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On the Transition of Europe's Power Sector: Economic Consequences of National Targets

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***Abstract*—**The prospects for the European power sector indicate that it has to almost fully decarbonize in order to reach the economy-wide target of CO_2-emission reduction. We apply the EU-REGEN model to explain the penetration of RES from an economic perspective, their spatial distribution, and the complementary role of conventional generation technologies. Furthermore, we identify economic consequences of national energy and climate targets. Our study shows that onshore wind power will be the most crucial generation technology for the future European power sector. Its geographic distribution is driven by resource quality. Gas power will be the major conventional generation technology for backing-up wind power. Moreover, a complete phase out of coal power proves to be not economically optimal. The paper demonstrates that existing national targets have a negative impact, especially on the German region with higher prices and lower revenues. The remaining regions profit are hardly affected. We encourage an EU-wide coordination on the expansion of wind power with harmonized policies. Yet, this requires profitable market structures for both, RES and conventional generation technologies.

***Keywords*—**European decarbonization pathway, power market investment, public policies, technology choice.

I. MOTIVATION AND RELATED WORK

SINCE the beginning of the century the energy policy of the European Union (EU) is mainly driven by the decarbonization of the supply side. Studies showed that the power sector will be one of the main leverages to the reach the ambitious decarbonization targets. On the one hand, sector coupling and the conversion of power to other energy commodities (e.g. power-to-gas) will result in soaring electricity demand [1], [2]. On the other hand, the electricity generation-mix has to reduce its CO_2-intensity.

Currently, there are three technology options that allow addressing both of the above-mentioned developments: Application of renewable energy sources, nuclear power, or conventional fuel-based generation in combination with carbon capture and storage (CCS).

The 1997, the Kyoto Protocol laid the ground for the first obligatory greenhouse gas (GHG) reduction target. For the member states of that time, the agreement was translated into a mandatory reduction target of 8% compared to 1990 levels. This was followed by the "Energy and Climate Package" in 2008, which resulted in the "20-20-20" targets [3]. Comprising a 20 % share of renewable energy sources in energy consumption, a 20% reduction of GHG emissions compared to 1990 levels, and a 20% reduction of final energy consumption compared to a business-as-usual scenario. Furthermore, each member state had to translate those EU-wide targets into national targets.

To address, the mid- and long-run perspective, the European Commission released "A roadmap for Moving to a Competitive Low Carbon Economy in 2050", emphasizing a GHG emission-reduction target of at least 80% compared to 1990 levels [1], [4]. In 2014, this decarbonization path was further specified by targets for 2030: a 27% share of renewable energy sources in energy consumption, a 40% reduction of GHG emissions compared to 1990 levels, and a 27% decrease of final energy consumption.

The EC's energy system-wide scenarios indicate that growth of existing load patterns, combined with the above-mentioned electrification and conversion of power, will double electricity generation in 2050 compared to 1990, an increase of 50% compared to the current level. At the same time, most scenarios assume a limited potential of GHG reduction in other sectors. Meaning, the electricity sector has to contribute 98% CO_2-emission reduction in its generation-mix by 2050 to reach the economy-wide target of 80% [2]. Fig. 1 indicates the required and contrary development of both – electricity generation and CO_2-emissions in the power sector. Moreover, Article 4 of the recently signed Paris agreement points at this by emphasizing the balancing of emissions and sinks by the middle of the century [5].

Simultaneously, we see member countries of the EU announcing additional national climate and energy targets. For instance, Germany targets a reduction of economy-wide emissions of 40% by 2020 and 80% by 2050. Electricity generation from RES should sum up to a share of 35% by 2020 and 80% by 2050. Recently, France introduced a law on the transition of its power sector limiting the share of generation from nuclear power to 50% from 2025 on, setting the share of generation from RES to at least 40% from 2030 on, and targeting a CO2-emission reduction of 50% by 2030 and 80% by 2050.

Most existing studies on the European power sector emphasize the future role of RES along this path. Their potential, especially for variable renewable energy sources (vRES), is vast and future cost estimates suggest economic viability [6], [7]. Yet, the resources are geographically dispersed and their quality is spatially varying.

A strong strand of literature emphasizes the future role of transmission grid extensions. References [8], [9] look into the role of transmission capacity expansion for the integration of

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high shares of vRES and show the advantages and costs. The authors in [10], [11] point at the benefits of electricity exchange and transmission capacity expansion in a fully RES-powered sector. Similarly, the general importance of transmission grid expansion for the future European power system is analyzed in [12]–[14] looking into the impact of the EC's RES generation targets for 2030 and the relationship between transmission capacity and RES capacity additions. Moreover, a pure resource perspective on vRES is taken in [15] by looking at correlations of time-profiles at different spatial locations within Europe. The authors propose to utilize the resulting balancing effect for the integration of vRES. The economics of vRES are analyzed in detail in [16] by emphasizing their market value. We add to this research by showing generation and capacity investment results in the EU-REGEN model.

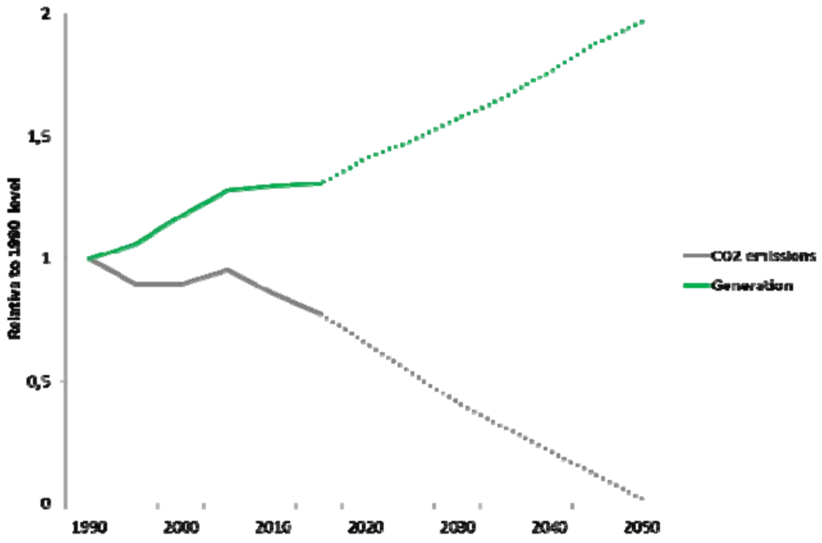

Fig. 1 Path of CO_2-emissions and generation relative to 1990

References [17], [18] focus on the supporting role of flexibility options in the European power system with high levels of vRES generation. This paper adds to this by looking at the sole target of decarbonization and analyzing the importance of CCS or nuclear power in allowing high shares of vRES.

