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Who benefits from cooperation? - A numerical analysis of redistribution effects resulting from cooperation in European RES-E support ☆

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Abstract

This paper numerically analyzes redistribution effects resulting from cooperation among European countries in achieving the 2020 targets for electricity generation from renewable energy sources (RES-E). The quantification of redistribution effects builds on the theoretical analysis by Unteutsch (2014), who shows that cooperation in RES-E support increases overall welfare but is not beneficial for all groups. In this paper, we use a dynamic investment and dispatch optimization model of the European electricity system to investigate which groups potentially benefit from cooperation and which groups would be worse off compared to a situation in which national RES-E targets are reached solely by domestic RES-E production. In the analysis, cooperation in RES-E support is implemented as a European-wide green certificate trading scheme. Main findings of the analysis include that in the European electricity system, effects of the change in the certificate price in most countries would overcompensate for the effects of the change in the wholesale electricity price. Thus, in most countries with comparatively high (low) generation costs for renewable energies, consumer rents increase (decrease) due to cooperation and producers yield lower (higher) profits. In addition, it is found that the magnitude of redistribution effects between the individual groups is quite large: In some countries, the change in consumer rents or producer profits resulting from cooperation is nearly twice as high as the overall welfare effect of cooperation in the whole European electricity system. Moreover, we find that the sign, but not always the magnitude, of redistribution effects is quite robust to different developments of interconnector extensions, the CO_2 price and RES-E investment costs.

Keywords: Cooperation Mechanisms, Tradable Green Certificates, Welfare, Consumer Rent, Producer Profit, Power System Optimization

JEL classification: Q40, F19, Q48, Q28, C61

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1. Introduction

An important target in European energy policy is to increase the share of renewable energy sources (RES) in primary energy consumption, mainly for reasons of environmental protection and security of supply (EU (2001), EC (2009)). The electricity sector plays an important role in reaching this target. By 2020, the overall RES share in primary energy consumption should reach 20%, whereas the renewable energy share in electricity consumption (RES-E) is targeted to increase up to 34%.[1] The contribution of the individual member states of the European Union (EU) in achieving this target has been agreed upon based on the member states´ GDP, their RES level in 2005 and their resource potentials for renewable energy generation (EC (2009)). As the resource potential is only one among several factors which influenced the target distribution, a cost-efficient regional allocation of RES-E production across Europe is not reached if the national targets are achieved purely by domestic production (e.g., EWI (2010), Aune et al. (2012)). Thus, in order to reduce target compliance costs, the European Directive 2009/28/EC on the promotion of renewable energy establishes the possibility of using cooperation mechanisms, including statistical transfers, joint projects and joint support schemes.

The use of cooperation mechanisms potentially enables the member states to benefit from low-cost generation options across Europe, either because support payments can be reduced (in member states with small potentials of low-cost generation options compared to their targets) or because additional revenues can be acquired (in member states with large potentials of low-cost generation options). Despite these potential benefits from cooperation, almost all member states plan to reach their 2020 targets solely by domestic RES-E production (Beurskens et al. (2011)). One reason why member states are reluctant to implement cooperation mechanisms is that cooperation induces redistribution effects (Fürsch and Lindenberger (2013)). For example, Portugal states in its National Renewable Energy Action Plan (NREAP) that it could easily produce more RES-E than required for achieving its national target if the interconnector between the Iberian Peninsula and France would be expanded. Without interconnector expansions, a larger RES-E share would devaluate the existing power plant fleet of Portugal (Portuguese Republic (2010)). Furthermore, in the history of the joint quota system of Norway and Sweden, redistribution effects played an important role. This joint RES-E support system was introduced in 2012 and is one of the few exceptions of a cooperation mechanism in use. An earlier attempt to establish the joint support scheme, however, failed in 2006 because

[1] Directive 2009/28/EC defines the contribution of each member state to reach the 20% RES target in primary energy consumption. This target includes the electricity, transportation and heating and cooling sectors. The sector-specific distribution of the targets were defined by the member states in their National Renewable Energy Action Plans (NREAP). An aggregation of the targets for the electricity sector of all member states leads to a EU-wide RES-E target of 34% by 2020 (EC (2012)).

the different parties could not agree on a sharing of costs and benefits (Klessmann et al. (2010)).

While the overall benefit of cooperation in RES-E support has been quantified in prior research, e.g., by Voogt et al. (2001), Ragwitz et al. (2007), EWI (2010), Capros et al. (2010) and Aune et al. (2012), the effects of cooperation on individual groups such as consumers or producers in individual countries have, to our knowledge, not yet been quantified.[2] However, in a theoretical analysis, this research question has recently been addressed by Unteutsch (2014), who relates cross-border cooperation in RES-E support to international trade theory and shows in a theoretical two-country model that cooperation in RES-E support increases overall welfare but is not beneficial for all groups. The author shows that as long as cooperating countries are not perfectly physically interconnected, cooperation has opposite effects on regional wholesale electricity prices and prices for green certificates.[3] For this reason, the net effect of cooperation on consumers and producers per country is theoretically not clear as long as grid congestions between different countries exist. Moreover, while the system-wide welfare always increases if cooperation is implemented, the net welfare effect of cooperation on the country level can be undetermined under certain conditions (including that a country is importer or exporter both of electricity and of green certificates). Therefore, redistribution effects resulting from cooperation depend on data that is specific to each electricity system and need to be determined by numerical analyses using real-world data.

