Market Uptake of Solar Thermal
Electricity through Cooperation

Market uptake of concentrating solar power in Europe: model-based analysis of drivers and policy trade-offs
Deliverable 8.2

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June, 2020

A report compiled within the H2020 project MUSTEC
Work package 8, D8.2

The project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 764626

This report should be cited as: Resch, G., Schöniger, F., Kleinschmitt, C., Franke, K., Sensfuß, F., Thonig, R., and Lilliestam, J. (2020): *Market uptake of concentrating solar power in Europe: model-based analysis of drivers and policy trade-offs.* Deliverable 8.2 of the Horizon2020 project MUSTEC, TU Wien, Vienna, Austria.

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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***.

Project information	
Project Number	764626
Project title	Market uptake of Solar Thermal Electricity through Cooperation – MUSTEC
Starting date	01/10/2017
Duration in months	36
Call identifier	H2020-LCE-2017-RES-CSA

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Executive Summary

As part of the European Green Deal, the European Union (EU) aims at full climate-neutrality of all sectors by 2050 and a 40 % reduction of greenhouse gas emissions (GHG) by 2030 compared to 1990 levels (European Commission, 2020a, 2020b) which is expected to be revised towards 55 %.(European Commission, 2019). The achievement of the European Union's (EU) energy and climate targets will require high shares of wind and photovoltaics (PV) in the power system as well as dispatchable renewable generation technologies to balance the fluctuating generation patterns of wind and PV. Concentrating Solar Power (CSP) is a dispatchable, renewable power technology that facilitates the transition towards a decarbonised electricity system in the EU. It provides flexible, CO_2-free electricity to the grid and supports the integration of other renewable electricity technologies. Since solar resources for CSP are richest in the southern countries, cooperation between Member States helps to make this potential also available to northern countries within the EU and facilitate overall energy and climate target achievements. The MUSTEC project aims at analysing the role of renewable energies (RES) cooperation for an enhanced market uptake of CSP in Europe. Cooperation is generally characterized by shared efforts and risks, cost optimised investments over all countries instead of separate, national strategies (e.g. cross-border renewable projects) and high shares of energy trading (physically or statistically).

This report informs on a model-based assessment of the future market uptake of CSP in Europe. The modelling works undertaken combined two core elements: a power system analysis, identifying the need for CSP in a decarbonised European electricity system of tomorrow, and an energy policy analysis to assess implications for and impacts of dedicated support policies for CSP and other renewables. This distinction is followed below when summarising key results and lessons learned.

Key results and findings from the power system analysis – identifying the need for CSP in a decarbonised European electricity system of tomorrow

We conducted a model-based analysis evaluating the role of CSP in the EU electricity system up to 2050. In particular, we analysed how cross-border cooperation ("Cooperation" vs. "National Preferences"), sector coupling and electricity demand levels ("High Demand" vs. "Low Demand"), underlying RES policy concepts and pathways ("Low Climate Ambition"), and infrastructural developments/prerequisites ("Limited Grid") impact the market uptake of CSP in the EU.

Concerning the question, whether cooperation among European countries leads to higher expansions of CSP power plants, our modelling results are ambiguous (see section 3.2). While in the case of very high electricity demand CSP generation is somewhat higher in the "Cooperation" scenario than in the "National Preferences" scenario, this tendency is reversed in the case of lower demand. However, a high electricity demand is more probable in a world with very ambitious decarbonisation targets, which may enhance the perspectives of CSP.

Furthermore, our results indicate that a higher electricity demand increases the need for CSP (see section 3.2.2). Because CSP is more expensive than other renewable technologies, CSP capacities are increasingly installed when the potentials of other renewable technologies like wind and PV are already exploited to a higher degree (which is the case for higher electricity demand).

High climate policy ambitions are a very important driver for CSP uptake (see section 3.2.4). This is because they hinder the use of fossil power plants, first, as a backup of fluctuating renewables and second, as supply of electricity demand exceeding the realizable potential of other renewables. Hence, CSP with its advantage of renewable dispatchability becomes more important under such conditions.

Finally, a highly developed transnational power grid proves to be an ambivalent factor for the development of CSP (see section 3.2.1). On the one hand, interconnections are an enabler of CSP, especially as the areas with largest and least expensive potential of CSP generation are located on the European periphery (Spain, Portugal, and Italy). Due to their peripheral location, especially Spain and Portugal depend on a strong power grid interconnection to the rest of Europe in order to export larger amounts of electricity from CSP (if the conversion of the electricity e.g. to hydrogen with subsequent international trading, which is less efficient than direct electricity trade, is excluded). On the other hand, a highly interconnected European power grid smooths the fluctuations of wind power and PV feed-in, so that the need for additional supply-side flexibility, including CSP, decreases.

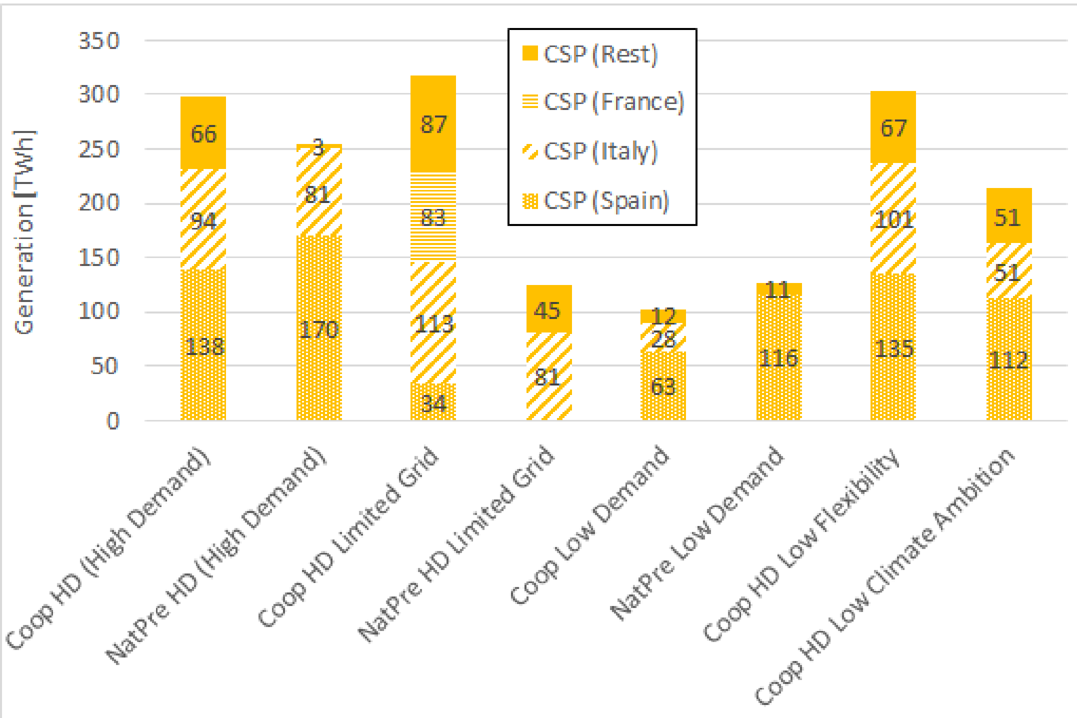

Figure 1: Electricity generation from CSP in the EU in 2050 for the different scenarios calculated for this report.

Figure 1 underlines these conclusions by comparing the generation of electricity from CSP in the considered scenarios and sensitivities. However, the figure also demonstrates that the different circumstances in the scenarios may have different (in some cases even opposite) effects on the CSP deployment in the individual countries. These effects are discussed in more detail in the respective result sections of the main report (cf. chapter 3).

Key findings from the energy policy analysis – implications for and impacts of dedicated support policies for CSP and other renewables

The uptake of renewables – a closer look at the diffusion of RES technologies

Below we summarise key trends concerning the expected uptake of renewables in Europe's electricity sector (as elaborated in detail in section 4.1). If we look back in time, we see that at EU28 level more than a doubling of RES deployment has been achieved throughout the past thirteen years. This impressive trend needs to be maintained: taking deep decarbonisation as our overall guiding principle implies an increase of the RES shares to about 56 % by 2030, and to at least 90 % by 2050: RES shares vary by then from ca. 90 % ("National Preferences", assuming a still strong nuclear deployment in France) to about 97 % ("Cooperation", assuming no built-up of new nuclear across the EU). In absolute terms the accompanying strong growth in electricity consumption imposes even a strengthening of RES developments in future years compared to the historic record. Electricity generation from RES needs to at least double within the next twelve years and to more than quadruplicate until 2050.

Key trends in technology-specific developments are that onshore wind dominates the picture – both by 2030 and by 2050 the largest share of newly established RES-based electricity generation will come from this particular technology. Offshore wind energy is the second largest contributor to the overall RES uptake in future years, followed by photovoltaics where residential and central PV systems are expected to increase significantly. CSP is the fifth largest contributor to RES generation serving as "gap filler" for the system flexibility to the EU power system that relies on large shares of variable renewables – as identified in the power system analysis. Other technologies like hydropower, biomass, geothermal electricity, tidal stream or wave power show only comparatively minor contributions in future years under the underlying framework conditions where least-cost options are prioritised in modelling.

Concerning country-specific contributions, currently strong differences in demand-related RES shares are observable across countries. Despite the assumed transformation of the electricity sector towards carbon neutrality by 2050, strong differences in country-specific RES deployment are also applicable under all assessed scenarios in future years. This also holds for 2050 when renewables reach a high demand share at EU level. Differences in RES shares across countries are smallest under a more limited expansion of the cross-border transmission grid since exchange of electricity across countries is then more limited and, in consequence, countries have to facilitate a stronger domestic RES expansion.

Strong investments in renewables are needed – CSP makes up 7-8 % of the total under default assumptions on demand growth and climate ambition

As elaborated in detail in section 4.2, strong investments in RES technologies are necessary for making the transition towards carbon neutrality in the EU'S electricity sector, average yearly investments range for the key scenarios analysed from 91 billion € ("National Preferences") to 100 billion € ("Cooperation"), reflecting the differences in RES ambition. Investments are slightly higher (96 to 106 billion € per year) in case of grid limitations, and lower in magnitude if demand grows less than expected (64 to 72 billion €).

For CSP in general similar observations can be drawn: Among the scenarios that follow a policy pathway of "Cooperation" average yearly investments in CSP range from 8.0 to 8.8 billion € when a high demand growth is expected, and to only 2.5 billion € in the case of low demand growth. The corresponding figures for the "National Preferences" scenarios are 6.4 billion € for the default case of high demand growth and 2.8 billion € for the low demand growth scenario. Compared to the total investment volumes that need to be dedicated to renewables in the electricity sector, these figures imply that on average about 7- 8% of these are for CSP if a high demand growth will arise and the target of carbon neutrality by 2050 is taken up seriously in energy and climate policy making. Only about 4% of the total RES investments fall on CSP if sector coupling and in consequence electricity demand will not increase as expected.

Support is needed to facilitate the strong uptake of CSP and other RES technologies – but new RES installations come at significantly lower cost thanks to technological progress

As outlined in section 4.3, there is a need for dedicated support of CSP and other RES in the near to mid future. The bulk of identified RES-related support expenditures within forthcoming years up to 2050 is however dedicated to existing RES, established in the years up to 2020 since they have come at higher cost. Support for new RES (installed post 2020) is expected to strongly decline over time due to technological progress and the projected increasing prices in wholesale electricity markets. A key element for achieving this decline in support for new RES installations, specifically for variable RES like wind and solar PV, is the expansion of the cross-border transmission grid since this facilitates RES integration and the balancing of under- and oversupply across countries in times of high variable RES infeed.

Figure 2 provides a comparison of the resulting average (2021-2050) yearly RES-related support expenditures across assessed scenarios. This graph indicates a comparatively broad spectrum for the average yearly support expenditures, ranging from 10.2 to 29.2 billion €. Expenditures are lowest in scenarios with low demand growth, and highest in the case of imitations in expanding the cross-border transmission grid. Support expenditures dedicated to CSP range from 0.4 billion € (both scenarios of "Low Demand") to 2.0 billion € ("Cooperation – High Demand" with or without less (demand-side) flexibility). This corresponds well to the underlying CSP deployment trends, and specific support for CSP (per MWh RES generation) is consequently hardly affected by analysed changes in input parameter like grid limitations, demand flexibility, etc.

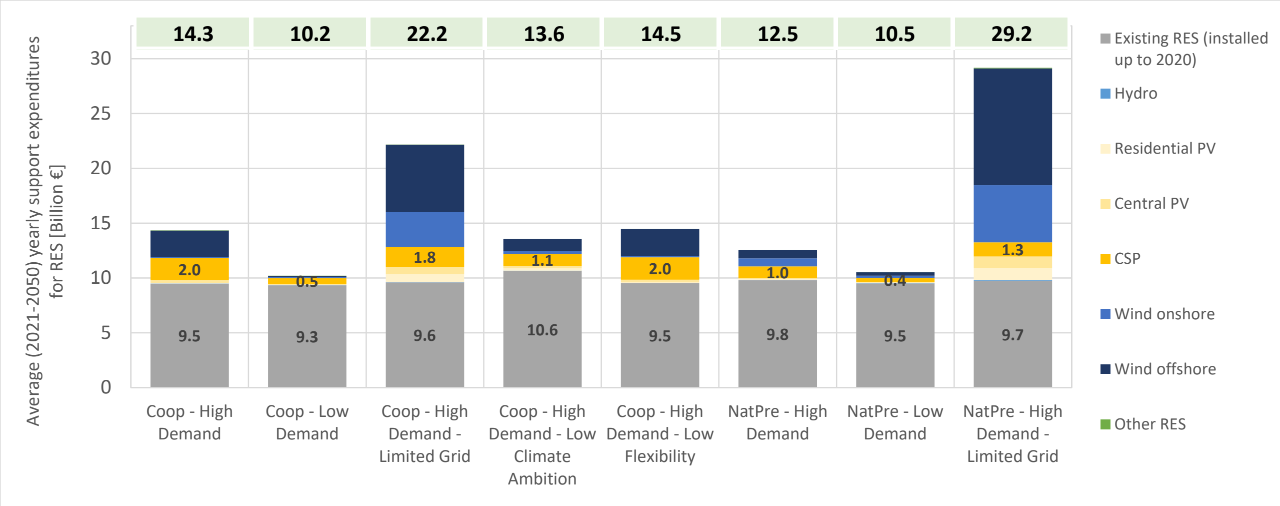

Figure 2: Comparison of the resulting average (2021-2050) yearly support expenditures for RES technologies in the electricity sector at EU28 level according to selected assessed scenarios (Source: Green-X modelling)

Dedicated support as alternative to high carbon prices

A focal assessment is conducted to shed light on the role of the EU Emission Trading Scheme (EU ETS) in reaching carbon neutrality at EU level by 2050 (see section 4.4). Today within the EU and its Member States (MSs) a broad portfolio of policy initiatives is implemented that aims for facilitating the decarbonisation of the energy system. The EU ETS acts as umbrella instrument to safeguard that GHG emission reduction targets are met within the sector covered, including large GHG emitters in power and heat supply and in industry as well as parts of certain transport modes. Within the electricity sector the EU ETS is accompanied by dedicated support instruments and various other measures like cheap loans, tax regulations etc. to facilitate the uptake of renewables and other decarbonisation options.

We can conclude that in the absence of high carbon prices in the EU ETS, i.e. reflecting a world where dedicated support is offered to individual decarbonisation options and implying, in turn, that the EU ETS is not acting as single driver for the take-up of decarbonisation options and needs, overall remuneration of CSP and other RES technologies and, consequently, also corresponding consumer cost are at a lower level than in an “ETS only” world. Here targeted support can be provided to individual RES technologies, for example via auctions for sliding feed-in premia, in accordance with technology- or even site-specific requirements. Such a policy approach helps to avoid overcompensation for “low hanging fruits” like onshore wind or solar PV.

There is a need for and positive impact of RES cooperation on the cost for the uptake of CSP and other RES technologies

Our second focal assessment focusses on identifying the need for and impact of RES cooperation between Member States from a quantitative perspective and it informs on how RES cooperation may facilitate the uptake of CSP in future years (see section 4.5). In general, RES cooperation is assumed to facilitate a levelling of country-specific risk for RES investors and to redistribute the cost of the RES uptake across the whole EU, so that host countries for the uptake of CSP and other RES technologies do no longer have to pay the whole bill. As default we have taken in modelling the assumption that RES cooperation is taking place post 2020. In the sensitivity analysis performed we showcase the consequences if attempts to initiate RES cooperation across the EU will not take place, meaning that RES investors in specifically southern European countries face a “High Country Risk”.

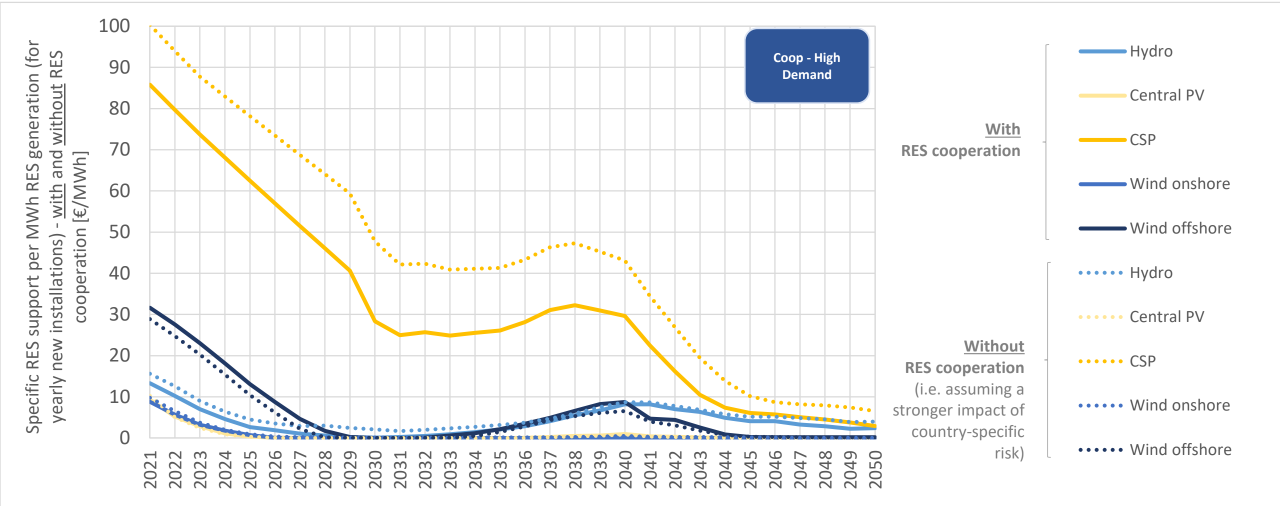

Figure 3: Development of the specific support per MWh RES generation up to 2050 on average at EU28 level according to selected assessed scenarios (“Cooperation – High Demand”, with and without RES cooperation (“High Country Risk”)) (Source: Green-X modelling)

Figure 3 shows how RES cooperation affects the need for dedicated support at technology level, here referring to the EU28 on average. More precisely, this graph indicates the future development of the specific support per MWh RES generation up to 2050 according to two variants of the “Cooperation – High Demand” scenario, i.e. the default case assuming RES cooperation and the sensitivity case assuming no RES cooperation and, in consequence, the influence of a (in some countries) “High Country Risk”. For CSP a strong impact of RES cooperation is getting apparent: In the absence of RES cooperation support when a “High Country Risk” is prevailing in many of the southern European host countries of expected future CSP developments a significantly higher specific support is required.

At the aggregated EU level for total RES one can also identify a clearly positive impact of RES cooperation, specifically of the levelling of country risk in financing, on RES-related support expenditures. More precisely, in the absence of levelling country risk in project financing across the EU support cost would increase 5-11 % at the aggregated EU level according to the scenarios assessed. This indicates that strong differences in financing conditions across EU countries as we still see them today are less preferential for the decarbonisation of the EU's electricity sector.

A (more) fair effort sharing can then be triggered by RES cooperation and the accompanying redistribution of support expenditures across countries, so that host countries do no longer have to pay the whole bill for the uptake of CSP and other comparatively costly RES technologies which are relevant for the achievement of decarbonisation aims and for supply security. That can be seen as crucial for countries like Cyprus, Portugal and Greece – all acting in the exemplified scenario as CSP hosts – but also for countries like Latvia and Estonia, acting as host for the wind uptake in the North of Europe.

1 Introduction

Energy and climate targets in the European Union (EU) comprise full climate-neutrality of all sectors by 2050 and a 40 % reduction of greenhouse gas emissions (GHG) by 2030 compared to 1990 levels (European Commission, 2020a, 2020b). As part of the European Green Deal, the Commission aims to propose raising the EU target to at least 50% and towards 55% in a responsible way (European Commission, 2019). Decarbonised electricity systems will need CO_2-free as well as dispatchable generation technologies to balance fluctuating generation patterns of high shares of wind and photovoltaics in the power system (Joos & Staffell, 2018). Concentrating Solar Power (CSP) is a solar electricity generation technology that is able to provide flexibility to the system due to the thermal energy storage system (TES) associated with it. In Europe, solar resource potentials are the richest in Southern countries which makes CSP a power technology suited for these countries. To make this potential available to other European countries as well and facilitate the achievement of overall EU targets, cooperation mechanisms can help. The MUSTEC project aims at analysing the role of renewable energies (RES) cooperation for an enhanced market uptake of CSP in Europe.

MUSTEC analyses the possible role of CSP in the future energy system, evaluating the factors driving or hindering CSP market uptake in the EU. Within this report, we present the model-based analysis of the market uptake of CSP in distinct scenarios evaluating different decarbonisation ambition levels, underlying RES policy concepts and pathways, infrastructural developments/prerequisites as well as development of other flexibility needs and options. As results, we find under which conditions and in which country CSP deployment takes place. Further, the implications for support policies for CSP are analysed as we show how different CO_2 price levels and country risk sharing impact the need for subsidies for CSP.

This report is the final outcome of the modelling activities within MUSTEC, building upon a range of previous analyses and tasks of this project. We especially build on the policy pathway conceptualisation where various promising pathways and opportunities as well as unsupportive policy developments for an enhanced uptake of CSP are defined for the EU as a whole and several Member States in detail (Lilliestam et al., 2019).

The findings of this report are based on comprehensive modelling activities using the two energy models Enertile (Fraunhofer ISI) and Green-X (TU Wien). A scenario-based assessment of prospects for the uptake of CSP within Europe is conducted from the integrated (top-down) perspective, indicating also how that can be facilitated by cross-border RES cooperation. This techno-economic policy analysis acts as key basis for our overall evaluation of prospects for CSP-tailored RES cooperation across the EU. It allows for identifying monetary savings associated with enhanced RES cooperation through CSP as well as resulting changes in costs, expenditures and benefits by region that come alongside the changes in installed RES capacities and generation across the assessed countries.

As outlined above, the scenario analysis builds on the policy pathway conceptualisation undertaken within WP7 of the MUSTEC project where dominant and minority pathways are defined under a more European or national energy policy orientation. We focus here on the role CSP can play within the necessary transformation of our energy system to combat climate change. Deep decarbonisation acts as the guiding principle that is taking up in modelling. In practical terms that implies specifically for the electricity sector to heavily rely on renewable energy sources, complemented by nuclear power within certain countries according to domestic preferences. A further implication of deep decarbonisation is a strong growth in electricity consumption where in addition to classical forms of electricity demand a strong growth is expected to come along with increased sector-coupling between the electricity and the transport sector as well as with heating and cooling, including building related as well as industry-related demands. Here the perception is followed that the electricity sector seems more prepared for a transformation towards carbon neutrality than others, cf. (European Commission, 2018) or (Crespo del Granado et. al., 2019)

A strong uptake of variable renewables like wind and solar power can consequently be expected in future years – but, according to our analyses, there are certain limits of growth that need to be respected, be it the availability of land, boundaries in social acceptance for the uptake of certain technologies and specifically the ability of the power system to cope with large shares of variable RES generation while safeguarding supply security and affordability. Here CSP may act as an option to add the necessary flexibility to the power system to achieve the necessary match between supply and demand – a key principle that needs to be respected in the power system during all and even short periods of operation. Thus, with our analyses we aim to identify the need for CSP in a deeply decarbonised European electricity system of the future, and we indicate how that may be facilitated through an enhanced use of cross-border RES cooperation.

1.1 Structure of this report

This report follows a classical structure. We start with an overview on the methods applied (chapter 2), introducing the policy pathways and scenarios assessed and the modelling system applied, and we inform on the assumptions taken in modelling.

Since our modelling involves two complementary energy system models that, albeit being closely linked in the modelling of future scenarios, take a distinct view on the future, we also distinguish in our result representation between two elements:

Chapter 3 is dedicated to discuss the results of the power system analysis where we identify the need for CSP in a decarbonised European electricity system in future. The results presented in this chapter origin from the Enertile model, a specialised energy system model that is used to analyse the interplay between supply, demand and storage in Europe's electricity sector at a high temporal resolution. Among others our results inform on how CSP may serve to provide some of the required system flexibility for the future EU power system that will last on high shares of variable renewables.

Complementary to above, chapter 4 is dedicated to discuss the results from the prospective energy policy analysis dedicated to CSP and other RES technologies, and on the role of RES cooperation to facilitate the RES uptake in forthcoming years. The main tool used for that purpose is the Green-X model, a specialised energy system model offering a sound coverage of support instruments for renewables as well as on the available resources and corresponding cost of individual RES technologies within Europe. Within this chapter we will inform on the dynamics of the RES uptake, the investments required and on corresponding policy cost, i.e. the expenditures that can be expected from dedicated support for CSP and other RES technologies. The analysis includes to shed light on the interplay between dedicated RES support instruments and the EU Emission Trading Scheme and the role of and need for RES cooperation.

This report concludes with a summary of key findings and lessons learned (chapter 5).

Remark: Please note that for increasing transparency in **the approach used and the underlying data and results, key modelling data is publicly available at https://zenodo.org/record/3905045**.

2 Method of Approach: Models and Assumptions

2.1 Incorporation of the policy pathways into the integrated modelling approach

One of the most important questions for CSP deployment is the market environment, electricity generation takes place in. These market conditions are determined by a broad range of factors like pricing mechanisms, development of different power technologies, and energy and climate policies. Within the MUSTEC project, WP7 collected and processed a broad range of policy pathways for renewables deployment and climate policy in the energy sector at the EU level and on the national level in Spain, Italy, France, and Germany. The identified policy pathways are classified into dominant pathways, describing the currently valid policy aims and measures, and minority pathways, which are the positions of parties currently not in government and may be picked up in case of future government changes. 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 presented in this report by defining central input parameters like electricity demand, renewable targets, decarbonisation levels and technology mix in future years (2030, 2050) in the different countries.

Table 1 provides an overview on the identified policy pathways from WP7. Complementary to that, Table 2 informs on how they are taken up within this integrated model-based assessment, from a work structure perspective part of WP8.

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. This world is represented by the EU dominant (market-centred) policy pathway as listed in Table 1.
- On the other hand, we model the four countries analysed in detail (i.e. France, Italy, Germany, and Spain) according to their own (dominant) preferences as stated in the 2030 National Energy and Climate Plans (NECPs), cf. the national dominant 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.

The EU dominant pathway was taken up in the cooperation scenario whereas the combination of the national dominant pathways forms the basis of the “National Preferences” scenario. In the “National Preferences” scenario, the renewable deployment in the rest of the EU28 countries has to be adapted to the national strategies of France, Germany, Spain and Italy so that the overall EU target is achieved. That means that if national ambitions in those countries are lower in the national preference scenario (e.g. in the case of France), RES deployment in other countries will be stronger than in the cooperation scenario so that the overall EU target is still achieved. As can be seen in Table 1, the “Grassroots” pathways which represent the policies with strongest climate ambitions were infeasible in the modelling process due to diffusion limits of RES technologies. That means that the development of renewables as it is foreseen in the grassroots pathways was not achievable with the RES diffusion rates of the Green-X model. The only pathway not taken up in the modelling was France’s “rassemblement national” pathway because of insufficient information and a lack of pendants in the other countries analysed in detail. Italy’s renewable electricity target for 2050 was not defined in the draft National Energy and Climate Plan 2030 (NECP) but was assumed as 100 % implicitly due to the overall decarbonisation needs.

The results presented in this report and in other modelling tasks of the MUSTEC project also were used and fed back to WP7 to derive policy implication with regard to CSP which are elaborated on in Schöniger et al. (2020).

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 for WP8. Renewable electricity (RES-E), RES, emissions trading scheme (ETS), and overall greenhouse gas (GHG) reduction targets. EU dominant pathways forms the basis of the "Cooperation" scenario, the combination of the national dominant pathways (FR, DE, IT + ES) the basis of the "National Preferences" scenario.*

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 dominant (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)
FRANCE						
France dominant (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 dominant paths of other countries and the (rest of) EU
France 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
France 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)
France 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
GERMANY						

Germany dominant (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 dominant paths of other countries and the (rest of) EU
Germany 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)
Germany 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
ITALY						
Italy dominant (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 dominant paths of other countries and the (rest of) EU
Italy 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 dominant path)
SPAIN						
Spain dominant (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 dominant paths of other countries and the (rest of) EU
Spain 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)
Spain 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.

Scenario	Acronym(s)	Characterisation	Policy pathway selection: Rest of EU	Germany	France	Italy	Spain
EU level							
Cooperation	Cooperation – High Demand (Coop HD)	Market-centred, aiming for full decarbonisation in a "least cost manner"	EU dominant	EU dominant	EU dominant	EU dominant	EU dominant
Grassroots	Grassroots	Grass-root centred across the EU, with accelerated full decarbonisation (2040), and with consideration of national preferences (Germany, France, Italy, Spain)	EU grassroots	Germany grassroots	France grassroots	Italy grassroots	Spain grassroots
National Preferences	National Preferences – High Demand (NatPref HD)	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 dominant	Germany dominant (state-centred)	France dominant (state-centred)	Italy dominant (market-centred)	Spain dominant (state-centred)
National Preferences, low demand	National Preferences – Low Demand (NatPref 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" (Germany, France, Italy, Spain)	EU dominant	Germany dominant (state-centred)	France dominant (state-centred)	Italy dominant (market-centred)	Spain dominant (state-centred)
National Preferences, with grid expansion restrictions	National Preferences – High Demand – Limited Grid (NatPref HD Limited Grid)	Market-centred, aiming for full decarbonisation in a "least cost manner". Grid expansion faces difficulties across the EU due to low public acceptance	EU dominant	Germany dominant (state-centred)	France dominant (state-centred)	Italy dominant (market-centred)	Spain dominant (state-centred)

Cooperation, low demand	Cooperation – Low Demand (Coop 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" (Germany, France, Italy, Spain)	EU dominant	EU dominant	EU dominant	EU dominant	EU dominant
Cooperation, deep but not full decarbonisation	Cooperation – High Demand – Low Climate Ambition (Coop HD Low Climate Ambition)	Market-centred, aiming for a deep but not full decarbonisation, done in a "least cost manner" (implies less emphasis on RES-E)	EU dominant	Germany market-centred (with low decarb targets)	France market-centred (with low decarb targets)	EU dominant	Spain market-centred (with low decarb targets)
Cooperation, with low flexibility from sector coupling	Cooperation – High Demand – Low Flexibility (Coop HD Low Flexibility)	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 dominant	EU dominant	EU dominant	EU dominant	EU dominant
Cooperation, with grid expansion restrictions	Cooperation – High Demand – Limited Grid (Coop HD Limited Grid)	Market-centred, aiming for full decarbonisation in a "least cost manner". Grid expansion faces difficulties across the EU due to low public acceptance	EU dominant	EU dominant	EU dominant	EU dominant	EU dominant

Please note that, complementary to the scenarios listed in Table 2 which were generally consistently incorporated into both parts of the model-based assessment – i.e. the power system analysis (cf. section 3) and the energy policy analysis (cf. section 4) – accompanying sensitivity cases have been assessed to shed light on specific aspects of the energy policy debate. These accompanying cases, representing variants to the main types of scenarios listed above, are introduced at the corresponding subsections of the energy policy analysis (cf. section 4.4 and 4.5).

2.2 Modelling framework

The MUSTEC modelling system

The modelling works within this task of MUSTEC have been conducted using two distinct energy system models in an integrated manner 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:** the energy system model, serving to shed light on the interplay between electricity supply, storage and demand in the EU electricity market.

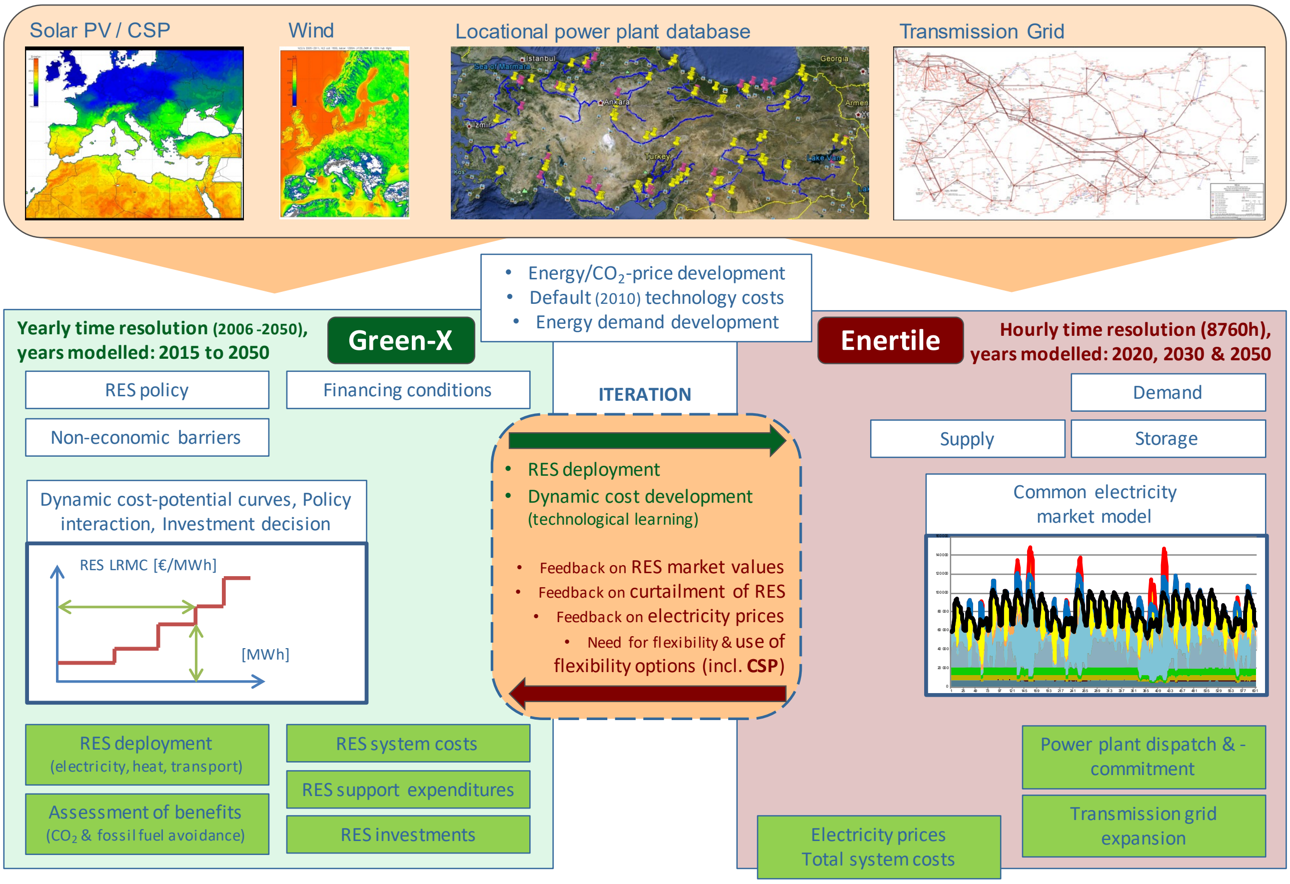

Figure 4: Interplay of Green-X and Enertile

[1] For detailed model descriptions, cf. Appendix. The model Balmorel was also used in the MUSTEC project - cf. Schöniger & Resch (2019) and Schöniger et al. (2020) – but not within the modelling activities for this report.

Green-X analyses the renewable energy (RES) investments, RES diffusion rates, and related impacts on costs, expenditures and benefits for the energy system. Enertile simulates the hourly dispatch of all components of the electricity system: supply, storage and demand in the electricity market. The covered geographic area is EU28[2] for the years 2030, 2040, and 2050. Moreover, Enertile is also used within this integrated assessment to identify the gap in power system flexibility that can economically best be filled by CSP (in conjunction with internal thermal storage) under the given system boundaries like heading towards carbon neutrality by 2050.

The combination of both models allows to make use of each model's particular strength:

- On the one hand, Green-X is well suitable to analyse the economic feasibility and prospects of future RES deployment in a dynamic context. Here policy impacts are well incorporated and diffusion limits of individual RES technologies serve to derive a realistic picture of the feasible RES uptake over time.
- On the other hand, Enertile allows for a detailed analysis of the power system for certain points in time (i.e. 2030, 2040, 2050), shedding light on the interplay between demand, supply and storage at a high timely and geographical granularity that also reflects infrastructural constraints concerning cross-border transmission of electricity.

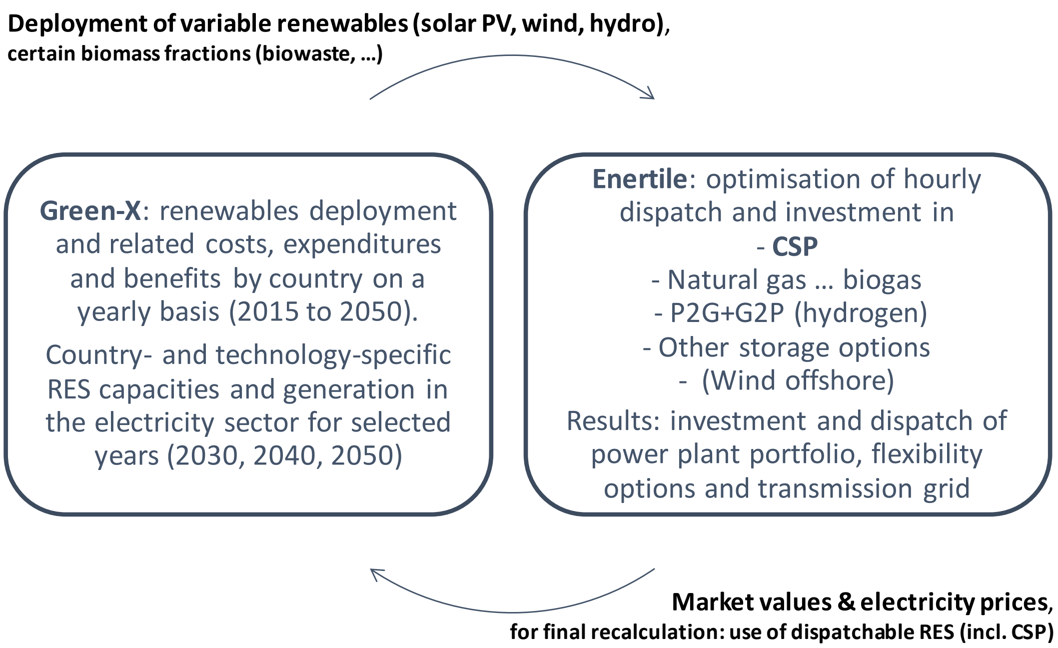

Figure 5: Iteration process between Green-X and Enertile

[2] Enertile additionally covered Norway and Switzerland within the power system analysis to account for cross-border flows and interactions with the local electricity markets within these two countries that are well interconnected with the EU electricity market.

The overall modelling of future RES developments in the EU and its neighbours is done for all energy sectors (i.e. electricity, heating & cooling, and biofuels in transport) by Green-X, whereas our detailed assessment of enhanced cross-border RES cooperation through the use of CSP is limited to the electricity sector.

Complementary to this and specifically for the electricity sector, grid and transmission needs or constraints, respectively, together with the physical integration possibilities are evaluated from a technical perspective in a power system analysis, done by use of Fraunhofer ISI's Enertile model. The output of Enertile is then be fed back into the RES investment model Green-X. In particular, the feedback comprises the amount of RES that can be integrated into the grids, the electricity prices and corresponding market revenues (i.e. market values of the produced electricity of variable and dispatchable RES-E) of all assessed RES-E technologies for each assessed country.

The iteration process between Green-X and Enertile is the following for each scenario:

1. **Green-X** calculates **default (variable) RES use**[3] *(iteration 0)*
2. **Enertile** calculates **optimal dispatch & investment in certain flex options** (CSP, Natural gas/biogas[4], P2G+G2P, other storage options) *(iteration 0)*
3. **Green-X** recalculates **(variable) RES use** based on adapted market values and electricity prices *(iteration 1)*
4. **Enertile** recalculates **dispatch & investments in certain flex options** (iteration 1)
5. **Green-X** recalculates **RES costs & support expenditures** (incorporating market values, electricity prices, dispatchable RES use) *(iteration 2)*

2.3 Scenarios and key assumptions

2.3.1 Cooperation vs. National Preferences

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 (for all countries together). In contrast, the scenario setting named "National Preferences" represents the dominant policy paths: in these, renewables are deployed and climate targets met in the way envisioned 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. That means that if national ambitions in those countries are lower in the

[3] Based on policy pathways (WP7) – see (Lilliestam et al., 2019).

[4] Assumption in case of full decarbonisation: natural gas is replaced by green gas/biogas until 2050 (at a higher price than natural gas).