The current political debate in Europe, and Germany especially, sees arguments for an early retirement of lignite and hard coal power plants to reach short- and mid-run climate targets [19], [20]. A recent policy letter on the phase out of coal power in Germany claims that the national climate targets cannot be met with any coal unit remaining online after 2040 [21]. Yet, there is little research on the optimal retirement schedule of conventional generation technologies across Europe with regard to the targeted decarbonization path. In that field, we contribute by analyzing the complementary role of fossil-fuel-based generation technologies and their optimal retirement path.

Additionally, the EC's long-run climate targets are only specified for Europe as a whole. This means a cost-efficient realization of the EU decarbonization will require the integration of national electricity markets and EU-wide coordination on climate and energy policy. Reference [22] looks at the economics of alternative policy measures for decarbonizing the European power sector. The impact of national policies on supranational power sectors for the example of Germany is analyzed in [23], [24].

With respect to that, we analyze the economic benefits of coordination along Europe's decarbonization path. This is done by comparing the default scenario that comprises EU-wide targets only with a scenario that additionally includes existing national energy and climate targets. Moreover, we identify regions that profit and suffer from the national targets.

Current national targets as a whole do not go beyond the established EU-wide targets. Therefore, the later target still determines the sum of system-wide emissions and national targets will not result in a reduction of overall emissions. A geographic shift of CO_2-emission from regions with national targets to neighboring regions will be expected. If binding, those national targets impose an additional constraint on the EU decarbonization path, disturb the least-cost capacity- and generation-distribution among countries, and finally result in additional economic costs.

To begin, Section II introduces the EU-REGEN model and the scenario set-up. Then, Section III presents the results of our analysis and a quantification of sensitivities. Finally, we close with a discussion of results and conclusions in Section IV.

II. METHODS

This chapter describes the EU-REGEN model used for this analysis, the scenarios set-up, and relevant data base.

A. *The EU-REGEN Model*

The EU-REGEN is a long-term dispatch and investment model for the European power sector. The model structure is based on the US Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model [25], [26]. EU-REGEN was built to generate quantitative scenarios that represent an optimal and consistent decarbonization path for the European power system towards 2050.

Fig. 2 EU-REGEN model regions and transmission links in the base year

It minimizes total system costs with respect to conventional and RES generation capacity investment, generation capacity conversion and retirement, generation dispatch and curtailment, transmission capacity investment, physical electricity exchange, storage capacity investment and operation, and carbon capture and storage capacity investment and operation. The model is set-up as a partial equilibrium model that assumes complete markets with perfect information and is subject to a wide range of constraints.

The model represents the entire European power sector. Its geographic scope includes all countries of the European Union (EU28) - except for the island countries of Malta and Cyprus. Additionally, we include Switzerland and Norway, which have a central position in the European system or are endowed with great resource potential. To reduce the size of the model we group those 28 countries into 13 model regions. Fig. *2* shows the EU-REGEN model regions.

The model horizon in this paper is 2050. The model starts at the base year 2015 and optimize dispatch and investment is set at five-year time intervals to 2050, which results in eight time steps. The model knows 25 different types of generation capacity. To account for different characteristics of power plants of the same type and varying resource quality of RES, we further distinguish each type into generation blocks. Resulting in 73 different generation blocks.

One specific characteristic of the EU-REGEN model is the detailed representation of the variable vRES wind and solar. We apply different resource quality classes to both resources, which is reflected in separate temporal availability profiles and capacity potentials for each quality class (A detailed model description can be found in [27]). In addition to the constraints in [27], we introduce a carbon policy and respective market for this analysis.

B. Scenarios

1. Coordination Scenario

The coordination scenario (COOR) is the default case in this analysis and assumes the current state of energy and climate policies brought forward by the EC. For 2020, the national CO_2-emission reduction targets and RES-shares in electricity generation, representing the "20-20-20" strategy have to be fulfilled by each country. For the years 2030 and 2050, the EU-wide targets (40% and 80% GHG-emission reduction, respectively) have to be reached by the whole European electricity system. This scenario allows for quantifying the development of the European power sector with ongoing and more intense coordination between countries.

Since the EC energy and climate policies are formulated as energy sector-wide targets only, for 2020, we assume the national targets set by each member state as implementation of the "20-20-20" strategy. For the remaining time horizon, we use power-market-specific values from the EC's "Impact Assessment on energy and climate policy up to 2030". Here, the "GHG40" scenario provides a first overview of the impacts on the power sector when reaching the 2030 and 2050 energy and climate policy targets. According to this assessment, the RES-share by 2030 and 2050 has to be at least 49.3% and 54.2%, respectively. The level of CO_2-emission has to reach a 56% reduction by 2030 and a 98% decrease of emissions by 2050. Furthermore, annual electricity generation in 2050 sums up to 5,040 TWh. For the time-steps in between we assume linearly increasing/decreasing targets for CO_2-emission reduction, RES-shares and electricity demand.

2. National Policy Scenario

The second scenario (NAT) models existing energy and climate policies as scenario COOR. Yet, we additionally include the national energy and climate targets set by countries. An overview on currently existing energy and climate targets by country can be found in [27]. This setup tries to model the economic costs of nationalization and covers the case where EU member countries fail in agreeing on how to share the burden from reaching the long-run targets.

C. Data Base

The input data used in the EU-REGEN model is described in [27].

III. RESULTS

This chapter presents the major results of our analysis. We start off with looking at Europe's future generation- and capacity-mix in the default scenario COOR. An analysis of the role of vRES follows this. In a second step, we present results on the optimal retirement of existing fuel-based generation capacity and describe the future relevance of dispatchable low-carbon technologies. The chapter closes with comparing the COOR and NAT scenarios and analyzing the economic consequences of national policies.

