled CSP plants was set to 8 full load hours. The ratio between the solar field and the generator of the CSP plant are site-specific. This can lead to a certain variance in cost. However, an indicative overview of the cost assumptions in SET-Nav is given in Table 11.

Table 11: Cost assumptions for CSP plants

Year	Lifetime (years)	Specific investment (€/kW)	Maintenance and operation cost (€/kW/a)	Efficiency
2021-2030	30	3,300	64.0	44%
2031-2040	30	3,050	54.5	49%
2041-2050	30	2,660	45.0	52%

This development of CSP cost and technological learning is very optimistic, which has to be taken into account when interpreting the model results. Furthermore, it is assumed that the WACC (Weighted Average Cost of Capital) for all technologies is constant within Europe and has a value of 7%. This may lead to a certain overestimation of investments into CSP in Southern Europe because, in reality, such investments would have higher capital cost.

In order to answer the question, what CSP needs to take off, four different scenarios of the SET-Nav project (Sensfuß et al., 2019) are taken into account. These scenarios were calculated with the Enertile model described before (combined with further models for energy demand, renewables and transmission grid). All scenarios had a 96% GHG emission reduction target of the electricity supply until 2050 and were calculated for the 28 EU member states as well as Switzerland and Norway.

Table 12 shows the most relevant differences between the four scenarios. Four parameters, which are varied throughout the scenarios and will be further discussed here, are: electricity demand, use of nuclear power generation, use of carbon capture and storage (CCS) in fossil power plants and the expansion of the electricity grid. These factors can be assumed to affect the use of CSP due to the

[11] For a detailed model description, please see Section 6.1 in the Appendix.

following reasons: **Electricity demand** has an impact on the installed capacity and therefore on the amount of renewable energies which have to be integrated into the electricity system. **Nuclear power plants** and **fossil power plants with CCS** are two dispatchable technologies that can provide low-carbon electricity whenever the fluctuating generation of renewable energies like photovoltaics and wind power requires it. An expansion of the **electricity grid interconnecting** large parts of Europe could help to balance the fluctuating generation of renewable energies, thereby reducing the need for dispatchable electricity generation (like e.g. CSP).

Table 12: Scenario design (semi-quantitative representation from "++" = highest to "--" = lowest)

Scenario	*Electricity demand*	*Nuclear*	*CCS in fossil power plants*	*Electricity grid*
Diversification	**++**	**--**	**No**	**++**
Directed Vision	**-**	**++**	**Yes**	**+**
Localization	**++**	**-**	**No**	**--**
National Champions	**--**	**+**	**Yes + higher cost**	**-**

In the following, the results for the different SET-Nav scenarios are shown. In

Table 13, the results for CSP capacity and generation (sum in 2050 over the 30 European countries considered) are listed. The highest share of CSP is reached in the Diversification scenario. This scenario is characterised by **high demand**, **no CCS plants**, **low nuclear power plant capacity** as well as a **high electricity grid extension**. The CSP capacity reaches 76 GW and the CSP share of the total European electricity generation is 5.3%. The lowest share with 0.7% can be seen in the Directed Vision scenario. Here, the electricity demand is low, the generation of nuclear power is high and fossil power plants with CCS are allowed.

Table 13: Results for CSP capacity and generation in the different scenarios

Scenario	**CSP capacity (GW)**	**CSP generation (TWh)**	**CSP share of electricity generation**
Diversification	**76**	**297**	**5.30%**
Directed Vision	**8**	**33**	**0.70%**
Localization	**55**	**211**	**3.70%**
National Champions	**13**	**51**	**1.20%**

Table 4 shows additional parameters like the total electricity generation, nuclear and CCS generation, the CO_2 price as well as the trading volume (as a proxy for the electricity grid extensions) for the scenarios in 2050. In 2040, the capacity of CSP is small compared to 2050 due to a lower **CO_2-price**, higher **costs of CSP-plants** as well as a higher **amount of conventional generation**. In the years before 2040, almost no CSP-plants are built in the model. In fact, the CSP capacity built in 2040 could be at least partly due to necessary capacities in 2050, as Enertile has perfect foresight and optimises over the whole time period from 2030 to 2050.