"National Preferences" scenario (e.g. in the case of France), RES deployment in other countries will be stronger than in the "Cooperation" scenario so that the overall EU target is still achieved

2.3.2 Electricity demand

In order to cover the effect of overall electricity demand levels, we compare two scenarios with high respectively low electricity demand.

High 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. The gross electricity demand was taken from the SET-Nav "Diversification" scenario for all countries.

Low Demand: For those countries where a detailed energy policy pathway analysis has been conducted within WP7 of the MUSTEC project, i.e. namely the in terms of population and size large EU member states Germany, France, Italy and Spain, gross electricity consumption projections were taken from their draft NECPs whenever these countries provided them.[5] [6] For the remainder of countries electricity demand projections are kept identical to the "High Demand" scenario.

For the year 2050, this results at EU28 level in a gross electricity consumption of 5816 to 6069 TWh in the "High Demand" scenarios and 4634 to 4672 TWh in the "Low Demand" scenarios.

2.3.3 Decarbonisation ambition

As default we take the assumption that a full decarbonisation of the energy system – zero CO_2 emissions –, and in particular of the power system is achieved until 2050 at EU level. In general terms, this has strong implications on future technology choices (e.g. fossil CCS is no viable generation option in the power sector, as it is not fully zero-carbon) 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 (75, 125 and 500 $€_{2010}$/t CO_2 for the years 2030, 2040 and 2050).

Complementary to that, in a sensitivity analysis we assess the impact of a lower climate ambition in a sensitivity analysis, assuming only a GHG reduction of 91% in the electricity sector until 2050 compared to 1990 levels instead of full decarbonisation (25, 75 and 225 $€_{2010}$/t CO_2 for the years 2030, 2040 and 2050).

[5] If there was no explicit demand projection available, expectations on future electricity demand are taken from the EU reference 2016 scenario (EC, 2016) as derived by PRIMES modelling (adapted for the increased 32.5 % energy efficiency target) to ensure maximum consistency with corresponding EU scenarios and projections.

[6] For the year 2050, Germany provided a gross electricity consumption of 464.3 TWh excluding new demand from sector coupling. This new demand from sector coupling for Germany was taken from the SET-Nav "Diversification" pathway (SET-Nav, 2019).

2.3.4 (Fossil) Fuel price trends

Fossil fuel price trends as illustrated in are taken from IEA modelling, specifically the IEA's 450 scenario (IEA WEO 2016). These trends reflect a strong climate ambition globally. Please note that these price trends are significantly lower than the assumptions taken by the European Commission in the latest EU reference scenario: if one compares the price of oil, on average 40% lower prices are expected for the forthcoming decades. For natural gas the difference in price trend assumptions is smaller but still amounts to ca. 25% (i.e. 25% lower than in EC recommendations).

Table 3: Fossil fuel price trends (Source: IEA, 2016)

Fuel prices in $€_{2010}$/MWhth	gas	hard-coal	oil	lignite	nuclear
2030	28.9	7.4	48.4	3.7	3.1
2040	30.5	6.6	44.5	3.7	3.1
2050	31.2	6.2	42.5	3.7	3.1

Please note that in accordance with the guiding principle to head towards carbon neutrality, natural gas is expected to be replaced by renewable gas by 2050. For this decarbonisation option price trends as illustrated in Figure 6 are assumed, reflecting first lessons learned from demo projects in the Netherlands and expert judgements concerning expected future progress.

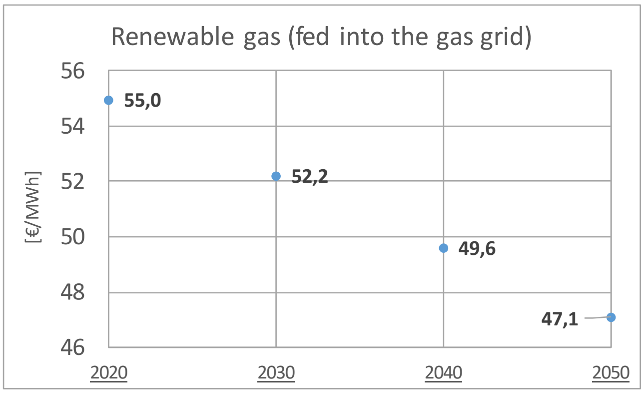

Figure 6: Assumptions on fuel price trends for renewable gas (used in Enertile modelling) (Source: own assessment)

2.3.5 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 two scenarios with grid limitations assume limitations in transmission grid expansion in order to evaluate this effect on CSP deployment.

2.3.6 Cost assumptions for RES technologies

For the CSP plants, an 11 hours thermal storage system and a site -specific ratio between field and generator is assumed. Investment costs for 2030, 2040 and 2050 are the average estimations of de Vita et al. (2018), ESTELA (2019), Zickfeld et al. (2012) and SET-Nav (2019) adapted for an 11 hours storage CSP plant. For validation, these cost trends were compared to current project costs (CSP.guru, 2019; Lilliestam, Ollier, Labordena, Pfenninger, & Thonig, 2020). Fixed operation & maintenance (O&M) costs are derived from a comprehensive literature collection of Schöniger, Thonig, Resch & Lilliestam (2019). Variable O&M costs are the average of de Vita (2018) and ESTELA (2019).

Table 4: 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%

For other RES technologies Figure 7 informs on the assumptions taken in modelling. More precisely, expected cost trends for RES technologies stem from Green-X modelling.

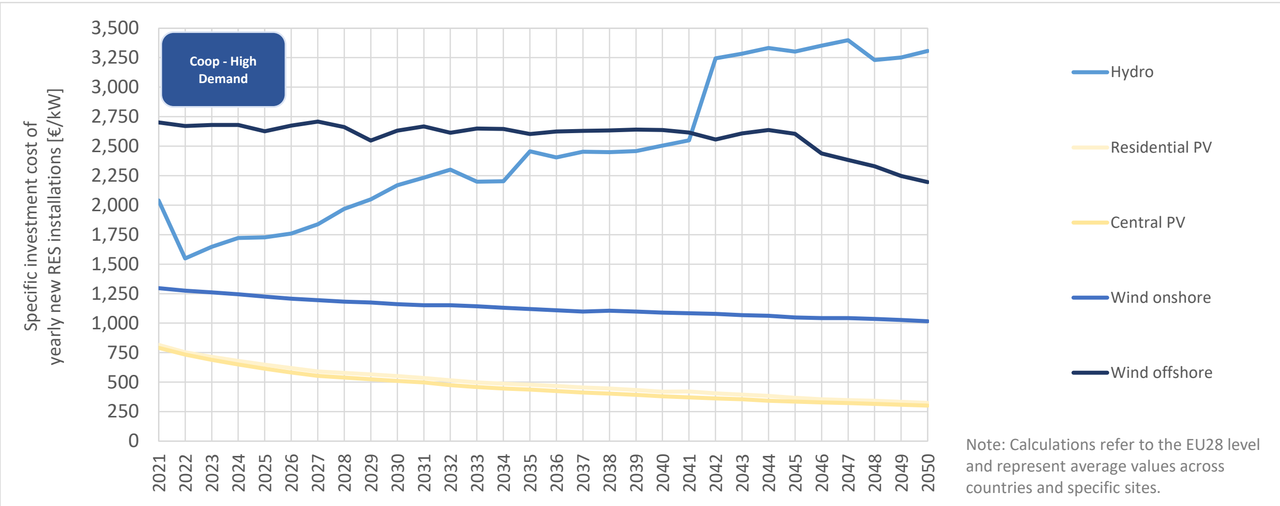

Figure 7: Development of specific investment cost of selected key RES technologies at EU28 level, exemplified for the "Cooperation – High Demand" scenario

The exemplified trends in investment cost refer to a specific scenario (i.e. the "Cooperation – High Demand" scenario) and showcase the specific investment cost for a new RES installation on average at EU28 level in a given year. As applicable from this graph, strong cost reductions are expected for key RES technologies like solar PV and wind. For hydropower the opposite trend is observable: on average at EU28 level specific investment cost are expected to increase in future years since the available future potential is comparatively limited, specifically for large-scale projects. Consequently, a tendency to invest in small-scale installations is presumed for this technology.

The general approach and the assumptions used in Green-X modelling on technology learning and corresponding cost reductions of RES technologies are briefly described in Box 1 below.

Box 1: Approach and assumptions used in Green-X on modelling technological learning of energy technologies

Thus, for most RES-E technologies, the future development of investment cost is based on technological learning. Two key parameters determine the development of investment cost of a certain RES technology: the deployment & the learning rate.

Assumptions on future RES deployment:
As learning is generally taking place on the international level (i.e. presuming a global learning system) the deployment of a technology on the global market must be considered. For the model runs, global RES deployment consists of the following components:

- *Deployment within the EU 28 Member States is endogenously determined, i.e. is derived from the model.*
- *Expected developments in the "rest of the world" are based on forecasts as presented in the IEA World Energy Outlook 2018 (IEA, 2018). For the analysis performed within MUSTEC we make use of the IEA New Policies scenario and the technology-specific global deployment indicated therein.*

Assumptions on learning rates:
Complementary to future RES deployment, assumptions on future learning rates for key RES technologies (apart from CSP as discussed above) are taken from corresponding recent topical studies and are as follows:

- *PV (central and residential): 20%*
- *Wind (on- and offshore): 7%*
- *Hydropower: zero – i.e. no future cost reductions are expected for this mature technology*

2.3.7 Data availability

For increasing transparency in the approach used and the underlying data and results, key modelling data is publicly available at **https://zenodo.org/record/3905045**.

3 RESULTS FROM THE POWER SYSTEM ANALYSIS – IDENTIFYING THE NEED FOR CSP IN A DECARBONISED EUROPEAN ELECTRICITY SYSTEM

This chapter presents the modelling results on the European electricity supply in the various scenarios introduced in the previous section. These results were obtained with the Enertile energy system optimization model, integrated in a modelling system with the Green-X model through multiple iterations.

In the first section we will discuss and compare the model results of the two main pathways in their default configuration (with high electricity demand). Subsequently, we will analyse the impact, especially on CSP, of varying certain assumptions like electricity demand or grid expansion.

Before discussing the results of the power system analysis in detail, it has to be noted that, as outlined under the modelling framework (cf. section 2.2), a large part of the generated electricity is already determined by the Green-X model and is given as a restriction to the system optimization within the Enertile model. This holds for the amount of electricity generated per country from the following technologies: wind (onshore and offshore), PV (rooftop and utility scale), hydro, geothermal, and certain fraction of biomass[7]. Due to this approach, the competition between CSP and other renewables (especially utility scale PV that would probably be installed on areas that are also suitable for CSP) is not fully covered. Furthermore, nuclear power generation is prescribed in order to depict the policy preferences and the corresponding pathways shown in section 2.1.

The electricity demand side is also largely determined by the general assumptions taken as prescribed in section 2.3.2. The total final electricity demand (including sector coupling, i.e. use of electricity for hydrogen production, heat supply, and electromobility) per country is given as a restriction to Enertile. Nevertheless, the electricity demand resulting from the system optimization in Enertile may be higher due to additional hydrogen production for re-electrification, a different choice of technology for the heat supply in heat grids, higher curtailment, and transport losses (factors being subject to the system optimization).

This modelling approach means that there remains only a certain fraction of the total electricity supply that can be optimized within Enertile. In the following, we will call this amount of electricity the “gap”. This gap between the actual total electricity demand and the prescribed generation can be filled with electricity from CSP, fossil fuels (taking into regard the assumed CO_2 price) and biogas (and, but only in one sensitivity scenario, additional offshore wind). Because of its importance for the interpretation of the model results, we will discuss the gap together with the results.

[7] In the case of biomass, only the amount of electricity generated from biowaste (but not biogas and solid biomass) in the Green-X model was prescribed as biomass in Enertile. This was because Enertile had the option to freely optimize the capacity and use of gas power plants using a certain share of biogas (0.5 % in 2030, 25 % in 2040 and 100 % in 2050).

The installed capacity of the technologies with prescribed generation follows directly from the underlying generation profiles in Enertile, while for the other technologies it can be optimized by the model.

Finally, it also has to be noted that the potentials of CSP (the maximum installable capacity and generation per country) used for the MUSTEC scenario calculations are based on relatively high land use factors (see model description in Section 6.1). This choice was made in order to obtain clearer results when studying the impact of various factors on the development of CSP. However, this also means that the total amount of electricity from CSP may be considerably smaller when assuming a lower availability of land.

3.1 "Cooperation" vs. "National Preferences"

In the following section, we focus on the two main scenarios "Cooperation (Coop) - High Demand" and "National Preferences (NatPref) - High Demand". We discuss the mix of generated electricity and installed capacity, the underlying electricity grid, the hourly dispatch, and the usage of renewable energy potentials. Where not otherwise stated, results refer to the sum of the EU28 countries and the year 2050. For a detailed overview of the scenarios modelled, please see Table 2.

3.1.1 Generated electricity

The development of the European supply mix of generated electricity for the two main pathways is shown in Figure 8. The underlying electricity demand stays the same for the two scenarios. From the figure it becomes obvious that wind power is the most important technology in the electricity supply. The amount of wind power in the "Cooperation - High Demand" scenario for 2050 reaches 2,412 TWh onshore and 1,381 TWh offshore. In the "National Preferences" scenario, the share of wind power is 2,387 TWh onshore and 1,109 TWh offshore.

Solar power is the most important energy source after wind. For ground-mounted PV, the amount of electricity generation reaches 642 TWh in 2050 for the "Cooperation" scenario and 603 TWh for the "National Preferences" scenario. In 2050, the electricity generation from rooftop PV is 744 TWh in the "Cooperation" scenario and 733 TWh in the "National Preferences" scenario. With regard to CSP, the proportion increases from 0 TWh in 2030[8] in both scenarios to 298 TWh in the "Cooperation" scenario and 254 TWh in the "National Preferences" scenario. The electricity generation of CSP per country is shown in Section 3.2.5.

[8] The modelled CSP generation may be zero, because RES installations existing today were not included in Enertile and no restrictions concerning CSP were made in the scenario calculations. Hence, CSP generation may be underestimated in countries with already existing installations, especially in the years 2030 and 2040.

In the “Cooperation - High Demand” scenario, the nuclear power generation declines from 219 TWh in 2030 to 29 TWh in 2050. However, the nuclear power generation remains relatively unchanged for the “National Preferences” scenario. Here the amount of nuclear power generation is 509 TWh in 2030 and 474 TWh in 2050. This is mainly due to the prescription that France has to cover 50 % of its electricity demand in 2050 with nuclear power.

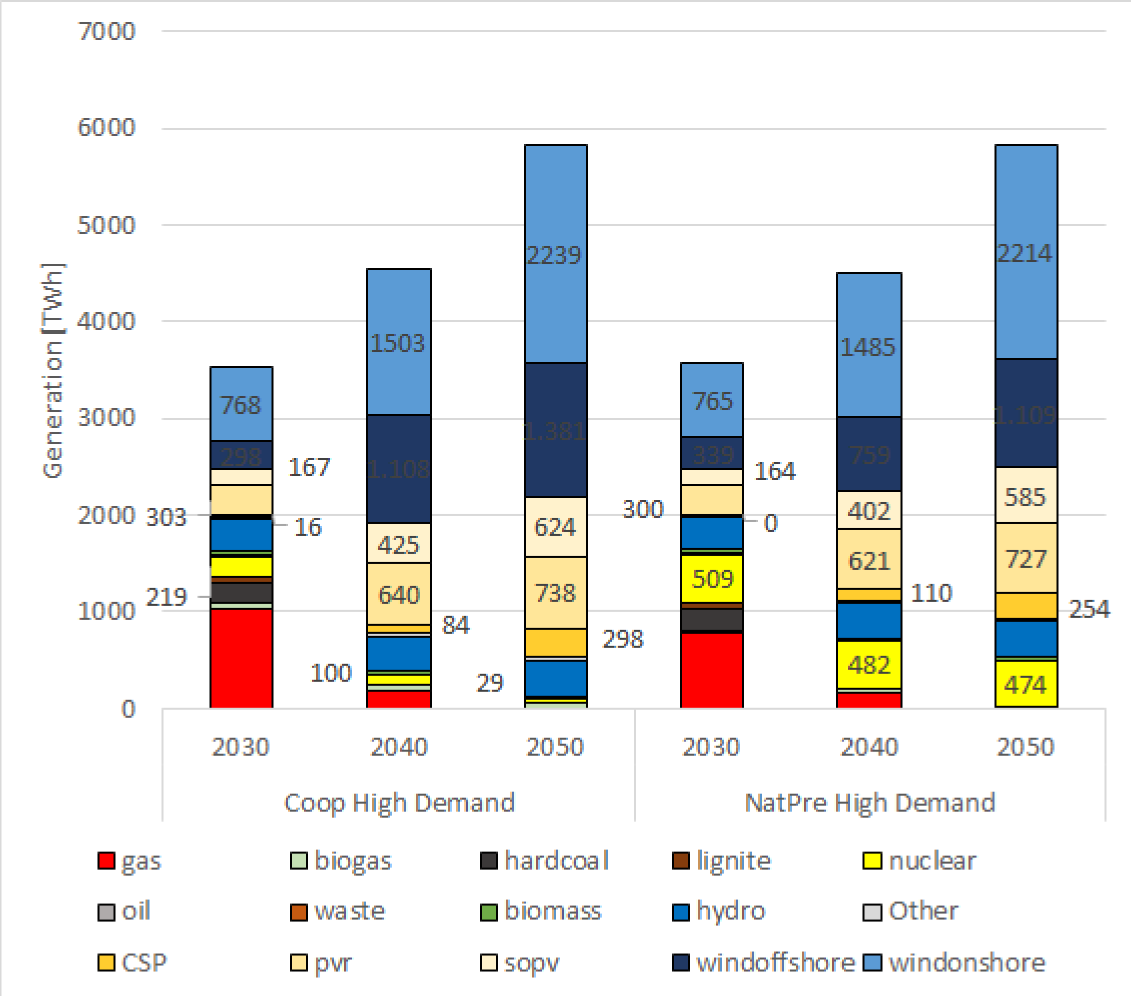

Figure 8: Evolution of the European electricity supply mix in the “Cooperation (Coop) - High Demand” and “National Preferences (NatPref) - High Demand” scenarios (other = geothermal, pvr = rooftop PV, sopv = utility scale PV)

Figure 9 shows the remaining generation gap which Enertile can freely optimize. In the “Cooperation - High Demand” scenario, the generation gap is 365 TWh. The generation of electricity by gas respectively biogas power plants is 18 %. CSP has a share of 81 %. The generation of electricity by CSP power plants in Spain reaches 138 TWh, 94 TWh in Italy and 66 TWh in other countries. In the “National Preferences - High Demand” scenario, the remaining gap diminishes to 280 TWh. In this pathway, nuclear power plants are enabled, which results in a smaller generation gap. The share of gas respectively biogas power plants declines to 9 % whereas the share of CSP reaches 91 %. Here, the CSP generation gap increases in Spain to 170 TWh, whereas in Italy the generation gap decreases to 81 TWh.

This finding (that the share of biogas in the generation gap is lower in the “National Preferences” scenario while the share of CSP is higher) may be explained by the fact that the substantial nuclear power generation in this scenario reduces the capacity of fluctuating renewables. Therefore, the need for balancing them via the fully dispatchable biogas plants also decreases in this scenario.

Overall, the system optimization in Enertile chooses much more CSP than biogas plants to fill the generation gap. Nevertheless, this result is strongly dependent on the cost assumptions used in the scenario calculations.

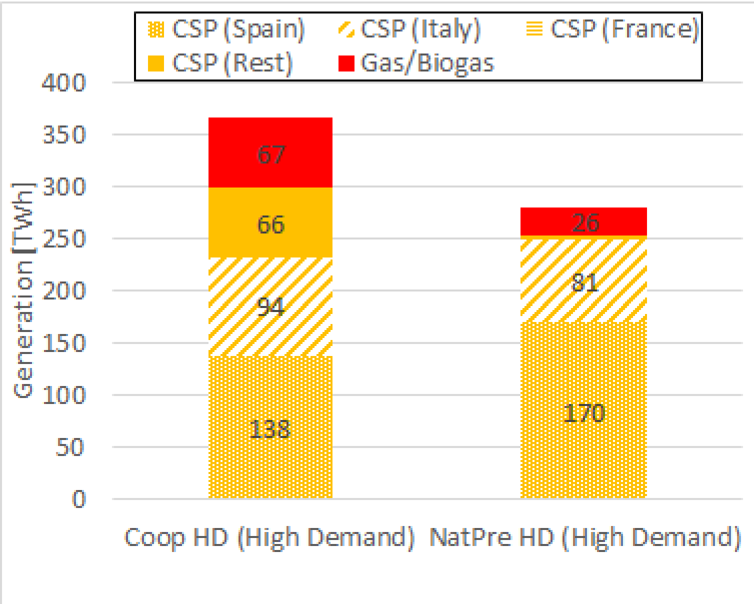

Figure 9: Generation gap, i.e. remaining amount of electricity for which the Enertile model can choose the supply technology (for EU28 in 2050) for the scenarios “Cooperation – High Demand” and “National Preferences – High Demand”. For the rest of the supply, the electricity generated per technology is determined by the Green-X model and given as a restriction to Enertile.

3.1.2 Installed capacity

The capacities of the power plant park in Europe for the years 2030, 2040 and 2050 are shown in Figure 10. The total capacities for the “Cooperation - High Demand” scenario increase from roughly 1,200 GW in 2030 to 2,700 GW in 2050. In the “National Preferences” scenario, the amount of installed capacity is 1,300 GW in 2030 and 2,600 GW in 2050. Therefore, roughly 1,500 GW power plant capacities are installed in 20 years.

In the two pathways, wind and solar power have the highest installed capacities, where solar capacities outnumber the installed wind power capacities by roughly 200 GW. However, the full load hours of wind power (about 3,000 hours/year onshore and 4,000 hours/year offshore) are higher than the full load hours of solar capacities (1,100 hours/year ground-mounted solar, 1,000 hours/year rooftop PV and 3,500 hours/year CSP). Therefore, the generated wind power is 2 to 3 times higher than the generated solar power.

The full load hours for biogas-fired power plants in 2050 are 630 hours/year for the "Cooperation" scenario and 380 hours/year for the "National Preferences". In this scenario, the capacity of nuclear power plants is 73 GW whereas in the "Cooperation" scenario the capacity reaches roughly 4 GW. As gas functions mainly as a balancing tool in the electricity system with a high share of volatile renewable energies, the installed capacities and full load hours are low.

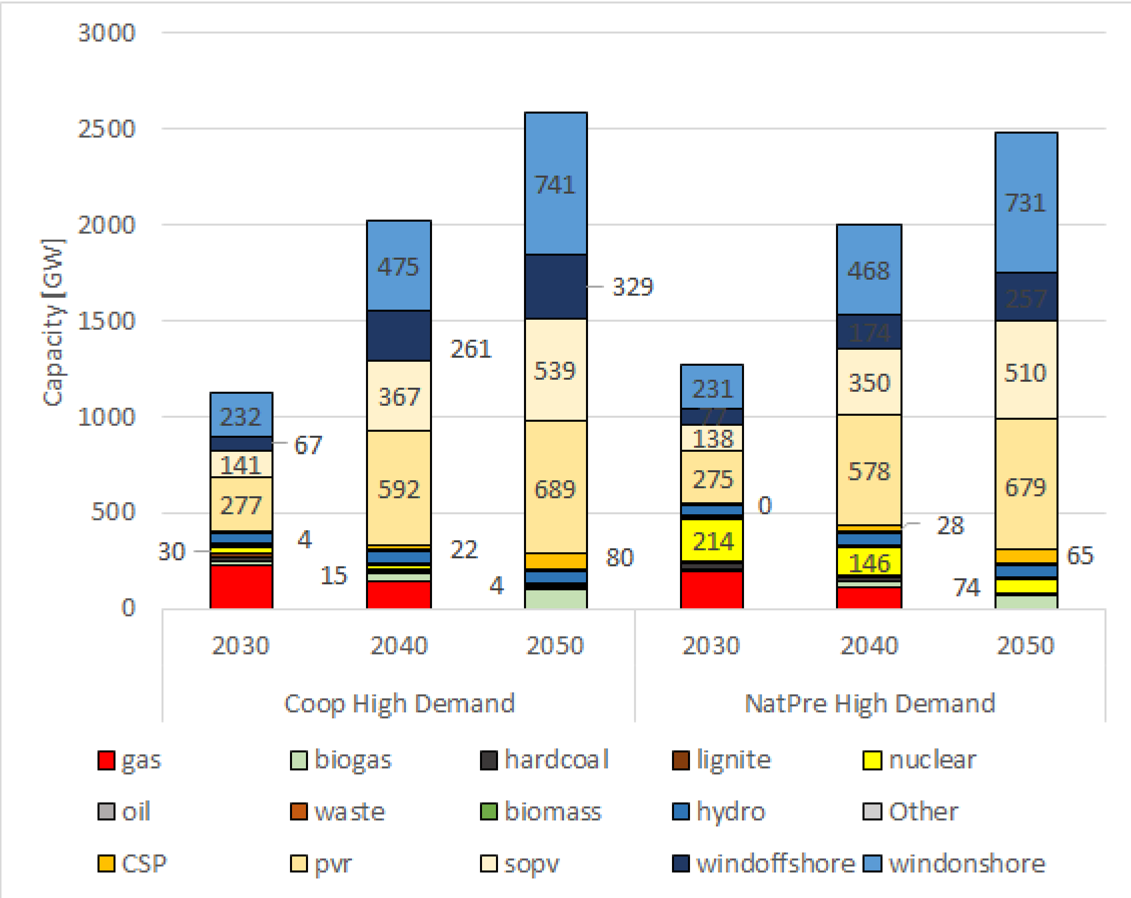

Figure 10: Evolution of the electricity generation capacity installed in Europe in the "Cooperation - High Demand" and "National Preferences - High Demand" scenarios (other = geothermal, pvr = rooftop PV, sopv = utility scale PV)

3.1.3 Electricity grids and trading

In this section, we show the trading volume and interconnector capacity for the two main scenarios. The electricity grid represents a flexibility option that can compensate the volatility of renewable energy generation. Since the modelling approach within the MUSTEC project does not include detailed electricity grid models, the interconnector capacities assumed in the various MUSTEC scenarios are taken from the Horizon 2020 project “SET-Nav” (Sensfuß et al., 2019), for which detailed grid modelling was performed.

The default grid (used for most of the scenarios discussed in this report) is based on the optimization result of the SET-Nav “Diversification” pathway and represents an almost unlimited grid expansion scenario. The lower limit of the cross-border grid capacities was set to the 2018 edition of the Ten Year Network Development Plan (TYNDP) of ENTSO-E for the transmission grid in 2030, but the optimization in Enertile within the SET-Nav scenario calculations resulted in much higher capacities for almost all interconnectors (see Figure 11).

In the context of electricity trading it is important to note that the Enertile model in its used configuration does not allow trading of hydrogen between countries. Therefore, hydrogen for the use in the power sector and in other sectors (industry, mobility, heat) has to be produced by every single country on its own. This setup also prevents outcomes like a centralised hydrogen production based on a strong expansion of certain renewable technologies (e.g. CSP) in countries having very good potentials. Hence, in the Enertile model, renewable electricity exceeding the domestic demand can only be exported via the power grid, making this grid an even more important factor for the development of renewables (see results of scenario with limited grid in Section 3.2.1).

Figure 11 shows a map with the cross-border transmission grid capacities in Europe for the scenarios without grid restrictions for the year 2050. The grid connection of France and Spain has the highest capacity with 40 GW. This is a result from the system optimization explained above, but still far away from the current state and even from current extension plans. In these pathways, other strong interconnections (in the order of their capacity) are Germany-Poland, France-Germany, Germany-Denmark, Poland-Lithuania, France-United Kingdom, France-Italy, and Norway-Sweden. This pathway without grid restrictions shows that the model tries to strengthen the connection North to South and East to West. The stronger the interconnections, the higher the flexibility of the grid.

Figure 11: Highly developed standard network in 2050 [in GW]

Figure 12 shows the trading capacity for the "Cooperation - High Demand" and the "National Preferences - High Demand" scenarios. The electricity grid of these two pathways is identical and represents all other pathways (except those with limited grid discussed in Section 3.2.1). The trading capacity in Europe is 425 GW in 2030 and doubles to 850 GW in 2050 for the scenarios with strong grid expansion.

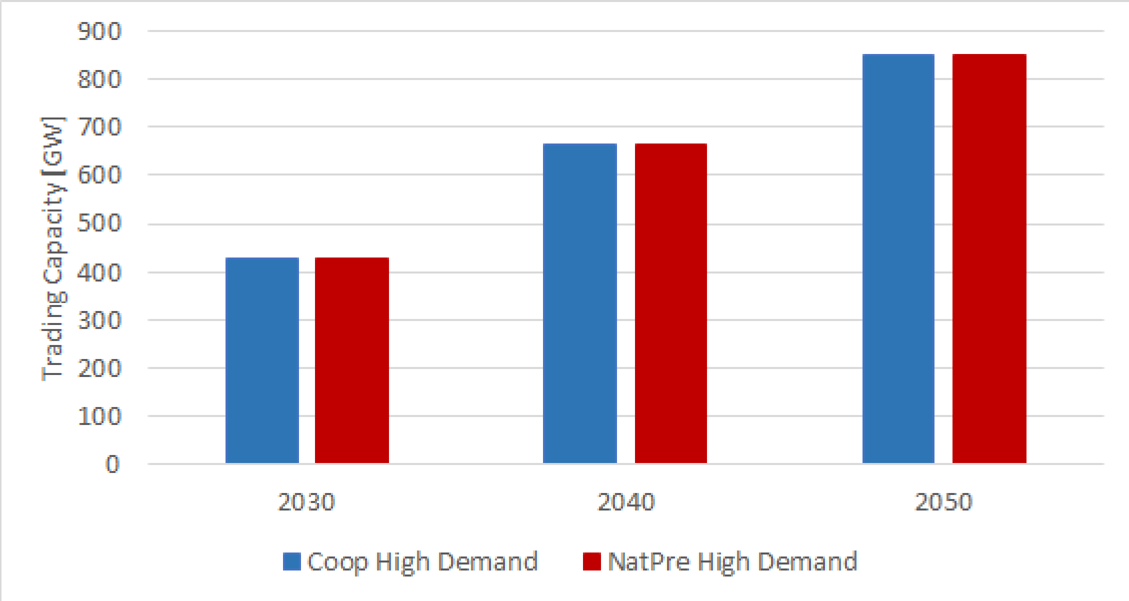

Figure 12: Trading capacity in GW for the "High Demand" scenarios. Capacities for the scenarios "Cooperation" and "National Preferences" are the same.

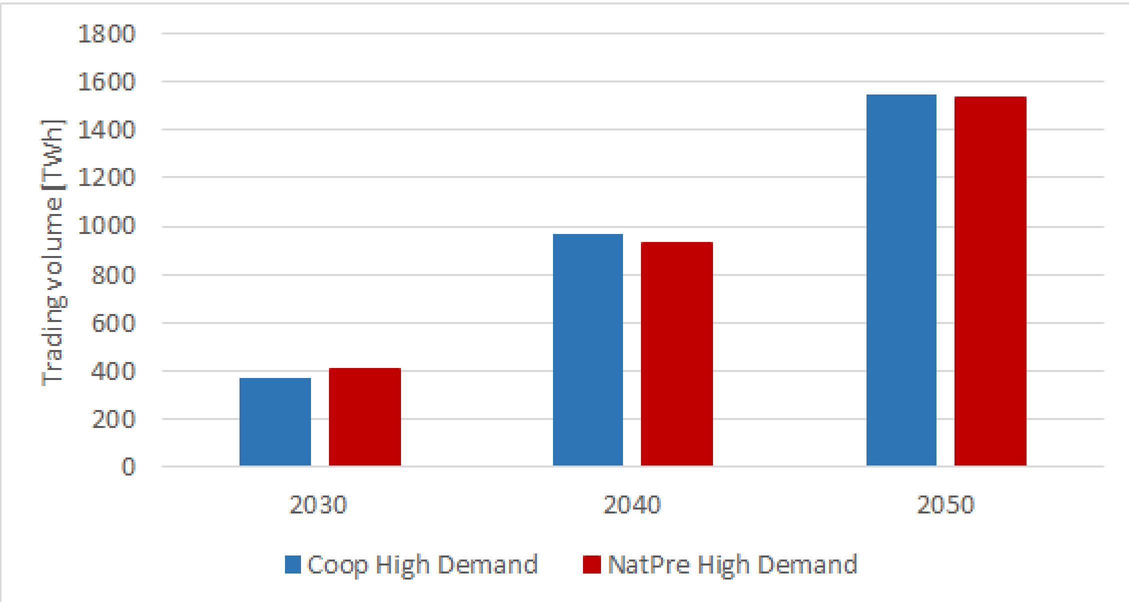

Figure 13: Trading volume in TWh for the "Cooperation - High Demand" and "National Preferences - High Demand"

In Figure 13, the trading volume for the two main scenarios is shown. As shown in Figure 12, the trading capacities of these scenarios are the same. Therefore, the trading volume differs only slightly. In 2030, the trading volume is 474 TWh in the "Cooperation - High Demand" scenario and 502 TWh for the "National Preferences - High Demand" scenario. The trading volume increases in the course of the years and reaches 1,829 TWh for the “Cooperation - High Demand” scenario in 2050. In the “National Preferences” scenario, the trading volume in 2050 is 1,826 TWh.

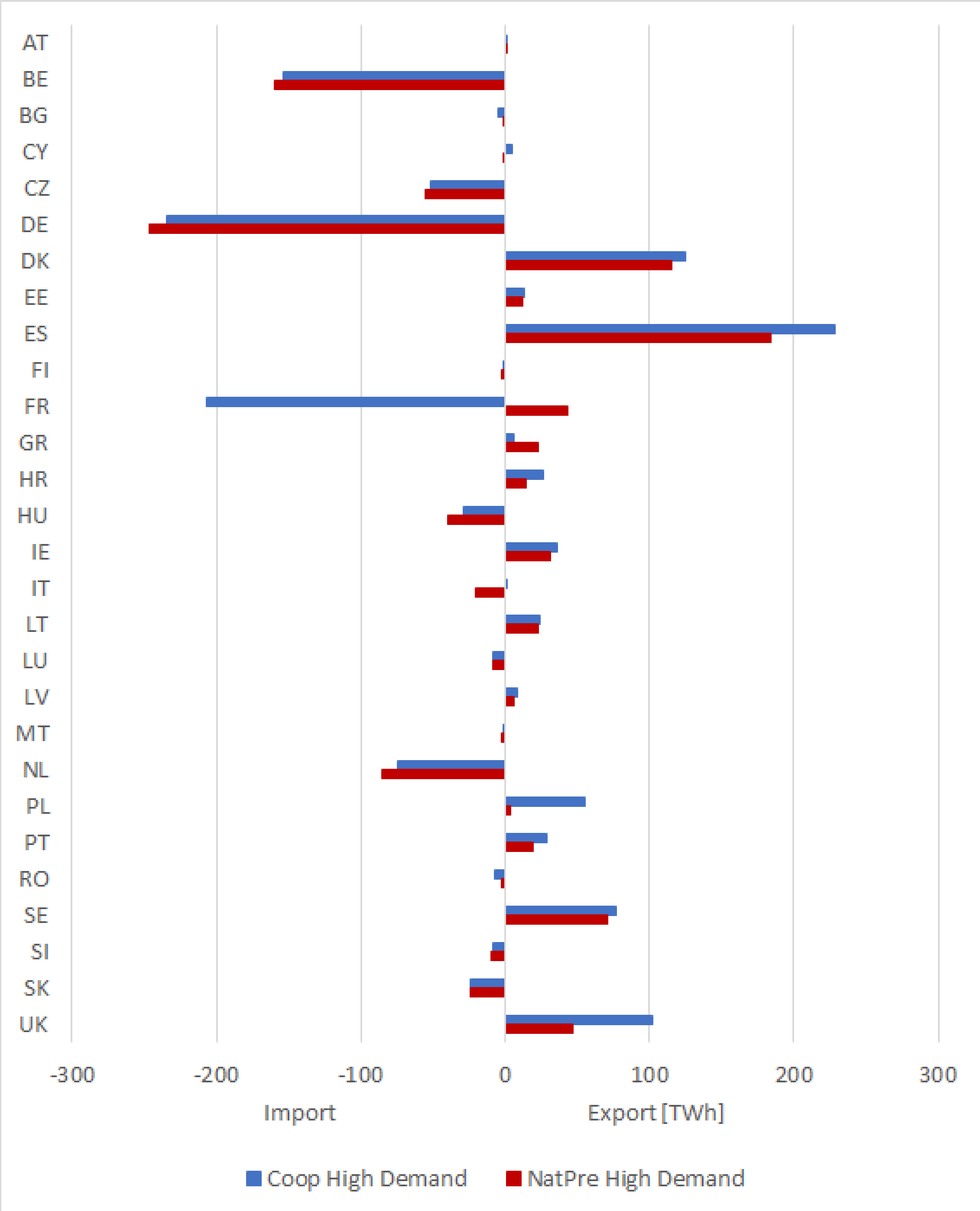

Figure 14: Net import/export in TWh for each EU-country for the two main scenarios

In Figure 14, the trading balance (net import/export) of electricity for each European country is shown for the two main scenarios. A negative trading balance indicates that the country is a net importer of electricity. For the “Cooperation – High Demand” scenario, the Netherlands, France, Germany, and Belgium are importing electricity of roughly 100 TWh to almost 250 TWh. In the “National Preferences – High Demand” scenario France becomes a net exporter of electricity mainly due to the much higher production of nuclear power. Spain with its high CSP generation is the most important exporting country in these scenarios. In addition, other CSP producing countries like Portugal and Greece show a positive trading balance, while Italy does not export a relevant amount of electricity.

3.1.4 Hourly dispatch

After having discussed results that were averaged over complete years, we will now look at the electricity dispatch on the hourly level for exemplary time periods. We selected one week in January and one week in June, for which the dispatch in the energy system of Spain and Italy (the most relevant countries for CSP) and France in the year 2050 is shown in Figure 15 to Figure 20. The figures show the hourly dispatch for the “Cooperation - High Demand” and the “National Preferences - High Demand” scenarios.

In the shown winter week, wind power generation is relatively high in Spain, so that the renewable electricity supply exceeds the demand for most of the time for both considered scenarios. This leads to high export and intensive hydrogen production, but also to some curtailment in hours with high wind and PV generation. CSP is mainly used to generate power before and after the PV peak, sometimes during the whole night. The picture is similar for both pathways, but less pronounced in the “National Preferences - High Demand” scenario due to lower wind and PV capacities. The same week in Italy looks considerably different. Here, the demand is higher and the renewable electricity generation lower than in Spain, resulting in extended periods of electricity import. Unlike in Spain and Italy, the hourly dispatch of the winter week in France results in two significantly different figures for the “Cooperation - High Demand” and “National Preferences – High Demand” scenarios. This is due to the high amount of nuclear power generation in France in the “National Preferences” scenario. In the “Cooperation - High Demand” scenario, the lack of wind and solar power generation leads to a high amount of imported electricity. However, in the “National Preferences” scenario, the low amount of solar and wind power generation is compensated by the base load generated by nuclear power plants. Therefore, the amount of imported electricity decreases significantly.