A. Default Scenario COOR

1. vRES Generation and Capacity

The generation mix for the scenario COOR is depicted in Fig. In addition to simulation results, the paper outlines the development of the historical generation mix from 1990 on. Moreover, Fig. 3 shows the regional generation mixes. From this (Figs. 3 and 4*)* it can be derived:

- Wind power is the dominating generation technology for the EU decarbonization path. Between 2015 and 2050, installed capacity and generation increase from 124 GW to 586 GW and 302 TWh to 1,536 TWh, respectively. The attractiveness of wind power can be explained by cost estimates, increasing availability factors, and its positive correlation with load. The latter one reflects the seasonal correlation of availability factors with demand. Both, maximum generation from wind power and demand peak, appear during winter periods. Note that new investments in wind power take place from the first model period on, where cost estimates are close to current numbers and connected to less uncertainty. The bulk of additions are from onshore capacity. New investment in wind offshore installations proves to be hardly economically viable with its accumulated capacity constantly staying below 10 GW.
- vRES as a whole increase their share in generation over the model horizon. The share in electricity generation of vRES more than triples from 12% in 2015 to 38 % in 2050. Yet, this is mainly driven by wind power. The generation share of all solar power technologies increase from 3 % in 2015 to 8 % in 2050 only. This weak market penetration is motivated in analogy to the attractiveness of wind power. In general, solar power technologies have lower availability factors and reduced investment costs are not able to compensate for that. Furthermore, we find a negative seasonal correlation with load in most model regions. A look at the timing of photovoltaic investments reveals the importance of decreasing investments costs. The majority of photovoltaic capacity is added in the mid- and long-run, where investment costs experience a strong decrease. In terms of technology, we only find photovoltaic power as an economically attractive technology. CSP does not penetrate the European power sector at all. Meaning, higher availability factors and flexibility though storage is not able to compensate for additional investment costs.
- We find the quality of wind and solar resources as the main driver for the geographic distribution of new wind and solar capacities. The model region "Britain" becomes dominating in wind power application, reaching a capacity and generation of 134 GW and 399 TWh in 2050 (compared to 11 GW and 140 TWh in 2015). Moreover, France and Scandinavia experience a significant increase in wind power capacity and reach an accumulated

capacity of 94 GW and 69 GW. New solar power capacity is mainly added in southern regions. Since the regional quality of solar resources correlates with latitude, the majority of new capacity is added in Italy, Iberia, and France. Those three regions reach capacities of 62 GW, 56 GW, and 48 GW in 2050.

2. Role of Dispatchable Generation Technologies

An overview on the development of conventional generation capacities is provided in Fig. 4. This figure depicts the net investments in each model period with columns above and below the x-axis representing positive net investments and a reduction in accumulated capacity, respectively. We want to emphasize the following key points:

- Gas power becomes the major conventional generation technology for backing-up the strong market penetration of wind power. After retiring excess-capacity in the short-run, the accumulated gas-power capacity increases from 171 GW to 488 GW and contributes 1,102 TWh of electricity in 2050. This is mainly driven by the need for flexible generation technologies as a complementary to vRES. Additionally, the targeted CO_2-emission reduction requires dispatchable generation technologies with low emission-intensity. In terms of gas power technologies, combined-cycle gas turbine is the dominating technology, reaching a capacity of 330 GW in 2050.

The capacity development of emission-intense coal power is clearly restricted by the decarbonization path. There are no additions to lignite and hard coal power capacity. Meaning, accumulated capacity is monotonically decreasing and characterized by retirement of old vintage capacities. The 181 GW of current coal power capacity is expected to decrease to 28 GW by 2050.

- We find nuclear power capacity to stay at a level constantly above 100 GW. Starting with 132 GW in 2015 and decreasing to 114 GW by 2050. The timing of new investment in nuclear power is simultaneous to the retirement of old vintages.
- The market penetration of CCS is limited to combined biomass-CCS capacity. Capacity additions start from 2040 on and reach an accumulated capacity of 58 GW by the end of the model horizon.

B. Consequences of National Policies in Scenario NAT

1. Changes in Generation

Scenario COOR showed the optimal geographic distribution of power capacity and generation for the EU-wide decarbonization path. We analyze the consequences of national policies in scenario NAT by looking at general system-wide effects and take a deeper look at the regions of France and Germany with the most ambitious national targets.

Fig. 5 depicts the system-wide generation mix for scenario NAT. Comparing this to generation in the COOR scenario (Fig) shows minor differences. For 2050, current national policies reduce generation from gas power, bio-CCS, and wind onshore power by 53 TWh, 13 TWh, and 16 TWh. This is mainly substituted by an increased contribution by nuclear power (31 TWh) and PV (57 TWh).

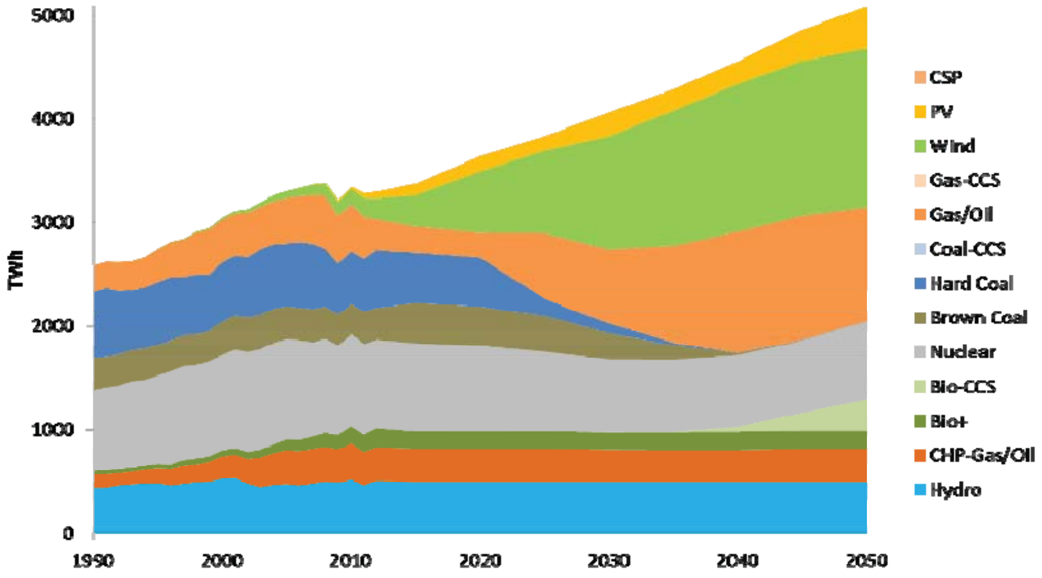

Fig. 3 System-wide generation mix in scenario COOR in [TWh]