The paper presented numerically analyzes the effects shown in Unteutsch (2014) for the European electricity system up to 2020. The purpose of this paper is to analyze the direction, magnitude and robustness of redistribution effects that could be induced in the European electricity system in reaching the 2020 RES-E targets by EU-wide cooperation (via cross-border trading of green certificates) rather than by national approaches. The analysis is carried out using the investment and dispatch optimization model DIMENSION of the Institute of Energy Economics, which captures the European electricity system in great detail. As shown in Unteutsch (2014), the degree of physical interconnection and the slopes of the RES-E and the conventional electricity supply curves have a large influence on the direction and the magnitude of redistribution effects. Therefore, we model different scenarios with regard to interconnector capacity extensions

[2]Moreover, redistribution effects of other policies in the electricity system have been subject to prior research, however, to our knowledge, we are the first to numerically analyze redistribution effects of cooperation in RES-E support. For example, Huang et al. (2005) and Billette de Villemeur and Pineau (2010) show effects of electricity trading on overall sectoral welfare, consumer rents and producer rents. Bauer et al. (2008) analyze redistribution effects of electricity transfers from North Africa to Europe. Hirth and Ueckerdt (2012) analyze redistribution effects between consumers and producers induced by support schemes for renewable energies and by CO_2 emission reduction policies. Neuhoff et al. (2013) investigate the distributional effects of increasing RES-E support payments in Germany on different household types and discuss different compensation mechanisms to lower the burden carried by low-income households.

[3]In Unteutsch (2014), cooperation in RES-E support is implemented as a cross-border green certificate trading scheme. A green certificate system is one of several RES-E support systems currently implemented in European member states. See Section 2 for a brief description.

between European regions as well as with regard to factors influencing the slopes of the supply curves (such as CO_2 - prices and RES-E investment costs).

Main findings of this paper include that, in the European electricity system, effects of a change in the green certificate price in most countries would overcompensate for the effects of a change in the wholesale electricity price. Thus, in most countries with comparatively high (low) generation costs for renewable energies, consumer rents increase (decrease) due to cooperation and producers yield lower (higher) profits. In addition, we find that the magnitude of redistribution effects between the individual groups is quite large: In some countries, the change in consumer rents or producer profits resulting from cooperation is nearly twice as high as the overall welfare effect of cooperation in the whole European electricity system. Moreover, the benefit different countries have from cooperation varies substantially. In our analysis, we find that Germany would by far have the largest (absolute) benefit of cooperation, achieved by significant reductions of RES-E target compliance costs via certificate imports. Finally, we find that the sign of redistribution effects is quite robust to different developments of interconnector extensions, the CO_2 price and RES-E investment costs. The magnitude of redistribution effects, in contrast, is in some countries sensitive to these assumptions (especially with regard to the assumption on the CO_2 price).

The remainder of the article is structured as follows: In Section 2, findings of Unteutsch (2014) are briefly summarized in order to provide the theoretical background for the analysis carried out in this paper. Section 3 outlines the modeling approach and covers the results of the numerical analysis. In Section 4, we draw conclusions and provide an outlook for future research.

2. Theoretical background

As described in the introduction, this paper directly builds on the theoretical analysis of redistribution effects by Unteutsch (2014), whose results are briefly summarized in this section. Unteutsch (2014) analyzes the impact of cooperation in RES-E support in a theoretical two-country electricity system model in which RES-E support is implemented as a green certificate system. In a green certificate system, a market for the green value of renewable electricity is created by obligating consumers or distributers of electricity to certify that a certain share of the electricity produced or consumed comes from renewable energy sources (see Amundsen and Mortensen (2001), Menanteau et al. (2003) or Agnolucci (2007) for a detailed description).

In the model presented by Unteutsch (2014), it is assumed that a country A has higher RES-E generation costs compared to a country B, whereas generation costs of conventional electricity in A can be equal, higher or lower than in B. Each country has a national RES-E target, expressed as a percentage share of (inelastic) electricity demand. Without cross-border trading of green certificates, the national RES-E target has to be achieved solely by domestic RES-E production. When trading of green certificates is possible, country B produces a higher RES-E amount than needed for national target achievement and exports certificates to country A until the certificate prices in the two countries converge. Note that the trading of green certificates is also possible without physical trading of electricity.

In this analytical framework, effects of cooperation in RES-E support (via cross-border green certificate trading) on consumer rents, producer profits and total welfare in both countries are analyzed for two different cases of physical interconnection between the two countries, i.e., the 'copper plate' case and the 'limited interconnection' case. The 'copper plate' case assumes that no grid congestion between the countries exist and that, consequently, the two regional electricity markets are perfectly interconnected. In the 'limited interconnection' case, electricity trade between the two countries is restricted - either because the interconnector is congested (the interconnector capacity M is > 0 but limited such that no complete electricity price convergence between the two markets is possible) or because no interconnector exists (M=0). Table 1 summarizes the results from the analysis by Unteutsch (2014).