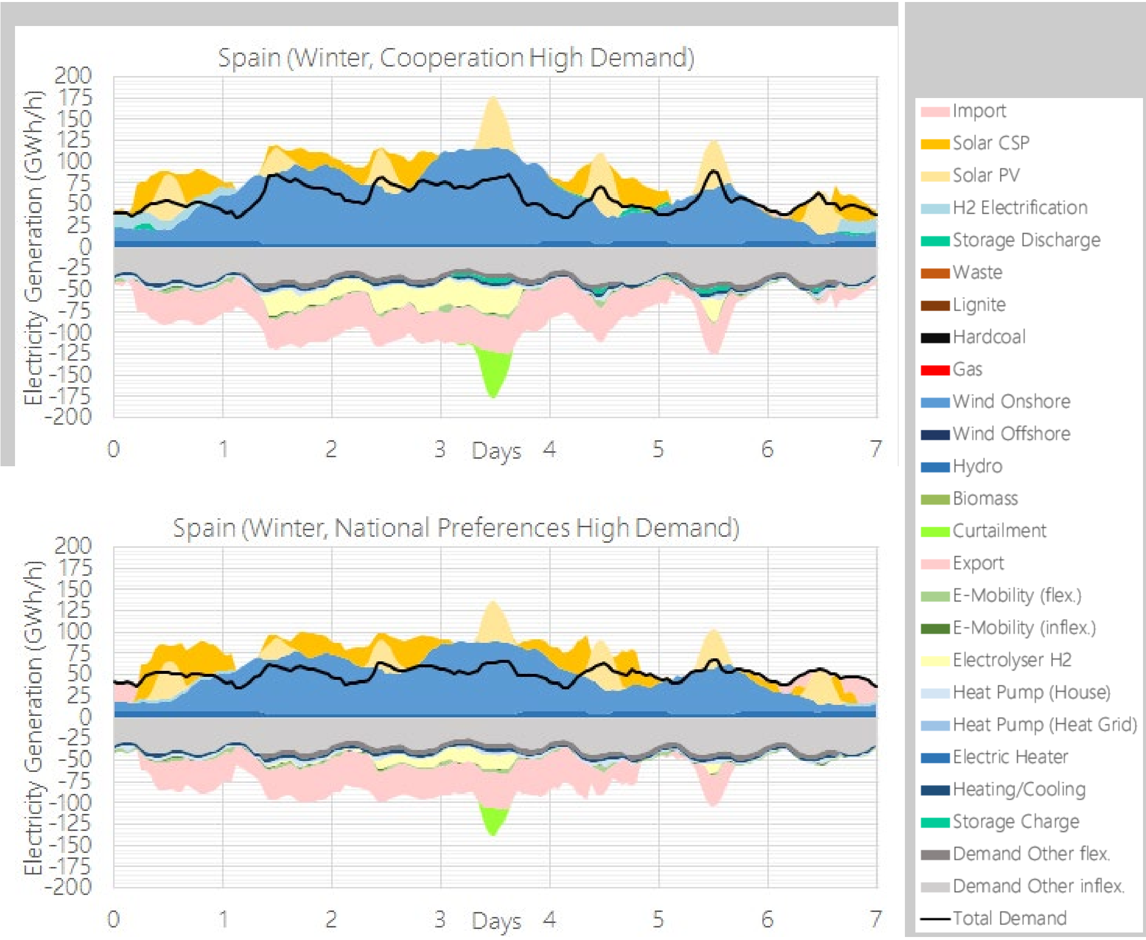

Figure 15: Dispatch of the energy system of Spain for a week in winter for the "Cooperation – High Demand" and "National Preferences – High Demand" scenarios

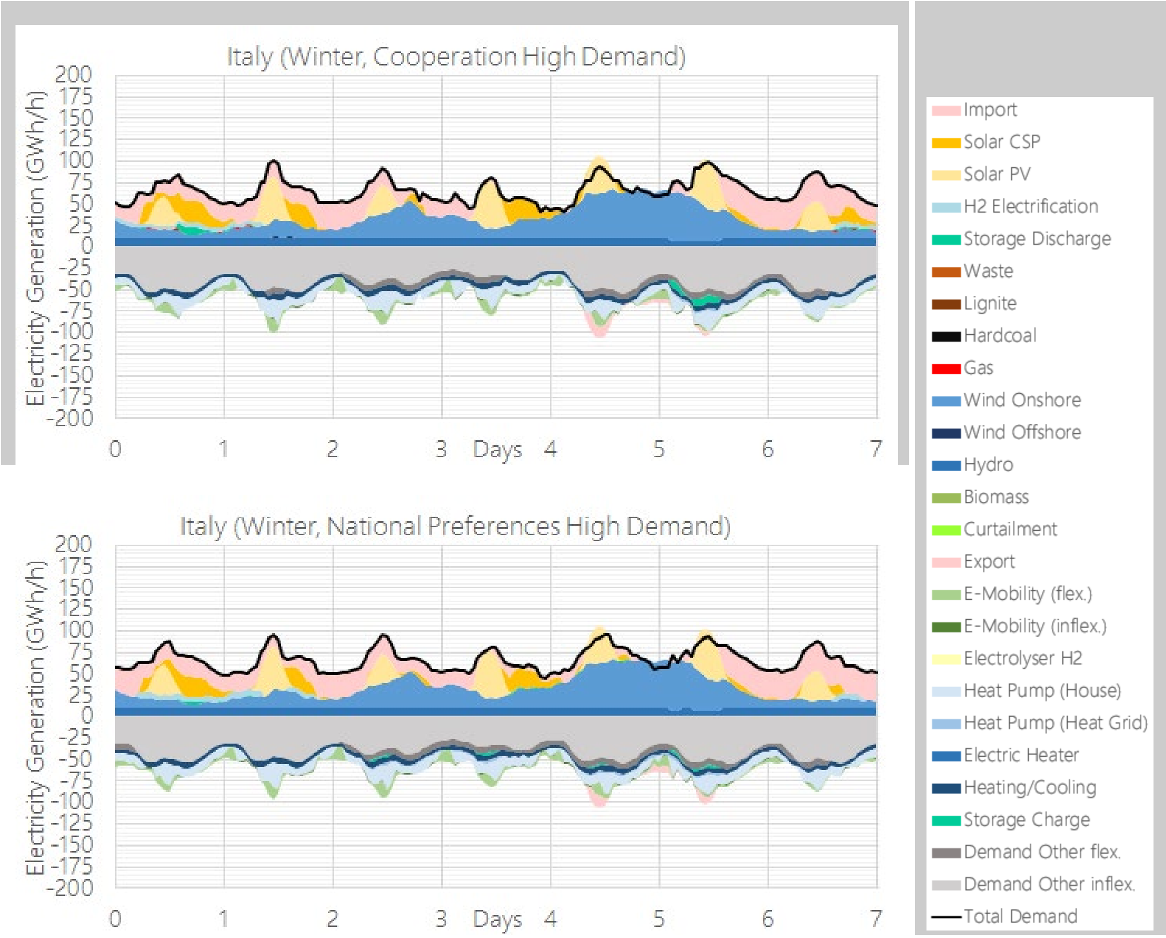

Figure 16: Dispatch of the energy system of Italy for a week in winter for the "Cooperation – High Demand" and "National Preferences – High Demand" scenarios

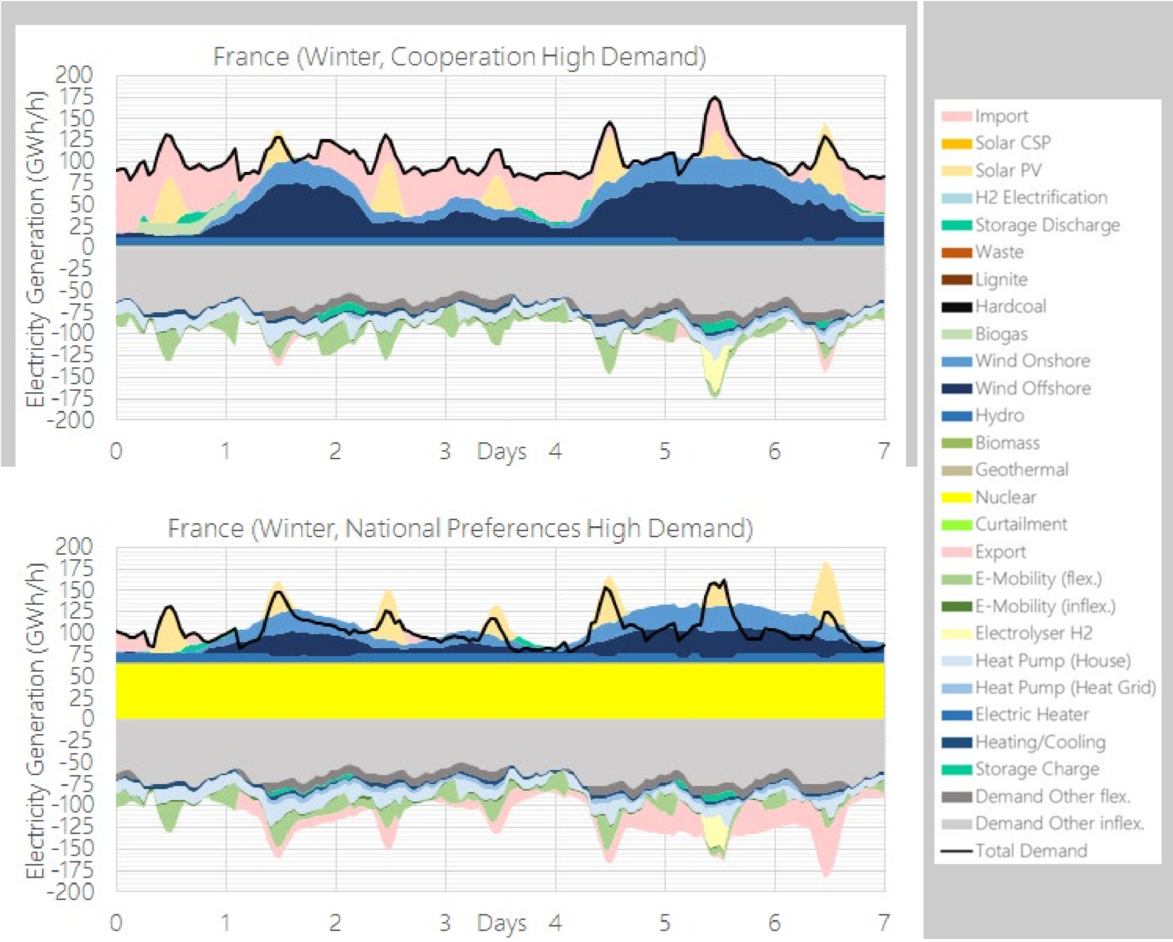

Figure 17: Dispatch of the energy system of France for a week in winter for the "Cooperation – High Demand" and "National Preferences – High Demand" scenarios

In the shown summer week, electricity generation is clearly dominated by solar PV and CSP (see Figure 18 and Figure 19). Their daily generation peak is partly absorbed by domestic flexible demand (cooling of buildings, hydrogen production, e-mobility, charging of electricity storage), but also a large amount of electricity is exported. Export from Italy is high only in periods of strong wind and solar generation, while Spain exports electricity very regularly. CSP is mainly used during the evening and night, but also partly when PV generation is already high. There is only very little curtailment, showing that the solar electricity can almost always be used in the system (as long as wind power generation stays low). Again, the differences between the two pathways are small for the chosen example. There is slightly more export in the "Cooperation" scenario and slightly more hydrogen production in the "National Preferences" scenario. In France the differences between the considered scenarios become clearer. In the summer, the demand in the "Cooperation – High Demand" scenario is covered by an interplay of solar PV and imports of electricity. In the "National Preferences – High Demand" scenario, the additional electricity generation by nuclear power plants leads to a continuous export of surplus wind and solar energy.

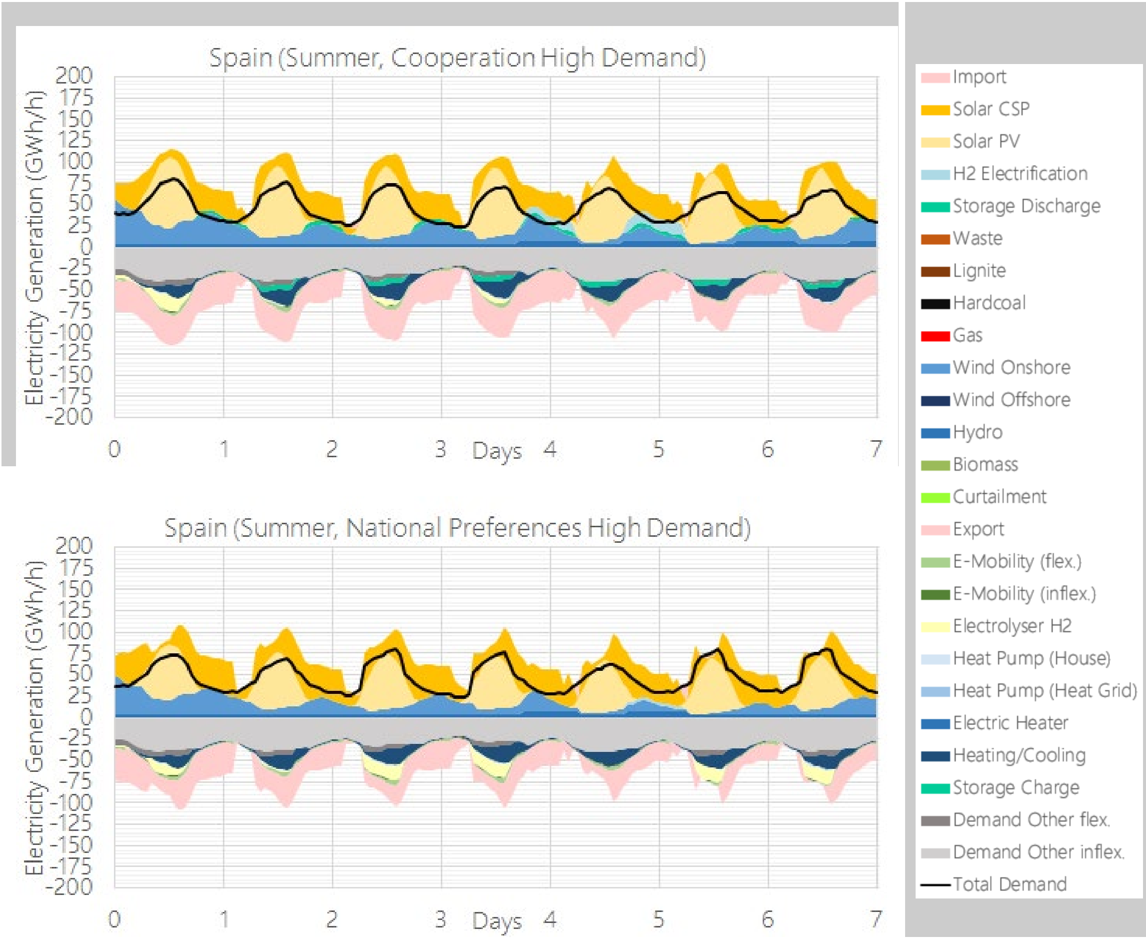

Figure 18: Dispatch of the energy system of Spain for a week in summer for the "Cooperation – High Demand" and "National Preferences – High Demand" scenarios

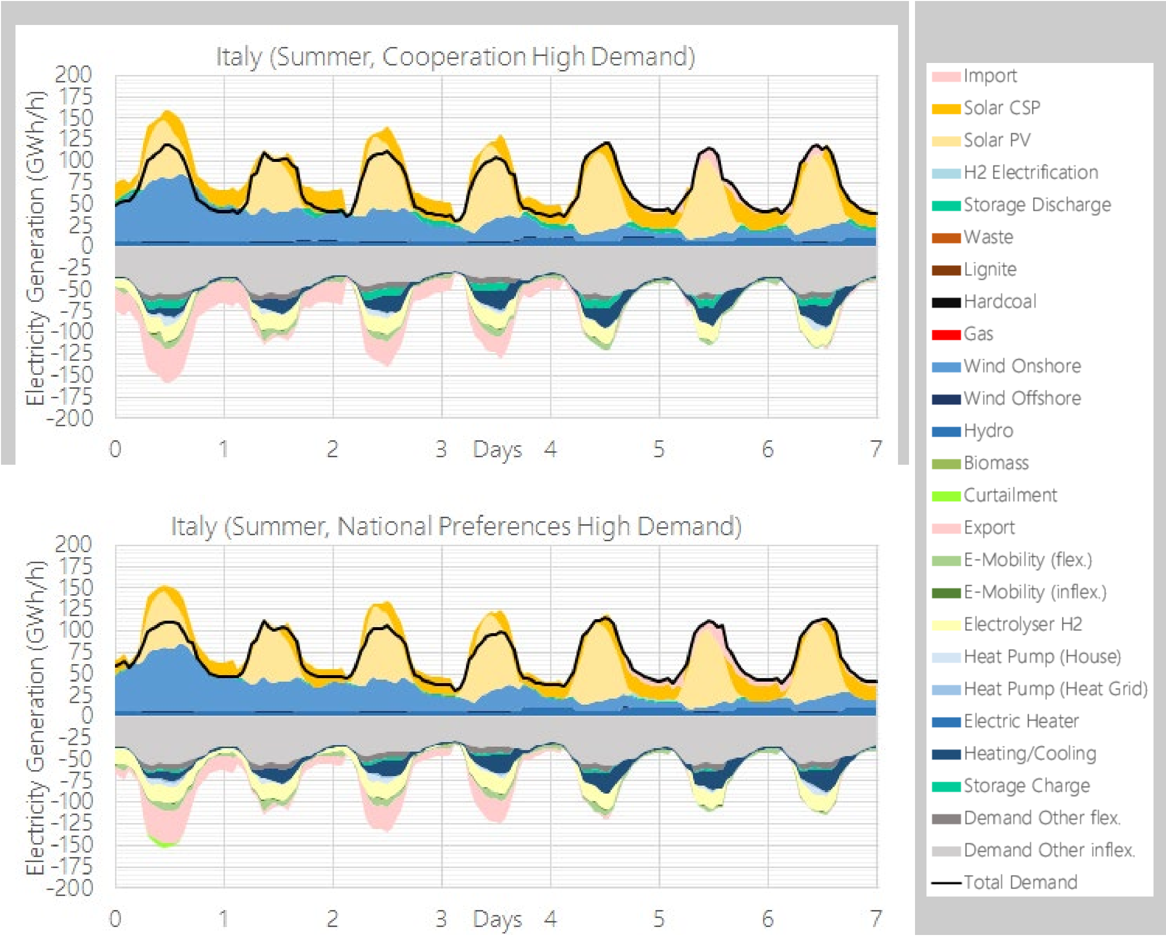

Figure 19: Dispatch of the energy system of Italy for a week in summer for the "Cooperation – High Demand" and "National Preferences - High Demand" scenarios

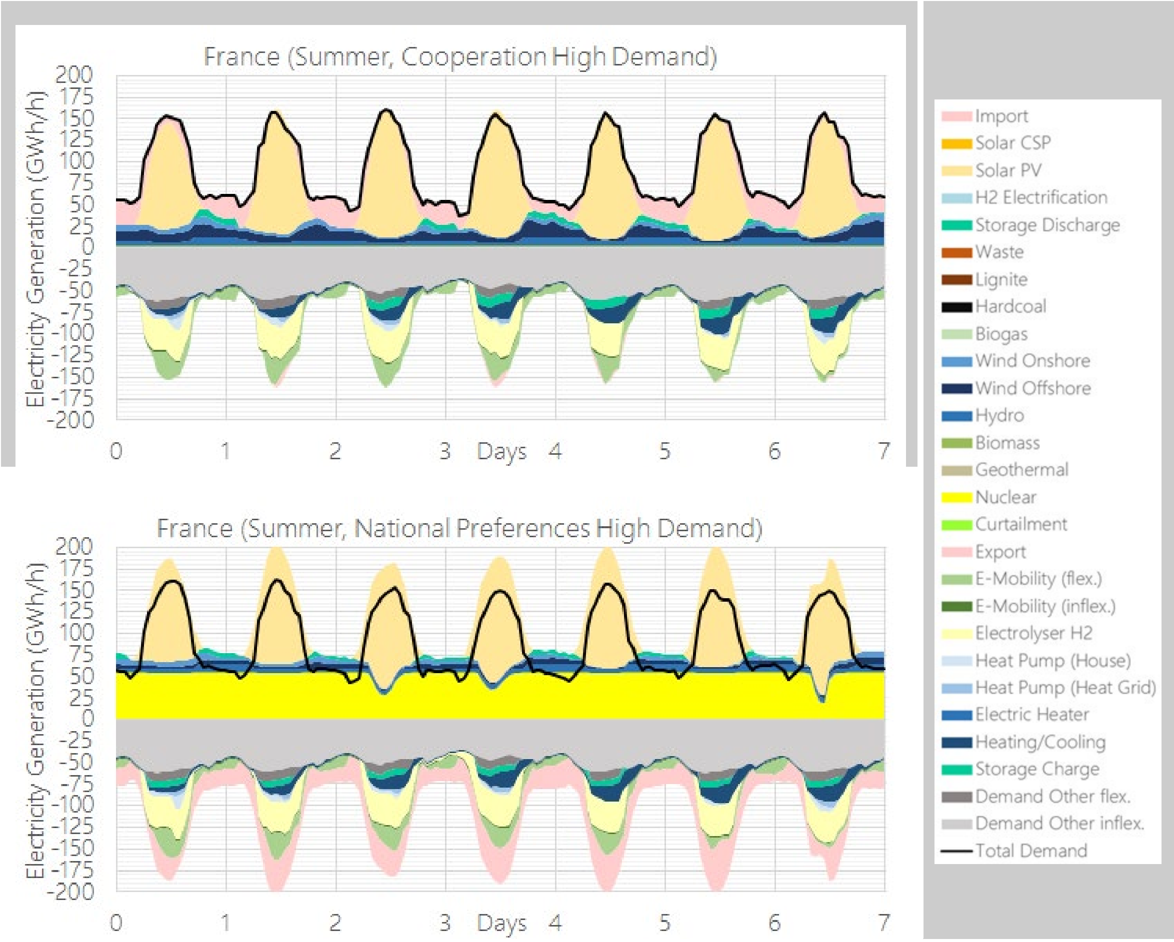

Figure 20: Dispatch of the energy system of France for a week in summer for the "Cooperation – High Demand" and "National Preferences – High Demand" scenarios

3.1.5 Renewable potential usage in 2050

In the following section, we show the potential usage (i.e. what fraction of the maximum installable capacity is actually installed in a certain scenario) of different renewable technologies in 2050 in Europe.

Table 5 shows the potential usage for each renewable technology for each considered country for the "Cooperation" scenarios with low or high electricity demand and the corresponding "National Preferences" (assuming again either a high or a low electricity demand growth in future years). From the figure we can derive that the differences between the scenarios with regard to the potential usage are minor for the solar PV and wind technologies due to the specifications of the Green-X model. For CSP the potential usage changes for the considered scenarios. In Italy the potential usage in the "Cooperation – High Demand" scenario reaches 77 %. In the "Cooperation – Low Demand" scenario, this amount diminishes to 23 %. In the "National Preferences – Low Demand" scenario, the potential usage decreases to 0. Furthermore, in Spain the degree of potential usage varies between the considered scenarios. In the "Cooperation – High Demand" scenario, the potential usage reaches 41 %. This amount decreases to 18 % in the “Cooperation – Low Demand” scenario. Other than in Italy, the potential usage in the “National Preferences” scenario increases compared to the “Cooperation” scenarios. Here, 50 % of the CSP potential in Spain is used in the “High Demand” scenario and 33 % in the “Low Demand” scenario.

Table 5: Potential usage for the renewable technologies CSP, PV, and wind per country.

	Coop High Demand					NatPre High Demand					Coop Low Demand					NatPre Low Demand				
Country	CSP	PV (rooftop)	PV (utility scale)	Wind offshore	Wind onshore	CSP	PV (rooftop)	PV (utility scale)	Wind offshore	Wind onshore	CSP	PV (rooftop)	PV (utility scale)	Wind offshore	Wind onshore	CSP	PV (rooftop)	PV (utility scale)	Wind offshore	Wind onshore
AT	0%	40%	89%	0%	84%	0%	40%	89%	0%	84%	0%	40%	89%	0%	84%	0%	40%	89%	0%	84%
BE	0%	54%	87%	78%	45%	0%	54%	87%	74%	45%	0%	54%	87%	39%	45%	0%	54%	87%	73%	45%
BG	0%	22%	27%	0%	25%	0%	22%	27%	0%	34%	0%	22%	27%	0%	32%	0%	22%	27%	0%	26%
CY	69%	16%	10%	0%	36%	0%	17%	10%	0%	40%	63%	16%	10%	0%	26%	5%	17%	10%	0%	38%
CZ	0%	56%	98%	0%	22%	0%	56%	98%	0%	22%	0%	56%	98%	0%	13%	0%	56%	98%	0%	13%
DE	0%	70%	79%	68%	51%	0%	70%	79%	67%	51%	0%	70%	79%	43%	51%	0%	68%	74%	40%	44%
DK	0%	26%	20%	9%	25%	0%	26%	20%	8%	25%	0%	26%	20%	4%	25%	0%	26%	20%	8%	25%
EE	0%	28%	4%	1%	33%	0%	23%	1%	1%	33%	0%	12%	1%	0%	25%	0%	11%	1%	0%	25%
ES	41%	97%	26%	1%	54%	50%	86%	18%	1%	42%	18%	95%	24%	0%	51%	33%	65%	11%	1%	31%
FI	0%	41%	9%	1%	21%	0%	41%	5%	0%	20%	0%	41%	8%	0%	21%	0%	40%	6%	0%	20%
FR	0%	58%	47%	90%	11%	0%	56%	45%	39%	10%	0%	57%	45%	26%	11%	0%	20%	14%	8%	6%
GR	33%	64%	31%	0%	17%	0%	73%	44%	0%	45%	1%	64%	36%	0%	18%	0%	73%	42%	0%	39%
HR	25%	26%	19%	0%	18%	0%	26%	19%	0%	18%	0%	25%	16%	0%	18%	0%	25%	16%	0%	18%
HU	12%	34%	27%	0%	14%	0%	34%	27%	0%	14%	0%	34%	20%	0%	9%	0%	34%	20%	0%	9%
IE	0%	65%	15%	12%	26%	0%	65%	11%	9%	26%	0%	65%	14%	2%	26%	0%	65%	14%	5%	26%
IT	77%	68%	79%	2%	93%	67%	68%	79%	2%	91%	23%	68%	74%	0%	71%	0%	66%	69%	0%	54%
LT	0%	13%	4%	16%	28%	0%	13%	4%	7%	28%	0%	9%	2%	2%	24%	0%	9%	2%	4%	24%
LU	0%	76%	98%	0%	94%	0%	76%	98%	0%	94%	0%	76%	98%	0%	94%	0%	76%	98%	0%	94%
LV	0%	21%	2%	4%	7%	0%	18%	1%	2%	7%	0%	10%	1%	0%	4%	0%	10%	1%	1%	4%
MT	100%	82%	54%	0%	89%	100%	82%	54%	0%	90%	100%	82%	54%	0%	90%	100%	82%	54%	0%	90%
NL	0%	68%	35%	16%	82%	0%	68%	35%	16%	82%	0%	68%	35%	10%	82%	0%	68%	35%	16%	82%
PL	0%	47%	20%	61%	41%	0%	47%	20%	36%	41%	0%	43%	10%	8%	38%	0%	42%	10%	25%	38%
PT	33%	51%	37%	1%	41%	5%	51%	37%	5%	48%	8%	50%	34%	0%	43%	14%	50%	34%	6%	42%
RO	0%	10%	17%	2%	19%	0%	10%	17%	2%	22%	0%	10%	16%	0%	22%	0%	10%	16%	1%	20%
SE	0%	53%	5%	1%	29%	0%	51%	3%	1%	28%	0%	53%	4%	1%	29%	0%	50%	4%	1%	28%
SI	33%	74%	95%	0%	20%	0%	74%	95%	0%	19%	0%	73%	95%	0%	20%	0%	73%	95%	0%	19%
SK	0%	54%	90%	0%	16%	0%	54%	90%	0%	16%	0%	53%	80%	0%	11%	0%	53%	80%	0%	11%
UK	0%	49%	49%	32%	24%	0%	49%	49%	28%	24%	0%	49%	49%	15%	24%	0%	49%	49%	27%	24%

This shows that, under the chosen scenario assumptions with high electricity demand and limited expansion of wind power and PV, CSP is expanded to a high level close to the potential limit. But we have to keep in mind that the CSP potential itself is already very high due to the assumptions on land availability used in the MUSTEC scenario calculations.

The potential usage of the renewable technologies is calculated in the resolution of a tile grid. In the following figure, this high resolution of the potential usage is shown as an example for wind onshore in Europe for the “Cooperation – High Demand” scenario.[9] A potential usage of 1 indicates that the

[9] For more detailed information, see Section 6.1.

previously calculated potential within this model grid cell is fully used. The highest utilisation of wind onshore potentials is shown in Italy. Here, a large part of the surface is used to install wind power plants. The expansion of wind onshore power plants is also high in Spain and Portugal. In Germany, the potential usage lies between 0.3 and 1. In France, the capacities of wind power are mainly located in the north on the Atlantic coast.

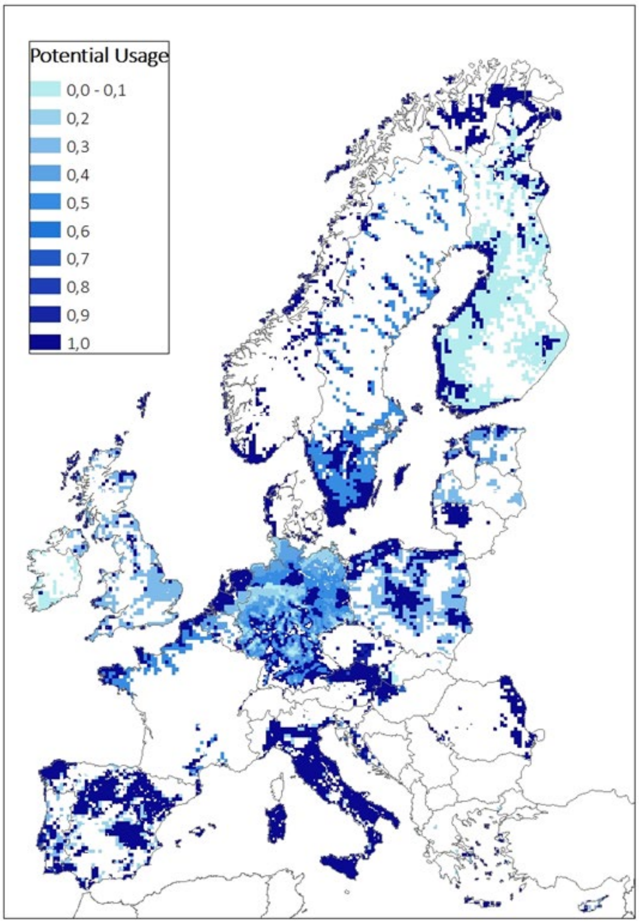

Figure 21: Fraction of the wind onshore potential used in 2050 in the „Cooperation - High Demand“ scenario

The distribution of renewable energies in Europe shows that wind onshore capacities are mainly located near the coast and PV technologies have a high potential usage in the South of Europe. Furthermore, the differences in the potential usage between the considered scenarios with regard to solar PV and wind technologies are minor. This is due to the predefined technology expansion from the Green-X model. However, the potential usage differs between the considered scenarios with a view to CSP. In the “Cooperation – High Demand” scenario, the CSP potential usage shows a high distribution over Europe. Here, nine different countries show potential usages of more than 10 %. The highest potential usage show Malta with 100 %, Italy with 77 % and Cyprus with 69 %. Spain has only a potential usage of 41 % in this scenario. With limited demand, the distribution of

CSP changes. In this scenario, the potential usage in Malta is not changed but the potential usage in Italy decreases to 23 %. In Italy, the electricity generation by CSP power plants is mainly used to cover the national demand. Therefore, with decreasing demand, the level of CSP potential usage decreases. As the demand in Cyprus and Malta is not changed and these islands are mainly generating electricity in order to meet their own demand, the potential usage of CSP changes only slightly.

In the “National Preferences – High Demand” scenario, only four countries have a CSP potential usage of more than 0 %. These are Malta with 100 %, Italy with 67 %, Spain with 50 % and Portugal with 5 %. Due to the additional energy generation by nuclear power plants, the potential usage of CSP is reduced in Europe for this scenario. By lowering the electricity demand, the potential usage declines even more. In Spain this leads to a potential usage of 33 %. In Italy the potential usage of CSP is reduced to 0 %. This high reduction in Italy is due to the low export of electricity. Therefore, Italy seeks to meet the national demand, and with a low electricity demand, the necessity of CSP installation decreases.

3.2 Sensitivity analysis

This subchapter focuses on different sensitivity scenarios. These are analysed with regard to the question which factors drive the expansion of CSP in the model results.

3.2.1 Limited Grid

The scenario with limited grid is, in principle, based upon the assumptions for the “Cooperation – High Demand “scenario. However, the electricity grid capacity expansion is much less dynamic than in the default case. Instead of grid modelling results from the SET-Nav “Diversification” pathway, results from the “Localization” pathway from the same project were used. In this case, the grid capacity in the year 2030 was set equal to the TYNDP values (used as lower limit in the other case). In the following decades until 2050, the expansion of every single interconnector was limited to a maximum of 15 % per decade. The interconnector capacities resulting from these SET-Nav scenario calculations were used as assumptions for the MUSTEC scenarios with limited grid.

Figure 22: European network of interconnectors with limited grid expansion[10] [in MW]

In Figure 22, the interconnections of the electricity grid for the pathways with limited grid are shown. For this pathway, the connection with the highest capacity lies between Germany and Austria with 9.75 GW. The formerly high grid connection between France and Spain diminishes to 6.5 GW.

There is one further difference in the setup between the main scenario ("Coop/NatPre – High Demand") and the sensitivity scenario with limited grid: The Enertile model is allowed to exceed the electricity generation from *offshore wind* determined by the Green-X model in the first step (while for wind onshore, PV, hydro, biomass, and geothermal the generation remains fixed to the Green-X results, just as in all other scenarios). This setup was chosen in order to allow countries with low CSP potential an alternative supply technology to CSP, biogas and fossil fuels in a situation with limited electricity import options.

[10] SET-Nav Localization

The generation gap is shown in Figure 23. In the “Cooperation – High Demand” scenario, the remaining gap is 365 TWh and in the “National Preferences – High Demand” scenario this gap is 280 TWh. In the scenarios with limited grid, the remaining generation gap increases, mainly due to increased curtailment and production of hydrogen for re-electrification. In the “Cooperation – High Demand – Limited Grid” scenario, the gap reaches 759 TWh. The share of CSP of this gap is 42 % with 317 TWh. The amount of generated electricity by CSP in Spain reduces from 138 TWh in the “Cooperation - High Demand” scenario to 34 TWh with grid limitations. But in return, the CSP generation in France increases from 0 to 83 TWh. This result is remarkable, as it is the only scenario in which CSP is deployed significantly in France. This is mainly due to the lack of imports from Spain (due to the grid limitations) and the lack of nuclear power (compared to the “National Preferences – High Demand” scenario). Without the French extra contribution, CSP generation in the EU would be considerably smaller in the “Cooperation” scenario with limited grid (compared to the main “Cooperation” scenario).

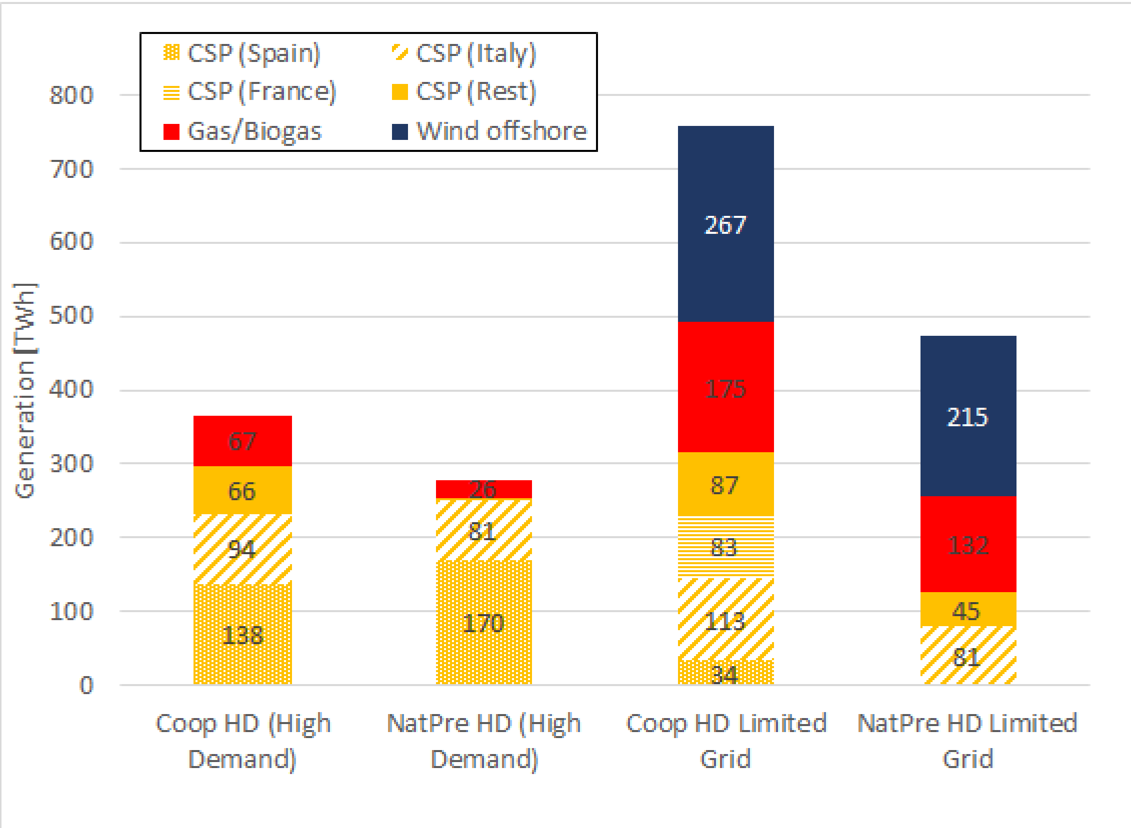

Figure 23: Generation gap, i.e. remaining amount of electricity for which the Enertile model can choose the supply technology (for EU28 in 2050) for the sensitivity of grid limitations. For the rest of the supply, the electricity generated per technology is determined by the Green-X model and given as a restriction to Enertile. For wind offshore, only the generation exceeding the Green-X result (given as a minimum restriction) is shown.

The possibility of additional expansion of offshore wind also has an impact on the size of the generation gap and the technology mix that is used to fill this gap. In the “Cooperation” scenario with limited grid, additional 267 TWh are generated from offshore wind, which makes a share of 35 % of the gap. Furthermore, the amount of gas respectively biogas increases to 175 TWh compared to the “Cooperation – High Demand” scenario. In the “National Preferences” scenario, the installation of nuclear power plants is still an option. Therefore, the generation gap is smaller than for the “Cooperation” scenarios. However, still 215 TWh of additional wind offshore are used by the model to fill the generation gap (in this scenario, the share is 46 %). As a result of the high amount of wind offshore generation, the CSP generation diminishes to 125 TWh, which is a share of 26 %. Here, the CSP generation in Spain is reduced to 0 TWh. The share of gas respectively biogas generation increases to 132 TWh and therefore a share of 28 %.

In Figure 24, the installed capacity for the two scenarios “Cooperation” and “National Preferences” are shown for the sensitivity scenario with limited grid. In the “Cooperation – High Demand” scenario, the installed capacity of CSP reaches 80 GW. For the “Cooperation” scenario with limited grid this amount increases to 100 GW. The “National Preferences” scenarios show a lower capacity of CSP. In the scenario with stronger grid expansion, the CSP power plant capacity is 65 GW and in the scenario with limited grid the capacity is reduced to 39 GW.

Due to the limited grid, the model seeks other options to balance the fluctuating energy generation of renewable energies. Therefore, the capacities of biogas plants increase. The full load hours of biogas plants are roughly 630 in the “Cooperation – High Demand” scenario. With limited grid, the full load hours increase to 1,370. In the corresponding “National Preferences” scenario, the differences are even higher. Here, the full load hours for the unlimited grid scenario are 380. This amount increases to 1,500 hours when the grid is limited. In addition to the expansion of (bio)gas plants, the flexibility options of electricity (pump) storage and hydrogen re-electrification are enforced in the scenarios with limited grid. In the “Cooperation” case, the amount of electricity generated from hydrogen increases from 70 TWh to 116 TWh, while the output of pump storages increases from 90 TWh to 137 TWh. In the “National Preferences” case, the increase in the limited grid scenario is from 73 TWh to 122 TWh for hydrogen and from 61 TWh to 132 TWh for pump storage.

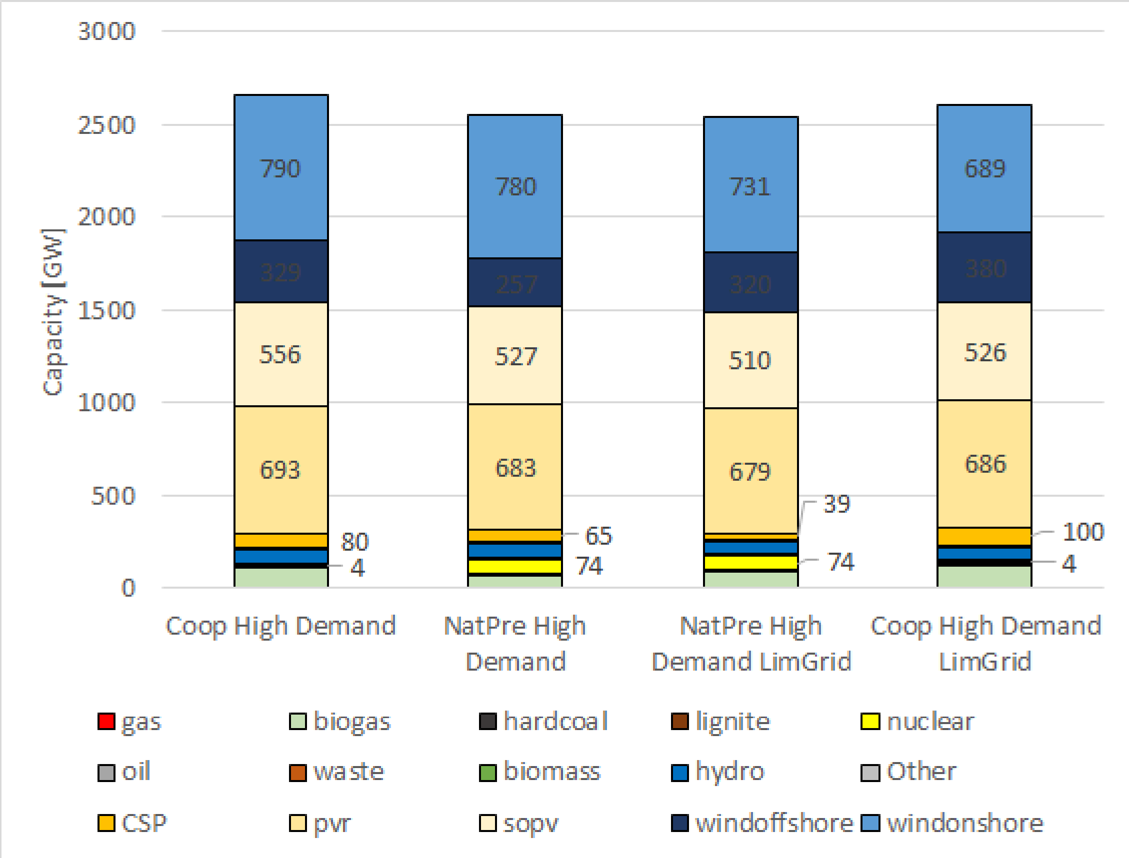

Figure 24: Installed Capacity for the "Cooperation – High Demand", "National Preferences – High Demand" and corresponding "Cooperation – High Demand – Limited Grid" scenarios in 2050 (other = geothermal, pvr = rooftop PV, sopv = utility scale PV)

The generated electricity by the installed capacities is shown in Figure 25. The scenarios with limited grid show a higher amount of wind offshore generation. In the "Cooperation – High Demand" scenario, the wind offshore electricity generation reaches 1,381 TWh. This amount increases for the "Cooperation" scenario with limited grid to 1,612 TWh. The generated electricity by wind onshore power plants decreases slightly from 2,239 TWh to 2,117 TW. Due to the limited grid, the high amount of wind onshore electricity generation cannot be transferred to other countries. Therefore, the amount of generated electricity of other flexibilities like CSP and gas power plants rises. In the "National Preferences" scenario, the amount of wind offshore power plants increases whereas the generated electricity from CSP is reduced to half. This effect is also due to the high amount of nuclear power plants in France, where this technology replaces CSP.