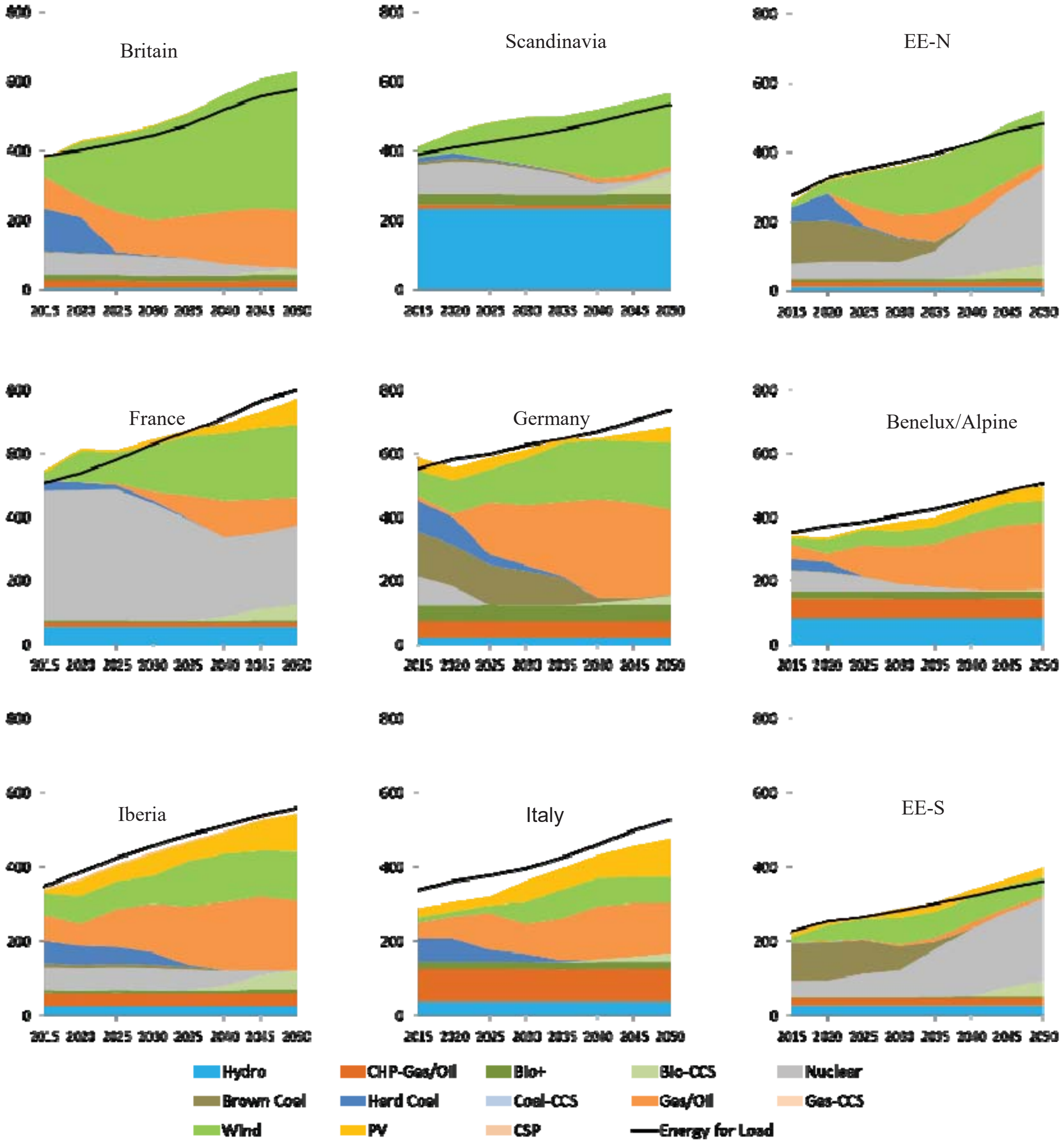

Fig. 3 Regional generation-mix in scenario COOR in [TWh]

Yet, comparing the regional generation patterns in Fig. 3 and Fig**. 6** reveals the following:

- Germany's target of an 80% RES-share in generation is mainly reached by reducing its gas power generation. This is compensated by additional generation from PV power. Yet, accumulated generation decreases significantly. Consequently, we find a geographic shift of generation from gas power to Norway, the north-eastern region, and Italy.
- The 50% upper bound on nuclear generation appears to be the binding feature of French policy. This constraint leads to an increased generation from gas and PV power in France. From a system perspective, we find a shift of generation from nuclear power to the south-east region.

2. Impact on Cross-Border Transmission Capacities

Furthermore, changing regional generation-mixes impact the optimal grid infrastructure. We find values for the NTCs in 2050 to hardly vary between scenario COOR and NAT. We can only identify a significant difference for the link between Benelux and Germany-N. The level of transmission capacity for this connection is 3 GW and 9 GW in scenario COOR and NAT, respectively. Though, it is important to note, that we apply upper bounds on the additions to each connection. This is done to account for the political and technical feasibility of grid-extensions. Since, the upper bound is already reached in the default scenario for most of the connections, the level of transmission capacity has only limited explanatory power. In that case, the shadow price on the transmission constraint could be thought of as a better indicator to compare both scenarios. The shadow prices reveal how much the total discounted system costs would decrease if one additional kW of transmission capacity for a specific connection would be allowed. Fig. 7 and Fig**. 8** present the shadow prices on each transmission link in 2050 for both scenarios. Numbers in those figures show:

- In the default scenario, high shadow prices for connections can be found either linking regions with a high wind-resource quality, such as Britain and Scandinavia, or eastern European countries, which are subject to conservative upper bounds on additions. We calculate the highest values for the connections from Britain to France and Benelux with of 172 €/kW and 126 €/kW. Similarly, links from Scandinavia to Benelux, the north-west of eastern Europe and northern Germany, are subject to a shadow price of 99 €/kW, 86 €/kW, and 78 €/kW. Concerning the eastern regions, there is a high value of 124 €/kW for the connection from north-east to the north-west of eastern Europe.