First, we compare the Diversification scenario with the Localization scenario, as the total electricity generation is similar. In the Diversification scenario with the highest share of CSP, the total electricity generation is one of the highest. The nuclear generation is lower than in the other scenarios and the CCS generation is not enabled. Furthermore, the trading volume is highest due to the unrestricted transmission grid. The Localization scenario differs from the Diversification scenario in the nuclear generation, which is higher in this scenario as well as in the CO_2 price, which is also higher. Furthermore, the trading volume is not even half of the volume in the Diversification scenario. These differences show an impact on the generation and capacity of CSP, which are around 16% lower than in the Diversification scenario.

Findings I from former studies:

A high trading volume due to strong power grid expansion and the exclusion of fossil power plants with CCS seem to be parameters that enable CSP.

Table 14: Results for different parameters in the scenarios

Scenario	Total electricity generation (TWh)	Nuclear generation (TWh)	CCS generation (TWh)	CO_2 Price (€/t)	Trading volume (TWh)
Diversification	**5,607**	**29**	**0**	**199**	**2,024**
Directed Vision	**4,836**	**801**	**472**	**183**	**1,077**
Localization	**5,627**	**164**	**0**	**296**	**959**
National Champions	**4,156**	**372**	**345**	**139**	**853**

Second, we compare the Directed Vision scenario with the National Champions scenario. In the Directed Vision scenario, the nuclear generation is the highest in comparison with the other scenarios. Furthermore, CCS generation is enabled and reaches 472 TWh. In the National Champions scenario, the nuclear generation is half of the generation in the Directed Vision scenario. The CCS generation is lower than in the Directed Vision scenario and reaches 345 TWh. The CO_2 price in the Directed Vision scenario is 183 €, in the National Champions scenario, the price is at 139 €. The trading volume is slightly lower in the National Champions scenario than in the Directed Vision scenario. The capacity and generation of CSP for the Directed Vision scenario is at 8 GW respectively 33 TWh and accordingly the lowest compared to the other scenarios. In the National Champions scenario, the capacity is at 13 GW and therefore 5 GW higher than in the Directed Vision scenario.

> ***Findings II from former studies:***
>
> ***A low electricity demand with a high share of nuclear power plants as well as the enabling of CCS could be parameters, which prevent CSP.***

We have now identified the scenarios in which CSP is a relevant part of the electricity generation. In the following, we will focus on the spatial distribution of the installed capacity. In Figure 18, the generation of CSP in different countries for each scenario is shown.