CSP power plants are another flexibility option which can supply energy to balance fluctuations. The CSP capacity in Europe is 80 GW in the "Cooperation - High Demand" scenario. With limited grid, this amount increases to 100 GW. In the "National Preferences" scenario, the CSP capacity is 65 GW for the scenario without grid limitations and diminishes to 39 GW for the scenario with grid limitations.

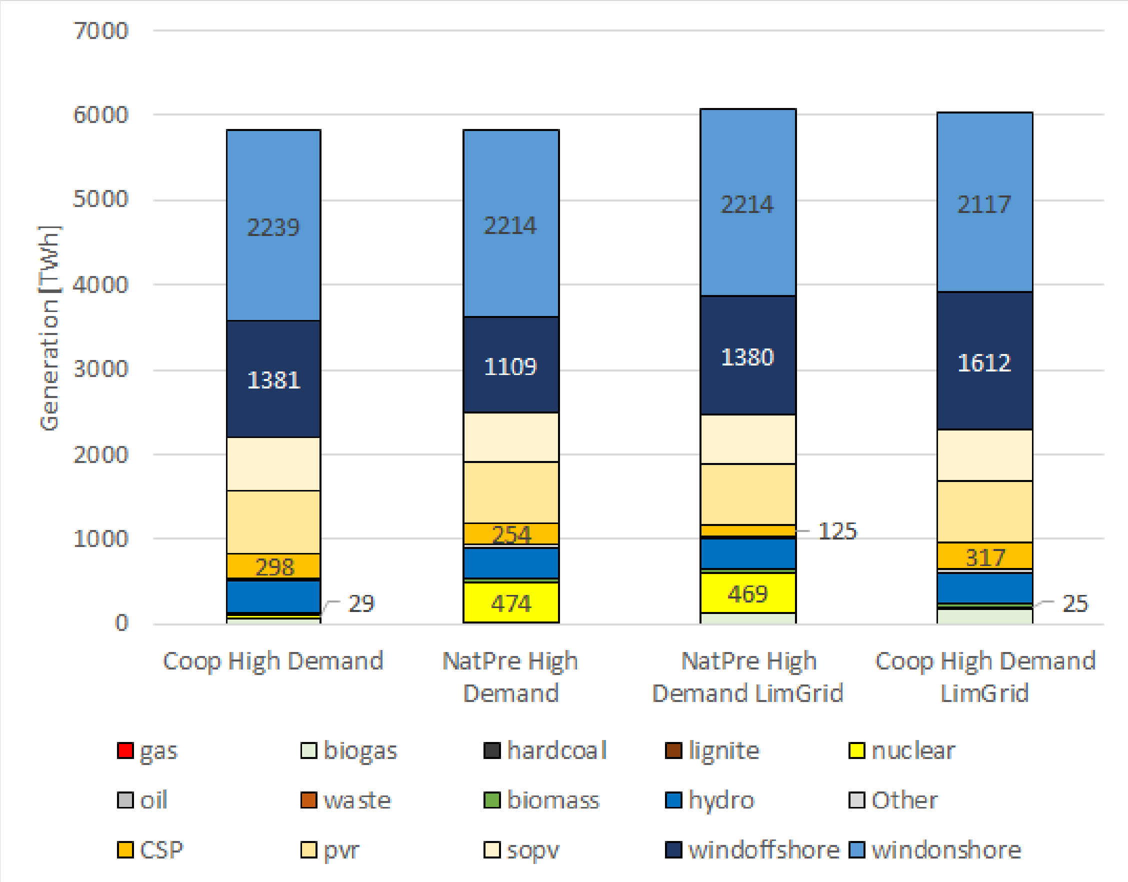

Figure 25: Generated electricity in the "Cooperation – High Demand" and "Cooperation – Low Demand" and "National Preferences – High Demand" and "National Preferences – Low Demand" scenarios in 2050 (other = geothermal, pvr = rooftop PV, sopv = utility scale PV)

In the following, we take a closer look at the capacity of CSP power plants in different countries in the year 2050. Figure 26 shows the results for the "Cooperation" and "National Preferences – High Demand" scenarios and the scenarios with limited grid. The highest installed capacity of CSP for the two main scenarios can be found in Spain. Here, the capacity is 34 GW for the "Cooperation" scenario and 42 GW for the "National Preferences" scenario. The amount of installed capacities decreases significantly for the "Cooperation – High Demand – Limited Grid" scenario to roughly 8.5 GW. This is due to the limited grid connection to France which functions as a bottle neck, also for the export from Portugal. In the main scenarios, the generated CSP electricity is exported from Spain to France and other parts of Europe. In the limited grid scenario this is no longer possible. Therefore, the CSP capacity increases in other parts of Europe with lower CSP potentials (France, Hungary, Croatia, Czech Republic). Especially the capacity of CSP in France increases. In the two main scenarios, no CSP capacities are located in France, whereas in the "Cooperation – High Demand – Limited Grid" scenario the capacity reaches 33 GW. In the "National Preferences – High Demand – Limited Grid" scenario, the capacity of CSP in Spain is reduced to 0 GW. In this scenario, the overall installed capacity in Europe is lowest. This is due to installed capacities of nuclear power plants and the additional possibility to expand the capacities of wind offshore power plants. The latter option leads to lower CSP capacities in countries with coastal regions and the expansion of CSP capacities in inland countries where CSP is still more competitive than biogas (under the chosen cost assumptions). Therefore, CSP capacities in Austria, Hungary, Slovakia, and Czech Republic are expanded in the scenarios with limited grid. But these modelling results should be treated with care, as CSP plants in Central Europe are not very likely to be built in the real world.

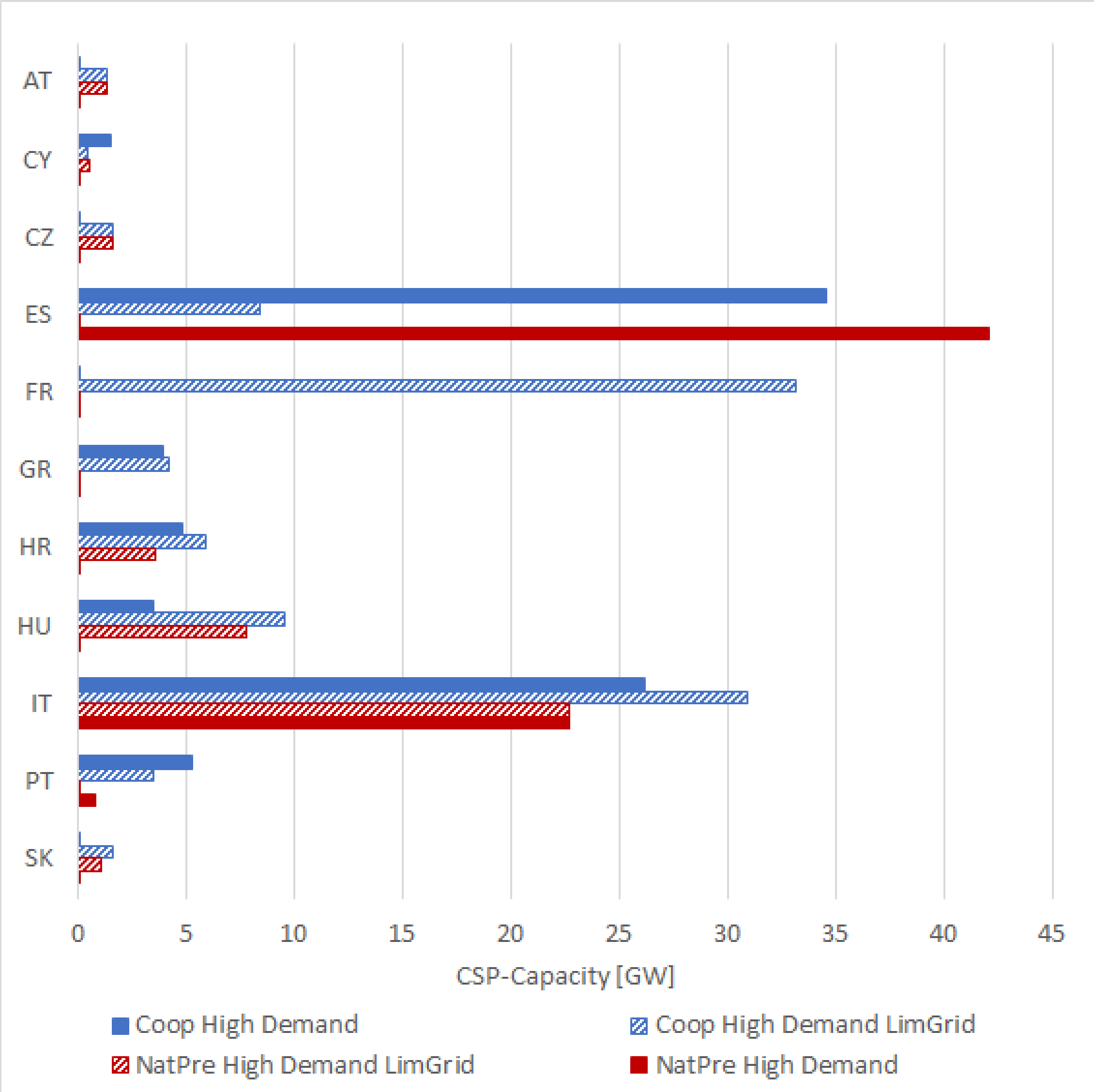

Figure 26: Installed CSP capacity per country for the two main scenarios and the variants with limited grid in 2050

Figure 27 and Figure 28 show the hourly electricity dispatch (i.e. the interplay between generation and the demand) for Spain and Italy in an exemplary summer week for the “Cooperation – High Demand” scenario and the corresponding “Limited Grid” variant. In the “Cooperation – High Demand” scenario, Spain is almost constantly exporting surplus solar power. This changes clearly in the scenario with limited grid. Here, the export of energy diminishes to almost 0 GWh as the installed capacities are reduced to 8 GW. The amount of energy stored and used for hydrogen production increases with limited grid. As the surplus energy cannot be exported it is stored in order to be used as a flexibility option instead of imports. In contrast to Spain, in Italy the generation of electricity changes only slightly in the considered week. However, the export of energy diminishes and the rate of curtailment increases due to the limited grid capacity. In Italy, the surplus energy which cannot be exported is used in electrolysers in order to generate hydrogen.

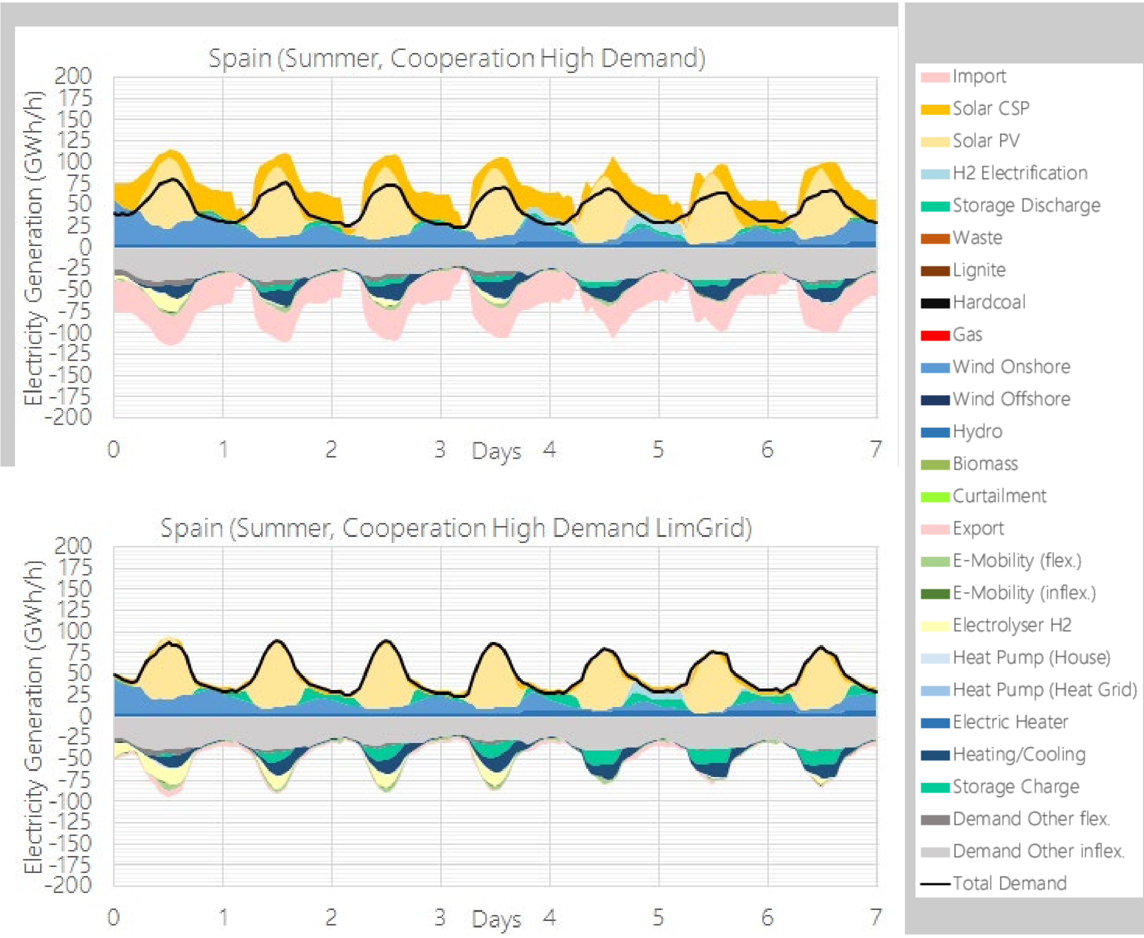

Figure 27: Dispatch of the energy system of Spain for a week in summer for the default "Cooperation – High Demand" scenario and the variant with "Limited Grid"

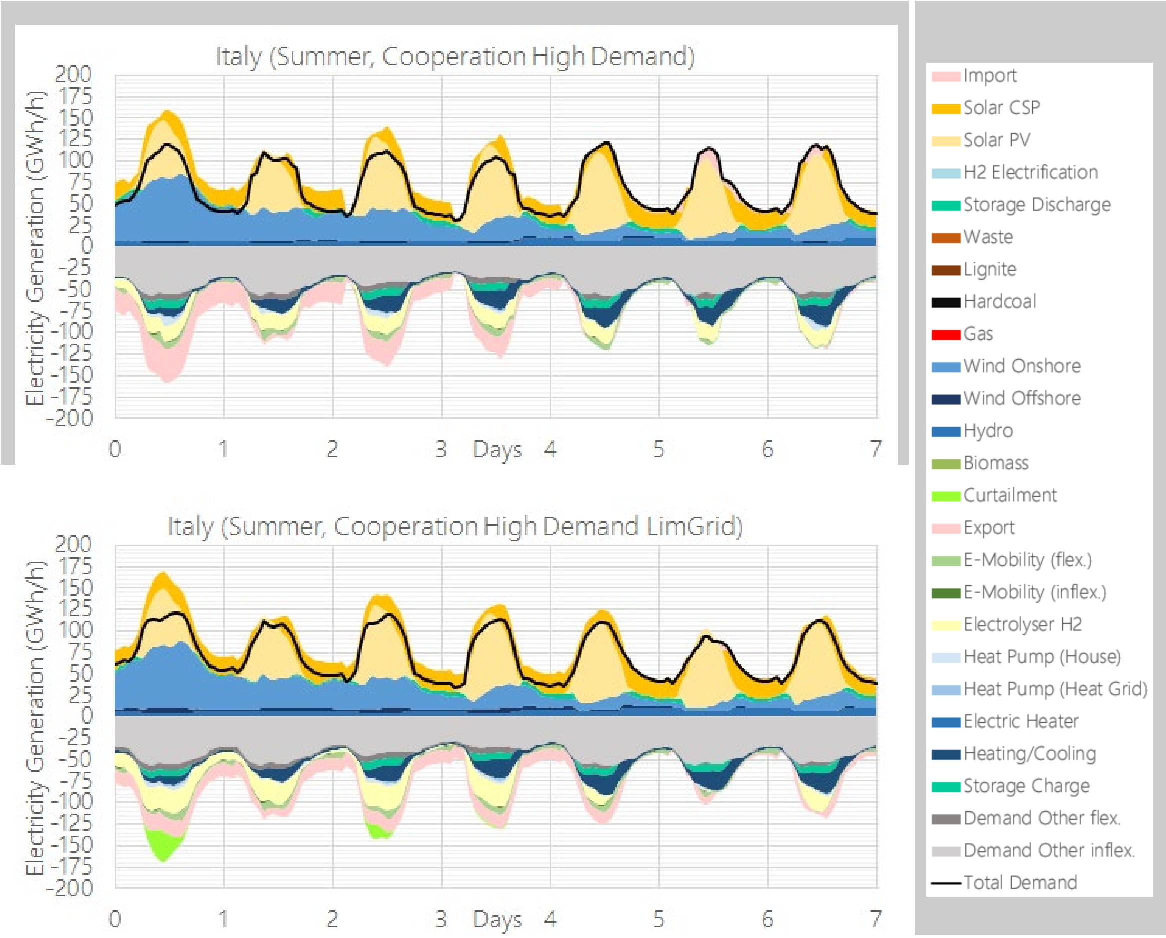

Figure 28: Dispatch of the energy system of Italy for a week in summer for the default "Cooperation – High Demand" scenario and the corresponding "Limited Grid" variant

The scenario "National Preferences - Limited Grid" indicates that a well-developed electricity grid can support the expansion of CSP in countries with high potentials. Here, the electricity grid is an option to export surplus energy in regions of Europe with lower renewable potentials. In the case of lower cooperation between European countries and a limited grid expansion, especially Spain and Portugal limit their expansion of CSP. In the "Cooperation Limited Grid" scenario, the CSP capacities increase, especially in France and Italy; whereas in Spain the installed capacities are reduced. This shows that in particular countries with a high potential of CSP and a limited connection to the European electricity grid, are dependent on a highly developed grid. But as stated before, the production of hydrogen with subsequent transport to other countries (an option not included in the Enertile model) might be an alternative to the direct export of electricity in the situation of limited power grids. However, the costs of this technical pathway would be considerably higher.

3.2.2 Lower electricity demand

This section focuses on the scenarios with reduced electricity demand. In 2050, the demand is 3,500 TWh in Europe for the scenario with low demand and 4,600 TWh in the scenarios with a high electricity demand. This deviation is due to a lower electricity demand in the four countries France, Germany, Italy, and Spain. The electricity demand in all other countries stays the same.

Figure 29 shows the remaining generation gap which Enertile has to fill. In the "Cooperation – High Demand" scenario this gap consists of 370 TWh of which roughly 300 TWh are filled by CSP. In the low demand scenarios, the gap diminishes to 150 TWh. In the "Cooperation – Low Demand" scenario 100 TWh are covered by CSP, whereas in the "National Preferences – Low Demand" scenario this amount is higher with roughly 126 TWh. In the "Cooperation – Low Demand" scenario, the CSP generation is reduced to 63 TWh compared to 138 TWh in the "High Demand" scenario. Furthermore, the CSP generation in Italy diminishes from 94 TWh to 28 TWh. In the "National Preferences – Low Demand" scenario, the CSP generation in Spain decreases from 170 TWh to 116 TWh. Furthermore, the CSP generation gap in Italy declines to zero. This can be explained by the higher nuclear power generation in this scenario, which reduces the generation from fluctuating renewables and therefore the need for completely dispatchable biogas plants, thereby favouring CSP.

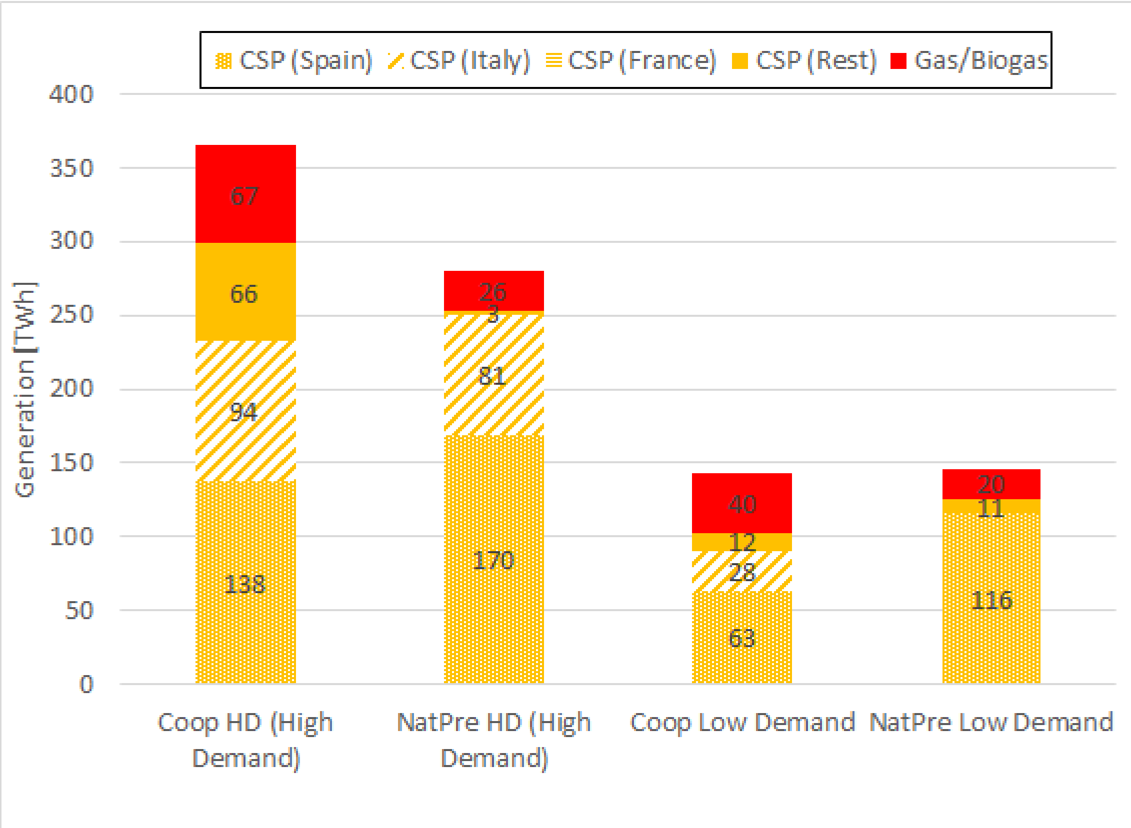

Figure 29: Generation gap, i.e. remaining amount of electricity for which the Enertile model can choose the supply technology (for EU28 in 2050), for the sensitivity of low demand. For the rest of the supply, the electricity generated per technology is determined by the Green-X model and given as a restriction to Enertile.

In the following, we compare the scenarios with high and low demand and draw our conclusions with regard to CSP expansion. Figure 30 shows the installed capacity for the two pathways "Cooperation" and "National Preferences" for the scenarios "High Demand" and "Low Demand". The capacity of installed renewable capacities diminishes in the scenarios with low demand. Especially the capacity of CSP installations declines by 68 % in the "Cooperation" scenario and 53 % in the "National Preferences" scenario. In the "Cooperation" scenario, the installed capacity of wind offshore decreases by 57 %. As wind offshore and CSP are more expensive than wind onshore and rooftop PV, these capacities only slightly extend in the low demand scenarios. For the other renewable energies, the reduction is 6 to 7 % in the "Cooperation" scenario. In the "National Preferences" scenario, the decrease in wind offshore capacities is 25 %. However, the reduction for the other renewable energies lies between 14 and 22 %. This higher reduction in the capacities of renewable energies is due to a higher share of nuclear power plants in the "National Preferences Low Demand" scenario. Therefore, fewer other capacities are needed to form the power plant park.

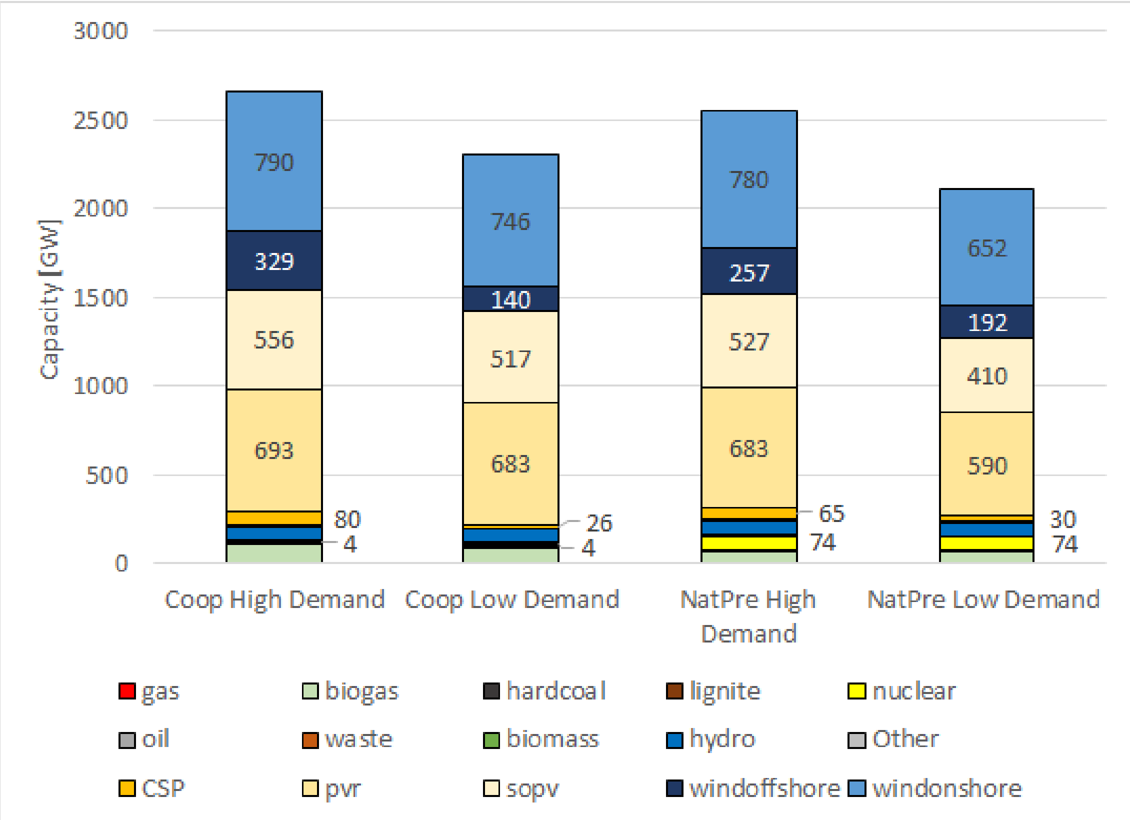

Figure 30: Installed Capacity for the "Cooperation" and "National Preferences" scenarios with high and low demand (other = geothermal, pvr = rooftop PV, sopv = utility scale PV)

Figure 31 shows the electricity generation for the considered scenarios. As the installed capacities of renewable energies are reduced in the course of lower demand, the generation of renewables also declines. This is especially true for wind offshore and CSP. Here, the generation falls from 1,381 TWh to 611 TWh in the "Cooperation" scenario and from 1,109 TWh to 840 TWh for the "National

Preferences” scenario. The generation of electricity from CSP power plants is cut in half for both pathways.

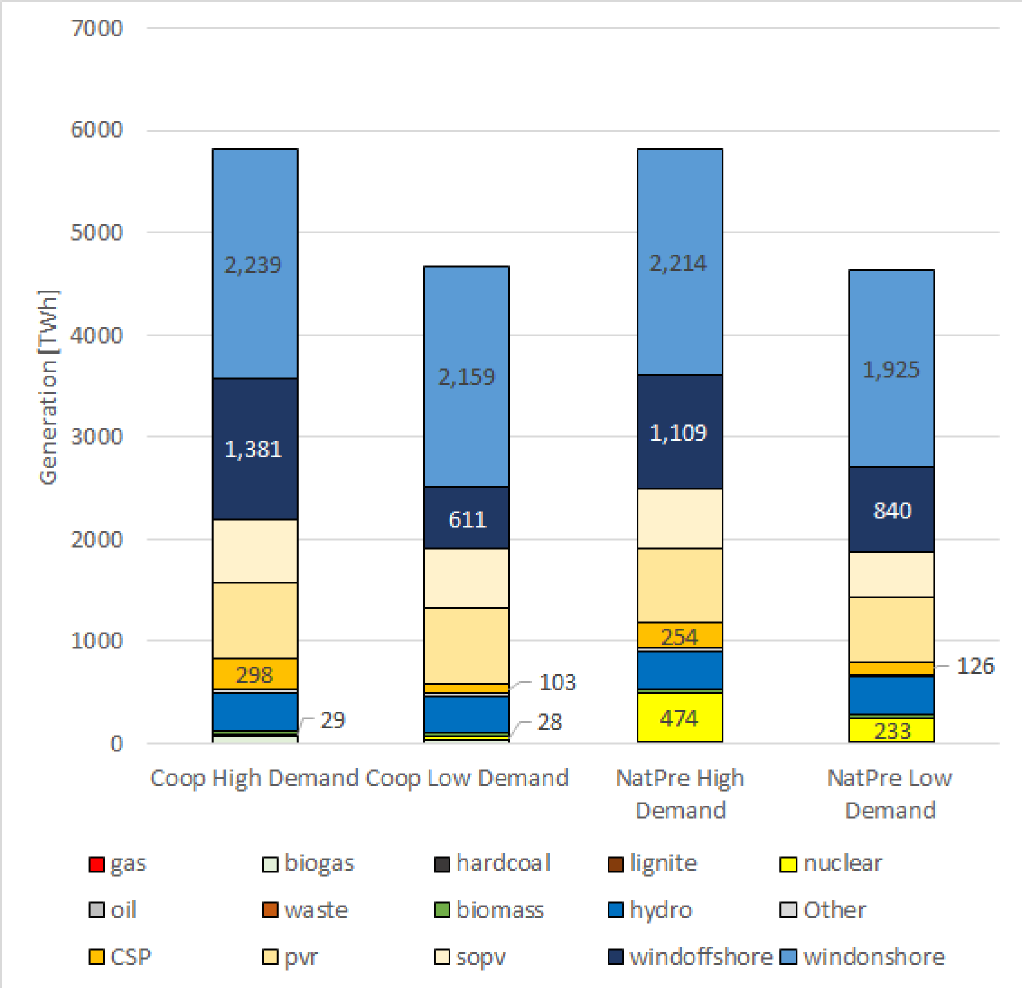

Figure 31: Generated electricity in the “Cooperation” and “National Preferences” scenarios with high and low demand (other = geothermal, pvr = rooftop PV, sopv = utility scale PV)

The reduction of installed CSP power plants is reflected in the distribution of CSP per country. The CSP capacity per country is shown in Figure 32. With lower demand in the “Cooperation” scenario, the installed capacity of CSP vanishes from countries like Hungary, Croatia, and Greece. In other countries, the capacity is significantly reduced. In Portugal from more than 5 GW to roughly 1 GW and in Spain from more than 34 GW to 15 GW. In the “National Preferences” scenario with low demand the overall installed capacity is more than halved. For example, the installed capacity in Spain is reduced from 42 GW in the high demand scenario to 28 GW and in Italy CSP completely vanishes. Only in Portugal the installed capacity increases considerably in the low demand scenario, which may be due to changes in the prescribed wind and PV generation leading to a growth of the generation gap in this specific country.

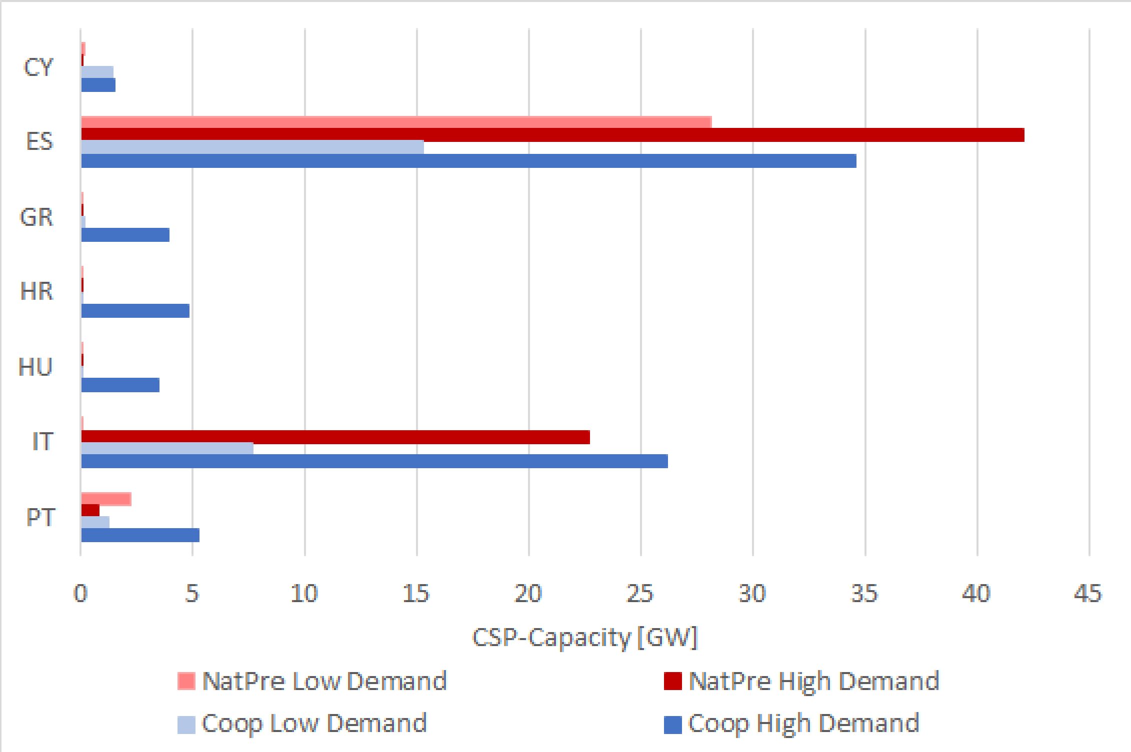

Figure 32: Installed CSP capacity per country for the "Cooperation" and "National Preferences" scenarios with high and low demand

In the scenarios with lower electricity demand, the installed capacities as well as the electricity generation of CSP decrease. This is mainly due to a smaller generation gap (resulting from the Green-X model calculations) that can be filled by CSP in the Enertile model. The shrinking of this gap can be explained by the fact that the generation of other (prescribed) renewables does not decrease as much as the total electricity demand, because these technologies are then further away from their realizable potential limits and generally less expensive than CSP. However, the competitiveness of CSP in relation to biogas plants does not decrease for lower electricity demand.

3.2.3 Lower flexibility from sector coupling

In order to analyse the impact of other flexibility options on CSP, we define a scenario with limited flexibility from sector coupling (based on the "Cooperation – High Demand" scenario). Here, the amount of e-mobility with flexible load profile is reduced by 50 % (e.g. from 354 TWh to 177 TWh for the EU in 2050), such that the other 50 % have an inflexible charging profile. Furthermore, for heat pumps in houses (having a demand of 289 TWh in the EU in 2050) the size of the heat storage is also reduced by 50 %, making their demand profile less flexible.

It has to be emphasized that through these changes in the model setup only a certain (probably minor) fraction of the overall energy system flexibility is switched off in this scenario. Important flexibility options that remain unchanged are e.g. the highly developed power grid, flexible electrolysers for hydrogen production and the flexible use of power-to-heat in heat grids.

In Figure 33, the remaining gap for the Enertile calculation is shown. For the scenario with lower flexibility, the gap differs only slightly from the default "Cooperation – High Demand" scenario. Furthermore, the distribution of CSP among the considered countries differs only slightly. The generation gap increases slightly for the scenario with less flexibility from 365 TWh to 370 TWh. The share of gas/biogas in the electricity generation stays the same for both scenarios with 18 %, leaving a share of 82 % for CSP.

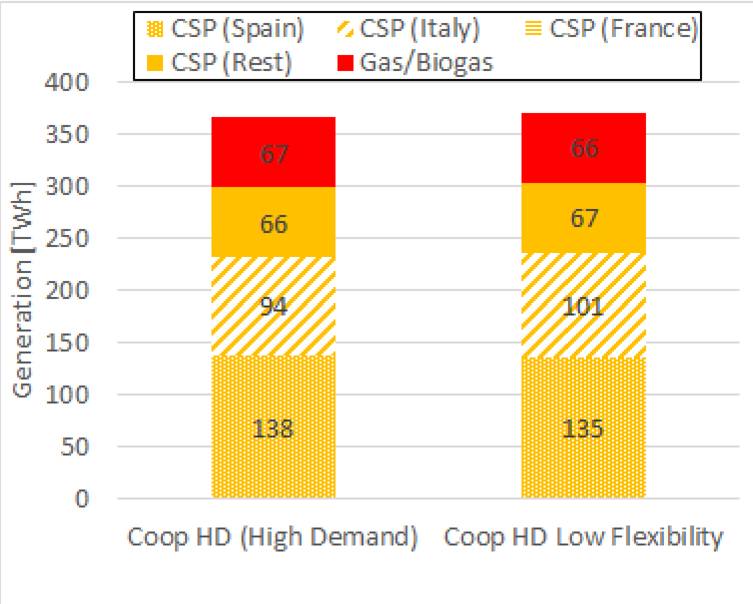

Figure 33: Generation gap, i.e. remaining amount of electricity for which the Enertile model can choose the supply technology (for EU28 in 2050), for the sensitivity of low flexibility. For the rest of the supply, the electricity generated per technology is determined by the Green-X model and given as a restriction to Enertile.

The generated electricity mix shown in Figure 34 is also very similar in the two scenarios. The generated electricity by CSP power plants increases marginally from 298 TWh to 304 TWh. Furthermore, the wind offshore power plants generate 3 TWh more electricity. However, such small changes may be caused by limited precision of the model algorithm.

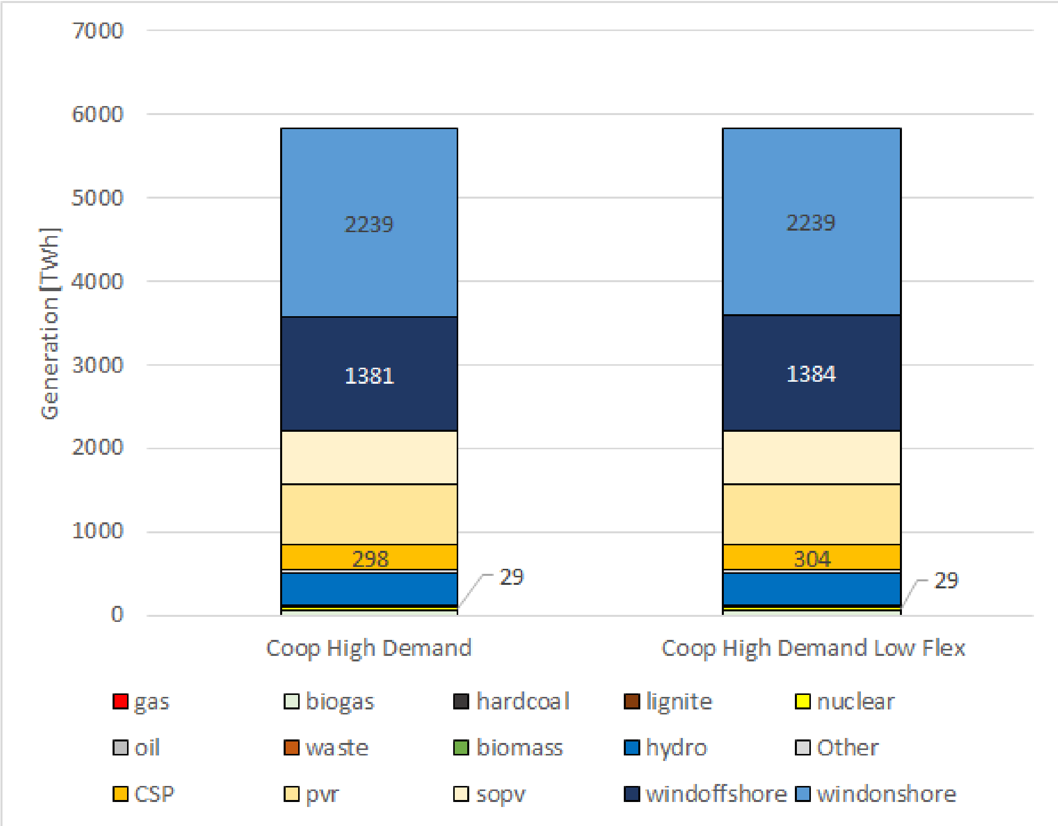

Figure 34: Generated electricity in the default "Cooperation – High Demand" scenario and the corresponding "Low Flexibility" variant in 2050 (other = geothermal, pvr = rooftop PV, sopv = utility scale PV)

As we have shown previously, the two scenarios differ only marginally. This is also represented in the distribution of installed CSP capacity per country shown in Figure 35. The installed capacity in Spain is slightly reduced from 34.5 GW to 33.8 GW, while in Italy it increases 26.1 GW to 27.9 GW. Also, in other countries, a marginal increase in capacity can be observed.