A comparison of values for both scenarios indicates big differences almost exclusively for connections linked to German regions. If national policies are in place, northern Germany experiences a high pressure on links from Benelux, Scandinavia, and the north-west of eastern Europe. Those shadow prices increase to 90 €/kW (8), 137 €/kW (78), and 77 €/kW (37). (Values for scenario COOR are shown in brackets.) The increase of shadow prices for connections to southern Germany is of a smaller order of magnitude. Values for links from France, Alpine, and EE-NW reach 72 €/kW (46), 46 €/kW (22), and 84 €/kW (63) in the NAT scenario. Vice versa, shadow prices for connections from southern Germany rise as well. Links to Benelux, northern Germany, and the Alpine region have shadow prices of 35 €/kW (13), 17 €/kW (1), and 36 €/kW (12). This can be explained by a higher generation from solar power in southern Germany that is caused by the 80 % RES-share target for the whole country

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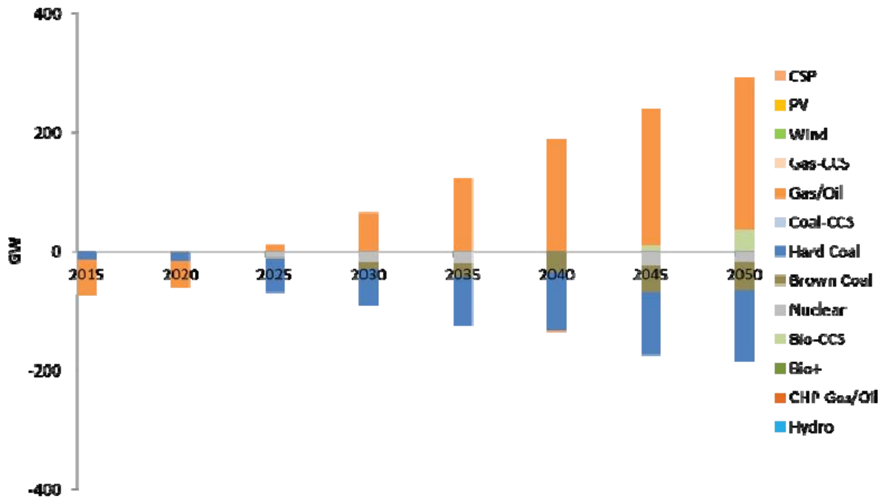

Fig. 4 Net investment in conventional generation technologies in [GW]

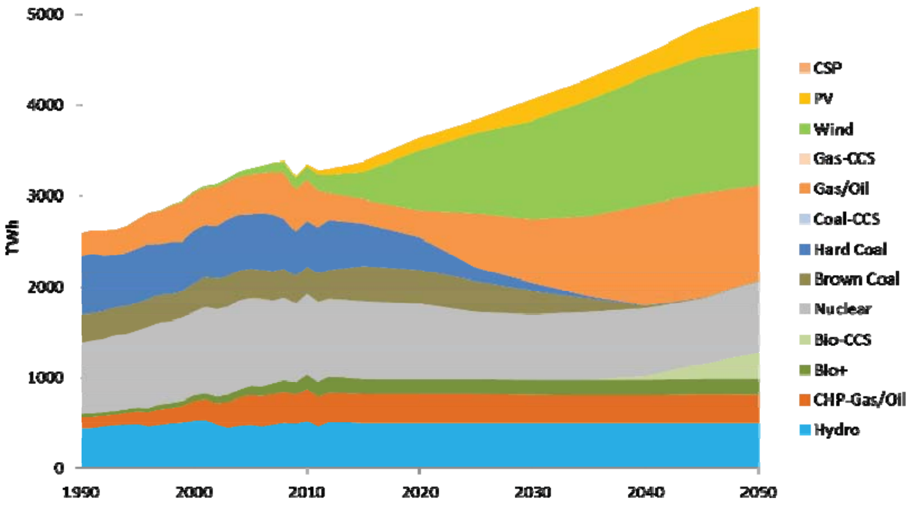

Fig. 5 System-wide generation mix in scenario NAT in [TWh]