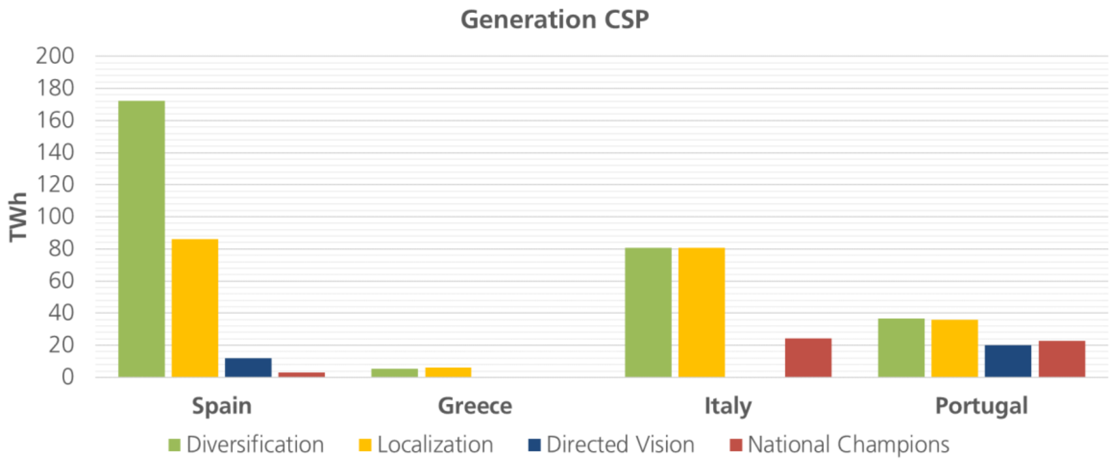

Figure 18: Location of CSP power generation in the different scenarios

CSP is only built in Southern Europe, more specifically in Spain, Greece, Italy, and Portugal. The power generation of CSP plants in these countries varies substantially between the scenarios. The highest amount of generated electricity from CSP is reached in the Diversification scenario with 297 TWh, which is about half of the European CSP generation potential determined in the Enertile renewable potential calculation (603 TWh at generation costs of up to 150 €/MWh). A great deal of this amount is produced in Spain with around 170 TWh and Italy with 80 TWh. The rest of the electricity is generated in Portugal with more than 35 TWh and Greece with around 5 TWh. In the Localisation scenario, the second highest amount of electricity is produced with 211 TWh. In this scenario, also the greatest deal is produced in Spain with around 90 TWh. The production in Italy, Portugal and Greece stays the same as in the Diversification pathway. The distribution of electricity generation changes in the National Champions scenario. Here, the highest amount of the 51 TWh is produced in Italy and Portugal with around 25 TWh. A small amount of electricity is produced in Spain with less than 5 TWh. The scenario with the lowest electricity generation of CSP plants with 33 TWh is the Directed Vision scenario. The electricity is produced in Portugal with 20 TWh as well as in Spain with around 10 TWh. The low amount of capacity build in Greece could be due to hindered export options as the Balkan countries are not modelled in the SET-Nav scenarios.

4.2 Conclusions from previous studies

In order to compare the findings on key factors and pivotal decisions in the MUSTEC project, we analysed the results of four different scenarios from the SET-Nav project. Overall, the scenarios showed that there are different factors that enable a relevant use of CSP:

An **ambitious GHG mitigation target** (e.g. represented by a high CO_2 price**)** is one of the factors. Another factor is a **high electricity demand**, which results in high usage of the potentials of other renewables. When the economically most attractive potentials of wind and photovoltaics (PV) power are already used and more expensive ones have to be utilized, CSP becomes more competitive in relation to these technologies. **Restricted availability of nuclear power, fossil power plants with CCS**, and **other dispatchable power plants** also favour the use of CSP. An **ambivalent factor** is **electricity grid extension** because, on the one hand, they allow the export of CSP power from Southern Europe, but on the other hand, they reduce the need for dispatchable CSP power (due to a more balanced generation of fluctuating wind and PV power connected over Europe). However, it has to be taken into account that the assumptions for the **development of CSP costs** used for the modelling were rather optimistic. In addition, it should be remembered that a knockout factor for the use of CSP plants would be the availability of cheap electricity storage combined with PV. This technology might provide dispatchable solar electricity at lower costs than CSP.

Additionally to what was shown in Section 3.2, we see from the SET-Nav results that the phase-out of nuclear power plants as well as other dispatchable conventional capacities creates a need for dispatchable renewable technologies. In such a market environment, CSP can play an important role if it is competitive to other dispatchable renewable sources.

Policy implication IX

National or international policies causing nuclear (and/or coal) phase-out create a need for alternative dispatchable technologies, which can be covered by CSP.

Overall, these findings are in line with what we find in MUSTEC.

5 CONCLUSION

In this report, we shed a light on key factors and pivotal decisions for successful CSP deployment in Europe in the future. From the wide range of factors that are relevant for CSP deployment in Europe's future electricity system, we elaborate in particular on the effect of cooperation, demand-side management, electricity grid expansion, decarbonisation ambition, technology cost developments of CSP and competing technologies, increasing shares of fluctuating renewables and nuclear phase-out on CSP deployment. This report compiles the key drivers and policy decisions for CSP deployment which have been derived from the policy pathway processing and modelling tasks in the integrated assessment of the MUSTEC project.

CSP is able to offer flexible and decarbonised power generation and is an enabler of the integration of large shares of fluctuating renewables. As a solar power-based balancing opportunity, this technology offers a highly valuable flexibility option for Europe. Cooperation - exploiting solar potentials in the southern European countries and combining it with the rest of Europe – can help the EU to reach the formulated energy and climate targets. Still, to have this technology available for the generation portfolio in Europe when it will be needed, certain market conditions in the electricity systems have to be met which have to be addressed by policy decisions.