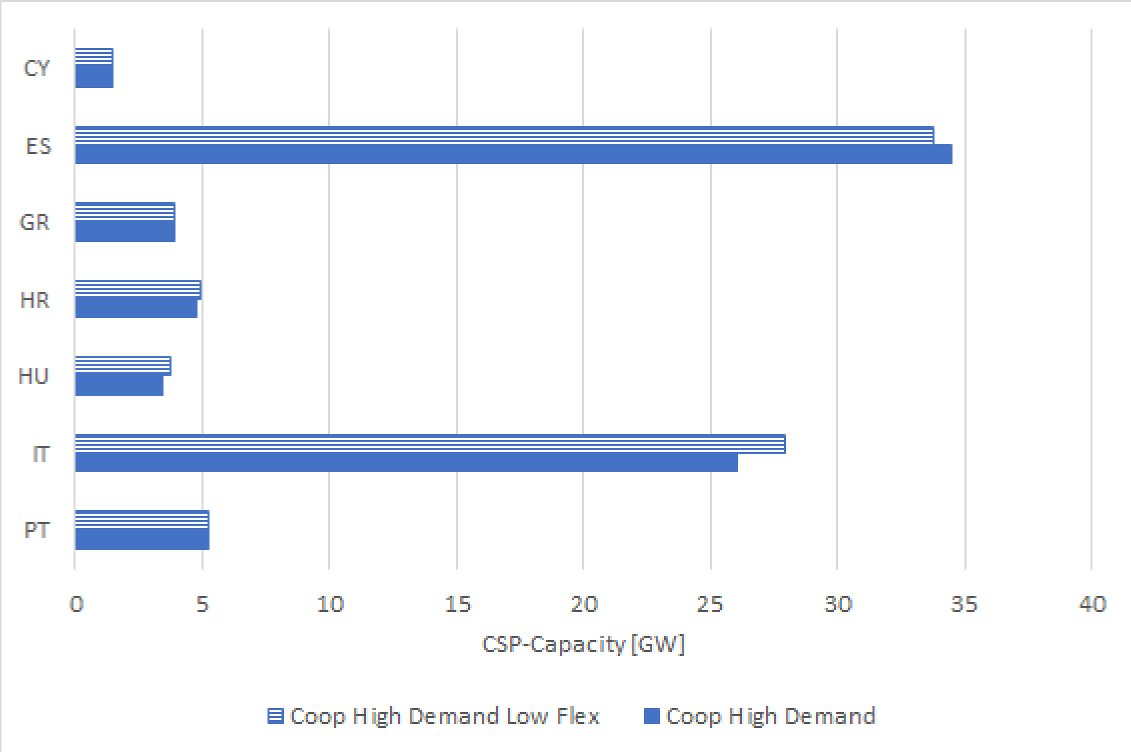

Figure 35: Installed CSP capacity per country for the scenario with low flexibility

The scenario with lower flexibility from sector coupling shows a low impact on the overall system results. This low impact is probably due to the fact that the chosen parameter changes in this scenario, concerning two of the flexibility options, are just too small. Therefore, the scenario results do not allow a qualified answer to the question, how sensitive the development of CSP is to the existence and magnitude of other flexibility options in an energy system based on a high share of fluctuating renewables.

In future research switching off more or even all flexibility options competing with CSP could be an interesting scenario. However, this may require considerable model changes and tuning of parameters in order to keep such an extreme scenario feasible, which is outside the scope of this project.

3.2.4 Lower climate ambitions (lower CO_2 price)

In this section, we compare the default “Cooperation – High Demand” scenario where carbon neutrality acts as guiding principle for 2050 with a scenario with lower climate ambitions, resulting in a lower CO_2 price post 2020 (and specifically post 2030). Table 6 lists the CO_2 price for the two scenarios. In the default “Cooperation – High Demand” scenario, the price for CO_2 rises up to 500 €/t in 2050. In the scenario with lower climate ambitions, the price for CO_2 reaches 225 €/t in 2050.

Besides the CO_2 price, there are two further differences between the “Cooperation - High Demand” scenario and the scenario with lower climate ambitions: the role of nuclear power and of biogas. In the scenario with lower climate ambitions, France keeps a relatively high share of nuclear power (50 % of the electricity demand, just as in the “National Preferences” scenario) and we do not prescribe a certain share of biogas used in gas power plants, but assume that the gas is always purely fossil (with corresponding lower price and higher CO_2 emissions).

Table 6: CO_2 price in the different scenarios in € 2010 per ton CO_2

Scenario	2030	2040	2050
Cooperation - High Demand (and all other scenarios)	75 €/t	125 €/t	500 €/t
Cooperation - High Demand Low Climate Ambition	25 €/t	75 €/t	225 €/t
Cooperation - High Demand (and all other scenarios)	75 €/t	125 €/t	500 €/t

In Figure 36, the remaining generation gap for Enertile is shown. In comparison to the “Cooperation – High Demand” scenario with high ambitions, the amount of CSP generation is reduced significantly from 298 TWh to 223 TWh. This reduction applies to all considered countries. In Spain, the generation gap diminishes from 138 TWh to 112 TWh. Furthermore, the generation gap in Italy decreases from 94 TWh to 51 TWh. The generation from gas is more than doubled with 151 TWh compared to 67 TWh. This is mainly due to the fact that in this special scenario we assume that the gas is always purely fossil (and not gradually replaced by biogas). In combination with the lower CO_2 price, this makes gas economically more attractive. Nevertheless, CSP still plays a substantial role in the European power system under these circumstances.

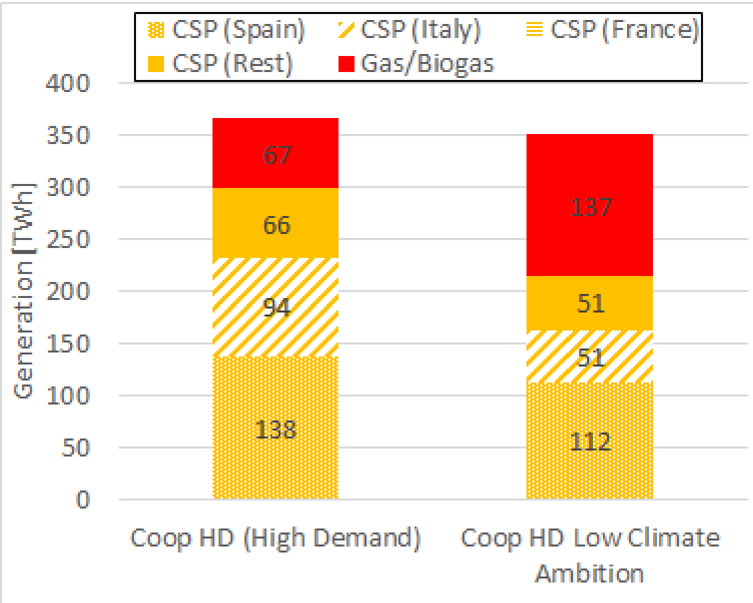

Figure 36: Generation gap, i.e. remaining amount of electricity for which the Enertile model can choose the supply technology (for EU28 in 2050) for the sensitivity of low climate ambitions. For the rest of the supply, the electricity generated per technology is determined by the Green-X model and given as a restriction to Enertile.

Figure 37 shows the installed capacity for the default “Cooperation - High Demand” scenario and the corresponding scenario variant assuming lower climate ambitions. The installed capacity of wind onshore and photovoltaics is slightly reduced. However, the amount of wind offshore capacity is reduced by more than 40 %. Furthermore, the installed capacity of CSP plants is diminished by almost 30 %. Due to lower climate ambitions, the installed capacity of CSP reaches only 4 GW in 2040 compared to 22 GW in the default “Cooperation – High Demand” scenario. The installed capacity of gas (here not biogas) plants rises from 105 GW to 180 GW in 2050. Another deviation between the considered scenarios is the installed capacity of nuclear power plants. In the default “Cooperation – High Demand” scenario, the capacity is 30 GW in 2030 and diminishes to 4 GW in 2050. In the scenario with lower climate ambitions, the capacity is 214 GW in 2030 and decreases to 74 GW in 2050.

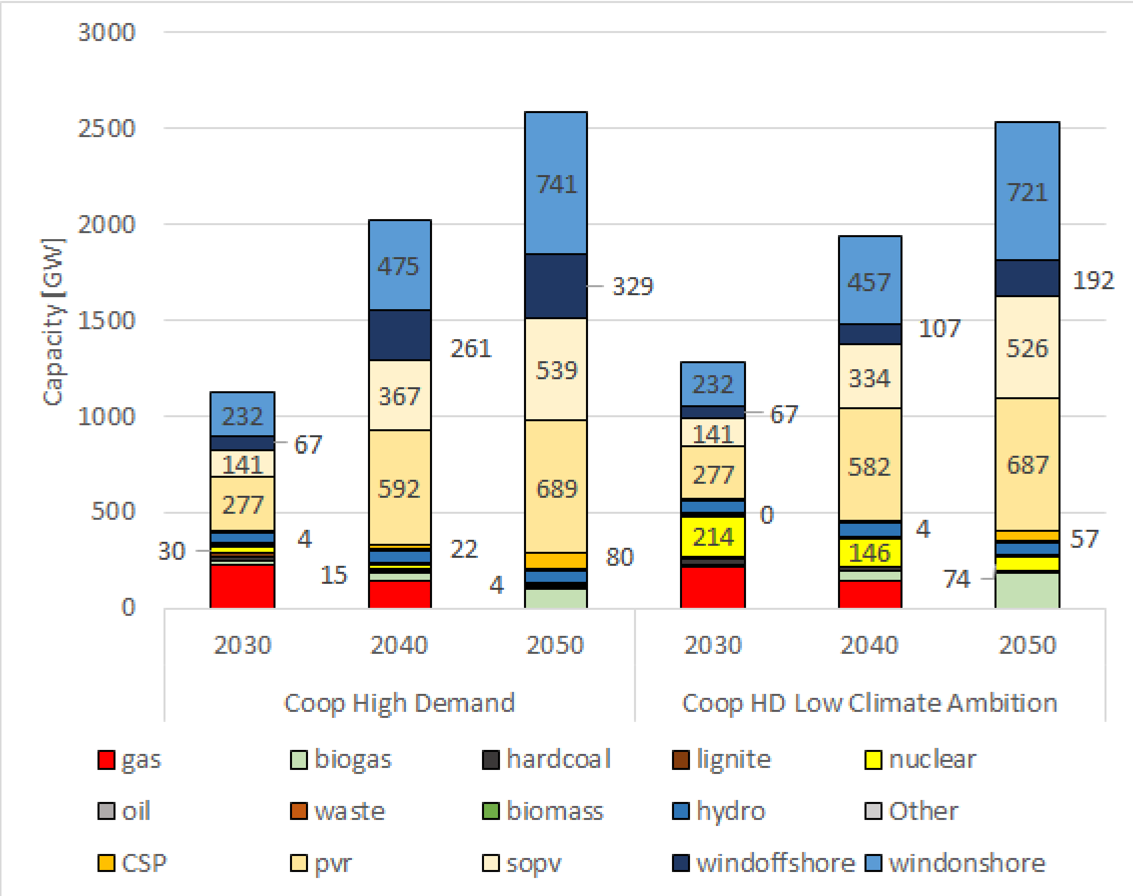

Figure 37: Installed Capacity for the default “Cooperation – High Demand” scenario and the corresponding variant with low climate ambition (other = geothermal, pvr = rooftop PV, sopv = utility scale PV)

The use of the installed capacity in Europe for the two scenarios is shown in Figure 38. As the full load hours are high for nuclear power plants, the higher nuclear capacities in the scenario with lower ambitions results in 470 TWh generated electricity in 2050 compared to 29 TWh in the “Cooperation

– High Demand" scenario. Due to the higher generated electricity by nuclear power plants, the amount of electricity generated by wind offshore power plants decreases to 829 TWh (from 1,381 TWh in the "Cooperation - High Demand" scenario). The electricity generated by CSP over the considered decades rises slower than in the "Cooperation - High Demand" scenario. Here, the generated electricity is 16 TWh in 2030, 84 TWh in 2040 and 298 TWh in 2050 whereas in the lower climate ambition scenario, the generated electricity is 0 TWh in 2030, 15 TWh in 2040 and 214 TWh in 2050.

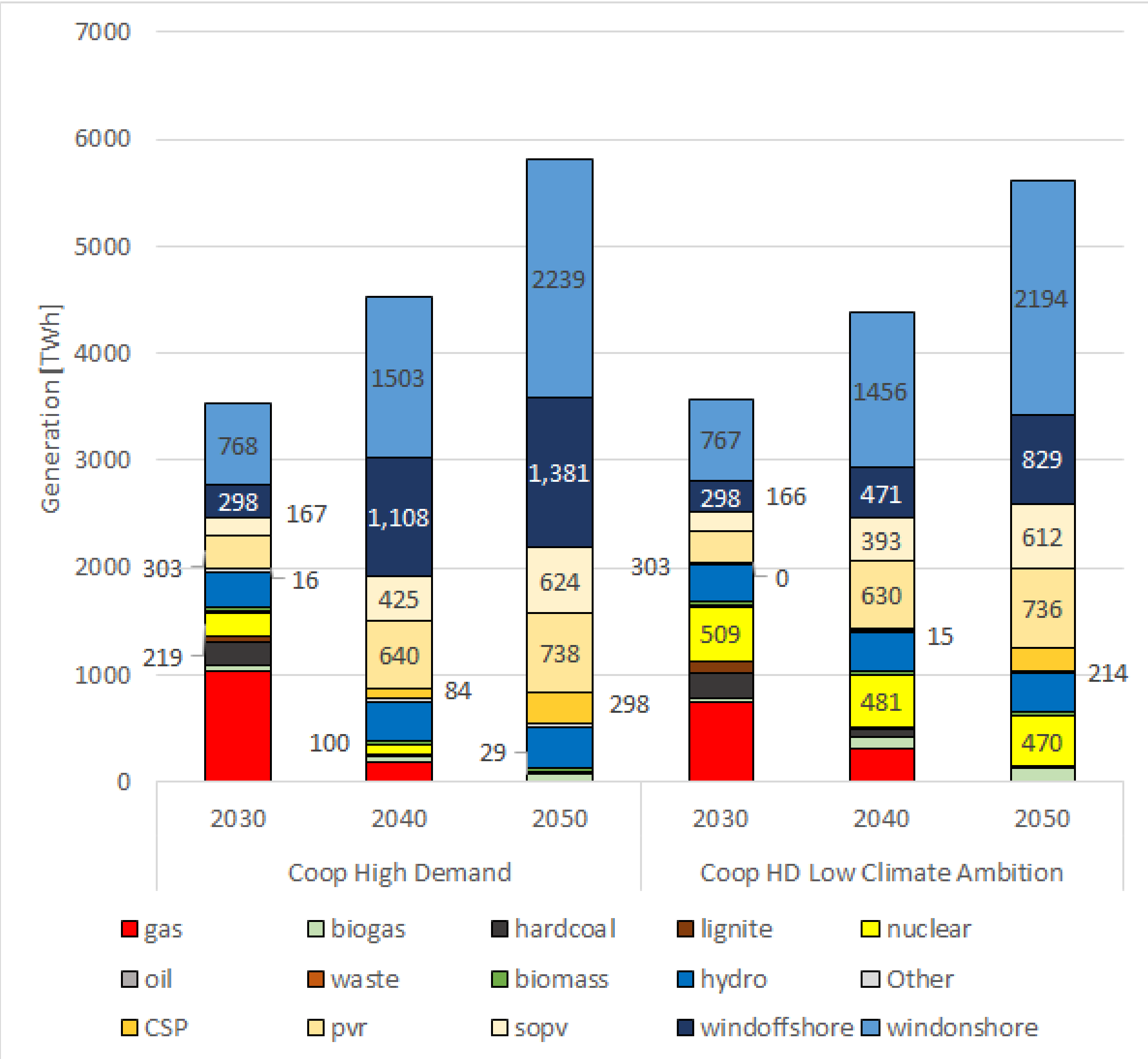

Figure 38: Evolution of the European electricity supply mix in the default "Cooperation - High Demand" and the corresponding variant with low climate ambition (other = geothermal, pvr = rooftop PV, sopv = utility scale PV)

The resulting CO_2 emissions per year from the generated electricity are shown in Figure 39. As the climate ambitions are the same for all calculated scenarios except the scenario with lower climate ambitions, the "Cooperation – High Demand" and "National Preferences - High Demand" scenario represents all other scenarios in their respective pathway. In 2030, the CO_2 emissions of the scenario with lower CO_2 costs are lower than in the "Cooperation - High Demand" scenario. This is due to the higher amount of nuclear power plants and their emission-free electricity generation. In the high ambition scenarios, the aim is climate neutrality in 2050. Therefore, the CO_2 emissions are reduced significantly from 2030 on. In 2040, the CO_2 emissions are 123 Mt for the "Cooperation - High Demand" respectively 121 Mt for the "National Preferences" and 376 Mt for the scenario with lower ambitions. These emissions are further reduced to less than 0.5 Mt in 2050 for both high ambition scenarios, while in the scenario with lower ambition the remaining emissions in 2050 are 111 Mt.

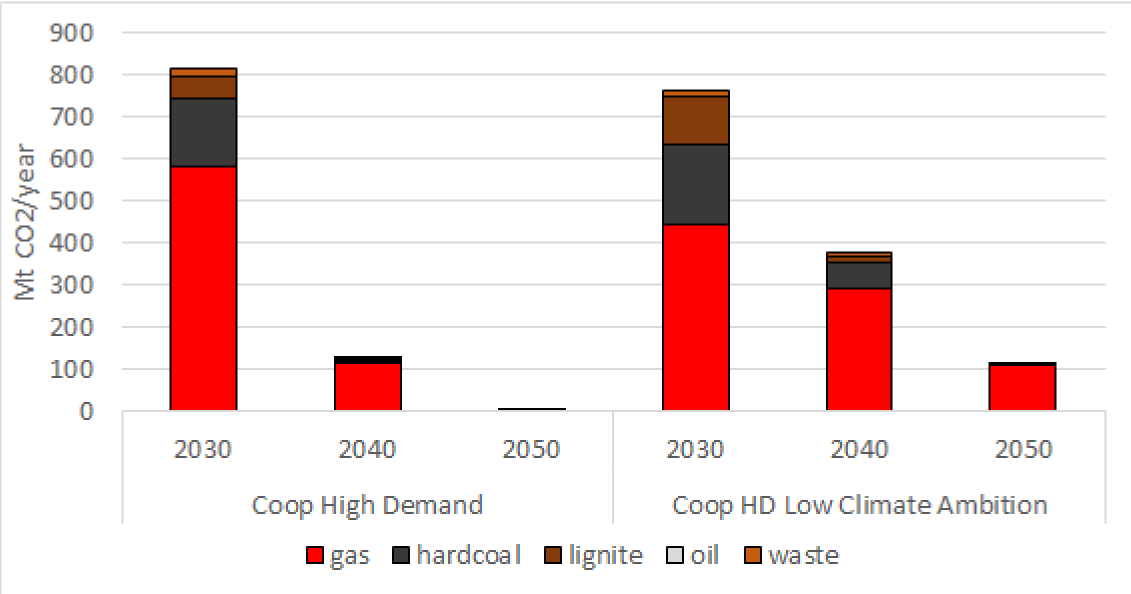

Figure 39: CO_2 emissions in the default "Cooperation – High Demand" scenario and the corresponding variant with low climate ambition

The installed capacity of CSP decreases by 84 GW in the scenario with lower climate ambitions. The distribution of installed CSP capacity per country is shown in Figure 40. This reduction is particularly evident in Italy and Spain where the installed capacity is reduced by 11.5 GW and 6.5 GW, respectively. However, in other countries like Cyprus and Greece, the CSP capacity does not decrease for lower climate ambitions.

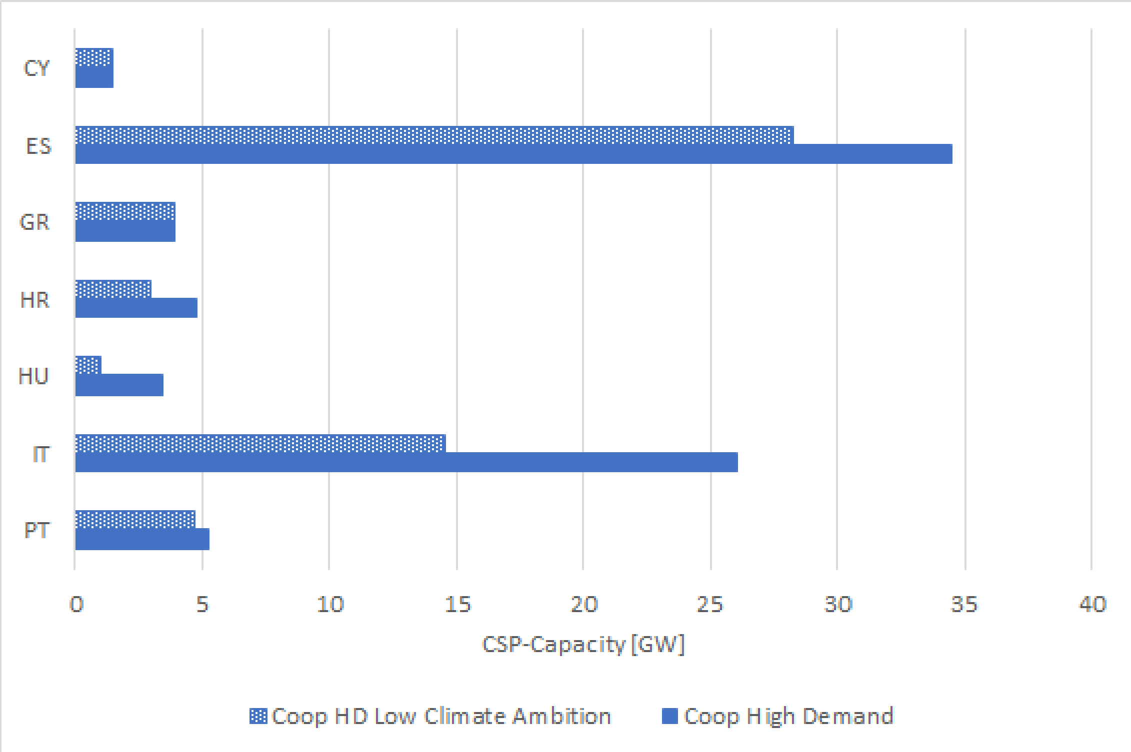

Figure 40: Installed CSP capacity per country for the default "Cooperation – High Demand" scenario and the corresponding variant with low climate ambition

Overall, the scenario with lower climate ambitions shows that the role of CSP diminishes when lower CO_2 prices allow the use of dispatchable fossil (gas) power plants. But under the given cost assumptions (with lower but still rather high CO_2 price and optimistic CSP cost development), there is still a relevant place for CSP in the energy system.

3.2.5 CSP in all calculated scenarios

In the following section, we compare all calculated sensitivity scenarios in order to draw conclusions with respect to the factors driving the expansion of CSP capacities in the future. First, we focus on the generation gap for each scenario. Second, we show the distribution of CSP capacity per country for all scenarios.

The generation gap for the calculated scenarios varies from 140 TWh to 750 TWh. This is due to the different defined scenario conditions discussed in the individual sections. These conditions are represented by the results of Green-X which function as a restriction for Enertile. Furthermore, the specifications regarding nuclear power plants vary between the scenarios. Additionally, the electricity demand in Enertile differs between the scenarios as the hydrogen demand, curtailment and grid losses vary. In two scenarios, the generation of electricity by wind offshore power plants is not restricted (only a minimum electricity generation is required). The share of CSP varies between the scenarios. In the "National Preferences - High Demand" scenario, CSP has the highest share with 91 %. In the scenario with limited grid and additional wind offshore capacities, the share is lowest with 27 % for the “National Preferences” scenario. In the “Cooperation – High Demand” scenario, the remaining gap is 366 TWh and in the “National Preferences – High Demand” scenario, this gap diminishes to 280 TWh. This is due to additional capacities of nuclear power plants.

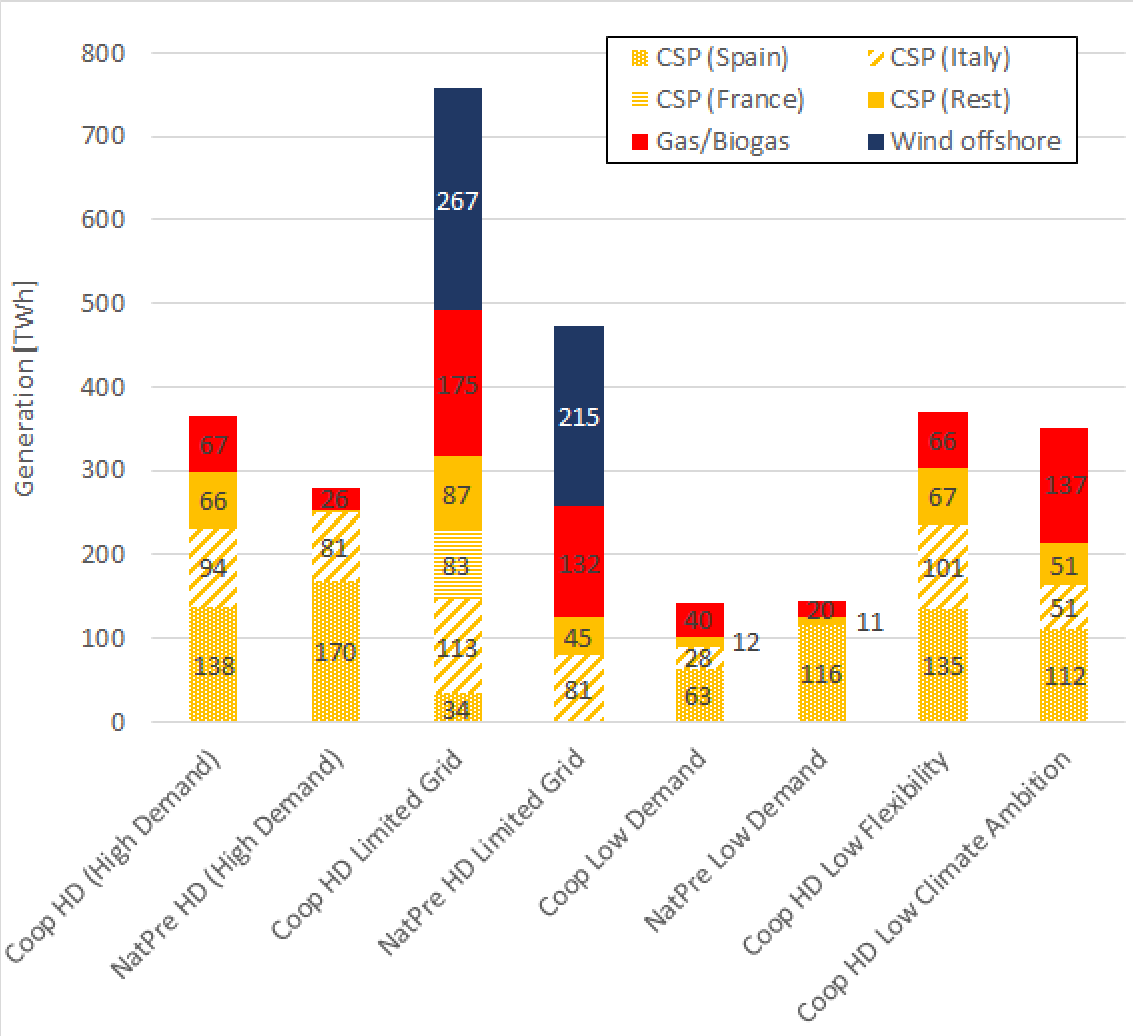

Figure 41: Generation gap, i.e. remaining amount of electricity for which the Enertile model can choose the supply technology (for EU28 in 2050) for all scenarios. For the rest of the supply, the electricity generated per technology is determined by the Green-X model and given as a restriction to Enertile.

The following figure shows the generation of CSP power plants in the considered countries. For reasons of simplicity, only countries with a CSP electricity generation are shown. In the scenarios with limited grid, Austria, Czech Republic and Slovakia generate electricity from CSP as well (see Figure 26). But due to the very special circumstances in the scenario setup leading to the CSP expansion in these countries, they are not considered here (because CSP plants in Central Europe are not very likely to be built in the real world). The highest amount of CSP electricity is generated in Spain and Italy for the scenarios “Cooperation - High Demand” and “National Preferences - High

Demand". In the scenarios with limited grid, the amount of installed capacities in Spain diminishes respectively goes to zero. Here, other countries like Hungary and Croatia expand the installed CSP capacity and therefore the generation. In the low demand scenarios, the CSP generation in Italy collapses for the "National Preferences" scenario.

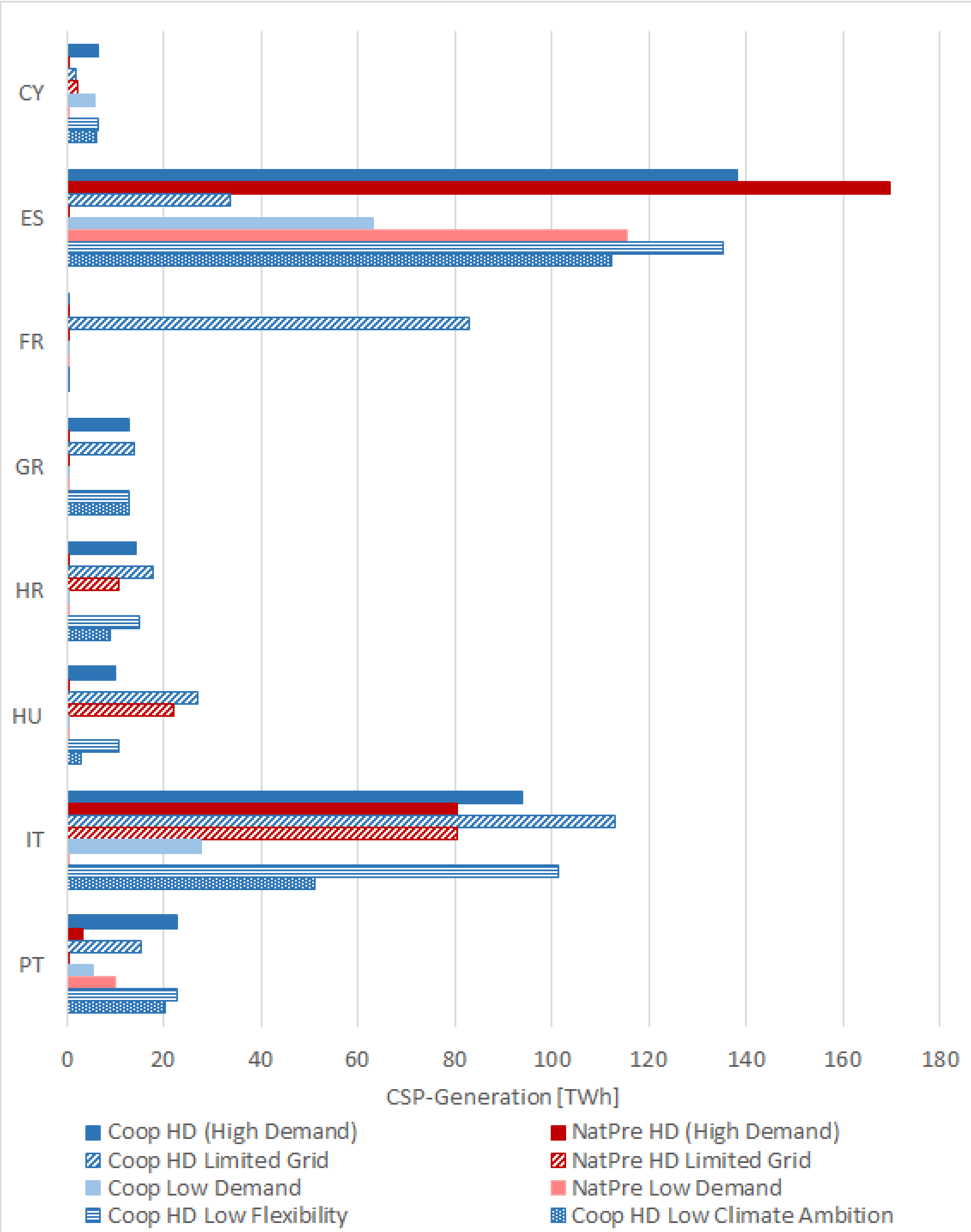

Figure 42: Distribution of electricity generation from CSP per country and pathway in 2050

![MUSTEC logo]

Figure 43 depicts the distribution of CSP capacities per country and calculated scenario. The allocation is similar to Figure 42. Therefore, we will focus on the different scenarios and their particularities in the subsequent description.

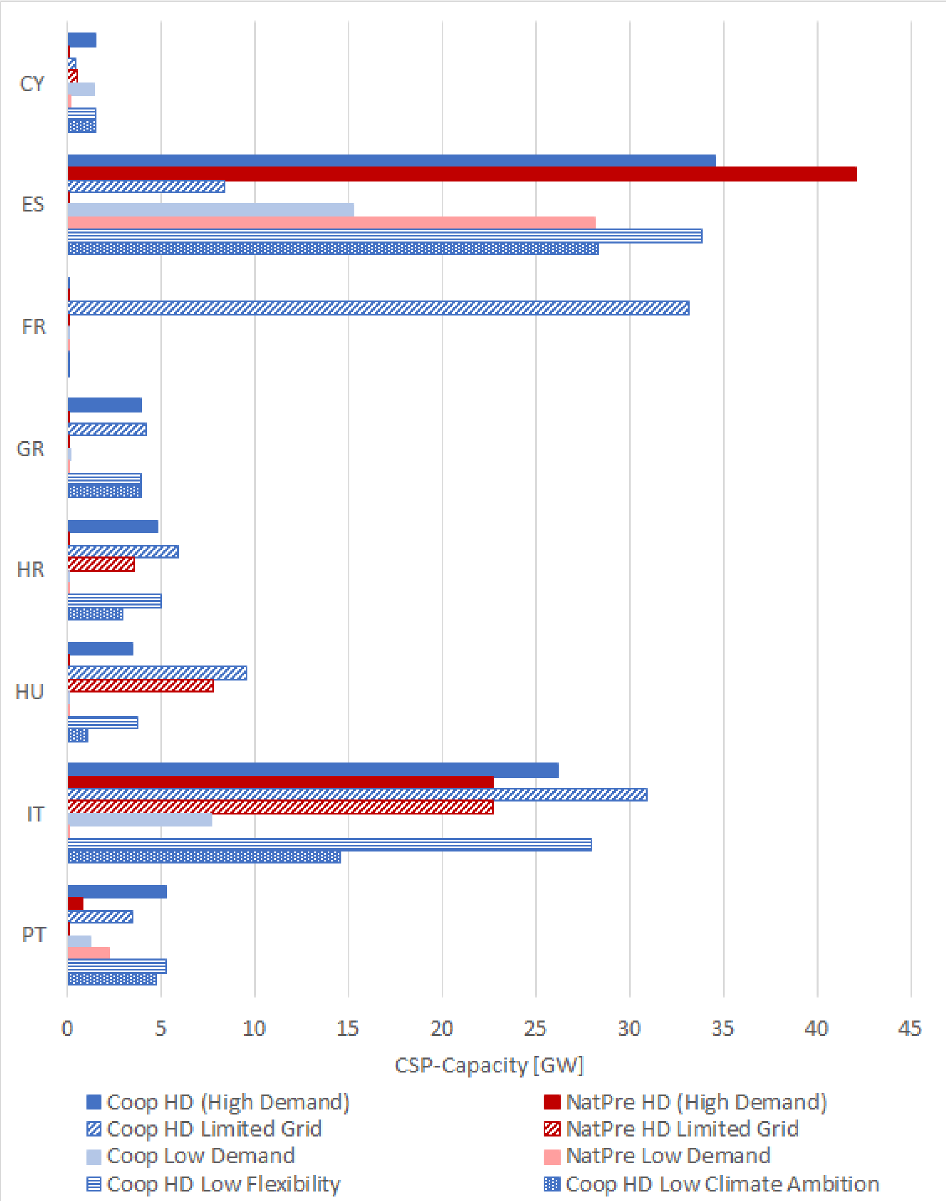

Figure 43: Distribution of CSP capacity per country and pathway/scenario in 2050

"Cooperation - High Demand" **and** ***"National Preferences - High Demand"***

In the "Cooperation - High Demand" scenario, CSP capacities are installed in all Southern European countries. The capacity is highest in Spain and Italy with 34.5 GW respectively 26 GW. In comparison, the installed capacities in the corresponding "National Preferences" scenario are concentrated in

Spain, Italy, and Portugal. In these countries, the full load hours of CSP are highest and therefore, the generation of electricity is less expensive.

“*Cooperation - Low Demand*” and “*National Preferences - Low Demand*”

The remaining generation gap is lowest in these scenarios. Therefore, in the “Cooperation” scenario with “Low Demand”, the installed capacities of CSP are significantly reduced. Furthermore, the only countries with installed capacities are Spain, Portugal, Italy and Cyprus. These differences are also noticeable in the “National Preferences Low Demand” scenario. Here, the capacity of CSP in Italy is reduced to 0. As the demand is lower and other (cheaper) technologies are sufficiently available, CSP is no longer an option in Italy.

“*Cooperation - High Demand - LimGrid*” and “*National Preferences - High Demand - LimGrid*”

In the “Cooperation - High Demand” scenario with “Limited Grid” expansion, the capacities in Italy rise up to 30 GW. However, in Spain and Portugal the capacities decrease drastically. This is due to the location of these countries, as they are located at the edge of Europe and are only connected to France by a transmission line of 6.5 GW. This is a reduction in transmission capacity of 83 % compared to the other scenarios. Simultaneously, the capacity of CSP is rising in other countries like Hungary and Croatia. Especially the CSP capacity in France is extended. Here, the capacity rises from zero to 33 GW. As there is no nuclear power in this scenario, the import gap of CSP electricity from Spain has to be filled. Furthermore, these scenarios differ from other scenarios by the possibility of additional offshore wind expansion. Therefore, countries with access to the sea and low CSP potentials can increase their wind offshore capacities. In the “National Preferences” scenario, the capacity in Italy does not change compared to the “National Preferences - High Demand” scenario. But the installed capacity in Spain and Portugal falls to zero. However, in this scenario nuclear power plants are enabled. This leads to a lower overall installed capacity of CSP. Therefore, the loss of CSP capacity in Spain and Portugal is not compensated by the expansion of CSP in other countries. Only in Hungary and Croatia the CSP capacities increase compared to the “National Preferences - High Demand” scenario.

“Cooperation – High Demand - Low Flexibility”

In the “Cooperation” scenario with “Low Flexibility” from sector coupling, the CSP capacities and generation differ only marginally from the main scenario.

“Cooperation – High Demand - Low Climate Ambition“

In this scenario, the climate ambition and consequently also the underlying future CO_2 price is significantly lower than in the other scenarios. Therefore, the generation of electricity with gas and other fossil fuels is not as expensive. As a result, the share of gas is twice as high as in the “Cooperation - High Demand” scenario. Due to this, the remaining generation gap for CSP diminishes. This is also reflected in the installed CSP capacity. In most European countries the CSP capacity diminishes, especially in Italy and Spain.

3.3 Conclusions on the Enertile modelling results

At the end of this chapter presenting the scenario results obtained with the energy system optimization model Enertile, we are able to draw first conclusions.

Overall, it has to be stated that the scenario results for CSP (aggregated over the EU) are not as clear as one might have expected in advance. This is because the modelled expansion of CSP is influenced by the individual circumstances within each country, which may lead to opposite trends in different countries within the same scenario. Furthermore, the result on the EU level is strongly driven by a small number of countries, especially Spain and Italy (but also France in one scenario). An important difference between these two dominating countries seems to be that CSP in Italy is mainly used for covering the relatively high domestic electricity demand, while Spain exports most of its electricity from CSP. Therefore, lowering the electricity demand has a higher impact on CSP in Italy, while limiting the export options through a restricted power grid strongly reduces CSP in Spain.

Concerning the question, whether cooperation among European countries leads to higher expansions of CSP power plants, our modelling results are ambiguous (see Section 3.2). While in the case of very high electricity demand CSP generation is somewhat higher in the “Cooperation” scenario than in the “National Preferences” scenario, this tendency is reversed in the case of lower demand. However, a high electricity demand is more probable in a world with very ambitious decarbonisation targets, which may enhance the perspectives of CSP.

In this context, a factor that certainly has an impact on CSP, is the role of nuclear power in the future European energy system. In scenarios with a higher share of nuclear power (due to France’s national preferences), the remaining generation gap (between the total electricity demand and the supply by other technologies) diminishes, thereby reducing the share of CSP.

Our results indicate that a higher electricity demand increases the generation gap for CSP (see Section 3.2.2). Because CSP is more expensive than other renewable technologies, CSP capacities are increasingly installed when the potentials of other renewable technologies like wind and PV are already exploited to a higher degree.

The question, how sensitive the development of CSP is to the existence and magnitude of other flexibility options in an energy system based on a high share of fluctuating renewables, cannot be answered on the basis of the calculated scenarios. This is because the chosen parameter changes, concerning two of the flexibility options, were too small and did not have a significant impact on CSP.