Table 1: Price, welfare and redistribution effects resulting from cross-border trading of green certificates

	Copper plate	Limited interconnection M>0 but limited	M=0
Green certificate price in A (ds_A)	≤ 0	≤ 0	≤ 0
Green certificate price in B (ds_B)	≥ 0	≥ 0	≥ 0
Wholesale electricity price in A (dq_A)	$=$	≥ 0	≥ 0
Wholesale electricity price in B (dq_B)	$=$	≤ 0	≤ 0
Consumer rents in A (dCR_A)	≥ 0	?	?
Consumer rents in B (dCR_B)	≤ 0	?	?
Profits of conventional elec. producers in A ($d\pi_A^C$)	$=$	≤ 0	≤ 0
Profits of conventional elec. producers in B ($d\pi_B^C$)	$=$	≥ 0	≥ 0
Profits of renewable-based elec. producers in A ($d\pi_A^R$)	≤ 0	?	?
Profits of renewable-based elec. producers in B ($d\pi_B^R$)	≥ 0	?	?
Total producer profits in A ($d\pi_A$)	≤ 0	?	?
Total producer profits in B ($d\pi_B$)	≥ 0	?	?
Welfare in A (dW_A)	≥ 0	?	≥ 0
Welfare in B (dW_B)	≥ 0	?	≥ 0
Congestion rent ($dE_{A,B}$)	$=$	?	$=$
System-wide welfare ($dW_A + dW_B + dE_{A,B}$)	≥ 0	≥ 0	≥ 0

Source: Unteutsch (2014)

In all cases, the certificate price in country A (with comparatively higher RES-E generation costs) decreases when cross-border cooperation in RES-E support is possible (s_A), whereas the certificate price in country B (s_B) increases. The opposite holds true for the wholesale electricity prices (q_A and q_B), except for the 'copper plate' case in which a different regional allocation of RES-E production does not affect the common wholesale electricity market. In country A, producers of conventional electricity yield higher profits (π_A^C) than without cooperation in RES-E support (due to the increased wholesale electricity price), while producer profits gained with conventional electricity generation decrease in country B (π_B^C) (except for the 'copper plate' case in which producer profits from conventional electricity generation are not affected by cooperation). Producer profits of RES-E (π_A^R, π_B^R), in contrast, increase in country B and decrease in country A. Except for the 'copper plate' case, the net effect on consumers (CR_A, CR_B) and total producers (π_A, π_B) in countries A and B cannot be determined without making further assumptions. While the decreasing green certificate price in country A is beneficial for consumers in this country, the increasing wholesale electricity price has an end-consumer price increasing effect. Similarly, in country B, the increasing certificate price leads to increasing end-consumer prices (ceteris paribus), while the decreasing wholesale electricity market price has an opposite effect. Welfare on the country level (W_A, W_B) always increases due to cooperation, except under certain conditions in the 'limited grid' case (as further discussed below). However, given the conditions under which welfare on the country level can decrease, congestion rents ($E_{A,B}$) increase such that overall system-wide welfare ($W_A + W_B + E_{A,B}$) always increases once cooperation in RES-E support is introduced. Moreover, these additional congestion rents could potentially be distributed between the two countries in a way which ensures that all countries benefit from the introduction of certificate trade.

Moreover, for the cases in which effects on consumers, producers and welfare per country cannot be determined (marked by a '?' in Table 1), Unteutsch (2014) shows under which conditions the effects are unambiguous, particular with respect to the slopes of the supply curves and the level of the RES-E targets. Generally, if the conventional electricity supply curve is relatively steep compared to the RES-E supply curve and the RES-E target is rather low, then the wholesale electricity price effect resulting from cooperation is likely to be dominant. In this case, producers in country A and consumers in country B benefit from cooperation, while producers in country B and consumers in country A lose compared to a situation in which each country achieves its RES-E target without cooperation. Similarly, if the RES-E supply curve is relatively steep compared to the conventional electricity supply curve and the RES-E target is rather high, the certificate price effect is likely to be dominant. In this case, cooperation is beneficial for consumers in country A and for producers in country B. Total welfare in country A and B always increases when cooperation in RES-E support is introduced and the two countries are not at all or perfectly interconnected. If, however, a bottleneck in the interconnector exists and country A is an importer of both certificates and electricity (and country B an exporter of certificates and electricity), welfare on the country level (defined as the sum of consumer rents and producer profits) can decrease under certain conditions. For example, the amount of certificates traded may be relatively small compared to the amount of electricity traded and the conventional electricity supply curve may be relatively steep compared to the RES-E supply curve. In this case, higher electricity import costs or lower revenues from electricity exports resulting from cooperation can overcompensate the benefit from certificate trading in terms of reduced RES-E production costs or additional incomes from certificate trading.

In summary, Unteutsch (2014) shows that redistribution effects of cooperation depend on the level of interconnection between the different countries as well as on the slopes of the supply curves and the level of the RES-E target(s). These factors are specific to each electricity system and can also change over time, e.g., when interconnectors are expanded or when fuel, CO_2 prices or investment costs change, leading to changing supply curves. Therefore, in order to determine the direction and the magnitude of redistribution effects in real-world electricity systems, a quantification based on real-world data is needed. In this paper, we analyze which redistribution effects would occur in the European electricity system up to 2020, if the 2020 targets were reached with EU-wide cooperation in RES-E support rather than with national RES-E support. As in the theoretical analysis presented in Unteutsch (2014), the model-based scenario analysis is built on the assumption that the RES-E targets are either cost-efficiently reached within national borders (when cooperation is not possible) or by using low-cost generation options throughout Europe (via cooperation).

3. Numerical analysis

We numerically analyze redistribution effects in the European electricity system that may potentially arise when reaching RES-E targets for 2020 with European-wide cooperation rather than by national approaches. According to the European Directive 2009/28/EC, the renewable energy share in the European Union´s (EU) final energy consumption (including the electricity, transportation and heating and cooling sectors) should increase to 20% by 2020. The contribution of each country to the European-wide target has also been defined in Directive 2009/28/EC, while the sector-specific breakdown of the national targets has been stated by each member state within its National Renewable Energy Action Plan (NREAP). Overall, the achievement of the national RES-E targets would lead to an EU-wide RES-E share of approximately 34% by 2020 (EC (2010)). Despite the possibilities to cooperate across borders in order to achieve the national targets, given by the Directive 2009/28/EC, most member states almost purely rely on national approaches. As described in the introduction (Section 1), one impediment of stronger cooperation seems to be (politically undesired) redistribution effects.