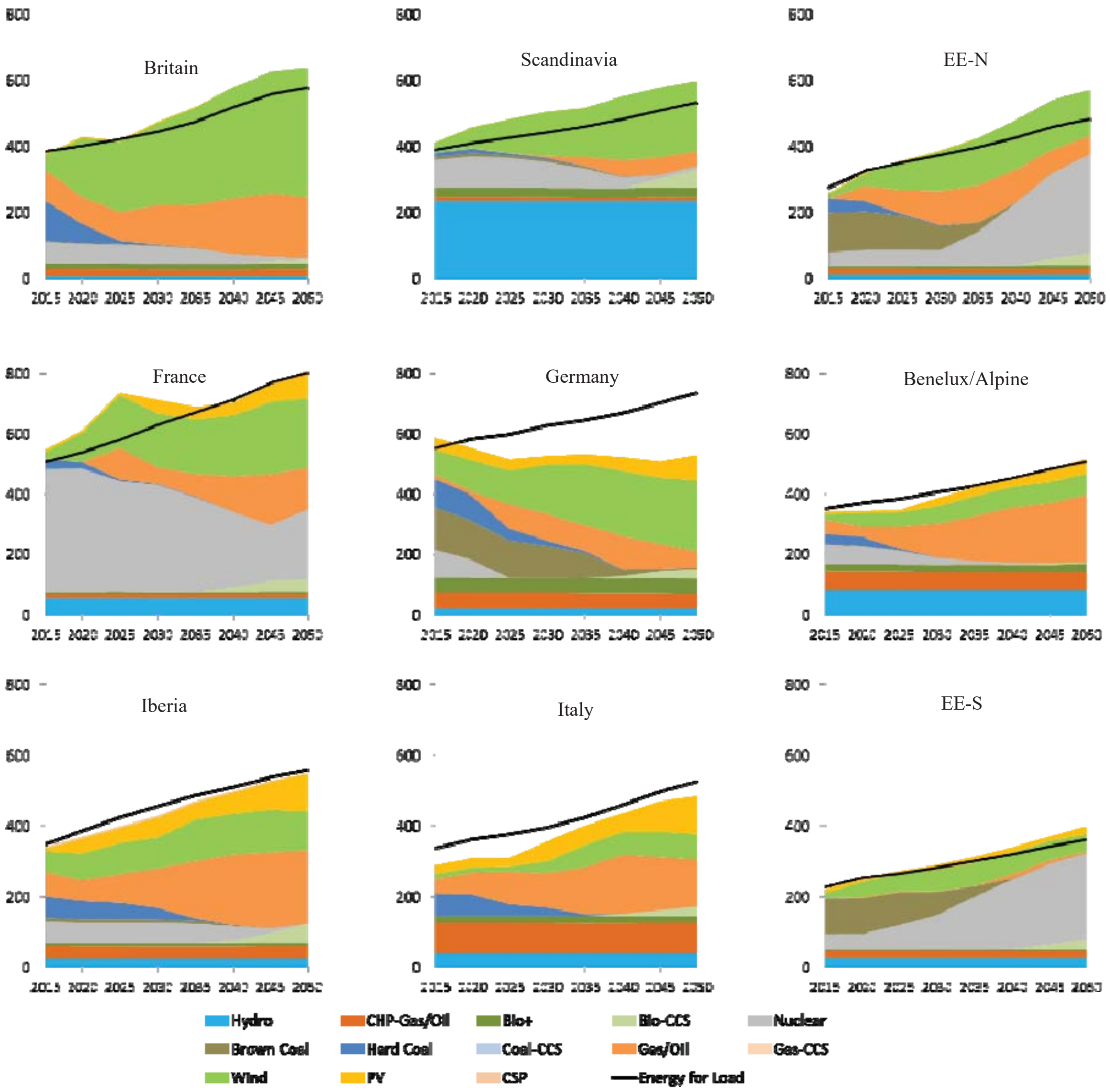

Fig. 6 Regional generation-mix in scenario NAT in [TWh]

3. Changes in Trade Flows

Consequently, also trade flows between regions change with national policies. Fig. 10 shows an analysis of the development of net exports for both the German regions and France. The measure shows to which extent a region is able to satisfy demand or depends on neighboring regions. Results indicate:

- In the COOR scenario, both German regions, especially the south, become a net importer in the long-run. Introducing additional national targets (NAT) leads to even more unbalanced trade flows. North Germany already becomes a net importer in the mid-run and the south increases the sum of annual imports.
- In contrast, France increases exports under a national policy. We find mid-run net exports to increase significantly and almost balanced flows by 2050.

4. Economic Consequences of National Policies

We use the total discounted system costs as a first indicator for the system-wide economic consequences of national policies. A comparison of system costs in scenario COOR and NAT shows an increase of 1% with national policies. Yet, it is important to note that only a small number of countries have national long-run targets. Moreover, those policies are binding in the long-run especially, which has less impact on the discounted system costs.

The economic perspective can be enhanced by looking at consumer and producers separately. Changing net imports are also reflected in electricity prices. Additionally, prices allow for identifying regions with consumers that win and lose from national targets. We look at average, energy only prices for consumed quantities. In general, any deviation from the cost-optimal generation pattern in scenario COOR leads to higher generation costs.

Electricity prices for both German regions in scenario NAT rise due to increased imports with higher average prices. Looking at both scenarios shows that by 2050 average prices in north and south Germany increase by 11% and 7% with national targets. We find a contrary development for France. Prices differ only in the mid-run with a reduction of up to 12% by 2030.

Finally, a changing power plant dispatch and prices impact producer's revenues. Looking at revenues allows identifying regions with producers that profit or suffer from national targets. Fig. 10 shows the relative change in total revenues for regions with a significant change. It can be observed that:

- Producers in both German regions suffer from a national target. Revenues of generators in northern Germany decrease by up to 25% in 2040 and reach a reduction of 18% in 2050. Revenues in south Germany drop even more with a level of -27% in 2050. This development is mainly driven by the drop of accumulated generation in both regions.
- The loss of revenues in Germany results in increased revenue streams in neighboring regions. The north-western of Eastern Europe profits the most from national targets and reaches a level of +14%. Moreover, Scandinavia and the Benelux region increase revenues by 8% and 9% in 2050.
- The French national targets have no negative impact on generators in the long-run. In the short-run revenues drop due to the cap on nuclear generation. Yet, from 2035 on, increased PV generation leads to higher revenues.

Fig. 7 Shadow prices on transmissions links in 2050 for scenario COOR in [EUR/kW]

Fig. 8 Shadow prices on transmissions links in 2050 for scenario NAT in [EUR/kW]

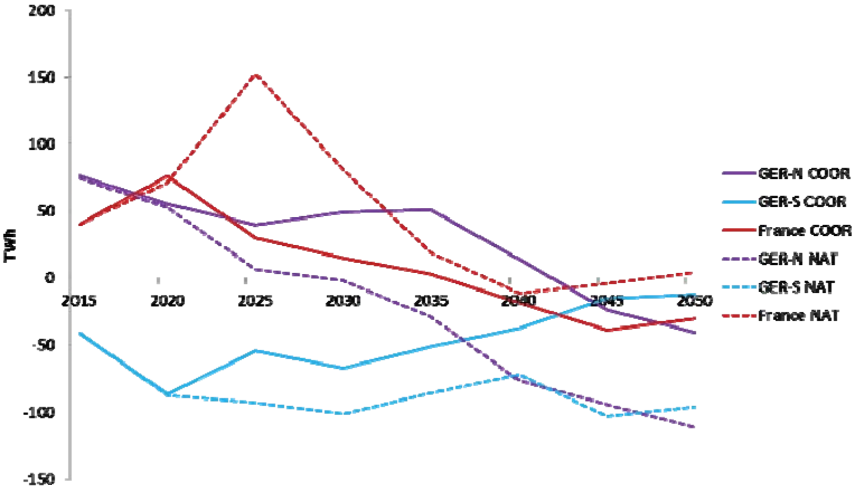

Fig. 9 Net exports in scenario COOR and NAT in [TWh]

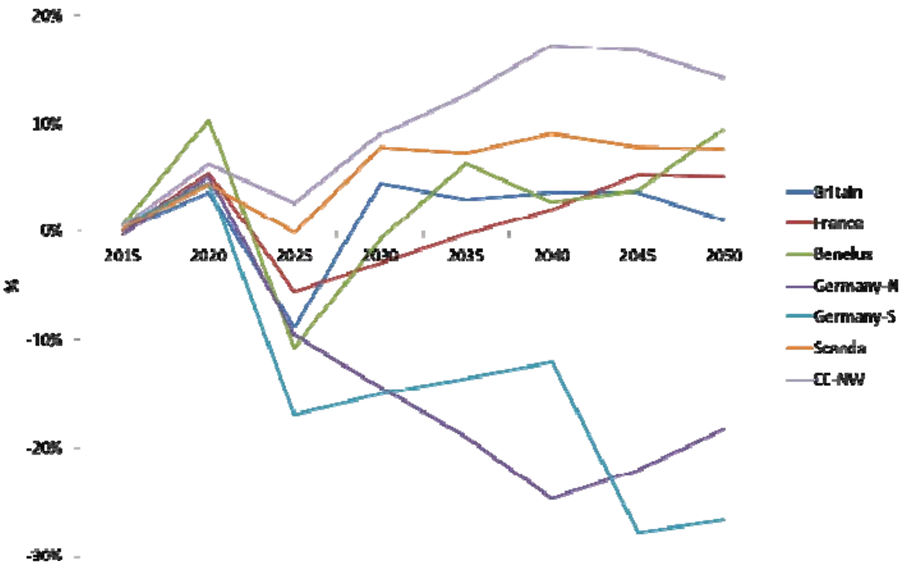

Fig. 10 Relative change in total revenues

C. Quantification of Sensitivity

Finally, we analyze the robustness of the 2050 generation-mix by a set of counter-factual scenarios. This analysis varies along two dimensions: on the one hand, the above-introduced default and policy scenario and, on the other hand, the following assumptions on transmission and generation technologies:

- Reduced investment cost for PV – 250 €/kW instead of 750 €/kW in 2050 (cheapPV)
- Reduced investment cost for nuclear power – 2,500 €/kW instead of 5,000 €/kW in 2050 (cheapNUC)
- No new transmission capacity additions (noTRANS)
- Unconstrained transmission capacity additions (unlTRANS)
- No CCS application (noCCS)
- No negative crediting of biomass-CCS (nonegCRED)
- No new nuclear power capacity (nonewNUC)

Fig. 11 shows the results with varying assumptions for scenarios COOR and NAT. The counter-factual scenarios are sorted by the order of magnitude of their change in generation-mix compared to the default parameter values. The main findings are:

- Model runs with no new transmission capacity (noTRANS), no upper bound on additions to transmission capacities (unlTRANS), and lower investment cost for PV (cheapPV) do not change the overall structure of the system generation-mix. Yet, we can note that more system flexibility through unconstrained investment into NTC leads to some substitution of generation from nuclear power by wind power. With more additions to existing NTC, more trade flows and a better utilization of low-marginal cost wind power becomes feasible. Low investment costs for PV result in a substitution of generation from wind power by PV and electricity from nuclear power by gas power.
- A strict phase out policy on nuclear power (noNUC) results in a shift of nuclear generation to gas, bio-CCS, and wind power. Here, the increased generation from wind power is backed-up by the flexibility from gas power generators. And, negative CO_2-credits from bio-CCS generation compensate for additional CO_2-emissions from the rising gas power generation.
- In contrast, lower investment costs for nuclear power (cheapNUC), no negative crediting of biomass-CCS (nonegCRED), and No CCS application (noCCS) leads to soaring generation by nuclear generators. Furthermore, in all those three counter-factual scenarios concentrated solar power (CSP) penetrates the market with more flexibility due to its storage feature. At the same time, cheap nuclear power substitutes combined generation from gas power and biomass-CCS. Similarly, a non-decarbonized biomass supply chain with no negative credits almost completely drives biomass-CCS and gas power out of the market and triggers a higher contribution from gas-CCS.
- The case with no CCS application brings more biomass generation into the market. With no geologic storage of CO_2, gas power or other conventional generation technologies experience little generation due to the tight decarbonization path.

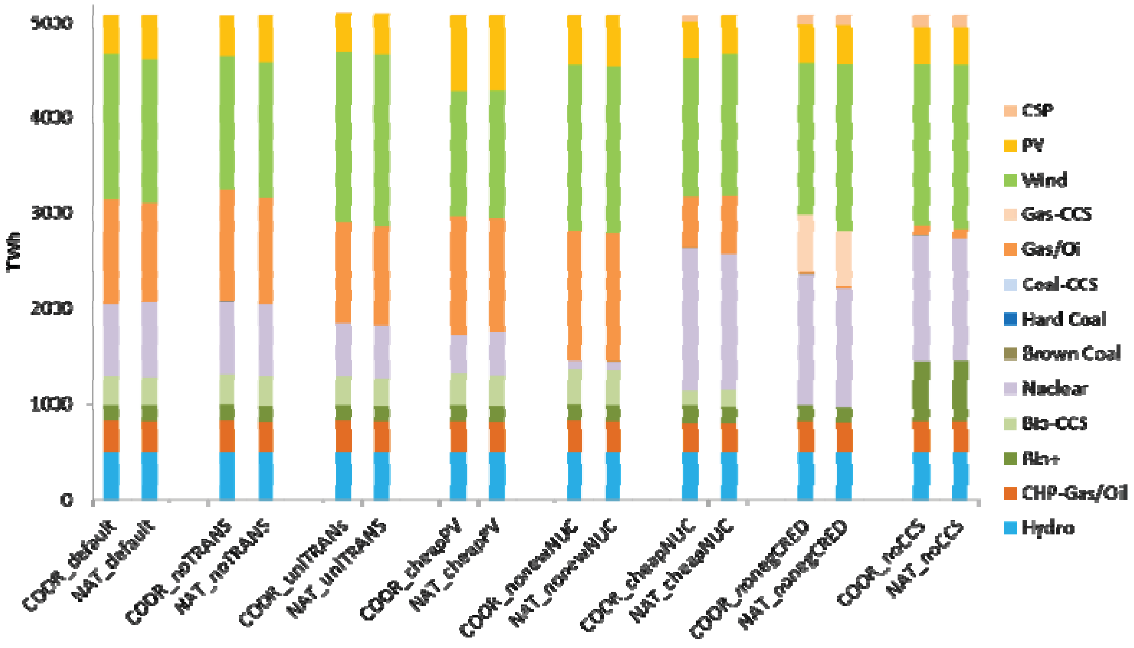

Fig. 11 Sensitivity of 2050 system generation-mix

Generally, few differences can be found between the results for scenario COOR and NAT. As mentioned above, the effect of national policies on generation is mainly reflected in regional generation-mixes. Therefore, Fig. 12 shows the sensitivity of the overall 2050 German generation-mix, from which the following key points can be concluded:

- For all counter-factual scenarios – except for noCCS - the main difference between COOR and NAT is reduced generation from gas power or gas-CCS. Generation from vRES partly compensates for that. Yet, none of those parameter values changes the trend of lower generation in the NAT scenario.
- Additionally, we want to point at the scenarios unlTRANS and noCCS. For both, there is even very little German generation in the COOR scenario. Those scenarios either require or support high shares of the carbon-free generation technologies nuclear power and vRES. Due to the relatively low resource quality and a legally-binding nuclear phase-out, Germany becomes a net-importing region even without its ambitious national policies.