Sufficiently high climate ambitions are another enabler of CSP development (see Section 3.2.4), because they hinder the use of fossil power plants (first, as a backup of fluctuating renewables and a second, as supply of electricity demand exceeding the realizable potential of other renewables). Hence, CSP with its additional advantage of dispatchability becomes more important under such conditions.

As expected before, a highly developed transnational power grid is an ambivalent factor for the development of CSP (see Section 3.2.1). On the one hand, due to their peripheral location, especially Spain and Portugal depend on a strong power grid interconnection to the rest of Europe in order to export larger amounts of electricity from CSP. This dependency on the power grid might decrease when including the conversion of renewable electricity e.g. to hydrogen with subsequent international trading (an option excluded in the Enertile model). But due to the higher cost of CSP, probably rather wind or PV would be used for hydrogen production. On the other hand, a more limited power grid interconnection can favour the use of CSP in some countries, because it hinders the import of electricity from neighbouring countries and reduces the system flexibility provided by the grid, thereby increasing the need for dispatchable CSP.

4 Results from the Energy Policy Analysis - Implications for and Impacts of dedicated Support Policies for CSP and other Renewables

This chapter is dedicated to inform on **results from the prospective energy policy analysis dedicated to CSP and other RES technologies, and on the role of RES cooperation to facilitate the uptake in forthcoming years**. The main tool used for that purpose is TU Wien's Green-X model, a specialised energy system model offering a sound coverage of support instruments for renewables as well as on the available resources and corresponding cost of individual RES technologies within Europe.

As outlined in section 2.2, within the integrated model-based analysis Green-X has been complemented by the Enertile model, serving to analyse the interplay between demand and supply in the power system of tomorrow. Enertile has been used to identify the gap in system flexibility that needs to be covered by CSP (and other options) for safeguarding supply security in future years when variable renewables like wind and solar PV times are the dominant generation assets and when fossil fuel based dispatchable generation assets are no longer viable options for doing so. For results on that part of the analysis we refer to the previous chapter.

Below we start with a brief recap on the role of renewables in Europe's electricity system of tomorrow. Complementary to the insights gained from the power system analysis (cf. section 3.1.1 and 3.1.2), we take a closer look at the uptake of renewables over time, and on how that is spread across countries and technologies. Subsequently we indicate the investments necessary for achieving that uptake in forthcoming decades, and we analyse how that may differ by scenario and which parameters are key influencer in this respect. A large part of the analysis is then dedicated to assess the energy policy needs and the corresponding impacts, informing on expected cost trends and on how large the financing gap may be that needs to be covered by dedicated support for CSP and other RES technologies. We thereby inform on the support required in specific and absolute terms, and on how the uptake can be facilitated by intensified cross-border RES cooperation.

Please note that in general, and if not stated otherwise, all figures and data refer to the aggregated EU28 level (incl. the UK). A broad set of scenarios concerning the future development of CSP and other RES technologies has been assessed in the course of the integrated model-based analysis within MUSTEC as defined in section 2.3 of this report. Subsequently we generally focus on the key policy pathways that stem from the in-depth assessment of policy discussions and trends at the national and European level undertaken in prior within MUSTEC (cf. Lilliestam et al. (2019)) and complement these with sensitivity cases concerning key input parameter and assumptions in accordance with the topical focus. With the exception of the sensitivity scenario "Cooperation – High Demand – Low Climate Ambition" all scenarios reflect the EU's attempt to head towards carbon neutrality by 2050, implying for the electricity sector a strong growth in demand that comes along with increased sector-coupling (with heating & cooling and transport) and a carbon-neutral supply by 2050 that heavily builds on renewables, complemented by nuclear power within certain countries (in accordance with domestic policy preferences, specifically in the "National Preferences" scenario).

4.1 The uptake of renewables – a closer look at the diffusion of RES technologies

Below **we take a closer look at the according to our modelling expected uptake of renewables in Europe's electricity sector**. We thereby complement the explanations and insights provided for the power system analysis undertaken by the Enertile model as provided in chapter 3 of this report.

The basket of scenarios taken up here includes the two key policy pathways, namely "Cooperation (Coop) – High Demand" and "National Preferences (NatPre) – High Demand". Both scenarios differ from a conceptual viewpoint for the four large EU MSs Germany, France, Italy and Spain whether their own (major) policy preferences are considered (i.e. "National Preference") or not – if not, all EU MSs would take a fully collaborative approach that facilitates cross-border cooperation and that leads to a least-cost allocation of RES investments across the EU28 ("Cooperation"). These key policy pathways are then complemented by two other scenarios that differ in their RES ambition: on the one hand, a low climate ambition is assessed as sensitivity case to the default "Cooperation" scenario, and, on the other hand, we also include below the "Grassroots" scenario that aims for even stronger RES ambitions in the short- to mid-term than in all other scenarios.

As starting point, Figure 44 offers **a comparison of the historic and expected future development of electricity generation from RES at EU28 level** according to the assessed scenarios. Complementary to that, Figure 45 indicates the corresponding RES shares in gross electricity consumption, again at EU28 level for the selected scenarios assessed.

If we look back in time, we see that more than a doubling of RES deployment has been achieved throughout the past thirteen years: electricity generation from RES has increased from 489 TWh in 2005 to 1,050 TWh by 2018 – in relative terms this corresponds to an increase of the RES share from 14.8% (2005) to 32.1% (2018). This impressive trend needs to be maintained if we take a look at the expected RES share developments in future years: taking deep decarbonisation as our overall guiding principle implies an increase of the RES shares to about 56.4% by 2030, and to at least 90.1% by 2050. In absolute terms the accompanying strong growth in electricity consumption imposes even a strengthening of RES developments in future years compared to the historic record. Electricity generation from RES needs to at least double within the next twelve years and to more than quadruplicate until 2050.

Concerning the strong RES uptake anticipated, the boundaries of what is, from a modelling perspective, classified as feasible can be seen in the "Grassroots" scenario: here Green-X modelling indicates that achieving carbon neutrality already by 2040 could work out for the electricity sector only, but for the overall energy sector this appears as "mission impossible" if one considers the differences in market readiness across the EU, and also the restrictions in resource availability and, even more challenging, limits in social acceptance for key RES technologies like wind and solar PV.[11]

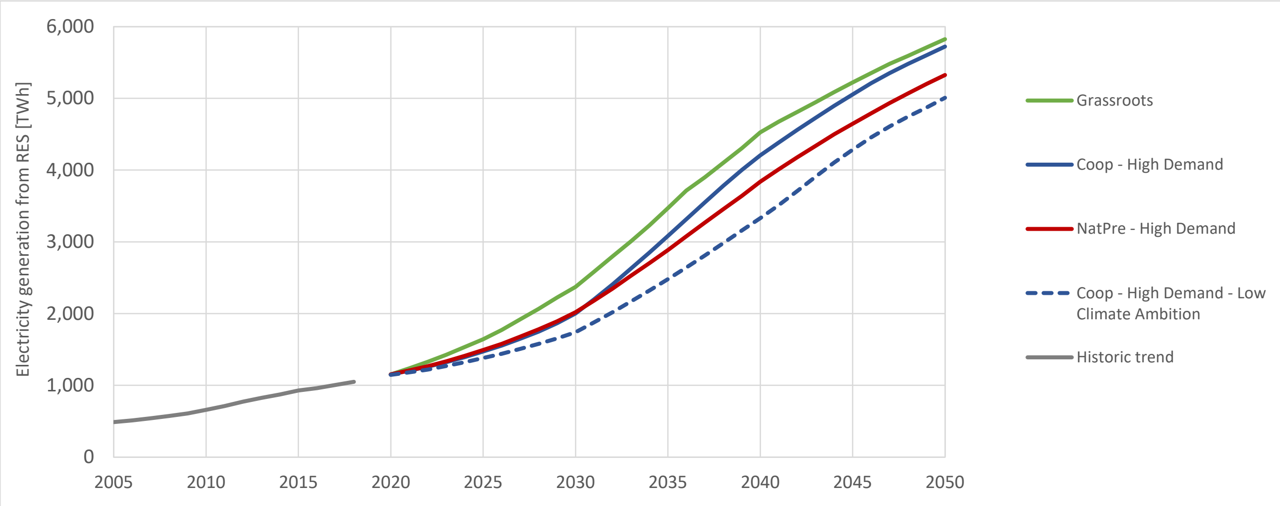

Figure 44: Comparison of the development of electricity generation from RES at EU28 level up to 2050 according to selected assessed scenarios (Source: Green-X modelling)

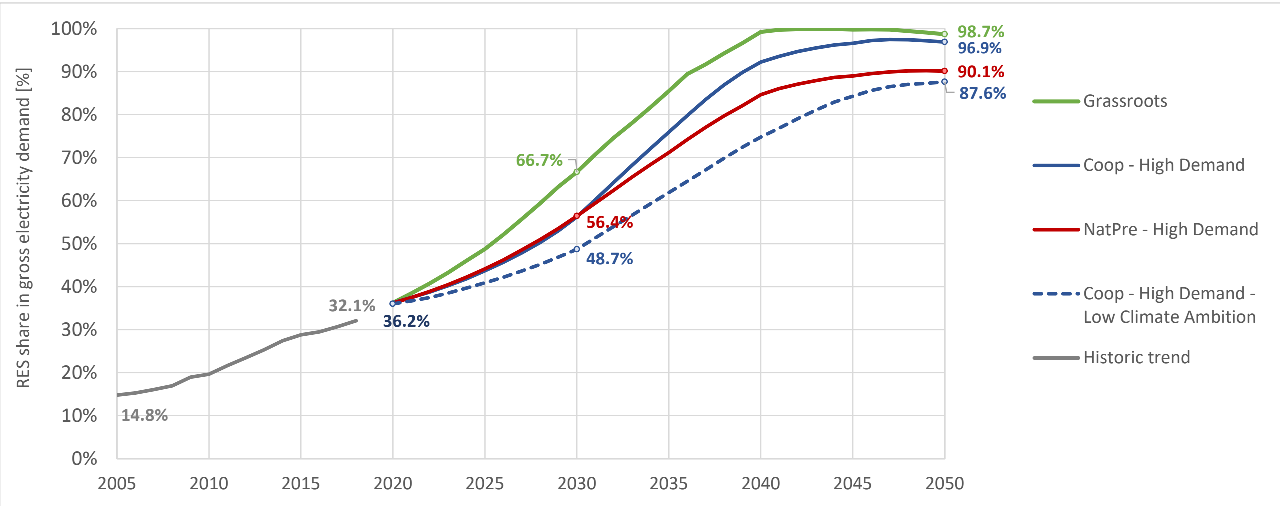

Figure 45: Comparison of the development of the overall RES share in gross electricity demand at EU28 level up to 2050 according to selected assessed scenarios (Source: Green-X modelling)

[11] Due to the failure to meet the given policy target, we have not taken up the "Grassroots" scenario further within our model-based assessment since it would provide limited additional insights on the overall objective of our analysis, aiming to identify the gap that can, or needs to be filled by CSP.

Further insights on the anticipated **trends in technology-specific developments** are given in Figure 46 below. These graphs provide a technology breakdown of expected future electricity generation from RES at EU28 level for two key policy pathways, namely the "Cooperation – High Demand" scenario (Figure 46, left) and the "National Preferences – High Demand" scenario (Figure 46, right). Please note that the technology-breakdown comprises only the modelled future expansion of RES, in order to provide further insights on that what comes new to the power system in future years.[12] The bulk of electricity generation that stems from already established RES plants (installed until 2020) is marked in grey at the bottom of each graph. This share is declining over time and by 2050 only hydropower facilities that typically have the longest technical lifetimes among all RES (and conventional) technologies are expected to remain in the power system by that point in time.

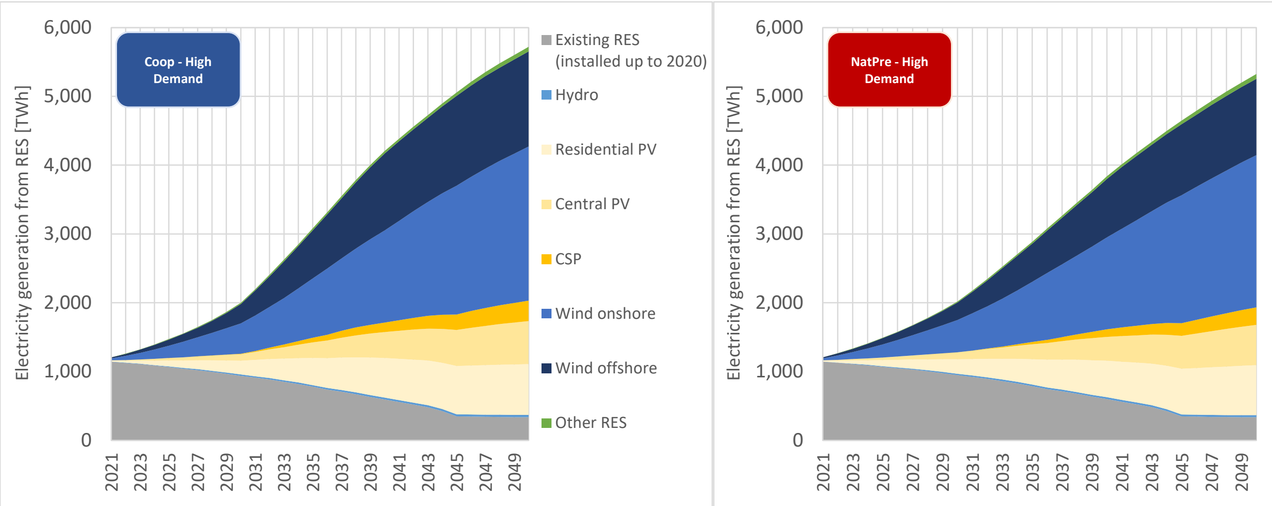

Figure 46: Technology breakdown of the development of electricity generation from RES up to 2050 at EU28 level according to the "Cooperation – High Demand" (left) and the "National Preferences – High Demand" scenario (right) (Source: Green-X modelling)

A comparison of the technology trends among the two illustrated scenarios indicates the following aspects:

- Apparently, **onshore wind energy dominates the picture** – both by 2030 and by 2050 the largest share of newly established RES-based electricity generation will come from this particular technology. Differences in deployment among the two exemplified scenarios are comparatively small – i.e. in the "Cooperation – High Demand" scenario post 2020 newly established wind onshore power plants generate 441 TWh by 2030 and 2,293 TWh by 2050, whereas in the "National Preferences – High Demand" scenario that technology reaches a

[12] This distinction between newly installed (post 2020) and already established existing (until 2020) power plants is consistently applied in all forthcoming sections on investments and support. The technology-specific information provided in that way complements consequently also the technology insights discussed already in the power system analysis within chapter 3.

slightly higher deployment by 2030 (471 TWh) but a to a small extent lower one by 2050 (2,214 TWh).

- **Offshore wind energy is the second largest contributor to the overall RES uptake in future years**. Here differences across the scenarios are larger: in the “Cooperation – High Demand” scenario electricity generation amounts to 1,381 TWh by 2050, and the corresponding figure for the “National Preferences – High Demand” scenario is 1,109 TWh. The decline by about 20% indicates that offshore wind may act as marginal generation option which is consequently less deployed if the overall RES ambition is slightly reduced.[13]
- **Apart from wind energy, photovoltaics is the other key technology in future years**. Modelling indicates a significant increase in PV deployment. Post 2020 newly established residential PV systems are expected to generate 738 TWh by 2050 in the “Cooperation – High Demand” scenario, and slightly less (727 TWh) in the “National Preferences – High Demand” scenario. Central PV systems rank next, achieving slightly lower but among the two scenarios comparatively similar levels of deployment.
- **Electricity generation from CSP is the fifth largest contributor to RES generation considering in future years newly established power plants**. As outlined in detail in the power system analysis (cf. chapter 3) CSP in conjunction with its internal storage acts as key flexibility provider to power system to safeguard operation and the necessary match between supply and demand. In contrast to the policy-driven deployment of variable RES within our modelling the deployment of CSP is derived directly from the power system analysis and is consequently discussed in detail in chapter 3 of this report.
- Other technologies like hydropower, geothermal electricity, tidal stream or wave power show only comparatively minor contributions by 2030 and by 2050 under the underlying framework conditions where least-cost options are prioritised in modelling.
- Similar to hydropower etc. also biomass is expected to provide only a limited contribution to future electricity generation. Here the approach taken in our modelling appears predeterminant: With the exception of biowaste, the deployment of biomass (similar to CSP) is determined by the power system analysis, specifically the “gap analysis” concerning the required system flexibility to cope with high shares of variable renewables, done by use of the Enertile model (cf. chapter 3). To recap briefly, within the Enertile model biomass, and thereby specifically biogas / renewable gas, stands in competition to other flexibility options (like CSP, storage via batteries, hydro or hydrogen etc.). As stated above, in consequence,

[13] The overall RES ambition in the “Cooperation” scenarios is slightly higher than in the “National Preferences” scenarios since in the latter electricity generation from nuclear power is stronger (in accordance with the national preference of France).

according to this approach taken in modelling, the overall biomass use in the electricity sector is comparatively low in future years – also compared to initial results derived by Green-X within the energy policy analysis only. This leaves room for biomass use in industry, transport and other sectors where options are more limited when moving towards climate neutrality.

Figure 47: Comparison of the historic and expected future (2030, 2040, 2050) country-specific RES shares in corresponding gross electricity demands according to selected scenarios (Source: Green-X modelling)

Next, Figure 47 (above) provides **an overview on the expected country-specific RES deployment in the electricity sector**. More precisely, this graph allows for a comparison of the historic and the expected future (2030, 2040, 2050) country-specific RES shares in corresponding gross electricity demands according to selected scenarios. The basket of scenarios included in this comparison are the two distinct key policy pathways "National Preferences" and "Cooperation", both represented by their (default) scenario of high electricity demand growth, and a sensitivity scenario of the latter one, assuming a more limited expansion of the cross-border transmission grid across the EU (i.e. "Cooperation – High Demand – Limited Grid"). Please note that details on the modelled country-specific RES deployment for all assessed scenarios can be found in our modelling database, openly accessible via https://zenodo.org/record/3905045.

Key results derived from the comparison of country-specific RES deployment are:

- **In the past (2010) and currently (2018) strong differences in demand-related RES shares are observable across countries**. Despite the assumed transformation of the electricity sector towards carbon neutrality by 2050, **strong differences in country-specific RES deployment are also applicable under all assessed scenario in future years**. This also holds for 2050 when renewables reach a high demand share at EU level, ranging from ca. 90% ("National Preferences", assuming a still strong nuclear deployment in France) to about 97% ("Cooperation", assuming no built-up of new nuclear across the EU).
- If we take a closer look at 2050, it can be seen that the **differences in RES shares across countries are smallest under a more limited expansion of the cross-border transmission grid** (cf. scenario "Cooperation – High Demand – Limited Grid"). This appears logic, since exchange of electricity across countries is then more limited and, in consequence, countries have to facilitate a stronger domestic RES expansion, including resources and sites that are economically less viable compared to abroad under the "ideal" situation of a well-interconnected EU electricity market.
- By 2050 the list of countries with a significantly higher domestic RES generation than the domestic demand under all illustrated scenarios includes Croatia, Estonia and Latvia. In these countries RES shares larger than 150% are expected for 2050. Denmark, Ireland, Lithuania and Spain can be added to that list of host countries from a RES cooperation perspective, if the cross-border transmission grid will be expanded as it appears economically optimal from a modelling perspective.[14] Greece, Poland, Portugal, Sweden and the UK are among those countries that achieve an oversupply of RES generation compared to domestic demand at a yearly balance under all discussed scenarios – but in these countries RES shares are smaller in magnitude compared to above. Cyprus may also act as host from a RES cooperation

[14] For details on that aspect we refer to the explanations provided in the corresponding section of the power system analysis (cf. section 3.2.1).

perspective, but only if the European perspective will be predominant in the future, meaning that the “Cooperation” route will be followed where “National Preferences” are less of influence.

- Austria, Bulgaria, Finland, Italy and Romania are countries that achieve an even balance between RES generation and overall domestic electricity demand. By 2050 one can expect for these countries that RES supply is around or slightly below domestic demand. The situation differs here slightly among assessed scenarios: for Austria, Finland and Italy a higher RES share can be expected if the “Cooperation” pathway is followed whereas in Bulgaria and Romania the opposite trend can be seen.
- Countries that have to heavily rely on (RES-based) electricity imports by 2050 are Belgium, Czechia, Luxembourg, Malta, Slovakia and Slovenia – i.e. in these countries the 2050 RES share is (well) below 75%. Hungary and Netherlands have to be added to that list for the default cases where grid expansion is not seen a[15]s constraint. That means, in turn, these countries have the resources to expand RES generation in future years – but certain sites or technologies would become economically attractive only if cross-border electricity is constraint.
- A comparison of 2050 RES shares in France and Germany indicates that in these countries the RES share is lowest in the “National Preferences” scenario. In Germany the differences are however less significant – i.e. in the default “Cooperation” scenario a RES share of 75% is achieved by 2050 whereas in the “National Preferences” scenario it amounts to 74%. The highest RES share (87%) is applicable under the case of limited grid expansion, indicating that, similar to Hungary or Netherlands, domestic resources are available but at (slightly) higher cost compared to abroad. For France our results indicate that the national energy policy preference puts a limit to the RES expansion – but not the economics.

4.2 Investments in RES technologies

Within this section **we indicate the investments required to achieve the amounts of electricity generation from RES in future years**. To sum up briefly, strong investments in RES technologies are necessary for making the transition towards carbon neutrality in the EU’S electricity sector (and the overall energy system as well as the economy – which goes beyond the analysis and results we discuss below).

[15] According to the policy analysis conducted within WP7 of MUSTEC, the dominant policy pathway of France is to maintain a high share of nuclear in its power mix in the future which, in turn, implies to give less weight on renewables.

As starting point, Figure 48 informs on the dynamics concerning RES investments at EU28 level, showing a technology breakdown of the development of the required yearly investments in RES technologies in the electricity sector up to 2050 according to the “Cooperation – High Demand” (left) and the “National Preferences – High Demand” scenario (right).

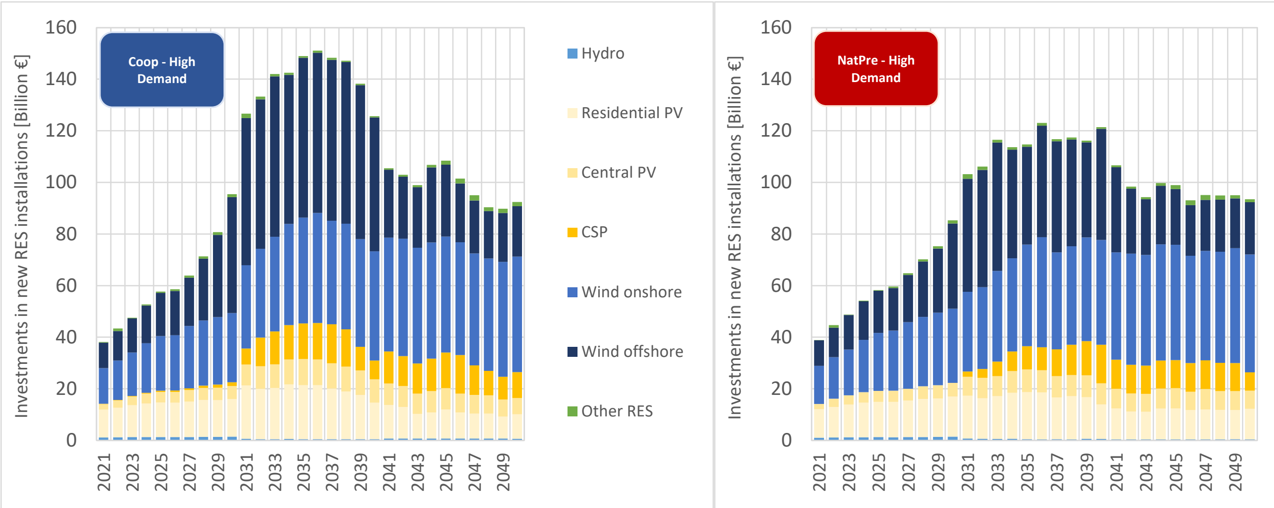

Figure 48: Technology breakdown of the development of the required yearly investments in RES technologies in the electricity sector at EU28 level up to 2050 according to the “Cooperation – High Demand” (left) and the “National Preferences – High Demand” scenario (right) (Source: Green-X modelling)

As a general trend, one can see a rapid increase of investments in RES technologies over the forthcoming decade: total RES investments increase at EU28 level from 38 billion € in 2021 to about 95 billion € by 2030 in the “Cooperation” scenario, and to slightly lower levels (85 billion € by 2030) in the “National Preferences” scenario due to slightly lower overall RES ambition under that policy pathway. In the subsequent decade (2031 to 2040) the differences in investment levels remain between the two policy tracks – i.e. within the “Cooperation” scenario average yearly RES investments amount to 140 billion € whereas in the “National Preferences” scenario these are at 115 billion € on average per year. Post 2040 both scenarios show a more identical pattern and average yearly investments range then between 97 (“National Preferences”) and 99 billion € (“Cooperation”). That decline of investments in later years is a consequence of technological progress, leading in general to a continues decline specific investment cost of the various RES technologies, combined with a steady and continues uptake of RES deployment.

The technology patterns in investments are in line with the postulated technology-specific RES deployment:

- Wind energy ranks first whereby, in contrast to deployment (where onshore wind clearly ranks first), onshore and offshore technologies require comparatively similar amounts of investments over the forthcoming years in the “Cooperation” scenario – i.e. about

34 billion € are dedicated on average yearly to offshore wind energy, and 35 billion € to onshore. In the "National Preferences" scenario offshore wind requires less investments (28 billion € on average per year over the whole period 2021 to 2050), whereas figures for onshore wind are identical. This indicates that offshore wind can be classified as a marginal option for meeting the given RES deployment targets (2030, 2050) in our least cost approach.

- Solar PV ranks next, whereby similar investment levels are applicable under both discussed policy pathways: average (2021 to 2050) yearly investments in residential PV amount to about 14 billion €, and to 7 billion € in the case of central PV systems.
- CSP is third on the list when we compare the investments in RES technologies over the next three decades. Within the "Cooperation" scenario average yearly investments amount to 8 billion € whereas in the "National Preferences" scenario they are 6.4 billion €. In accordance with corresponding deployment, the large part of these investments is however expected for the period post 2030.
- Other RES technologies like hydropower, geothermal, biomass etc. require comparatively small amounts of investments according to our analysis.

Complementary to the above, Figure 49 provides a comparison of the required yearly average (2021 to 2050) investments for all assessed scenarios. More precisely, this graph indicates the technology specific amounts as well as the total volumes that are required on average over the whole period.

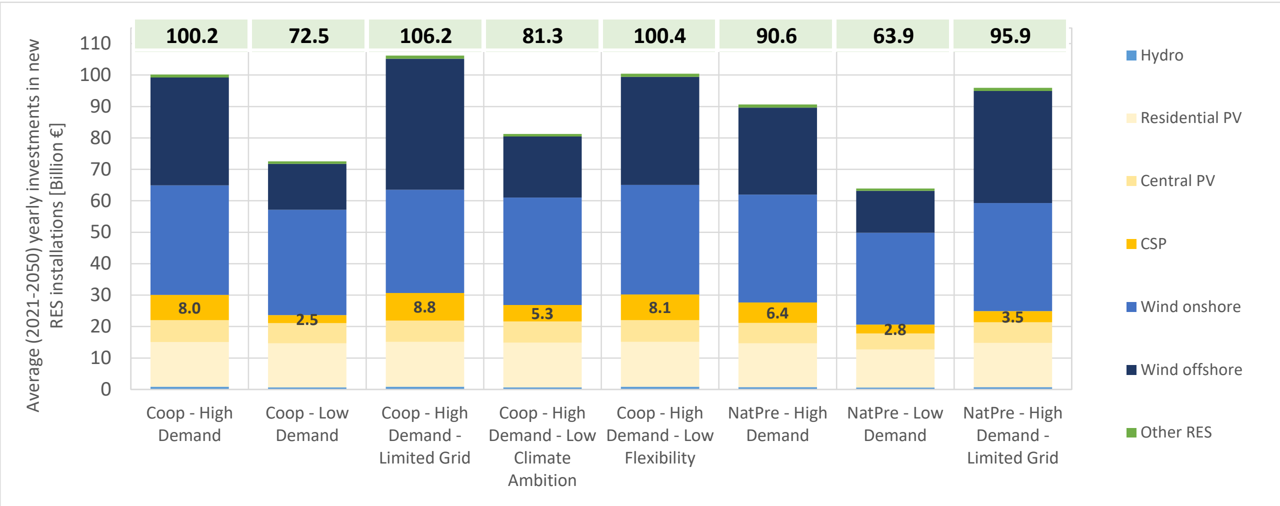

Figure 49: Comparison of the required average (2021-2050) yearly investments in RES technologies in the electricity sector according to selected assessed scenarios (Source: Green-X modelling)

Key results derived from Figure 49 are:

- As a general trend, in line with the underlying RES ambition, higher overall RES investments are required under the "Cooperation" than in the corresponding "National Preferences" scenarios. Here the sensitivity cases where the cross-border transmission grid expansion is limited (i.e. scenarios named "Limited Grid") rank first – i.e. yearly average total RES investments amount to 106 billion € in the case of "Cooperation" and to 96 billion € in the case of "National Preferences", respectively. As next follow the default cases where, as in general, a high electricity demand growth is expected. Here **average yearly investments range from 91 billion € ("National Preferences") to 100 billion € ("Cooperation")**. Furthermore, among the "Cooperation" scenario the sensitivity variant "Cooperation – High Demand – Low [demand-side] Flexibility" shows hardly any changes to the default scenario concerning the overall RES investments required. Total RES investments are lowest in the scenarios of low electricity demand growth (see scenarios named "Low Demand"), ranging from 64 billion € ("National Preferences") to 72 billion € ("Cooperation").

- **For CSP in general similar observations can be drawn**. Among the scenarios that follow a policy pathway of "Cooperation" **average yearly investments in CSP range from 8.0 to 8.8 billion € when a high demand growth is expected**, and to **only 2.5 billion € in the case of low demand growth**. The corresponding figures for the "National Preferences" scenarios are 6.4 billion € for the default case of high demand growth and 2.8 billion € for the low demand growth scenario. An exception to that general trend is however the scenario "National Preferences – High Demand – Limited Grid": for this particular case average CSP investments amount to only 3.5 billion € despite the assumed high demand trend. According to the power system analysis, this is caused by the phase-out of CSP in Spain under the specifics of this particular case, with a strong nuclear fleet in France and lack of sufficient cross-border transmission capacity between Spain and France. For details on the reasoning behind this particular trend we refer to the explanations provided in the corresponding section of the power system analysis (cf. section 3.2.1).
- Compared to that total investment volumes that need to be dedicated to renewables in the electricity sector, these figures imply that **on average about 7% to 8% of these are for CSP** if a high demand growth will arise and the target of carbon neutrality by 2050 is taken up seriously in energy and climate policy making. Only about 4% of the total RES investments fall on CSP if sector coupling and in consequence electricity demand will not increase as expected, cf. the "Low Demand" scenarios. Under the combination "Low Climate Ambition" and "High Demand" the share of CSP in total RES investments stands at on average 6% throughout the next three decades.

4.3 Support for RES technologies

This section is dedicated to inform on the required financial support for RES in the electricity. For assessing these requirements, we start with a brief recap on assumed cost trends concerning renewables underlying our model calculations, complementing the explanations provided in the corresponding section 2.3.6 in the chapter dedicated to the methodology underlying our modelling.

4.3.1 Trends in Levelized Cost of Electricity of key RES technologies

Below Figure 50 shows **the development of Levelized Cost of Electricity (LCOE) for key RES technologies at EU28 level**, considering yearly new RES installations according to the "Cooperation – High Demand" scenario and default assumptions for Weighted Average Cost of Capital (WACC) (6%) and depreciation time (20 years). Trends in the development of specific investment cost of RES technologies as shown in Figure 5 (cf. section 2.3.6) serve as basis for these calculations. As applicable from Figure 50, strong cost reductions are expected for key RES technologies like solar PV, CSP and wind, albeit the decline in LCOE is here comparatively less pronounced. For hydropower the opposite trend is observable: on average at EU28 LCOE of yearly new hydropower installations are expected to increase in future years since the available future potential is comparatively limited, specifically for large-scale projects, leading also to an increase in underlying investment cost and in LCOE. In general, for wind on- and offshore as well as for PV the depicted trends in LCOE combine two opposing effects: on the one hand, technological progress leads to a decline of specific investment cost and, as in the case of wind, an increase of the capacity factors / full load hours (since new turbines are expected to increase in scale and hub height over the years). This triggers a decline of LCOE. On the other hand, the available potentials for these technologies are not unlimited, and there are differences in site qualities. Thus, when best sites are used within a country or region, other sites with less preferential wind or solar conditions have to be used, leading generally to an increase of LCOE. As we can learn from Figure 50, technological progress is however expected to dominate, since LCOE of new RES installations decline over the forthcoming decades. At the aggregated level, i.e. for the sum of all yearly new RES installations at EU28 level, one can also see a declining trend concerning LCOE (cf. the dotted green line in the graph below).

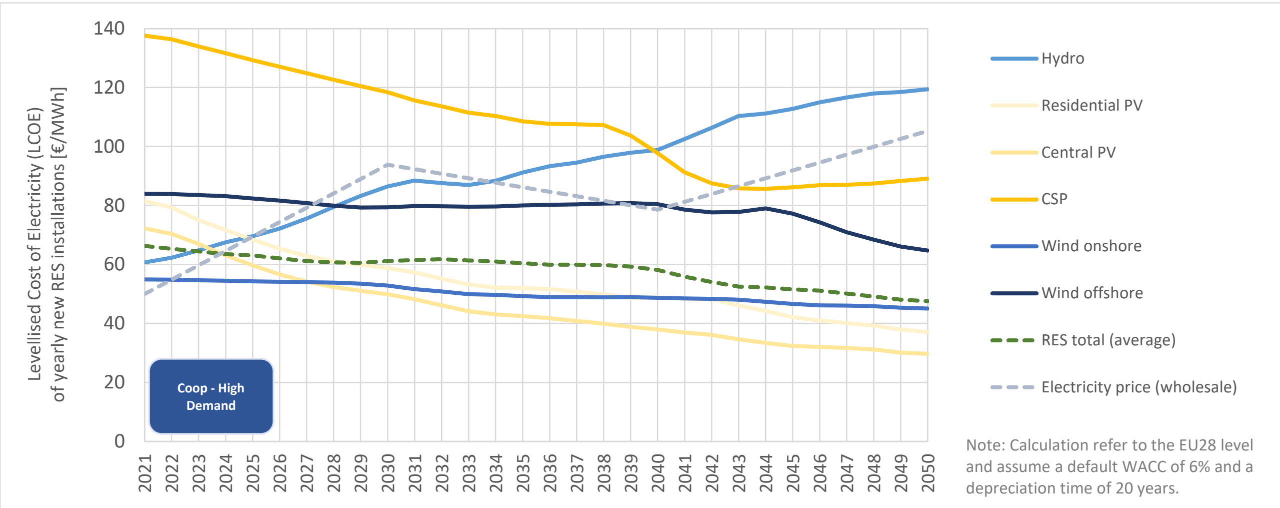

Figure 50: Development of Levelized Cost of Electricity (LCOE) for key RES technologies at EU28 level, considering yearly new RES installations according to the "Cooperation – High Demand"

scenario and default assumptions for WACC (6%) and depreciation time (20 years) (Source: Green-X modelling)

Apart from LCOE trends, Figure 50 also indicates another key parameter that determines the need for financial support: the electricity price on the wholesale market. Here a steep increase is expected from the low levels as of today towards 2030. In the period from 2030 to 2040 follows however a decline in electricity prices, driven by increasing shares of variable renewables that come at low to zero short-term cost – wind and solar installations do not have to pay for their fuel, and, in turn, declining shares of fossil fuel generation. In the final period post 2040 we then see again an increase in wholesale electricity prices, here driven by the strong rise of carbon prices within the European Emission Trading System (EU ETS) that are required if the EU ETS shall act as core driver for deep decarbonisation.

The **simplified conclusion may now be drawn from a comparison of aggregated LCOE trends for RES and the wholesale price trends that already by the middle of this decade the break-even point is reached**, indicating that there is no further need for public or private support for renewables. **That appears incorrect and simplistic** for various reasons:

- Firstly, **differences in financing cost across countries** and technologies are not accounted for in our simplified LCOE calculations.
- Secondly, **market revenues that can be gained by individual RES technologies / producers may differ from the average wholesale prices** as variable RES like PV or wind may have a high electricity infeed in times when prices are low.
- Thirdly, the **average figures**, specifically the aggregated dotted line for total RES represents an average across RES technologies, also **imply that there are certain technologies or sites with cost lower than the average, and others with cost higher than the average**. The latter ones then probably still require support to close the financing gap.

4.3.2 Support expenditures for RES

Next, we shift the attention to our focal point: **the required support expenditures for RES in the electricity sector in forthcoming years (up to 2050)** as identified from our model-based energy policy analysis. The required support is an output of our Green-X model and is consequently derived for each assessed scenario.

As outlined in the scenario definition (cf. section 2.3) our analysed scenarios differ in the policy pathway and the corresponding RES ambition that is followed (i.e. "Cooperation" vs. "National Preferences" vs. "Grassroots"), the assumptions taken concerning electricity demand growth (high or low) and certain specific sensitivity aspects like grid expansion limitations ("Limited Grid") or a less ambitious climate ambition ("Low Climate Ambition") compared to default (where achieving carbon neutrality by 2050 is imposed as binding target).

Despite these differences in conception, all our scenarios follow a common approach for the RES policy framework dedicated to facilitate the RES uptake: for the final reiteration / recalculation[16] done by Green-X we assume that (technology-specific) auctions for sliding feed-in premiums are implemented within all EU MSs in future years. We further assume that auctions follow a pay-as-bid principle and that for new RES installations support payments are granted for a period of 20 years.

Below we first show the aggregated picture concerning the required RES support in future years: As starting point, Figure 51 allows for a comparison across assessed scenarios of the development of the resulting support expenditures for RES in the electricity sector up to 2050 in absolute terms (left) and in specific terms (right), where support expenditures are expressed as premium per MWh electricity consumption.

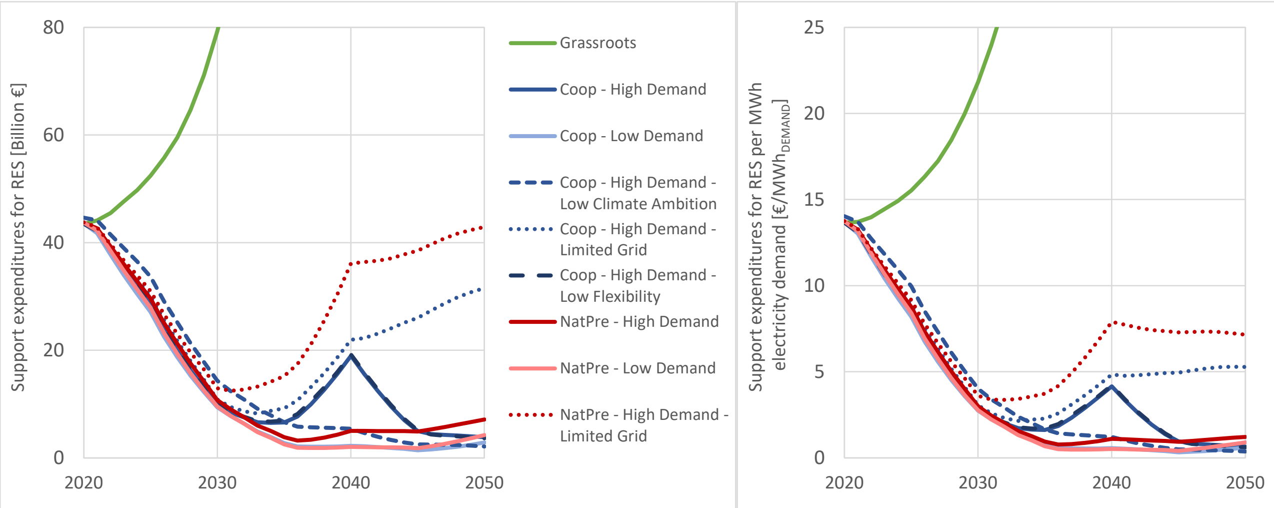

Figure 51: Comparison of the development of the resulting support expenditures for RES in the electricity sector at EU28 level up to 2050 in absolute terms (left) and expressed in specific terms as premium per MWh electricity consumption (right) according to selected assessed scenarios (Source: Green-X modelling)

With the exception of the “Grassroots” scenario where a rapid transition of the electricity system towards RES-based carbon neutrality is postulated already for 2040, and where support expenditures in consequence sky-rocket, we see **a decline of total RES-related support expenditures within the forthcoming decade until 2030 in all assessed scenarios. This decline is strong both in absolute and in specific terms** – i.e. in absolute terms this implies a decrease from currently (2020) about 43-44 billion € to 9.4-14.3 billion € in 2030. In specific terms, indicating the consumption-specific cost to consumer of the RES uptake, one can see a decrease of RES-related

[16] For details on the modelling approach, specifically the model linkage between Green-X (used for the energy policy analysis as discussed in this chapter of the report) and the Enertile model (used for the power system analysis discussed in chapter 3) we refer to the explanations provided in the description of the modelling framework (cf. section 2.2 of this report).

support payments from currently 13.7 €/MWh_{DEMAND} to 2.7-4.0 €/MWh_{DEMAND}. In both graphs the upper range of support expenditures refers to the scenario of “Low Climate Ambition” since in that case electricity prices are lower compared to the other scenarios thanks to lower carbon prices in the EU ETS that come along with the reduced climate ambition. This indicates the strong impact of wholesale electricity prices on support requirements. This appears not surprising, since support needs to compensate the difference between generation cost of RES technologies and the corresponding electricity market revenues. Thus, if wholesale prices are low support increases and vice versa.