Therefore, we compare consumer rents, producer profits and total welfare per country in the event that the 2020 RES-E targets are reached either on a national level or with EU-wide cooperation. In both cases, we assume that targets are reached with a technology-neutral support system. It is important to note that, in reality, many EU countries currently have technology-specific support systems.[4] Thus, we do not quantify redistribution effects that would arise when changing from the currently implemented country-specific support systems to a cooperative support design. Instead, we show which effects would arise when changing from purely national, technology-neutral support systems to a system in which RES-E is supported as technology-neutral *and* with European-wide cooperation. Thereby, we quantify the effects that have been theoretically shown by Unteutsch (2014) for the European power system up to 2020 and focus on the welfare and redistribution effects explicitly induced by cross-border cooperation. In contrast, we do not take into account effects which could arise from inefficient national support systems. In specific, the numerical analysis in this paper aims at investigating the following questions:

1. Who benefits and who loses when the 2020 RES-E targets in Europe are achieved with cross-border cooperation in RES-E support?
2. How large are these redistribution effects?
3. How robust are these redistribution effects (in terms of their sign and magnitude) with regard to different developments of interconnector extensions and with regard to changes in the CO_2 price, fuel prices or investment costs, which influence the slope of electricity supply curves?

In Section 3.1, we define the scenarios to analyze and provide information on the most important assumptions. In Section 3.2, the modeling approach is described. In Section 3.3, we describe and analyze the model results.

3.1. Scenario definition and assumptions

As discussed in Unteutsch (2014), the level of grid interconnection between countries influences the optimal amount of certificates traded as well as the redistribution and welfare effects resulting from cooperative RES-E support. Therefore, the numerical analysis presented in this paper also distinguishes between different grid interconnection settings. The current European power system is, on the one hand, already deeply intermeshed and is, on the other hand, still subject to substantial bottlenecks between some regions. Interconnector extensions are planned but often delayed (EWI and energynautics (2011)). Thus, we model two main scenarios that differ with regard to the progress in interconnector extensions. In the first scenario, we

[4] See www.res-legal.eu for an overview of renewable energy support system designs currently implemented in European countries.

assume that interconnectors are not extended at all from today onwards. In the second scenario, we assume that all planned interconnector extensions, as stated in the Ten-Year Network Development Plan (TYNDP; see ENTSO-E (2010)), are realized.

Moreover, as discussed in Unteutsch (2014), price effects, which in turn induce redistribution effects, depend on the slopes of the supply curves for renewable and conventional electricity generation. Thus, we run sensitivities with regard to three factors which influence the slopes of the supply curves. First, we analyze the effects of a higher CO_2 price than in the reference case (30 €/t compared to 20 €/t in 2020). Second, we analyze the effects of lower photovoltaic investment costs and third, of lower offshore wind investment costs (- 10 % compared to the investments costs in the reference case, which are shown in Table A.2 in the Appendix). In all sensitivity runs, we assume that the TYNDP is realized. Table 2 provides an overview of the main scenarios and the sensitivities.

Table 2: Overview of modeled scenarios

		Interconnector extension	
		no extension	TYNDP
Reference assumptions		x	x
Sensitivities	higher CO price		x
	lower photovoltaic costs		x
	lower offshore wind costs		x

All scenarios depicted in Table 2 are modeled twice: Once assuming purely national RES-E support systems and once with EU-wide cooperation. RES-E targets in 2020 and electricity demand in 2020 are depicted in Table 3. Electricity demand is assumed to develop according to the 'additional energy efficiency' scenario of the NREAPs (see Beurskens et al. (2011)).[5]

[5] The analysis covers the EU-27 countries (with the exception of Cyprus and Malta), Norway and Switzerland. As Norway and Switzerland are not part of the European Union and have no NREAP, assumptions on electricity demand are based on EWI and energynautics (2011). RES-E targets are assumed to be slightly above historical RES-E generation in 2010.

Table 3: Final electricity demand and NREAP target in 2020 [TWh_{el}]

	electricity demand	RES-E target
Austria (AT)	74	52
Belgium (BE)	111	23
Bulgaria (BG)	37	8
Czech Republic (CZ)	84	12
Denmark (DK)	38	21
Estonia (EE)	11	2
Finland (FI)	102	33
France (FR)	546	155
Germany (DE)	562	217
Greece (GR)	68	27
Hungary (HU)	51	6
Ireland (IE)	33	14
Italy (IT)	375	99
Latvia (LV)	9	5
Lithuania (LT)	9	3
Luxembourg (LU)	7	1
Netherlands (NL)	136	50
Norway (NO)	119	114
Poland (PL)	170	32
Portugal (PT)	65	36
Romania (RO)	74	31
Slovakia (SK)	33	8
Slovenia (SL)	16	6
Spain (ES)	375	150
Sweden (ES)	155	97
Switzerland (CH)	67	45
United Kingdom (UK)	377	117

Table 4 depicts the assumed fuel price developments up to 2020, based on Prognos/EWI/GWS (2010) and EWI and energynautics (2011) (biomass solid and biogas). In addition, CO_2 emission factors are shown. The CO_2 price is assumed to increase up to 20 EUR_{2010}/t in 2020.