We identify the following key factors and related pivotal policy decisions for CSP deployment:

- ***RES cooperation can act as important driver for CSP*** thanks to the increased demand for CSP, and the expectable ***decrease in financing cost driven by cooperation policies.*** This is (partly) confirmed by modelling where the CSP uptake is significantly stronger in scenarios assuming strong RES cooperation combined with strong electricity demand growth. In these cooperation scenarios, it makes long-term economic sense to invest in CSP.
- There are ***different niches for different flexibility options***. We showed that in the case of reduced flexibility (-50%) provided by decentral heat storage (linked to heat pumps) and e-mobility, the need for CSP is rarely impacted because it is needed in both cases due to its generation characteristics combined with (short-term) storage opportunities.
- If exporting countries decide to ***expand and diversify their transmission and interconnection capacities beyond what EU rules require***, they are able to better exploit the full capacity for deployment of dispatchable CSP.
- A ***full decarbonisation*** of the energy system in line with the Paris agreement as intended by the EU policy ***requires strong increases in sector-coupling*** and, consequently, ***in electricity demand***. This is a ***key driver for an enhanced uptake of CSP*** within Europe in future years.
- CSP needs ***effective price signals valuing dispatchable and CO2-free electricity generation***. If policies on market design ensure these price signals without allowing for CCS, CSP is able to play an important role.

- ***Technology cost reductions*** of all CSP components are necessary to keep this technology competitive and available for the transformation of our electricity systems. Since absolute CSP capacities installed are relatively small, policies for ***targeted support for CSP*** are needed and able to foster high learning rates.
- ***Thermal energy storage*** is a valuable and ***cost-effective flexibility option*** for future electricity systems. Under current cost assumptions, CSP becomes more competitive than PV + battery at around 4-5 hours storage duration. Support for the CSP enhances at the same time thermal storage technologies as flexibility options for the electricity system.
- ***CSP and PV can fulfil complementary tasks*** which have to be addressed by renewable policies. Competitive specific auctions can help to rate the system contribution of different technology options and value the dispatchability of CSP. Both, PV and CSP, are needed in the electricity system of 2050 according to our modelling.
- National or international policies causing ***nuclear (and/or coal) phase-out create a need for alternative dispatchable technologies, which can be covered by CSP***. National acceleration of the transition that aims for reaching fully renewable systems as early as possible increase these flexibility needs accordingly.

We show in detail how these factors can enhance the uptake of CSP in Europe and how they can be addressed in policy decisions. An important finding is also that many of the identified factors are closely linked to each other and significant synergies can be achieved by combinations of different key drivers (like e.g. strong decarbonisation ambition in the energy system and technology cost reductions of CSP) in policy decisions supporting the deployment of CSP.

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6 APPENDIX

6.1 Enertile model description

Enertile is a model for energy system optimization developed at the Fraunhofer Institute for Systems and Innovation Research ISI. The model strongly focuses on the power sector but also covers the interdependencies with other sectors such as the heating and transport sector. It is used for long-term scenario studies and is explicitly designed to depict the challenges and opportunities of increasing shares of renewable energies. A major advantage of the model is its high technical and temporal resolution.

Enertile conducts an integrated optimization of investment and dispatch. It optimizes the investments into all major infrastructures of the power sector, including conventional power generation, combined-heat-and-power (CHP), renewable power technologies, cross-border transmission grids, flexibility options, such as demand-side-management (DSM) and power-to-heat and storage technologies. The model chooses the optimal portfolio of technologies while determining the utilization of these in all hours of each analysed year.

The model currently depicts and optimizes Europe, North Africa and the Middle East. In this project, only Europe is analysed. Each country is usually represented by one node, although in some cases it is useful to aggregate smaller countries and split larger ones into several regions. Covering such a large region instead of single countries becomes increasingly necessary with high shares of renewable energy, as exchanging electricity between different weather regions is a central flexibility option. The model features a full hourly resolution: In each analysed year, 8760 hours are covered. Since real weather data is applied, the interdependencies between weather regions and renewable technologies are implicitly included.

Enertile includes a detailed picture of renewable energy potential and generation profiles for the optimization. The potential sites for renewable energy are calculated on the basis of several hundred thousand regional data points for wind and solar technologies with consideration of distance regulations and protected areas. The hourly generation profile is based on detailed regional weather data.