Post 2030 the picture changes and the **differences in support expenditures among assessed scenarios are getting stronger.** The upper range of support expenditures (i.e. 31.5-42.9 billion € by 2050) refers now to the scenarios with limited transmission grid expansion (“Limited Grid”) due to the changes in the allocation of RES installations across the EU – i.e. certain least-cost sites might now no longer be used due to the grid constraints – and the changes in country-specific electricity prices – i.e. here we see stronger differences across countries compared to default. Among all other scenarios total RES-related support expenditures range from 2.9-7.1 billion € in 2050. In the “Cooperation” scenarios with high demand growth (“High Demand”) and default (strong) climate ambition one can also observe an intermediate peak in support expenditures by 2040 (ca. 19.0-19.2 billion €) as a consequence of low electricity prices at that point in time, as calculated by the Enertile model within the corresponding power system analysis. Remarkably, another general trend, in specific terms the decline in support expenditures is stronger in the long term since, thanks to the growing electricity demand, specific RES-related payments per kWh electricity consumption decline stronger than absolute volumes.

Details on the resulting **trends in technology-specific developments concerning support expenditures** are given in Figure 52 below. These graphs provide a technology breakdown of the support requirements for RES at EU28 level for two key policy pathways, namely the “Cooperation – High Demand” scenario (Figure 52, left) and the “National Preferences – High Demand” scenario (Figure 52, right). Please note that the technology-breakdown comprises only the support cost related to the future expansion of RES, in order to provide further insights on the cost related to those RES installations newly added to the power system in future years. The bulk of support dedicated to already established RES plants (installed until 2020) is marked in grey at the bottom of each graph. This share is declining over time and by 2045 no further payments need to be provided to these plants.

A comparison of the technology trends among the two illustrated scenarios indicates the following aspects:

- **The bulk of support expenditures within forthcoming years is dedicated to existing RES**, established in the years up to 2020. These plants have come at higher cost in the past, specifically PV systems and wind turbines required higher support compared to new ones in future years thanks to technological progress achieved and expected, respectively. In aggregated terms, more money needs to be transferred to existing RES than to new RES installed post 2020 until 2035 in the "Cooperation" scenario and until 2037 in the "National Preferences" scenario, respectively.

- Among the support expenditures for new RES (installed post 2020) **two technologies are dominating the picture** in the "Cooperation" scenario: **Offshore wind energy** requires support in size of 2.4 billion € on average per year throughout the forthcoming three decades – this is half of the total RES-related support expenditures dedicated to new installations (4.8 billion €). The second technology is **CSP**, requiring 2.0 billion €. All other RES technology account for a comparatively small part of the overall support payments under this scenario.
- In the "National Preferences" scenario the overall situation slightly changes, both concerning overall support volumes for new RES (2.7 billion € instead of 4.8 billion €) as well as with respect to the technology distribution: In the "National Preferences" scenario CSP ranks first (1.0 billion €), followed by offshore and onshore wind (each at 0.7 billion €).

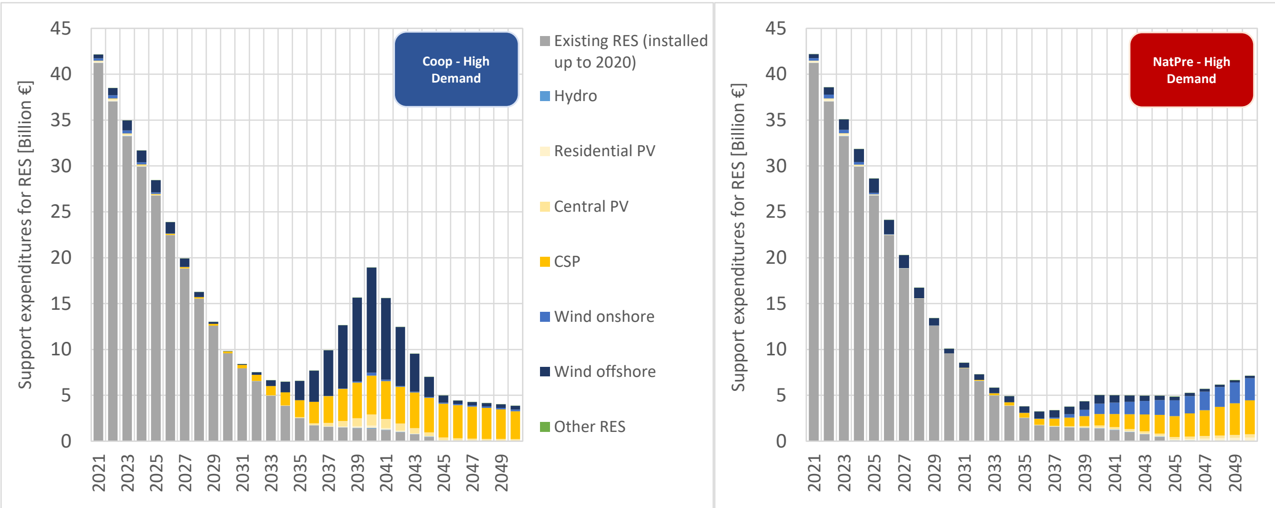

Figure 52: Technology breakdown of the development of the resulting support expenditures for RES in the electricity sector up to 2050 at EU28 level according to the "Cooperation – High Demand" (left) and the "National Preferences – High Demand" scenario (right) (Source: Green-X modelling)

Complementary to the above, Figure 53 (below) provides a comparison of the required yearly average (2021 to 2050) RES-related support expenditures for all assessed scenarios. More precisely, this graph indicates the technology specific amounts as well as the total volumes that are required on average over the whole period from 2021 to 2050.

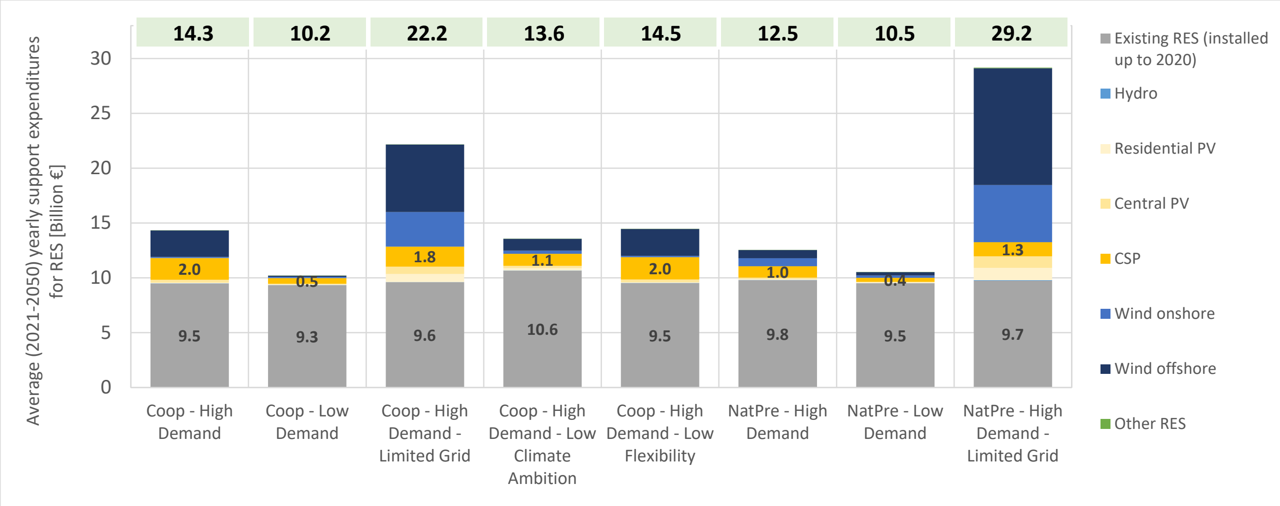

Figure 53: Comparison of the resulting average (2021-2050) yearly support expenditures for RES technologies in the electricity sector at EU28 level according to selected assessed scenarios (Source: Green-X modelling)

Key results derived from Figure 53 are:

- The comparison of the **resulting average (2021-2050) yearly RES-related support expenditures** across assessed scenarios indicates a comparatively broad spectrum, **ranging from 10.2 billion € in the "Cooperation – Low Demand" scenario up to 29.2 billion € according to the "National Preferences – High Demand – Limited Grid" scenario.**
- In this context, a key cost driver can be identified: limitations in expanding the cross-border transmission grid. In the scenarios **with "Limited Grid" support expenditures for new RES (installed post 2020) increase significantly, specifically in later years post 2030**, leading to high average (2021-2050) yearly support expenditures that range from 22.2 ("Cooperation") to 29.2 billion € ("National Preferences"). **The uptake in support expenditures concerns variable RES, and thereby specifically wind on- and offshore that comes a long with increases in curtailment and a drop of market revenues that can be earned by wind producers**. Thus, a well interconnected European power system facilitates the integration of variable renewables, and helps to balance under- and oversupply across countries. Wind energy is here more affected since weather fronts and accompanying winds move across the continent at a given wind speed, leading to an uptake in wind generation within one part of Europe while the remainder might face the opposite trend. Thus, strong interconnectors would consequently allow for the balancing across country borders. In contrast to wind and solar PV, support expenditures for CSP are only to a minor extent affected, mainly here due to changes in the geographical allocation of these plants.
- If we exclude the "Limited Grid" scenarios from our comparison the range in average yearly support expenditures is significantly smaller, varying then only between 10.2 and

14.5 billion €. At the lower end we see the "Low Demand" scenarios (i.e. 10.2 billion € under "Cooperation" and 10.5 billion € in the "National Preferences" scenario), followed by the "Cooperation" variant where a "Low Climate Ambition" is presumed (13.6 billion €). For the default scenarios of "Cooperation", assuming a high demand growth, support expenditures amount to 14.3 billion € and with less (demand-side) flexibility cost slightly increase to 14.5 billion €. Under the default "National Preferences" scenario slightly lower support is required (12.5 billion €) due to the reduced RES ambition (caused by the presumed higher uptake of nuclear in France).

- With the exception of the "Limited Grid" scenarios the previously taken statement holds that the bulk of RES-related support expenditures within forthcoming years up to 2050 is dedicated to existing RES, established in the years up to 2020. These plants have come at higher cost in the past, and account for a high share in the expressed total RES-related support expenditures, ranging from 66% to 92%.
- Support expenditures dedicated to CSP range from 0.4 billion € (both scenarios of "Low Demand") to 2.0 billion € ("Cooperation – High Demand" with or without less (demand-side) flexibility). This corresponds well to the underlying CSP deployment trends, and specific support for CSP (per MWh RES generation) is consequently hardly affected by analysed changes in input parameter (like grid limitations, demand flexibility, etc.).

We can conclude that **there is a need for dedicated support of CSP and other RES in the near to mid future**. **The bulk of identified RES-related support expenditures within forthcoming years** up to 2050 is however **dedicated to existing RES**, established in the years up to 2020 since they have come at higher cost. **Support for new RES (installed post 2020) is expected to strongly decline over time due to technological progress and the projected increasing prices in wholesale electricity markets**. **A key element for achieving this decline in support** for new RES installations, specifically for variable RES like wind and solar PV, is **the expansion of the cross-border transmission grid since this facilitates RES integration and the balancing of under- and oversupply across countries** in times of high variable RES infeed.

4.4 Focal assessment I: Dedicated support as alternative to high carbon prices

A focal assessment is conducted to **shed light on the role of the EU Emission Trading Scheme (EU ETS) in reaching carbon neutrality at EU level by 2050**. Today within the EU and its MSs a broad portfolio of policy initiatives is implemented that aims for facilitating the decarbonisation of the energy system. The EU ETS acts as umbrella instrument to safeguard that GHG emission reduction targets are met within the sector covered, including large GHG emitters in power and heat supply and in industry as well as parts of certain transport modes. Within the electricity sector the EU ETS is accompanied by dedicated support instruments and various other measures like cheap loans, tax regulations etc. to facilitate the uptake of renewables and other decarbonisation options.

In our default model-based assessment, specifically within the power system analysis that aims to identify the need for CSP and other flexibility options to safeguard a reliable and affordable electricity supply in the future, **carbon prices serve to account for the underlying decarbonisation objectives**.[17] For 2050 we impose as default **carbon neutrality** as constraint, causing that **carbon prices within the EU ETS reach 500 €/t CO_2** at that point in time. In consequence of high carbon prices, the within the power system analysis applied Enertile model projects a significant increase in wholesale electricity prices in future years, specifically in the last years until 2050 as applicable in the graphs on the left-hand side of Figure 54.

Within this focal assessment we assess how high dedicated RES support needs to be if carbon prices will not increase to these significant heights. We consequently recalculate the required support expenditures for achieving a similar RES deployment as postulated in the default “Cooperation” and “National Preferences” scenarios where apart from high carbon prices a strong growth in electricity consumption and a significant extension of the (cross-border) transmission grid was presumed. For this exercise our combined modelling system had to be applied, meaning that as a first step the Enertile was used to recalculate electricity prices and, later on, the Green-X model was applied, taking up the results of Enertile concerning electricity price and technology-specific market value developments. This analysis serves as a sort of reality check and builds on the assumption that current policy practices are maintained, meaning that we see also in future rather a bunch of dedicated measures and instruments to facilitate decarbonisation at the various ends instead of solely one single instrument – i.e. the EU ETS. Table 7 informs on the assumed carbon price trends used in this focal assessment. The default high carbon price trend builds on own assumptions but acknowledges findings of EC (2018) whereas the alternative low carbon price trends is based on the latest PRIMES reference scenario of the EU (EC, 2016).

Table 7: Assumed carbon price trends in the focal assessment on dedicated support as alternative for high carbon prices (Source: Own assumptions and EC, 2016)

Assumptions on carbon price developments (in the EU ETS) in $€_{2010}/t\ CO_2$	2030	2040	2050
Default assumptions (high carbon prices)	75.0	125.0	500.0
Alternative trend (low carbon prices)	31.0	46.3	81.5

[17] The energy system model Enertile that has been applied for that analysis does not directly account for complementary support measures that might in future be dedicated to RES and probably also to other flexibility options.

The results of this focal assessment are discussed below. As starting point, Figure 54 shows the **required support of individual RES technologies in specific terms, i.e. per MWh RES generation**, and the underlying wholesale electricity price trends and for all assessed cases – i.e. the default cases of “Cooperation” and “National Preferences”, assuming high carbon prices as dominant driver for decarbonisation (cf. the graphs on the left-hand side of Figure 54), and the corresponding alternative scenarios where in future years comparatively “Low Carbon Price[s]” are presumed (cf. the graphs on the right-hand side of Figure 54).

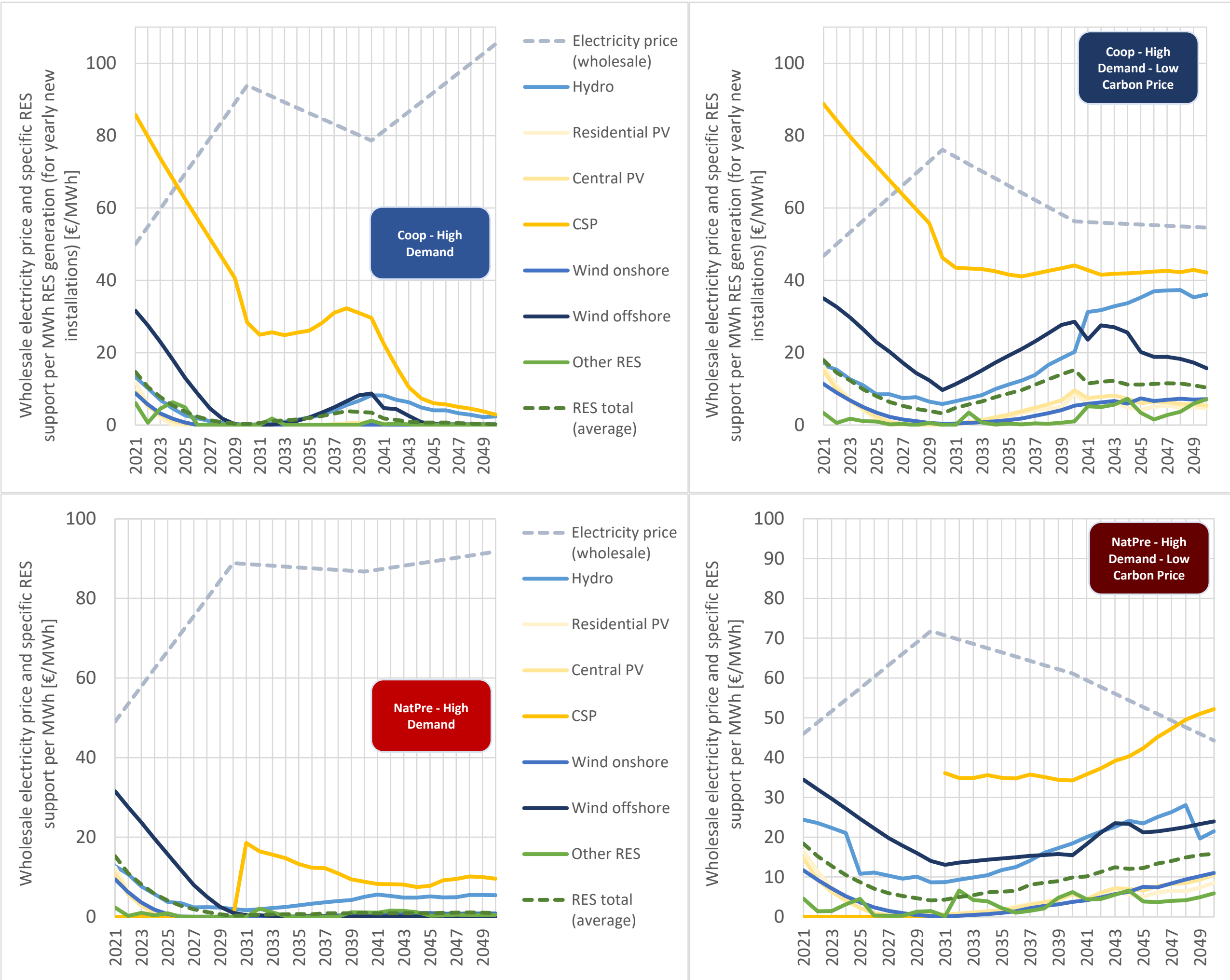

Figure 54: Development of wholesale electricity prices and specific support per MWh RES generation up to 2050 on average at EU28 level according to selected assessed scenarios (with default and with low carbon prices) (left-top: “Cooperation – High Demand”, right-top: “Cooperation – High Demand – Low Carbon Prices”, left-bottom: “National Preference – High Demand”, right-bottom: “National Preferences – High Demand – Low Carbon Prices”) (Source: Green-X modelling)

Figure 54 points out that in the alternative scenarios of "Low Carbon Prices" in the forthcoming years up to 2030 still an increase in electricity prices compared to today can be expected which comes along with the incline of carbon prices and demand as well as a phase-out of certain fossil and nuclear capacities across the EU. The increase in wholesale prices is however lower in magnitude than under default assumptions because of the (compared to default) lower carbon prices expected for 2030. Post 2030 electricity prices are declining in the alternative scenarios which, in turn, triggers an increase of specific support for the clear majority of assessed RES technologies. At the aggregated level we consequently see also for total RES (on average) an increasing or partly constant development of the required specific support. These alternative developments differ to the default cases where high carbon prices and, in consequence, high electricity prices provide sufficient income to RES producers so that dedicated support can significantly decline in the years up to 2050.

For informing on the overall impacts arising from such developments we subsequently provide **a comparison of support requirements on average across the whole assessed period 2021 to 2050** (cf. Figure 55, left) and we also indicate **the impacts electricity consumers may face, showing the average yearly consumer cost in specific terms (per MWh electricity consumption)** in Figure 55 (right). The cost elements taken up in that latter comparison comprise the wholesale electricity price and the RES-related support, distinguishing between existing (up to 2020) and new (post 2020) RES installations.[18] As in general within this focal assessment, the scenarios covered in this comparison are the default cases of "Cooperation" and "National Preferences" where high carbon prices are presumed, and the alternative cases of those, assuming comparatively "Low Carbon Prices".

The **comparison of average yearly support expenditures** as shown in Figure 55 (left) indicates that **support cost triple if the current trend and policy practice of using a bunch of dedicated policy instruments to facilitate the energy transition** complementary to the "umbrella tool" EU ETS is pursued in the years up to 2050, as a consequence of the comparatively "Low Carbon Prices" within the EU ETS. More precisely, in the default "Cooperation" scenarios (of high carbon prices) average yearly RES support at EU28 level stands at 14.3 billion € and in the variant of "Low Carbon Prices" support triples to 44.3 billion €. The corresponding figure for the "National Preferences" scenario is 12.5 billion € in the case of as default high carbon prices, and 39.6 billion € if "Low Carbon Prices" will remain in future years. Compared to today this means that the magnitude of support

[18] Our comparison of cost impacts on electricity consumer does however not provide the "full picture" since network charges as well as energy-related or general taxes are not taken into consideration. Taking these missing elements into consideration would require a detailed analysis by country, distinguishing between the various costumer groups (e.g. households, industry, tertiary) for the tax or charging practices. This would also not add value to the scope of our analysis where we aim to assess impacts from the carbon price developments in the EU ETS on wholesale price developments and corresponding market revenues of RES investors as well as RES-related support requirements, and the overall consequences of these from a consumer perspective.

expenditures will roughly be the same in the future – i.e. for 2020, the start year of our modelling, RES-related support amounts to ca. 43.5 billion €.

The picture changes from the perspective of an electricity consumer if we add to our comparison the price changes in the wholesale electricity market: As applicable from Figure 55 (right), **consumer cost in specific terms (per MWh electricity consumption) that take into account wholesale prices and RES-related support expenditures on average throughout the whole time period 2021 to 2050 are lower in the alternative cases where "Low Carbon Prices" are presumed**. Despite the significant increase in dedicated support for RES, electricity consumer will pay 19 % ("Cooperation") to 21 % less ("National Preferences"), if the current policy practice of combining the EU ETS with strong sectoral policies that provide dedicated support to RES (and possibly also other decarbonisation options) is maintained in future years. Under these circumstances targeted support can be provided to individual RES technologies, for example via auctions for sliding feed-in premia, in accordance with technology- or even site-specific requirements. Such a policy approach helps to avoid overcompensation for "low hanging fruits" like wind onshore or solar PV. To clarify on that we depict the timely development of the total remuneration per MWh electricity generation in Figure 56 below, exemplified here for key two technologies, namely onshore wind and CSP, according to both assessed variants of the "Cooperation" pathway, i.e. with default ("Cooperation – High Demand") and with low carbon prices ("Cooperation – High Demand – Low Carbon Prices").

Under the default scenario of high carbon prices total remuneration for wind onshore increases in the forthcoming decade until 2030 due to the projected increase of prices in the electricity wholesale market, despite the diminishing of dedicated RES support. In the period 2030 to 2040 follows a decline, and post 2040 we see again an increasing trend so that total remuneration exceeds by 2050 the prior peak level of 2030. With "Low Carbon Prices" one can see a compared to above less pronounced increase of remuneration in the period up to 2030, due to the significantly lower increase in carbon and wholesale prices. After 2030 a steady decline of total remuneration is observable, driven by the strong decline of electricity prices. This price drop requires a relaunch of dedicated support for onshore wind post 2035 in order to fill the financing gap for this decarbonisation option on average at EU level. The comparison of both variants makes clear that on average total remuneration, and accordingly also the consumer burden, is 23 % lower in the case of "Low Carbon Prices" (compared to high ones under the default "ETS only" case). The difference is in early years small and in later years close to 2050 significant, peaking at a 42% cost saving by 2050.

For CSP the cost savings are smaller – i.e. on average they amount only to 4 % – but the general tendency is the same. More precisely, under the default case of high carbon prices a slow decline of total remuneration is observable in early years, followed by an overage steeper one post 2030, and beyond 2043 remuneration increases again. The variant of "Low Carbon Prices" shows an (almost) identical trend and also comparatively similar heights of remuneration compared to above in early years until 2030 but beyond that point in time a steady downward trend of total remuneration is observable, leading to cost savings of about 10% by 2050.

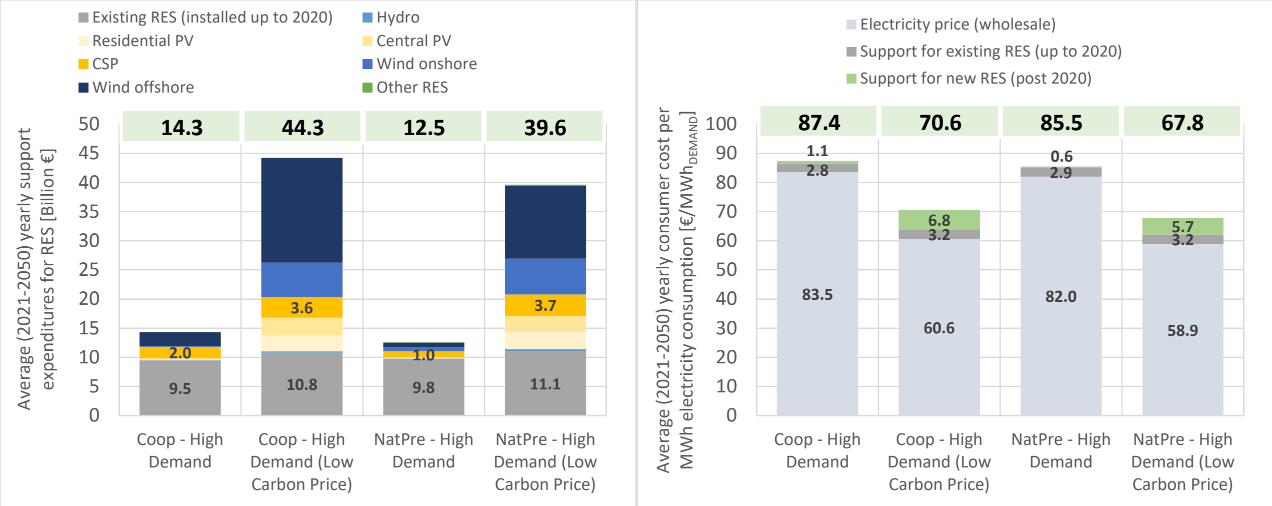

Figure 55: Comparison of the resulting average (2021-2050) yearly support expenditures for RES technologies in the electricity sector (left) and of the average (2021-2050) consumer cost in specific terms (per MWh electricity consumption) (right) according to selected assessed scenarios (with default and with low carbon prices) (Source: Green-X modelling)

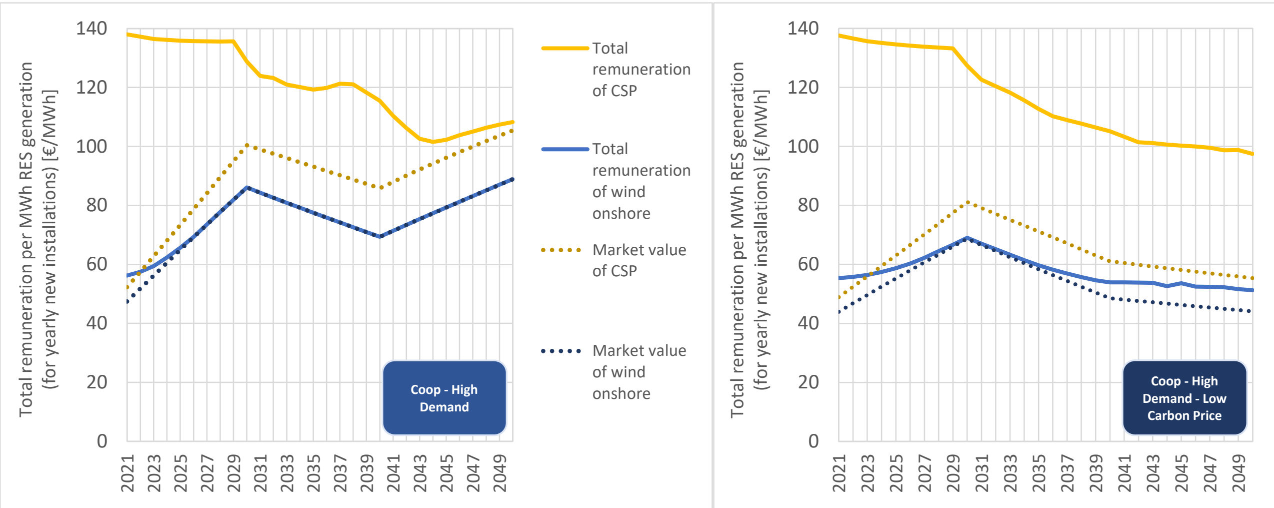

Figure 56: Comparison of total remuneration per MWh RES generation of CSP and wind onshore according to selected assessed scenarios – with default (“Cooperation – High Demand” (left)) and with low carbon prices (“Cooperation – High Demand – Low Carbon Prices” (right)) (Source: Green-X modelling)

We can conclude that **in the absence of high carbon prices** in the EU ETS, i.e. reflecting a world where dedicated support is offered to individual decarbonisation options and implying, in turn, that the EU ETS is not acting as single driver for the take-up of decarbonisation options and needs, **overall remuneration of CSP and other RES technologies and, consequently, also corresponding consumer cost are at a lower level than in an “ETS only” world**. Here targeted support can be provided to individual RES technologies, for example via auctions for sliding feed-in premia, in accordance with technology- or even site-specific requirements. **Such a policy approach helps to avoid overcompensation for "low hanging fruits"** as demonstrated for wind onshore in Figure 56 above.

4.5 Focal assessment II: The need for and impact of RES cooperation

This section aims to shed light on **the need for and impact of RES cooperation between Member States from a quantitative perspective**, complementing the modelling presented above to identify the cost-saving potential arising from a strong use of cooperation mechanisms at European as well as at country or regional level. A focal point in this analysis is **how RES cooperation may facilitate the uptake of CSP in future years**.

The work on RES cooperation builds on previous related modelling activities and in particular provides an update of the work conducted in Resch et al. (2016) within the DIA-CORE study, at that point in time conducted in the 2020 context, and in Resch et al. (2017) in the Towards2030-dialogue project, there already in the 2030 context but under less ambitious RES planning.

All scenarios previously analysed within from an energy policy perspective contain already in their conception the principle ideas of RES cooperation, with some of them more prominent – like all variants of the "Cooperation" pathway – than others. Nevertheless, also the "National Preferences" policy pathway, despite acknowledging the dominant national RES policy preferences, specifically future RES targets of France, Germany, Italy and Spain, builds on the idea of EU-wide cooperation in the field of renewables and power system infrastructure.[19] Apart from their similarities and differences in conception, results from these policy pathway may hardly serve as basis for a sound analysis on RES cooperation due to their differences in RES ambition.[20]

In general terms, RES cooperation aims for allocating RES investments across the EU where from an economic perspective most beneficial. If such a least cost pathway is followed for the future RES expansion, this may then allow for meeting given EU RES or decarbonisation targets in, from an EU perspective, cost effective manner. In practical terms this requires collaboration in RES planning, RES policy design and the corresponding implementation. Support instruments for RES could also be opened up beyond national boundaries as already prescribed by the revised RES directive

[19] For example, under the "National Preferences" policy pathway a least-cost approach is followed by the remainder of EU countries (excl. the big four France, Germany, Italy and Spain), and concerning cross-border grid expansion a collaborative approach is presumed as default.

[20] Both the "National Preferences" and the "Cooperation" pathway aim for carbon neutrality of the EU energy system by 2050 whereby renewables serve as the key decarbonisation option in the power sector. The overall RES ambition is however in the "National Preferences" lower due to the dominant policy preference of France where nuclear is expected to remain as other key decarbonisation in future years, covering about 50% of the domestic electricity demand by 2030 and beyond.

2018/2001/EU concerning cross-border auctions etc… In future, EU-wide instruments may then complement or, to the ultimate extent, replace national policy initiatives to facilitate EU-wide RES cooperation. Such a “Europeanisation” of RES policy approaches has an impact on the financing side of RES projects and it affects the accompanying cost and benefits.

Within this focal assessment we **shed light on financing impacts**, and **we showcase how the country-specific allocation of cost, specifically of RES-related support expenditures, may be affected by RES cooperation**. This complements the general analysis of RES-related investments and support expenditures as presented and discussed previously mainly at EU or at technology level.

4.5.1 Assumptions on how RES cooperation affects project financing

As starting point **we take a look at the financing side and illustrate how we have incorporated the idea of “Europeanisation” in assumptions** that serve as input for the model-based energy policy analysis. Our Green-X model incorporates the impact of risks to investors on RES deployment and corresponding (capital / support) expenditures by taking an aggregated view at the national and European level with fewer details on individual direct financing instruments. More precisely, the debt and equity conditions resulting from specific financing instruments are incorporated by applying different **weighted average cost of capital (WACC)**[21] levels. Within the model-based analysis, a range of settings is applied to accurately reflect the risks to investors. Risk refers to three different issues: policy-, technology- and country-related risk. Whereas the former two are, at least within our analysis, not directly affected by RES cooperation we presume an impact on the latter one, i.e. **the country-specific risk of RES investors**. Below we elaborate on what is meant with country-specific risk and we present our assumptions taken in this respect.

As outlined in further detail in section 6.3 in the Appendix, at present differences across Member States with respect to financing conditions are commonly acknowledged, see e.g. Boie (2016). This leads to a higher risk profiling of investments in countries more strongly affected by the financial and economic crisis compared to more stable economies within Europe.

As illustrated in Figure 57, two scenarios of country-specific risk factors serve in modelling to reflect possible future developments – i.e. with and without RES cooperation:

- <u>With RES cooperation (default setting):</u> We assume as default that an alignment of these conditions will take place, driven by a further “Europeanisation” of RES policy making, e.g. through a market opening of national policy schemes, enhanced RES cooperation between Member States or at the ultimate extent via harmonisation. More precisely, as default we do not assume a full alignment but a smoothening / levelling of currently prevailing country-specific risk factors that is driven by RES cooperation.

[21] In our modelling the determination of the necessary rate of return of a RES project is based on the weighted average cost of capital (WACC) methodology. For details on that and on our corresponding modelling approach we refer to section 6.3 in the Appendix of this report.

- Without RES cooperation ("High Country Risk"): As alternative to above, we add within this focal assessment an alternative scenario of country-specifics WACC assumptions. Thus, in the "High Country Risk" sensitivity variant we take the assumption that national policy approaches set the scene in future, and that, consequently, no levelling of country-specific risks will occur. This scenario reflects in conception the idea of no future RES cooperation.

The assumptions taken concerning country-specific risks, exemplified by the resulting WACCs, are shown in Figure 57.

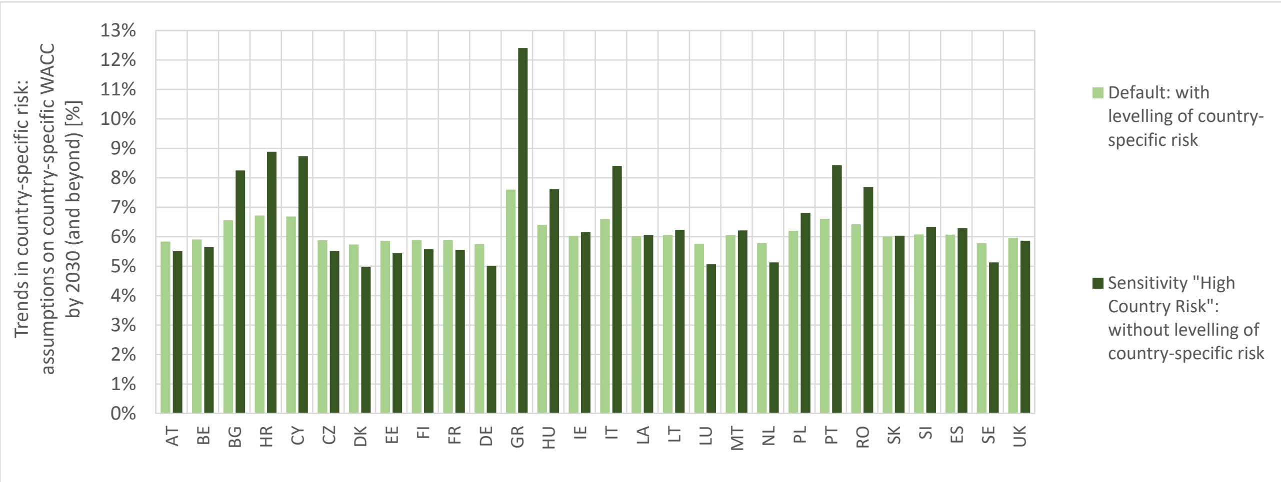

Figure 57: Assumptions on country-specific WACC by 2030 and beyond (with and without RES cooperation) (Source: Green-X modelling)

4.5.2 Impact of RES cooperation on RES-related support expenditures at EU level

The impact of RES cooperation on the required support for RES is discussed next. We start with an analysis at the aggregated EU level before digging into country details in the subsequent section. Please note that **at EU level any impact of RES cooperation on the resulting cost is clearly driven by the changes in financing conditions** for new RES projects as elaborated above.

Figure 58 shows how RES cooperation affects the need for dedicated support at technology level, here referring the EU28 on average. More precisely, this graph indicates the future development of the specific support per MWh RES generation up to 2050 on average at EU28 level according to two variants of the "Cooperation – High Demand" scenario, i.e. the default case assuming RES cooperation and the sensitivity case assuming no RES cooperation and, in consequence, the influence of a (in some countries) "High Country Risk".

For CSP a strong impact of RES cooperation is getting apparent:[22] In the absence of RES cooperation support when a "High Country Risk" is prevailing in many of the southern European host countries

[22] Please compare the dotted (without RES cooperation) and the bold lines (with RES cooperation) in dark yellow that refer to CSP.

of expected future CSP developments a significantly higher specific support is required. For the exemplified “Cooperation” scenario this increase is strong: on average (2021-2050) 57 % higher support needs to be paid per MWh of electricity produced from CSP. The good news here, differences between both scenarios (with and without RES cooperation) are larger in later years when specific support has already declined strongly thanks to increasing electricity prices and cost reductions triggered by technological learning.

For certain other RES technologies, e.g. for offshore wind, the opposite trend occurs: here a levelling of country-specific risk across the EU as presumed under the default RES cooperation scenario leads on average to higher cost – i.e. specific support for offshore wind decreases by 25% on average in the absence of RES cooperation / a levelling of country-risk. Reason is here that western and northern EU countries being the hosts of future wind offshore developments are generally more stable economies with a low risk rating. A levelling of country-risk across the EU would consequently increase the financing cost for these countries.

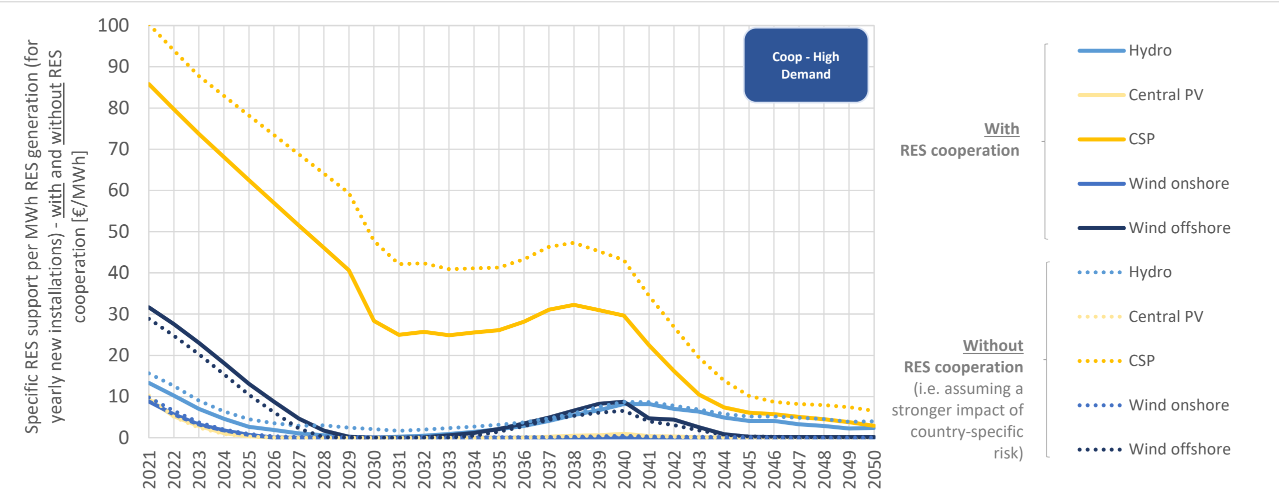

Figure 58: Development of the specific support per MWh RES generation up to 2050 on average at EU28 level according to selected assessed scenarios (“Cooperation – High Demand”, with and without RES cooperation (“High Country Risk”)) (Source: Green-X modelling)

At the aggregated level for total RES, as illustrated Figure 59 for all analysed scenarios under this focal assessment, one can identify **a clearly positive impact of RES cooperation on RES-related support expenditures**. RES-related support expenditures in the period 2021 to 2050 increase in the absence of RES cooperation (i.e. the “High Country Risk” variants) by 5-7 % under the assessed “Cooperation” scenarios (with as default high or low carbon prices), and by 5-11 % according to analyses “National Preferences” scenarios (again with default or low carbon prices).