Table 4: Fuel prices [EUR_{2010}/MWh_{th}]and CO_2 emission factor [t CO_2 /MWh_{th}]

	Fuel price		CO_2 factor
	2008	2020	
	[EUR_{2010}/MWh_{th}]		[t CO_2 /MWh_{th}]
Nuclear	3.6	3.3	0
Coal	17.28	10.1	0.335
Lignite	1.4	1.4	0.406
Natural gas	25.2	23.1	0.201
Biomass (solid)	15.0-27.7	15.7-34.9	0
Biomass (gas)	0.1-70.0	0.1-67.2	0

Assumptions on technical and economic parameters of power plants correspond to those described in

EWI and energynautics (2011) and Fürsch and Lindenberger (2013). A table depicting these assumptions is provided in the Appendix.

3.2. Model description

For the numerical analysis, we use the dynamic investment and dispatch optimization model DIMENSION developed at the Institute of Energy Economics at the University of Cologne. The model minimizes total costs required to meet an inelastic hourly electricity demand in each market region. Hourly demand is represented by a typical day approach, reflecting typical demand and RES-E feed-in structures on a weekday and a weekend-day in autumn/winter and in spring/summer. Different meteorological conditions throughout Europe are taken into account by modeling different wind speed conditions in 47 onshore and 42 offshore wind regions. Different levels of solar radiation throughout Europe are captured by modeling 38 photovoltaic regions. Meteorological data is taken from EuroWind (2011). Hourly dispatch decisions include ramping procedures of thermal power plants, pumping and generation operations in storage units and import and export streams between market regions. Furthermore, RES-E infeed can be curtailed if this option is beneficial for minimizing total costs, e.g., when curtailment is cost-optimal compared to ramping procedures of thermal power plants. The model optimizes investment and dispatch decisions of thermal power plants (possibly equipped with combined-heat-power technology (CHP)), storage units and renewable plants. The existing power plant fleet is taken into account by several vintage classes, representing typical technological characteristics (e.g., conversion efficiencies) of power plants build at different points in time. Renewable technologies covered by the model include: onshore wind, offshore wind (shallow and deep water), biomass solid, biogas, concentrated solar power (equipped with thermal energy storage), geothermal and photovoltaics (ground and roof). The generation in biomass or biogas plants is restricted by yearly fuel potentials. Investments in wind- and solar-based technologies are restricted by area potentials. The technological progress of wind turbines is taken into account by modeling different technology classes which can be deployed at different future time periods. The option of repowering is also included in the modeling.

A detailed documentation of the basic model is provided by Richter (2011). In this analysis, we use an extended model version including the option of endogenous investments in renewable energy plants. For a documentation of this extended model version, the reader is referred to Jägemann et al. (2012) and Fürsch et al. (2013).

In this paper, we use the DIMENSION model to analyze redistribution effects of EU-wide cooperation compared to national RES-E support. Equations (1) to (4) show how redistribution effects in terms of consumer rents, producer profits as well as welfare on the country level and on the European electricity system level are determined. A list of the abbreviations used in the equations for model sets, parameters and variables, is provided in Table 5. The difference in consumer rents (in country i and year y) between EU-wide cooperation and national RES-E support is defined by Eq. (1), i.e., the difference in expenditures that consumers pay to meet their electricity demand multiplied by (-1).[6] These expenditures include costs for buying electricity on the wholesale electricity market, RES-E support expenditures and costs for ensuring security of supply. In the model, 'security of supply' is defined by the requirement that an amount of 'securely available' electricity generation capacity exists that is sufficient to meet peak demand including during times of low wind infeed and low solar radiation (see, e.g., Fürsch et al. (2013)).[7] Producers may earn incomes on the wholesale electricity market, for selling green certificates on the certificate market and by providing securely available generation capacities. In addition, producers can earn incomes by selling heat that is generated by combined-heat-and-power plants on the heat market. Producer profits are determined as the sum of these incomes, from which the following costs are deducted: variable generation costs (including fuel and CO_2 costs), additional variable costs arising from ramping procedures, costs for pumping electricity into storage units, fixed operation and maintenance costs and annualized investment costs. Equation (2) shows the difference in producer profits between cooperative and national RES-E support. The difference in the national welfare of country i is defined as the sum of differences in consumer rents and in producer profits in this country (Eq.(3)). Differences in the overall European-wide welfare are determined as the sum of differences of all national welfares and of the congestion rents that the transmission system operators (TSO) earn (Eq.(4)). Congestion rents cannot be allocated to a particular TSO of a specific country. In reality, often agreements regarding the allocation of these rents exist (see, e.g., Nordpool Spot (n.a.)). However, as these agreements can change over time, we do not allocate congestion rents to specific countries.

[6]As DIMENSION is a linear optimization model, no absolute values for consumer rents can be determined. However, we are only interested in differences of consumer rents between scenarios with cooperative and national RES-E support. Assuming an inelastic electricity demand, these differences in consumer rents correspond to the differences in expenditures that consumers pay to meet their demand.