6.2 Balmorel modelling framework description

6.2.1 *General model description*

Balmorel (the BALtic Model for Regional Electricity Liberalisation) is a partial equilibrium model, analysing the electricity and district heat sector on an international level. International trade as well as different price zones within a country can be modelled. Balmorel uses linear programming to minimize the annualized cost of the energy system (electricity and district heat).

Balmorel is a deterministic bottom-up energy system model that is able to co-optimize energy dispatch and investments. Investments are thereby optional and can be used additionally to the dispatch model. Further, policy restrictions in terms of fuel constraints (e.g. coal phase-out) can be considered (The Balmorel Open Source Project, 2019).

Table 15 and Table 16 give an overview of required input parameters and expected output parameters in the dispatch and investment optimization in Balmorel.

Table 15: Input and output parameters for dispatch optimization in Balmorel

Dispatch optimization	
Input	**Output**
• Electricity and district heat demand and hourly profiles • Fuel prices • Generating capacities and their characteristics • Resource characteristics for wind, hydro and solar resources • Transmission capacities and transmission and distribution losses	• Electricity and district heat generation per generation unit • Electricity distribution and transmission • System cost • System emissions

Table 16: Input and output parameters for investment optimization in Balmorel

Investment optimization	
Input	**Output**
• Investment cost for different technology types • Investment cost for transmission capacity • Interest rate • Economic life time of technologies	• Endogenously installed generation capacity per technology type • Endogenously installed transmission capacity between regions

There are three geographic levels in Balmorel: countries, regions, and areas. Electricity demand and generation are balanced within regions whereas district heat demand and generation is balanced within areas. Heat transfer is not possible between areas in the default mode, but electricity transmission is allowed between regions and countries. Table 17 shows the model characteristics of Balmorel. The objective function minimizes investment costs, operation and maintenance costs (fixed and variable costs), and fuel costs. For this, equations on electricity and district heat balance, capacity and energy constraints, production of dispatchable and non-dispatchable units, operational constraints, storage operation, transmission constraints, emission caps, and several more are considered. As a result, the model delivers energy conversion characteristics, fuel consumption, electricity exports and imports, emissions, investments in plants and transmission lines, prices on traded energy, and total costs. All optimization is done by perfect foresight over the year.

Table 17: Balmorel model characteristics (adapted from Münster (2019)*)*

Balmorel model characteristics	
System aggregation	Flexible at three levels (geographical levels of countries, regions, and areas)
Optimization type	Linear programming
Optimization focus	Minimizing annualized costs of the energy system
Optimization object	Dispatch and investment
Output	Energy production by unit, fuel consumption, emissions, electricity import/export, investments in plants and transmission, as well as electricity price
Model run-time	Depending on the size of the problem, varying from minutes to days
Access	Complex interface, open source (demands GAMS license and linear programming software), direct access to code and data

Figure 19 shows the core structure of the Balmorel model. Within the system boundaries of the model, the energy flows of electricity and district heating are simulated. District heat demand and electricity demand are given exogenously. Storages – electric as well as thermal – can be simulated as well. The additional demand caused by the storage facilities is added endogenously. In the Balmorel model, an electricity price is calculated for each region and each time segment of the year. This price represents the electricity producers' marginal cost of generation (including fuel costs, fuel and emission taxes, operation and maintenance costs, and investment costs).