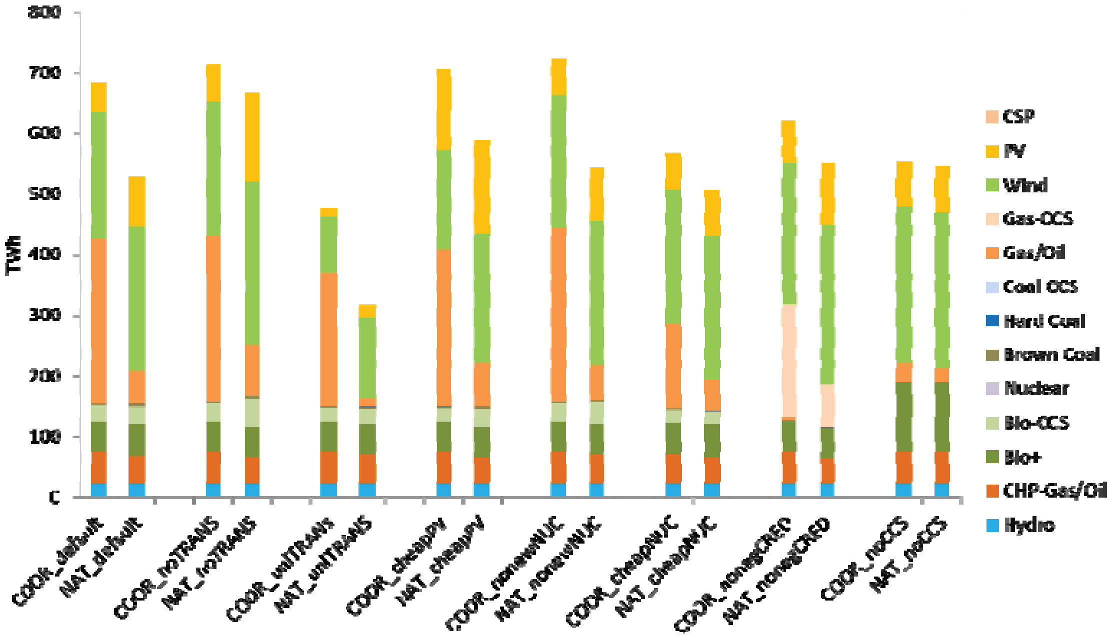

Fig. 12 Sensitivity of 2050 German generation-mix

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IV. DISCUSSION AND CONCLUSION

A. Model Limitations

The set-up of the EU-REGEN model captures the core dynamics that influence the long-run dispatch and investment in the European power sector. Nonetheless, the following characteristics are out of the model scope:

- EU-REGEN is a perfect foresight model that neglects uncertainty about input parameters, e.g. investment costs, fuel prices, and demand levels. Moreover, parameter values are not subject to path-dependence. Meaning that investment and dispatch decisions have no impact on parameter values in subsequent periods.
- The EU aims at an economy-wide decarbonization. With the focus on the power sector we are not able to capture the interaction with other energy sectors, EU-ETS sectors, and the economy. The results presented in this paper focus on power sector specific implications.
- As a partial equilibrium representation of the power sector with complete markets and perfect information, CO_2-emission reductions are realized where this can be done at lowest costs. EU-REGEN does not capture self-interest and motives such as protectionism.
- The model does not value benefits from introduced climate and energy policies. Any kind of policy leads to higher costs compared to a non-policy baseline scenario. Consequently, the model setting only allows for a cost-based analysis.
- EU-REGEN has a long-run perspective, which only considers political boundary conditions, e.g. the attitude towards nuclear power. Existing technology support schemes are not modeled.
- Due to computational constraints, we group the EU-28 countries to 12 model regions. The loss of a regional resolution limits our conclusions and the explanatory power on transmission and distribution grid extensions, among others.
- For the same reason, we apply a representative-hour approach with 130 time-segments instead of 8,760 hours. This means the loss of the chronological order of hours, which compromises the modeling quality of e.g. electricity storage.
- The future European power sector will be driven by the dynamics of the supply as well as demand side. With deterministic demand levels and fixed demand profiles, the current model setting does not cover the potential contribution of demand to additional system flexibility.

B. Summary of Results

Despite those shortcomings, we can draw the following conclusions on the cost-optimal infrastructure investment and electricity generation for the European power sector until 2050:

Our results reveal that onshore wind power will be the most crucial generation technology for the decarbonization of Europe's power sector. The geographic distribution of vRES capacities is driven by resource quality and not by a geographic balancing effect as proposed by others. Great Britain, France, and Scandinavia become the dominating regions in wind power application. Concerning solar, capacity is added in the Mediterranean regions of Italy, Iberia, and France. We identify gas power as the major conventional generation technology for backing-up the strong market penetration of wind power. This is mainly driven by the need for flexible generation technologies as a complementary to vRES. Additionally, the targeted CO_2-emission reduction requires dispatchable generation technologies with low emission-intensity. Moreover, we see a smooth retirement path of coal power. Yet, in contrast to the current public debate, a complete phase out proves to be not economically optimal. Even under a 98% CO_2-emission reduction target by 2050, 15% of current capacity is still active by then. CCS takes a crucial role in providing dispatchable carbon-neutral generation.

We showed that national targets disturb the cost-optimal distribution of capacity and generation. Especially the German goals lead to a geographic shift of generation due to its target on generation from RES in combination with a relative low vRES quality. As a consequence, German consumers and generators suffer from higher prices and lower revenues. The French policy appears to be less disturbing and increases generation in the region. Missing generation from nuclear power is shifted to Eastern Europe. Moreover, those national targets have a positive impact on consumers and producers. Prices for consumption decrease and total revenues increase. Though, a sensitivity analysis shows that France would profit even more without its policy in place. The remaining regions profit or are hardly affected from announced national targets. Yet, this is due to the fact that there are no ambitious additional targets announced there.

C. Policy Implications

Based on our findings we suggest EU-wide coordination on the expansion of solar and wind power, especially. Nonetheless, profitable market structures with remuneration schemes for conventional generation technologies are required in order to back-up the market penetration of vRES. Certainty regarding the EU climate policy is essential to push the substitution of coal power by new investments into gas power. Additionally, this impacts the market conditions for CCS. Prices in the EU-ETS must be high enough to create a business case for its application. Since CCS could become a crucial technology, uncertainties concerning its social and technical feasibility must be addressed. If not so, a decarbonization path based on a different technology-mix has to be realized.

Furthermore, the current development of announcing national energy and climate targets should be reversed. EU-wide policies are needed to keep the costs for the transition of the European power sector at a bearable level.

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