[7]Due to limited computed hours in the model, not all combinations of demand and RES-E infeed that may occur with some probability can be explicitly modeled. Thus, in this modeling approach, investments that are only required to meet security of supply are incentivized by a capacity price. Note that, in real-world electricity markets, investments in plants which are only necessary for a few hours can also be incentivized by price peaks in the electricity wholesale market (see Nagl (2013)).

$$
\begin{aligned}
dCR_{i,y} =& \phi_y \cdot (-1) \cdot [\sum_h (q^{CO}_{i,h,y} - q^{N}_{i,h,y}) \cdot x_{i,h,y} && (1) \\
&+ (s^{CO}_y - s^N_{i,y}) \cdot \alpha_{i,y} \cdot \sum_h x_{i,h,y} \\
&+ \omega_a (\sum_a C^{CO}_{i,a,y} \cdot \gamma^{CO}_{i,y} - \sum_a C^N_{i,a,y} \cdot \gamma^N_{i,y}) \\
d\pi_{i,y} =& \phi_y \cdot [\sum_{h,a} (q^{CO}_{i,h,y} \cdot Z^{CO}_{a,i,h,y} - q^N_{i,h,y} \cdot Z^N_{a,i,h,y}) && (2) \\
&+ (s^{CO}_y \cdot \sum_{r,i,h,y} Z^{CO}_{r,i,h,y} - s^N_{i,y} \cdot \sum_{r,i,h,y} Z^N_{r,i,h,y}) \\
&+ \omega_a (\sum_a C^{CO}_{i,a,y} \cdot \gamma^{CO}_{i,y} - \sum_a C^N_{i,a,y} \cdot \gamma^N_{i,y})] \\
&+ h_y (\sum_{d,h} H^{CO}_{d,i,h,y} - \sum_{d,h} H^{CO}_{d,i,h,y})] \\
&- (\sum_{h,a} v_{a,y} \cdot (Z^{CO}_{a,i,h,y} - Z^N_{a,i,h,y})) \\
&- (\sum_{h,a} vr_{a,y} (R^{CO}_{a,i,h,y} - R^N_{a,i,h,y})) \\
&- (q^{CO}_{i,h,y} \cdot P^{CO}_{p,i,h,y} - q^N_{i,h,y} \cdot P^N_{p,i,h,y}) \\
&- \sum_a (C^{CO}_{i,a,y} - C^N_{i,a,y}) \cdot fom_{a,y} \\
&- \sum_a (I^{CO}_{i,a,y} - I^N_{i,a,y}) \cdot ann_{a,y} \\
dW_{i,y} =& dCR_{i,y} + d\pi_{i,y} && (3) \\
dW_y =& \sum_i dW_{i,y} + \phi_y \cdot [[(q^{CO}_{i,h,y} \cdot (1 - \lambda_{i,i'}) - q^{CO}_{i',h,y}) \cdot M^{CO}_{i,i',h,y}]] && (4) \\
&- [(q^N_{i,h,y} \cdot (1 - \lambda_{i,i'}) - q^N_{i',h,y}) \cdot M^N_{i,i',h,y}]
\end{aligned}
$$

Table 5: Model abbreviations including sets, parameters and variables

Abbreviation	Dimension/Unit	Description
indices		
a		Technology
p	Subset of a	Storage technology
r	Subset of a	RES-E technology
d	Subset of a	Combined-heat-and-power technology
i,i'		Countries
h		Hour
y		Year
CO		Coordinated Support
N		National Support
Model parameters		
$\mathrm{ann}_{a,y}$	$\mathrm{EUR}_{2010}/\mathrm{MW}$	Annuity for technology specific investment costs
$\mathrm{x}_{i,h,y}$	MW_{el}	Demand
ϕ_y	%	Discount rate
$\mathrm{fom}_{a,y}$	$\mathrm{EUR}_{2010}/\mathrm{MW}$	Fixed operation and maintenance costs
$\mathrm{v}_{a,y}$	$\mathrm{EUR}_{2010}/\mathrm{MWh}_{th}$	Variable generation costs
$\mathrm{vr}_{a,y}$	$\mathrm{EUR}_{2010}/\mathrm{MWh}_{th}$	Additional variable costs for ramping
ω_a	%	Capacity factor
$\alpha_{i,y}$	%	Quota on RES-E generation
$\lambda_{i,i'}$	%	Transmission losses
Marginal values		
$\mathrm{q}^N_{i,h,y}$,$\mathrm{q}^{CO}_{i,h,y}$	$\mathrm{EUR}_{2010}/\mathrm{MWh}_{el}$	Power price (marginal on power balance)
$\mathrm{s}^N_{i,y}$,$\mathrm{s}^N_{i,y}$	$\mathrm{EUR}_{2010}/\mathrm{MWh}_{el}$	Green certificate price (marginal on RES-E quota)
$\gamma^N_{i,y}$, $\gamma^{CO}_{i,y}$	$\mathrm{EUR}_{2010}/\mathrm{MWh}_{el}$	Capacity price (marginal on peak capacity constraint)
h_y	$\mathrm{EUR}_{2010}/\mathrm{MWh}_{th}$	Heat price
Model variables		
$\mathrm{Z}^N_{a,i,h,y}$,$\mathrm{Z}^N_{a,i,h,y}$	MW_{el}	Electricity generation
$\mathrm{R}^N_{a,i,h,y}$, $\mathrm{R}^{CO}_{a,i,h,y}$	MW_{el}	Capacity which is ramped up in hour h
$\mathrm{M}^N_{i,i',h,y}$, $\mathrm{M}^{CO}_{i,i',h,y}$	MW_{el}	Net electricity trade between regions
$\mathrm{C}^N_{i,a,y}$,$\mathrm{C}^{CO}_{i,a,y}$	MW_{el}	Installed capacity
$\mathrm{I}^N_{i,a,y}$,$\mathrm{I}^{CO}_{i,a,y}$	MW_{el}	Capacity Additions
$\mathrm{P}^N_{p,i,h,y}$, $\mathrm{P}^{CO}_{p,i,h,y}$	MW_{el}	Consumption in storage operation
$\mathrm{H}^N_{d,i,h,y}$, $\mathrm{H}^{CO}_{d,i,h,y}$	MW_{th}	Heat generation in combined-heat-and-power plants
Variables calculated ex-post		
$\mathrm{dCR}_{i,y}$	EUR_{2010}	Difference in consumer rents
$\mathrm{d}\pi_{i,y}$	EUR_{2010}	Difference in producer profits
$\mathrm{dW}_{i,y}$	EUR_{2010}	Difference in country-wise sectoral welfare
dW_y	EUR_{2010}	Difference in overall sectoral welfare

3.3. Model results

In this section, we present results from our scenario analysis with regard to price, redistribution and welfare effects of EU-wide cooperation in reaching the 2020 RES-E targets. First, we present model results of the main scenarios (Section 3.3.1). Second, we discuss the results of the sensitivity analysis (Section 3.3.2).