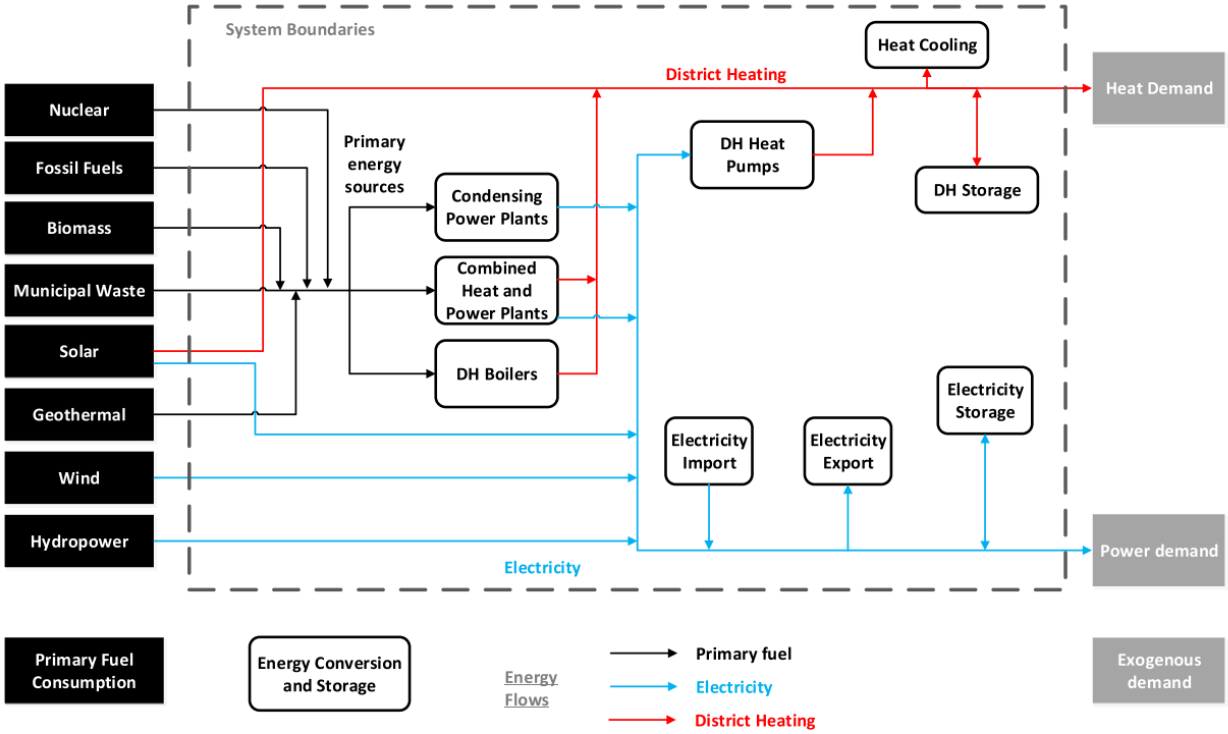

Figure 19: Balmorel core structure (Wiese et al. (2018)*)*

6.2.2 *Modelling of CSP in Balmorel*

CSP plants consist of three independent but closely interrelated components with different characteristics: the solar field producing solar thermal energy, the thermal storage system, and the electricity producing unit/power block. All of these components can be sized differently and require different assumption regarding their techno-economic parameters.

6.2.2.1 Solar field

Depending on the technology concept, the amount of thermal energy output is determined by the size of the solar field and the amount of solar irradiance – relevant in the case of CSP is the amount of Direct Normal Irradiance (DNI). Varying the size of the solar field has an impact on the capacity factor of the electricity generating unit. This is, however, a complex interplay of solar field size, storage capacity, and electricity generation capacity. The size of the solar field can either be expressed in terms of actual covered land or by using the concept of a solar multiple. The solar multiple is the ratio of the thermal energy collected by the receiver at the reference point to the amount of thermal energy required to generate the rated turbine gross power (Kariuki, Machinda, & Chowdhury, 2012).

6.2.2.2 Thermal energy storage

According to ESTELA (2019), storage sizes of at least 8 hours are considered as realistic for the future. The efficiency of the thermal energy storage is assumed to be 99.25% (ESTELA, 2019).

6.2.2.3 Emissions

The only emissions which are taxed in the modelling context are CO_2 emissions.

6.2.2.4 Economics

In the modelling, the three components solar receiver, thermal energy storage, and power generation unit (steam turbine) have to be modelled separately. Since most of the operating expenses are fixed (e.g. O&M contract with a third party, certain amount of spare parts and, depending in each specific case, other associated costs such as insurances, land cost/rent, water, etc.), it is assumed that the variable O&M cost are not significant.

The investment cost for CSP plants differ a lot due to different local conditions, requirements, and many more varying external factors. In order to get a reference value for the investment cost, we looked at more recent projects and took the average CAPEX of Noor III in Morocco (6.022 M€/MW) and DEWA-IV in Dubai (4.846 M€/MW). For the modelling, the cost were further split between the three components of CSP in the following way according to the method presented by Fedato (2018) and Mehos et al. (2008): receiver 61 %, ST 22%, and TES 17%.