That indicates that **strong differences in financing conditions across EU countries as we still see them today are less preferential for the decarbonisation of the EU’s electricity sector**. Any European initiative that may help to equalize RES project financing across the EU appears useful and from an EU-wide economic perspective beneficial or, as for some countries and technologies, even necessary as we will elaborate further in the subsequent section.

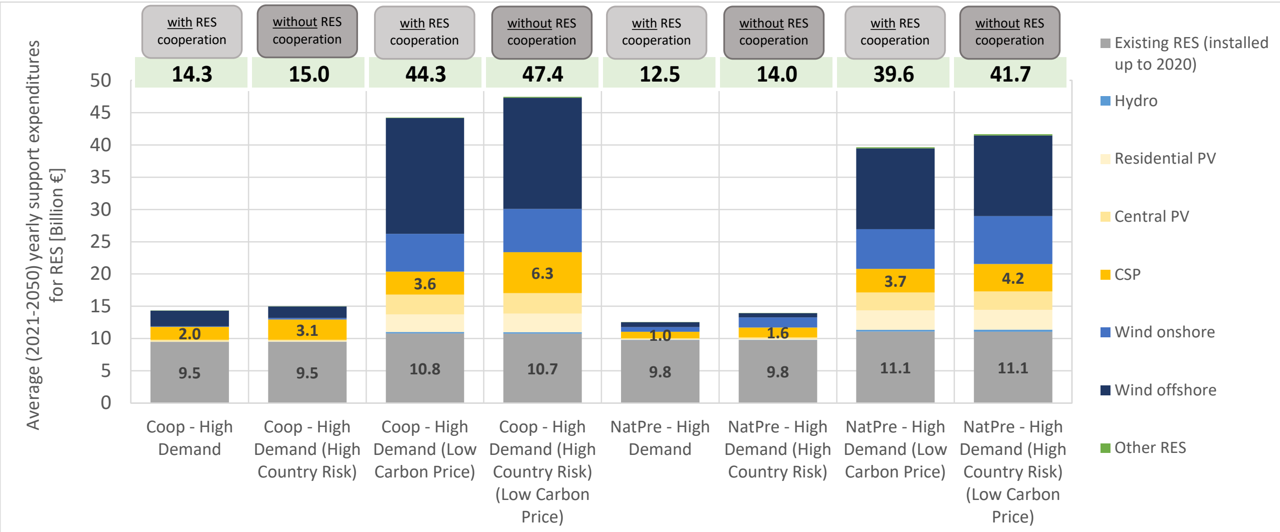

Figure 59: Comparison of the resulting average (2021-2050) yearly support expenditures for RES technologies in the electricity sector according to selected assessed scenarios (with and without RES cooperation) (Source: Green-X modelling)

4.5.3 Country-specific impacts of RES cooperation on support expenditures

Complementary to the above, this final subsection is dedicated to undertake **a closer look at the country-specific impacts of RES cooperation**, indicating how that might facilitate the uptake of CSP and other RES technologies as expected in future years.

In this context, Figure 60 provides a detailed comparison of the resulting country-specific RES support expenditures in future years (2030, 2040, 2050), exemplified for the scenario "Cooperation – High Demand" with (as default) and without RES cooperation ("High Country Risk"). For a meaningful comparison among large and small MSs we thereby expressed the support expenditures in specific terms, i.e. as premium per MWh electricity consumption according to (Source: Green-X modelling). Please note that the graphs contain also a breakdown of cost for existing (installed up to 2020) and new RES plants (installed post 2020), since only the latter are affected by future changes in project financing conditions. Shaded bars (in grey and green) refer thereby to the sensitivity variant of no RES cooperation.

Apart from a change in country-specific financing conditions, RES cooperation has also another strong impact: it leads to a **redistribution of cost**. In general, under RES cooperation host countries do no longer have to cover the full amount of support expenditures on their own balance. Costs are then redistributed among the host and the off-taker. In our focal assessment we take the assumption that a full "Europeanisation" of the efforts taken is applied which is however limited to the direct policy cost – i.e. the RES-related support expenditures.[23] More precisely, we assume in the case of RES cooperation that support expenditures for the future uptake of renewables within EU28 are equally shared among all electricity consumers, and that this is done EU-wide. This imposes the concept of an EU-wide harmonised policy initiative, specifically an EU-wide harmonised support instrument for the RES uptake. Contrarily, we do not assume such an effort sharing to take place for the cost associated with the stock of RES plants installed in prior (here, until 2020) since both the prior RES uptake and corresponding cost are a consequence of in the past implemented purely national RES policy initiatives.

Figure 60 indicates that by 2030 **RES cooperation**, impacting financing conditions for new RES investments and the allocation of corresponding support expenditures, **has generally a small impact on the country-specific consumer cost**. For the large majority of MSs, specifically for the off-taker, only a small increase in support expenditures, expressed as premia on top of electricity consumer bills, is getting apparent. For several host countries of comparatively costly RES technologies like CSP, namely for Croatia, Cyprus, Greece and Italy, a comparatively significant reduction of support expenditures is observable. The reason for the generally small impact of RES cooperation on country-specific policy cost is that the vast majority of RES support expenditures (i.e. 98% at EU level) is dedicated to existing RES (installed up to 2030) at that point in time – and their cost allocation is not affected by RES cooperation.

If we move on in time we see that the impact of RES cooperation and the corresponding effort sharing is getting stronger: By 2040 when support for currently already established RES plants (installed up to 2020) is largely phased out, **the reallocation of support expenditures across countries has a strong impact on the support-related premia on top of electricity bills**. Generally, consumer in off-taker countries have to pay significantly more compared to the situation without effort sharing, demonstrated here by the case assuming no RES cooperation (i.e. "Without RES cooperation"). In turn, electricity consumer in host countries have to pay significantly less and one can see already by then almost equal RES-related premia to consumer. For RES hosts like Cyprus, Denmark, Italy and the UK it appears of key relevance to follow the RES cooperation idea in order to keep the consumer burden at an acceptable level. A specific situation occurs in Sweden since there the cost for existing RES plants are still significant b 2040, and RES cooperation leads to a further increase of consumer bills.

[23] A fair sharing of the efforts may involve other cost associated with the RES uptake in the power sector, e.g. system integration cost, cost for grid extension etc. Effort sharing may however also involve to acknowledge the benefits that may arise in the host country since the RES investments taken typically have positive impacts on the local economy. Accounting all these costs and benefits transparently and applying a fair effort sharing represents in practice a challenging task. Taking a pragmatic view, we limit our analysis to support expenditures and assess under scenarios where RES cooperation is presumed the impacts of sharing only these efforts equally across the EU.

Figure 60: Comparison of the resulting country-specific RES support expenditures in future years (2030, 2040, 2050), expressed in specific terms as premium per MWh electricity consumption according to the scenario "Cooperation – High Demand" with and without RES cooperation (Source: Green-X modelling)

By 2050 comparatively **similar impacts as discussed in the 2040 context arise from RES**

cooperation. The list of host countries positively affected by RES cooperation is getting longer: Cyprus, Portugal, Greece, Italy, Latvia, Estonia, Spain, Finland and Sweden are hosts which then have to bear a smaller part of the policy cost. **At aggregated EU28 level one can also see the overall positive impacts of RES cooperation on the height of support expenditures** – these decline by 42 % with RES cooperation compared to the case without.

Since the impact of RES cooperation as illustrated in Figure 60 above includes two effects – i.e. the change in financing conditions and the redistribution of support expenditures across MSs (effort sharing) – we decompose these effects subsequently. Thus, Figure 61 provides a comparison of the resulting country-specific RES support expenditures in 2050, expressed in specific terms as premium per MWh electricity consumption. The data shown in this graph refers to the scenario "Cooperation – High Demand". It aims for illustrating exemplarily the impacts that arise from the two distinct effects that are included in our assessment of RES cooperation impacts. Three cases are consequently included:

- As reference we make use of our sensitivity case where no RES cooperation, consequently no redistribution of support cost across MSs is assumed, and where additionally a "High Country Risk" in certain EU MSs remains (cf. variant "Without RES cooperation & without levelling of country-specific risk").
- The second case comprises again no (full) RES cooperation, so no effort sharing concerning support expenditures across MSs, but a change in financing conditions, meaning a levelling of country-specific risk (cf. variant "Without RES cooperation & with levelling of country-specific risk") that might have been facilitated by any targeted EU measure like a WACC equaliser.
- The third case includes the full impacts that come along with RES cooperation, a redistribution of cost (effort sharing) and a change in financing conditions across MSs, causing a levelling of country-specific risk across the EU (cf. variant "With RES cooperation & with levelling of country-specific risk").

In order not to overload the picture, within Figure 61 compared to above (cf. Figure 60) no distinction between existing (up to 2020) and new RES plants (installed post 2020) is undertaken, meaning we show only the total of support dedicated to renewables in the electricity sector.

This graph reconfirms some of the statements taken above, e.g. that in the long-term (2050) RES cooperation or, more precisely, the levelling of country risk across the EU is beneficial at the aggregated EU level – i.e. cf. 1.1 €/MWh$_{DEMAND}$ ("Without RES cooperation & without levelling of country-specific risk") vs. 0.7 €/MWh. ("With or without RES cooperation & with levelling of country-specific risk"). Focussing on the aspect of improving financing conditions via a levelling of country risk one can see that for several countries this appears of key importance. The specific support premia decline in Cyprus, Greece, Italy, Portugal and Spain significantly if only that measure is taken. Since these countries act as host for the CSP uptake we can conclude that this is a crucial aspect in this respect. EU measures for equalising WACCs across MSs would definitely help to simplify the financing of CSP projects in the South of Europe – this can be even classified as a necessity for a cost-effective CSP uptake within the EU. **A (more) fair effort sharing can then be triggered by RES cooperation and the redistribution of support expenditures across countries**, so that host countries do no longer have to pay the whole bill for the uptake of CSP and other comparatively costly RES technologies. That can be seen as crucial for countries like Cyprus, Portugal and Greece – all acting here as CSP hosts under this specific scenario – but also for countries like Latvia and Estonia acting as host for the wind uptake in the North of Europe.

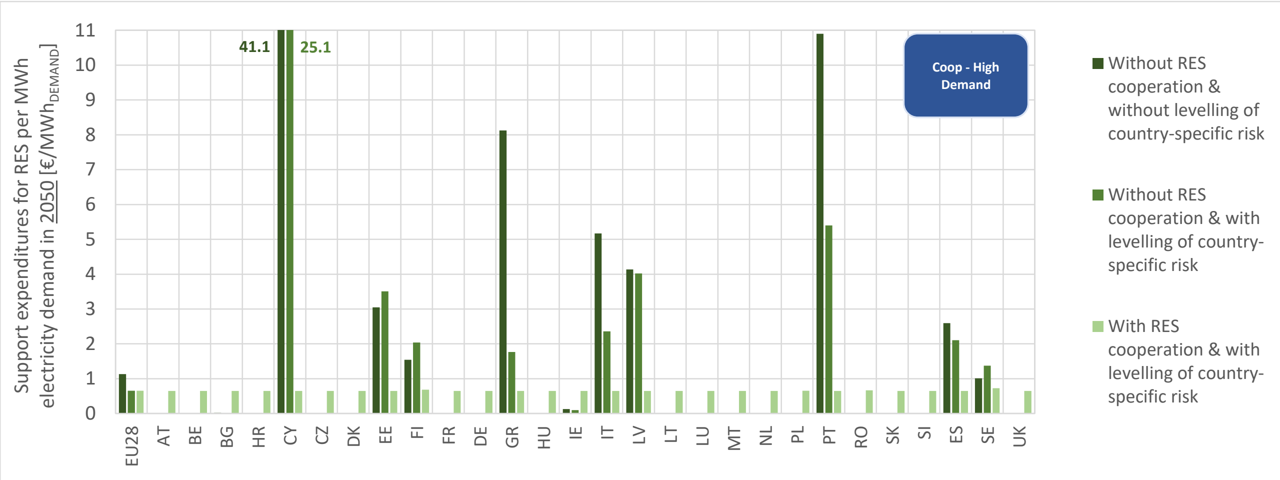

Figure 61: Comparison of the resulting country-specific RES support expenditures in 2050, expressed in specific terms as premium per MWh electricity consumption according to the scenario "Cooperation – High Demand" with and without RES cooperation and the complementary levelling of country-specific investor risk (Source: Green-X modelling)

Summing up, RES cooperation is assumed to facilitate a levelling of country-specific risk for RES investors and to redistribute the cost of the RES uptake across the whole EU, so that host countries for the uptake of CSP and other RES technologies do no longer have to pay the whole bill. As default we have taken in modelling the assumption that RES cooperation is taking place post 2020. In the sensitivity analysis performed here we showcase the consequences if attempts to initiate RES cooperation across the EU will not take place, meaning that RES investors in specifically southern European countries face a "High Country Risk".

At the aggregated EU level for total RES one can identify a clearly positive impact of RES cooperation, specifically of the levelling of country risk in financing, on RES-related support expenditures. More precisely, in the absence of levelling country risk in project financing across the EU support cost would increase 5-11 % at the aggregated EU level according to the scenarios assessed. That indicates that strong differences in financing conditions across EU countries as we still see them today are less preferential for the decarbonisation of the EU's electricity sector.

A (more) fair effort sharing can then be triggered by RES cooperation and the accompanying redistribution of support expenditures across countries, so that host countries do no longer have to pay the whole bill for the uptake of CSP and other comparatively costly RES technologies which are relevant for the achievement of decarbonisation aims and for supply security. That can be seen as crucial for countries like Cyprus, Portugal and Greece – all acting in the exemplified scenario as CSP hosts – but also for countries like Latvia and Estonia, acting as host for the wind uptake in the North of Europe.

5 CONCLUSIONS

Below we present the main findings from our model-based assessment of the future market uptake CSP in Europe. The modelling works undertaken combined two core elements: a power system analysis, identifying the need for CSP in a decarbonised European electricity system of tomorrow, and an energy policy analysis to assess implications for and impacts of dedicated support policies for CSP and other renewables. This distinction is followed in the result representation and consequently we present also the lessons learned in accordance with that structure.

5.1 Key findings from the power system analysis - identifying the need for CSP in a decarbonised European electricity system of tomorrow

The achievement of the EU's climate and energy targets will require immense amounts of fluctuating renewable generation by technologies like wind and PV. To integrate this generation into future electricity systems up to 2050 and beyond, flexibility options and dispatchable renewable generation technologies have to be deployed accordingly at the same pace. Ensuring an optimal generation structure in the system is a necessity to minimise fossil-fuelled back-up technologies, emissions and overall system costs. CSP can contribute significantly to a sustainable and stable electricity generation mix in Europe in the future. How large this contribution will be, depends on different factors. These factors were analysed in the scenarios presented in this report.

With the definition and calculation of two different pathways and four different sensitivities, we studied the parameters enabling CSP in Europe. Concerning the question, whether cooperation among European countries leads to higher expansions of CSP power plants, our modelling results are ambiguous (see section 3.2). While in the case of very high electricity demand CSP generation is somewhat higher in the Cooperation pathway than in the National Preferences pathway, this tendency is reversed in the case of lower demand. However, a high electricity demand is more probable in a world with very ambitious decarbonisation targets.

In this context, a factor that certainly has an impact on CSP, is the role of nuclear power in the future European energy system. In scenarios with a higher share of nuclear power (due to France's national preferences), the remaining generation gap (between the total electricity demand and the supply by other technologies) diminishes, thereby reducing the share of CSP.

Our results indicate that a higher electricity demand increases the generation gap for CSP (see section 3.2.2). This is due to the fact that CSP is more expensive than other renewable technologies. Therefore, CSP capacities are increasingly installed when the potentials of other renewable technologies like wind and PV are already exploited to a higher degree.

Sufficiently high climate ambitions are another enabler of CSP development (see section 3.2.4), because they hinder the use of fossil power plants (first, as a backup of fluctuating renewables and a second, as supply of electricity demand exceeding the realizable potential of other renewables). Hence, CSP with its additional advantage of dispatchability becomes more important under such conditions.

As expected before, a highly developed transnational power grid is an ambivalent factor for the development of CSP (see section 3.2.1). On the one hand, due to their peripheral location, especially Spain and Portugal depend on a strong power grid interconnection to the rest of Europe in order to export larger amounts of electricity from CSP. On the other hand, a more limited power grid interconnection can favour the use of CSP in some countries, because it hinders the import of electricity from neighbouring countries and reduces the system flexibility provided by the grid, thereby increasing the need for dispatchable CSP.

Main results from the power system analysis:

- *European cooperation may be an enabler of CSP.*
- *A high share of nuclear power can hinder the expansion of CSP.*
- *A high electricity demand favours CSP.*
- *Higher climate ambitions lead to a higher share of CSP.*
- *The role of the electricity grid with regard to the expansion of CSP is ambiguous.*

5.2 Key findings from the energy policy analysis – implications for and impacts of dedicated support policies for CSP and other renewables

A strong uptake of renewables is required for meeting our decarbonisation aims

If we look back in time, we see that at EU28 level more than a doubling of RES deployment has been achieved throughout the past thirteen years. This impressive trend needs to be maintained: taking deep decarbonisation as our overall guiding principle implies an increase of the RES shares to about 56 % by 2030, and to at least 90 % by 2050. In absolute terms the accompanying strong growth in electricity consumption imposes even a strengthening of RES developments in future years compared to the historic record. Electricity generation from RES needs to more than quadruplicate until 2050.

Key trends in technology-specific developments are that onshore wind dominates the picture, followed by offshore wind and photovoltaics where residential and central PV systems are expected to increase significantly. CSP is the fifth largest contributor to RES generation, serving as “gap filler” for the system flexibility to the EU power system that relies on large shares of variable renewables.

Concerning country-specific contributions, currently strong differences in demand-related RES shares are observable across countries and that will remain. This also holds for 2050 when renewables reach a high demand share at EU level. Differences in RES shares across countries are smallest under a more limited expansion of the cross-border transmission grid since exchange of electricity across countries is then more limited and, in consequence, countries have to facilitate a stronger domestic RES expansion.

Strong investments in renewables are needed – CSP makes up 7-8 % of the total under default assumptions on demand growth and climate ambition

Strong investments in RES technologies are necessary for making the transition towards carbon neutrality in the EU'S electricity sector, average yearly investments range for the key scenarios analysed from 91-100 billion €. Investments are slightly higher in case of grid limitations, and lower in magnitude if demand grow less than expected. Investments in CSP make up 7-8 % of the total according to key scenarios, and patterns for other cases are comparatively similar to total RES.

Support is needed to facilitate the strong uptake of CSP and other RES technologies – but new RES installations come at significantly lower cost thanks to technological progress

There is a need for dedicated support of CSP and other RES in the near to mid future. The bulk of identified RES-related support expenditures within forthcoming years up to 2050 is however dedicated to existing RES, established in the years up to 2020 since they have come at higher cost. Support for new RES (installed post 2020) is expected to strongly decline over time due to technological progress and the projected increasing prices in wholesale electricity markets. A key element for achieving this decline in support for new RES installations, specifically for variable RES like wind and solar PV, is the expansion of the cross-border transmission grid since this facilitates RES integration and the balancing of under- and oversupply across countries in times of high variable RES infeed.

Dedicated support as promising alternative to high carbon prices

From our focal assessment on the role of dedicated support instruments as complement to the EU ETS we can conclude that in the absence of high carbon prices in the EU ETS, i.e. reflecting a world where dedicated support is offered to individual decarbonisation options and implying, in turn, that the EU ETS is not acting as single driver for the take-up of decarbonisation options and needs, overall remuneration of CSP and other RES technologies and, consequently, also corresponding consumer cost are at a lower level than in an "ETS only" world. Here targeted support can be provided to individual RES technologies, for example via auctions for sliding feed-in premia, in accordance with technology- or even site-specific requirements. Such a policy approach helps to avoid overcompensation for "low hanging fruits" like onshore wind or solar PV.

There is a need for and positive impact of RES cooperation on the cost for the uptake of CSP and other RES technologies

For CSP a strong positive impact of RES cooperation is getting apparent: In the absence of RES cooperation support – i.e. when a "High Country Risk" is prevailing in many of the southern European host countries of expected future CSP developments – significantly higher specific support is required. At the aggregated EU level for total RES one can also identify a clearly positive impact of RES cooperation, specifically of the levelling of country risk in financing, on RES-related support expenditures. This indicates that strong differences in financing conditions across EU countries as we still see them today are less preferential for the decarbonisation of the EU's electricity sector.

A (more) fair effort sharing can then be triggered by RES cooperation and the accompanying redistribution of support expenditures across countries, so that host countries do no longer have to pay the whole bill for the uptake of CSP and other comparatively costly RES technologies which are relevant for the achievement of decarbonisation aims and for supply security.

Main results from the energy policy assessment:

- *A strong uptake of renewables is required for meeting our decarbonisation aims.*
- *Strong investments in renewables are needed – CSP makes up 7-8 % of the total under default assumptions on demand growth and climate ambition.*
- *Support is needed to facilitate the strong uptake of CSP and other RES technologies – but new RES installations come at significantly lower cost thanks to technological progress and increasing electricity prices.*
- *Dedicated support for CSP and other renewables is a useful and cost-effective alternative to high carbon prices.*
- *There is a need for and positive impact of RES cooperation on the cost for the uptake of CSP and other RES technologies.*

Concluding remark on the design of support instruments for CSP

Whether we will see CSP as part of the EU's future electricity system will mainly depend on the price signals this technology receives from the market. These price signals could take the form of targeted support, e.g. in the form of RES auctions. One of the most important features of auctions to facilitate CSP market uptake is that they value dispatchability of electricity generation (cf. e.g. del Río, Kiefer, Winkler, & Anatolitis, 2019). This can be achieved by requiring firm power with a specified generation profile which is complementary to fluctuating RES generation which will be mainly characterised by PV in places with rich solar resources. Other possibilities for CSP to receive the right market signals are higher remuneration levels at times of higher demand or a required minimum storage time for RES projects.

REFERENCES

Boie Inga (2016). Determinants for the market diffusion of renewable energy technologies - An analysis of the framework conditions for non-residential photovoltaic and onshore wind energy deployment in Germany, Spain and the UK. PhD-Thesis. Karlsruhe, Germany, 2016.

Boie, Inga

Crespo del Granado et. al. (2019). SET-Nav – Comparative assessment and analysis of pathways, SET-Nav project, http://www.set-nav.eu/content/pages/library.

CSP.guru. (2019). *CSP.guru (Version 2019-09-01) [Data set]*. http://doi.org/10.5281/zenodo.3466625.

De Vita, A., Kielichowska, I., Mandatowa, P., Capros, P., Dimopoulou, E., Evangelopoulou, S., … Dekelver, G. (2018). *Technology pathways in decarbonisation scenarios*. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

del Río, P., Kiefer, C., Winkler, J., & Anatolitis, V. (2019). *Auctions for the support of renewable energy from Concentrated Solar Power (CSP). Main results and lessons learnt. Deliverable 2.1. AURES II*. Retrieved from http://aures2project.eu/wp-content/uploads/2020/02/AURES_II_case_study_CSP.pdf

ESTELA. (2019). *CSP Technology Cost Assumptions*.

European Commission. (2018). A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. COM(2018) 773 final..

European Commission. (2019). *The European Green Deal*. Retrieved from https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

European Commission. (2020a). *2030 climate & energy framework*. Retrieved from https://ec.europa.eu/clima/policies/strategies/2030_en

European Commission. (2020b). *Going climate-neutral by 2050: A strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy*. Retrieved from https://ec.europa.eu/clima/sites/clima/files/long_term_strategy_brochure_en.pdf

Lilliestam, J., Ollier, L., Labordena, M., Pfenninger, S., & Thonig, R. (2020). The near- to mid-term outlook for concentrating solar power: mostly cloudy, chance of sun. *Energy Sources Part B*. https://doi.org/10.1080/15567249.2020.1773580

Lilliestam, J., Ollier, L., Thonig, R., Del Río, P., Kiefer, C., Caldés, N., … Lázaro Touza, L. (2019). *Updated policy pathways for the energy transition in Europe and selected European countries. Deliverable 7.3 MUSTEC project, Institute for Advanced Sustainability Studies (IASS), Potsdam*. Retrieved from http://mustec.eu/sites/default/files/reports/Lilliestam_et al_2019_Policy_pathways_for_the_energy_transition_in_Europe_and_selected_European_countries.pdf

Resch G., Ortner A., Welisch M., Busch S., Liebmann L., Totschnig G., Zehetner G., Breitschopf B., Ragwitz M. (2016). Costs and benefits of RES in Europe. A report compiled within the IEE project DIA-CORE. TU Wien, Vienna, 2019. Accessible at www.diacore.eu.

Resch G., Ortner A., Liebmann L., Busch S., Welisch M., Hiesl A., Geipel J. (2017). towards2030-dialogue - a quantitative assessment of RES policy pathways and 2030 RES targets. A report compiled within the IEE project towards2030-dialogue. TU Wien, Vienna, 2017. Accessible at www.towards2030.eu.

Schöniger, F., & Resch, G. (2019). *Case Studies analysis of prospects for different CSP technology concepts. Deliverable 8.1 MUSTEC project*. Retrieved from http://mustec.eu/sites/default/files/reports/MUSTEC_Deliverable_8.1_final.pdf

Schöniger, F., Resch, G., Kleinschmitt, C., Franke, K., Sensfuß, F., Lilliestam, J., & Thonig, R. (2020). *Pivotal decisions and key factors for robust CSP strategies. Deliverable 7.4 MUSTEC project, TU Wien, Vienna*.

Schöniger, F., Thonig, R., Resch, G., & Lilliestam, J. (2019). Making the sun shine at night: comparing concentrating solar power and photovoltaics with storage. *Energy Sources, Part B: Economics, Planning, and Policy*, (Special Issue: Dispatchable RES and Flexibility in High RES Penetration Scenarios: Solutions for Further Deployment).

Sensfuß, F., Bernath, C., Kleinschmitt, C., Resch, G., Geipel, J., Liebmann, L., … Ploussard, Q. (2019). *SET-Nav D7.8: Summary report - Energy Systems: Supply Perspective*. Retrieved from http://www.set-nav.eu/sites/default/files/common_files/deliverables/WP7/D7.8_SET-Nav_SummaryReport_WP7_final.pdf

SET-Nav. (2019). SET-Nav. Strategic energy roadmap. Retrieved from EU Horizon 2020 project No 691843 website: http://www.set-nav.eu/

Zickfeld, F., Wieland, A., Blohmke, J., Sohm, M., Yousef, A., Pudlik, M., … Sensfuß, F. (2012). *2050 Desert Power. Perspectives on a Sustainable Power System for EUMENA.* Retrieved from https://dii-desertenergy.org/publications/desert-power-2050/

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 from the year 2010 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.

The calculation of the potentials for renewable energies takes place in five steps:

1. determination of the usable area
2. determination of the installable capacity
3. calculation of the possible output
4. calculation of specific generation costs
5. aggregation of potentials within a region

The method for determining the usable area is methodically identical for all technologies. The starting point for modelling the potentials of renewable energies is a model grid that is applied to the entire modelled region. This model grid has an edge length of 10 km at the height of the equator. Due to the shape of the earth, this edge length decreases with increasing distance from the equator. In Germany the edge length is about 7 km. On the basis of this grid different geographical information and meteorological data are combined.

In a first step, those areas within the tiles that are unsuitable for the use of the respective technology are removed. These include, for example, well-known nature reserves and areas with very steep slopes. The remaining area is assigned to a specific land use category based on available land use data. For each of these land use types, shares of the area are released for the use of renewable electricity generation. In case of PV and CSP the required area is actually covered by the plant, in case of wind energy utilized area is defined as area that is influenced in terms of wind speed by the rotor of the plant. An overview of land use types and land shares that can be used for renewable energies can be found in Table 1.

Table 8: Overview of land use utilisation factors for renewable energies

Type of land use	Utility scale PV	CSP	Wind Onshore
Fallow land	20%	45%	25%
Cultivation areas	2%	6%	20%
Forest	0%	0%	10%
Grassland	3%	6%	25%
Savannah	3%	45%	25%
Bush land	3%	45%	25%
Ice rinks	5%	0%	15%
Constructed area	0%	0%	0%
Water surface	0%	0%	0%
Wetlands	0%	0%	0%

In the case of rooftop PV, it is assumed that 20% of the built-up area are suitable for use. This assessment was made for Germany with a detailed projection of suitable roof areas using map evaluations and satellite data for the state of North Rhine-Westphalia as an example. In the case of offshore wind energy, the use of 50% of the available sea surface with water depths of less than 50 m is assumed. In total, the available area on a "tile" for a given power generation technology is calculated according to the following formula:

$$Available\ area = \sum tile\ size \cdot share_{land\ use} \cdot factor_{utilisation}$$

CSP in Enertile

In Enertile, the underlying CSP technology are tower plants as we assume that this technology will be dominant in the future due to higher efficiency. Therefore, the underlying cost assumptions refer only to this technology (see also Table 3). The CSP technology is connected to an 11-hour thermal storage system in the framework of the MUSTEC project (see e.g. also Schöniger et al. (2020)). Therefore, this technology can also provide electricity in hours with low solar irradiation and can be an additional flexibility option in the power system. This is an advantage compared to the less expensive PV technologies considered in the Enertile model.

6.2 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 electricity 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, additional 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 emission savings). Results are calculated at both at 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, investment 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 biomass 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 constraints 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, additionally, applied parameters may change over time.

6.3 Interest rate / weighted average cost of capital - the role of (investor's) risk in Green-X modelling

The model-based energy policy assessment as outlined in chapter 4 of this report incorporates the impact of risks to investors on RES deployment and corresponding (capital / support) expenditures. In contrast to detailed bottom-up analyses of financing cases, Green-X modelling aims to provide an aggregated view at the national and European level with fewer details on individual direct financing instruments. More precisely, the debt and equity conditions resulting from specific financing instruments are incorporated by applying different weighted average cost of capital (WACC) levels.

Determining the necessary rate of return is based on the weighted average cost of capital (WACC) methodology. WACC is often used as an estimate of the internal discount rate of a project or the overall rate of return desired by all investors (equity and debt providers). This means that the WACC formula[24] determines the required rate of return on a company's total asset base and is determined by the Capital Asset Pricing Model (CAPM) and the return on debt.

Formally, the pre-tax cost of capital is given by:

$$WACC^{pre\text{-}tax} = g_d \cdot r_d + g_e \cdot r_e = g_d \cdot [r_{fd} + r_{pd}] \cdot (1 - r_{td}) / (1 - r_{tc}) + g_e \cdot [r_{fe} + \beta \cdot r_{pe}] / (1 - r_{tc})$$

Within the model-based analysis, a range of settings is applied to accurately reflect the risks to investors. Risk refers to three different issues:

- A "policy risk" is related to the uncertainty about future earnings caused by the support scheme itself – e.g. refers to the uncertain development of certificate prices within a RES trading system and / or uncertainty related to earnings from selling electricity on the spot market. The range of settings used in the analysis with respect to policy risks varies from 6 % (default risk) up to 7.8 % (high risk). The different values are based on a different risk assessment, a standard risk level and a set of risk levels characterised by a higher expected / required market rate of return. 6 % is used as the default value for stable planning conditions as given, e.g. under advanced fixed feed-in tariffs. The higher value is applied in scenarios with less stable planning conditions, i.e. in the cases where support schemes cause a higher risk for investors as associated with e.g. technology-uniform RES trading (and related uncertainty about future earnings on the certificate market). An overview of the settings used by the type of policy instrument or pathway, respectively, is given in Table 9.
- A "technology risk" refers to uncertainty about future energy production due to unexpected production breaks, technical problems, etc... Such problems may cause (unexpected) additional operational and maintenance costs or require substantial reinvestments which (after a phase-out of operational guarantees) typically have to be borne by the investors

[24] The WACC represents the necessary rate a prospective investor requires for investment in a new plant.

themselves. In the case of biomass, this also includes risks associated with the future development of feedstock prices. Table 10 (below) illustrates the default assumptions applied to consider investors' technology risks. The expressed technology-specific risk factors are used as a multiplier of the default WACC figure. The ranges indicated for several RES categories reflect the fact that risk profiles are expected to change over time and that specific RES categories cover a range of technologies (and for instance also a range of different feedstocks in the case of biomass) and unit sizes. The lower boundary for PV or for several RES heat options also indicates a different risk profile of small-scale investors who may show a certain "willingness to invest", requiring a lower rate of return than commercial investors.

- The third risk component is named as "country risk". At present differences across Member States with respect to financing conditions are commonly acknowledged, see e.g. Boie (2016). This leads to a higher risk profiling of investments in countries more strongly affected by the financial and economic crisis compared to more stable economies within Europe. In modelling we assume that an alignment of these conditions might take place, depending on the chosen policy framework: On the one hand, this might be driven by a further "Europeanisation" of RES policy making, e.g. through a market opening of national policy schemes, enhanced RES cooperation between Member States or at the ultimate extent via harmonisation. The assumptions taken concerning country-specific risks are shown in Figure 62, distinguishing between the default risk profiling for the year 2030 (and beyond) where a smoothening / levelling of risk factors is assumed to take place, driven by RES cooperation, and a "High Country Risk" variant where the assumption is taken that national policy approaches set the scene and, consequently, no levelling of country-specific risks will occur. Country-specific risk profiling used in our modelling builds on statistical data concerning current (2016) financing conditions as specified in Table 11. Here we specifically take into account indicators on long-term governmental bonds and national credit rating. Please note further that country risk settings are assumed to change over time, aligned to general GDP/capita trends taken from PRIMES modelling.

Please note that all risk components are considered as default in the assessment, leading to a different – typically higher – WACC than the default level of 6 %.

Table 9: Policy risk: Instrument-specific risk factor (Green-X modelling)

Policy risk: Instrument-specific risk factor (i.e. multiplier of default WACC)	
FIT (feed-in tariff)	1.00
FIP (feed-in premium – specifically a sliding feed-in premium scheme)	1.05
QUO (quota system with uniform TGC) & Cross-sectoral quota ("Least cost approach")	1.20
QUO banding (quota system with banded TGC)	1.15
ETS (no dedicated RES support)	1.30
TEN (tenders for sliding premium at RES-E technology level)	1.15

Table 10: Technology-specific risk factor (Green-X modelling)

Technology-specific risk factor (i.e. multiplier of default WACC)			
RES-electricity		***RES-heat***	
Biogas	1.00-1.05	Biogas (grid)	1.05
Solid biomass	1.05	Solid biomass (grid)	1.05
Biowaste	1.05	Biowaste (grid)	1.05
Geothermal electricity	1.1	Geothermal heat (grid)	1.05
Hydro large-scale	0.95	Solid biomass (non-grid)	0.95-1.00
Hydro small-scale	0.95	Solar thermal heat. & water	0.90
Photovoltaics	0.85-0.90	Heat pumps	0.90
Solar thermal electricity	1.1	***RES-transport / biofuels***	
Tide & wave	1.20	Traditional biofuels	1.05
Wind onshore	0.9-0.95	Advanced biofuels	1.05
Wind offshore	0.9-1.0	Biofuel imports	-

Table 11: Country-risk profiling: Statistics on financing conditions used for deriving default and alternative risk profiling

Country risk profiling		Austria	Belgium	Bulgaria	Croatia	Cyprus	Czech Republic	Denmark	Estonia	Finland	France	Germany	Greece	Hungary	Ireland	Italy
Statistics on financing parameter (2016 data)	weighting factor															
Eurostat - long term government bond yields	10%	0.36	0.47	2.42	3.64	3.87	0.41	0.33	0.00	0.37	0.43	0.07	8.64	3.12	0.74	1.40
RES deployment times risk ranking		19.2	9.1	46.9	30.1	8.7	11.2	12.7	0.0	26.2	111.9	18.2	279.6	64.6	14.2	160.9
National Credit Rating	90%	0.89	0.89	0.56	0.56	0.56	0.89	1.00	0.89	0.89	0.89	1.00	0.44	0.67	0.78	0.67
RES deployment times risk ranking		47.0	17.1	10.7	4.6	1.2	24.2	37.9	9.2	62.7	232.3	255.6	14.4	13.8	14.9	76.7
Ease of getting credit	0%	0.60	0.45	0.70	0.55	0.60	0.70	0.70	0.70	0.65	0.50	0.70	0.50	0.75	0.70	0.45
RES deployment times risk ranking		31.7	8.7	13.5	4.5	1.3	19.1	26.5	7.2	45.9	130.8	178.9	16.2	15.5	13.5	51.9
Average risk rating (post 2030):																
High Country Risk (moderate levelling)		**92%**	**94%**	**138%**	**148%**	**146%**	**92%**	**83%**	**91%**	**93%**	**93%**	**83%**	**207%**	**127%**	**103%**	**140%**
Default assumption (strong risk levelling due to Europeanisation)		**97%**	**99%**	**109%**	**112%**	**111%**	**98%**	**96%**	**98%**	**98%**	**98%**	**96%**	**127%**	**107%**	**101%**	**110%**

Country risk profiling		Latvia	Lithuania	Luxem-bourg	Malta	Nether-lands	Poland	Portugal	Romania	Slovakia	Slovenia	Spain	Sweden	United Kingdom	**EU28**
Statistics on financing parameter (2016 data)	weighting factor														
Eurostat - long term government bond yields	10%	0.53	1.09	0.26	0.93	0.28	2.94	3.05	3.30	0.49	1.26	1.42	0.58	1.20	**1.17**
RES deployment times risk ranking		7.2	15.8	0.6	0.5	14.6	293.0	120.2	196.9	5.8	10.4	210.6	52.1	237.5	**1978.5**
National Credit Rating	90%	0.78	0.78	1.00	0.78	1.00	0.78	0.56	0.67	0.78	0.78	0.67	1.00	0.89	**0.84**
RES deployment times risk ranking		10.5	11.2	2.3	0.4	52.1	77.4	21.8	39.8	9.3	6.4	98.8	90.3	176.2	**1418.8**
Ease of getting credit	0%	0.85	0.70	0.15	0.70	0.50	0.75	0.45	0.85	0.65	0.35	0.60	0.55	0.75	**0.62**
RES deployment times risk ranking		11.5	10.1	0.4	0.4	26.0	74.7	17.7	50.8	7.8	2.9	89.0	49.6	148.8	**1054.9**
Average risk rating (post 2030):															
High Country Risk (moderate levelling)		**101%**	**104%**	**84%**	**104%**	**85%**	**114%**	**141%**	**128%**	**101%**	**105%**	**105%**	**85%**	**98%**	**100%**
Default assumption (strong risk levelling due to Europeanisation)		**100%**	**101%**	**96%**	**101%**	**96%**	**103%**	**110%**	**107%**	**100%**	**101%**	**101%**	**96%**	**99%**	**100%**

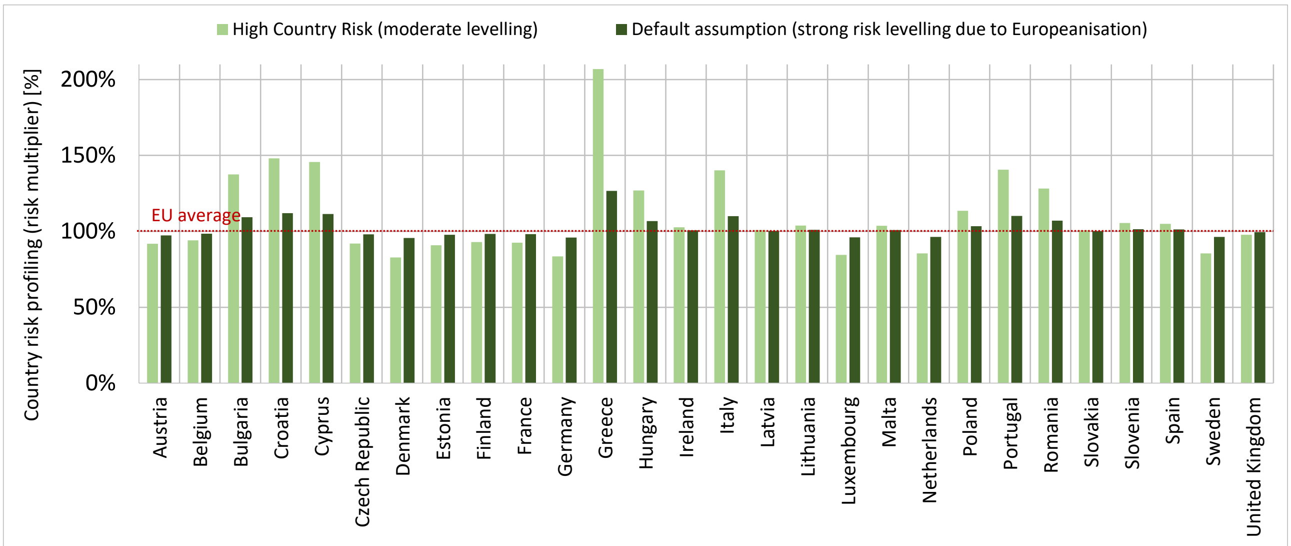

Figure 62: Country risk profiling used for the period post 2030 (Green-X modelling)

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 Energéticas, Medioambientales y Tecnológicas – CIEMAT.

Name	Country	Logo
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas – **CIEMAT**	ES	
University of Piraeus Research Center – **UPRC**	GR	
Institute For Advanced Sustainability Studies e.V. – **IASS Potsdam**	DE	
Technische Universität Wien – TU WIEN	AT	
European Solar Thermal Electricity Association – **ESTELA**	BE	
COBRA Instalaciones y Servicios S.A – **COBRA**	ES	
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Agencia Estatal Consejo Superior de Investigaciones Científicas – **CSIC**	ES	
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The project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 764626.

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