3.3.1. Analysis of the main scenarios

As described in Section 3.1, the main scenarios differ with regard to the assumed level of physical interconnection between European regions. For the two different grid extension scenarios ('no extension', 'TYNDP'), we compare consumer rents, producer profits and welfare in reaching the 2020 RES-E targets with either (technology-neutral) national support or (technology-neutral) cooperative RES-E support. In addition, before discussing welfare and redistribution effects, the general effects of cooperation on the optimal technological and regional generation and capacity mix in the European power system are briefly presented.

Effects of cooperation on generation patterns and welfare

Table 6 shows electricity generation and capacity differences by energy source on the European level, resulting from the introduction of cooperation. It can be seen that in 2020, European generation from onshore wind plants and concentrated-solar-power (CSP) plants is higher with cooperation, while biomass-based electricity generation is lower compared to the case where each country achieves its national target on its own. Generation from onshore wind plants mainly increases because sites with high load factors in Poland, the Czech Republic and Ireland can be used to a larger extent (note that the installed European onshore wind capacities are identical with and without cooperation). The higher CSP generation is mainly of Spanish origin and the lower biomass generation is mainly driven by a reduction in German biomass generation. Moreover, offshore wind generation is higher with cooperation when the TYNDP can be realized, because in this case offshore generation in Norway and Denmark is significantly higher with cooperation and clearly overcompensates for a lower offshore wind generation in Germany. In contrast, if the TYNDP is not realized, the favorable offshore wind sites in Northern Europe can only be used to a smaller extent. Therefore, if the TYNDP is not realized, European wind offshore generation decreases once cooperation is introduced because the effect of lower offshore wind generation in Germany dominates.[8] Photovoltaic generation is mainly higher in Spain and lower in Italy, when cooperation is introduced. The increase in Spanish photovoltaic generation resulting from cooperation is higher when the TYNDP is not realized because in this case offshore wind generation from Northern Europe can be used to a lesser extent to achieve the European RES-E target cost-efficiently. Therefore, photovoltaic-based electricity generation on the European level increases once cooperation is introduced when the TYNDP is not realized and decreases in the TYNDP case.

[8] In the model, grid connection costs (as well as grid extension and other grid related costs) have not been included. In the case of offshore wind plants, grid connection costs are substantially higher compared to other technologies and depend on the shore distance of the wind parks. In Germany, potential wind offshore areas are located relatively far from shore (Skiba and Reimers (2012)). Therefore, when including offshore grid connection costs, the benefit of cooperation achieved by replacing German offshore wind generation by less costly generation options may, ceteris paribus, increase.

Table 6: Generation and capacity differences between cooperative and national RES-E support scenarios in the year 2020 [TWh and GW] on the European level (in the TYNDP and in the 'w/o TYNDP' scenario)

	Generation differences		Capacity differences	
	TYNDP	w/o TYNDP	TYNDP	w/o TYNDP
Nuclear	-4.3	2.6	-0.5	0.6
Lignite	0.2	-1.5	0.6	-0.2
Gas	50.2	9.7	5.4	-1.1
Coal	-41.5	-9.3	-3.9	-1.0
Storage	-0.4	-1.0	0.0	0.0
Hydro	0.0	0.0	-0.4	-2.7
Biomass	-29.2	-19.6	-4.5	-3.1
Onshore Wind	14.0	12.8	0.0	0.0
Offshore Wind	31.8	-14.8	4.3	-6.2
Photovotaics	-8.5	9.2	-6.9	5.2
CSP	8.0	10.4	1.7	2.3
Geothermal	-17.5	1.3	-2.4	0.2

Positive (negative) values indicate that electricity generation or generation capacities are higher (lower) once cooperation is introduced.

Taking a look at generation differences of non-renewable-based electricity sources, a switch from coal to gas-based electricity generation can be observed, once cooperation is introduced. Coal-based electricity generation is lower in Spain and Poland, where, in turn, RES-E generation is significantly higher with cooperation. In the TYNDP case, gas-based electricity generation increases significantly in Italy, which is an importer of green certificates once cooperation is introduced. An overview of changes in the generation and capacity mixes on country level is provided in Table A.4 in the Appendix for the largest certificate importing and exporting countries, which are also analyzed in the following.

In Table 7, certificate trade streams in 2020 for the largest certificate importing and exporting countries are shown. The amount of certificates traded is, in some countries, independent of the level of interconnection between countries (e.g., in Germany, Poland and Italy). In these countries, the trade in green certificates mainly leads to a switch between domestic renewable and conventional electricity generation. Moreover, Germany is already today well interconnected with neighboring electricity markets. In other countries, e.g., in Denmark and Norway, the enforcement of interconnectors is a critical factor in determining to what extent sites with high wind speeds can be used to generate more RES-E than required for national target achievement. For example, in Norway, most electricity generation comes from renewable energy sources. Thus, due to low conventional generation that could be reduced, an increase in RES-E generation has to be exported. Furthermore, in Spain, the amount of exported certificates significantly depends on whether the TYNDP is realized or not. As explained above, in Spain certificate exports are substantially lower when the TYNDP is realized because, in this case, many other and more cost-efficient RES-E generation options (e.g., offshore wind in Norway) are accessible.