An interest rate of 5% is taken into account. For all parts of the CSP plant, an economic life time of 25 years is assumed (CSP Guru, 2019; Lilliestam, Labordena, Patt, & Pfenninger, 2017).

6.3 Green-X model description

The model Green-X has been developed by the Energy Economics Group (EEG) at TU Wien under the EU research project "Green-X–Deriving optimal promotion strategies for increasing the share of RES-E in a dynamic European electricity market" (Contract No. ENG2-CT-2002-00607). Initially focussed on the elec-tricity sector, this modelling tool, and its database on renewable energy (RES) potentials and costs, has been extended to incorporate renewable energy technologies within all energy sectors.

Green-X covers the EU-28, the Contracting Parties of the Energy Community (West Balkans, Ukraine, Moldova) and selected other EU neighbours (Turkey, North African countries). It allows the investigation of the future deployment of RES as well as the accompanying cost (including capital expenditures, addi-tional generation cost of RES compared to conventional options, consumer expenditures due to applied supporting policies) and benefits (for instance, avoidance of fossil fuels and corresponding carbon emis-sion savings). Results are calculated at both a country- and technology-level on a yearly basis. The time-horizon allows for in-depth assessments up to 2050. The Green-X model develops nationally specific dynamic cost-resource curves for all key RES technologies, including for renewable electricity, biogas, biomass, biowaste, wind on- and offshore, hydropower large- and small-scale, solar thermal electricity, photovoltaic, tidal stream and wave power, geothermal electricity; for renewable heat, biomass, sub-divided into log wood, wood chips, pellets, grid-connected heat, geothermal grid-connected heat, heat pumps and solar thermal heat; and, for renewable transport fuels, first generation biofuels (biodiesel and bioethanol), second generation biofuels (lignocellulosic bioethanol, biomass to liquid), as well as the impact of biofuel imports. Besides the formal description of RES potentials and costs, Green-X provides a detailed representation of dynamic aspects such as technological learning and technology diffusion.

Through its in-depth energy policy representation, the Green-X model allows an assessment of the impact of applying (combinations of) different energy policy instruments (for instance, quota obligations based on tradable green certificates / guarantees of origin, (premium) feed-in tariffs, tax incentives, invest-ment incentives, impact of emission trading on reference energy prices) at both country or European level in a dynamic framework. Sensitivity investigations on key input parameters such as non-economic barriers (influencing the technology diffusion), conventional energy prices, energy demand developments or technological progress (technological learning) typically complement a policy assessment.

Within the Green-X model, the allocation of biomass feedstock to feasible technologies and sectors is fully internalised into the overall calculation procedure. For each feedstock category, technology options (and their corresponding demands) are ranked based on the feasible revenue streams as available to a possible investor under the conditioned, scenario-specific energy policy framework that may change on a yearly basis. Recently, a module for intra-European trade of biomass feedstock has been added to Green-X that operates on the same principle as outlined above but at a European rather than at a purely national level. Thus, associated transport costs and GHG emissions reflect the outcomes of a detailed logistic model. Consequently, competition on biomass supply and demand arising within a country from the conditioned support incentives for heat and electricity as well as between countries can be reflected. In other words, the supporting framework at MS level may have a significant impact on the resulting bio-mass allocation and use as well as associated trade.

Moreover, Green-X was extended throughout 2011 to allow an endogenous modelling of sustainability regulations for the energetic use of biomass. This comprises specifically the application of GHG con-straints that exclude technology/feedstock combinations not complying with conditioned thresholds. The model allows flexibility in applying such limitations, that is to say, the user can select which technology clusters and feedstock categories are affected by the regulation both at national and EU level, and, addi-tionally, applied parameters may change over time.

MUSTEC
Market Uptake of Solar Thermal Electricity

WHO WE ARE

The MUSTEC consortium consists of nine renowned institutions from six European countries and includes many of the most prolific researchers in the European energy policy community, with very long track records of research in European and nationally funded energy policy research projects. The project is coordinated by Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas-CIEMAT.

Name	Country	Logo
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University of Piraeus Research Center – **UPRC**	GR	
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