Taking a look at the amount of certificates traded by the individual countries, it can be seen that Germany is the largest importer, with certificates corresponding to 91 TWh of green electricity and making up 42% of its NREAP target. Similarly, Finland and Greece import large amounts of certificates and cost-efficiently fulfill one third or more of their national target by using cooperation mechanisms (in the TYNDP case). Large exporters of certificates are mainly countries with large potentials of sites with high wind speeds, either for onshore or for offshore wind. In relation to its national target, Denmark is the largest exporter of certificates (204% when the TYNDP is realized, 83% when interconnectors are not enforced).

Table 7: Green certificate trade streams in 2020 [TWh and % of NREAP targets], overall welfare gain from cooperative RES-E support [bn. EUR_{2010}, cumulated 2010-2020 and discounted by 5 %] and certificate price in 2020 [EUR_{2010}/MWh] in the scenarios 'TYNDP' and 'w/o TYNDP'

	TYNDP		**w/o TYNDP**	
Certificate trade of largest certificate importing countries [TWh]	TWh	% of target	TWh	% of target
Finland (FI)	-11	33%	-5	14%
Germany (DE)	-91	42%	-91	42%
Greece (GR)	-8	37%	-3	10%
Italy (IT)	-9	9%	-9	9%
Portugal (PT)	-7	20%	-3	8%
Sweden (SE)	-10	10%	-9	10%
United Kingdom (UK)	-6	5%	-4	3%
Certificate trade of largest certificate exporting countries [TWh]				
Czech Republic (CZ)	9	80%	9	80%
Denmark (DK)	28	204%	11	83%
France (FR)	5	3%	11	7%
Ireland (IE)	7	50%	6	44%
Norway (NO)	51	45%	21	18%
Poland (PL)	19	60%	19	60%
Spain (ES)	23	15%	38	25%
Overall welfare gain [bn. EUR_{2010}]	12		10.6	
European certificate price [EUR_{2010}/MWh]	47.4		52.1	

In addition, Table 7 depicts the overall welfare gain of cooperation as well as the European certificate price (in the case that cooperation is possible), depending on the level of interconnection between regions. Generally, stronger interconnections between the European regions facilitate the use of low-cost generation options throughout Europe as well as the balancing of supply and demand over large distances (Fürsch et al. (2013)). Therefore, the European-wide benefit of cooperative, compared to purely national, RES-E support increases because sites with high wind speeds or high solar radiation are more easily accessible (see also Fürsch and Lindenberger (2013)). The overall welfare gain of introducing cooperation is 12 bn. EUR_{2010} when the TYNDP is realized and 10.6 bn. EUR_{2010} when interconnector capacities are not extended. Note that the results in terms of cost figures presented in this section refer to the period 2010-2020 and are discounted by 5%. As we use a dynamic model and amortization times of power plants are long (typically around 20 years, depending on the technology), these costs do not include all costs induced by the 2020 target (and vice versa, the presented welfare gains do not include the total long-term benefit of introducing cooperation in the achievement of the 2020 target).

The largest welfare gain of cooperation on the country level is achieved in Germany, as can be seen in Table 8 which depicts welfare differences per country between cooperative and national RES-E support scenarios (cumulated from 2010 to 2020).

Table 8: Country-wise welfare differences between cooperative and national RES-E support scenarios [bn. EUR_{2010}, cumulated 2010-2020, discounted by 5%]

Certificate importing countries	TYNDP	w/o TYNDP
Finland (FI)	0.1	0.3
Germany (DE)	5.3	4.3
Greece (GR)	0.1	0.0
Italy (IT)	0.1	0.2
Portugal (PT)	0.0	0.0
Sweden (SE)	0.4	-0.1
United Kingdom (UK)	0.0	0.1
Certificate exporting countries		
Czech Republic (CZ)	0.8	0.9
Denmark (DK)	0.1	0.1
France (FR)	0.3	0.1
Ireland (IE)	-0.1	0.1
Norway (NO)	0.6	0.1
Poland (PL)	0.7	1.0
Spain (ES)	1.3	0.3

Positive (negative) values indicate that welfare is higher (lower) once cooperation is introduced.

On the country level, welfare generally increases with cooperation because either increasing consumer rents overcompensate for decreasing producer profits or vice versa. The country that benefits (in absolute terms) most from cooperation is Germany. It is the country with the highest electricity demand and the highest RES-E target (see Table 3) and also trades the highest amount of certificates (see Table 7). Certificate exporting countries which benefit most from cooperation are Poland, the Czech Republic and, if the TYNDP is realized, Spain and Norway. In relation to their electricity demand, countries which benefit most from cooperation are smaller countries such as Latvia and Luxembourg.

In some few countries, however, welfare decreases. In Ireland (if the TYNDP is realized) and Sweden (if the TYNDP is not realized), cumulated welfare up to 2020 is lower under cooperation. In these two countries, the welfare decreasing effect is temporary and occurs because not all costs and incomes from electricity generation are realized in the same period.[9] In contrast, in Portugal and France (in the TYNDP scenario), welfare decreases in the long term. As shown theoretically by Unteutsch (2014), the change in welfare on the country level, resulting from cooperation, can be negative if a) a country is an exporter of both electricity and certificates, and the additional incomes gained from certificate exports do not outweigh lower incomes gained from the export of electricity or if b) a country is an importer of both electricity and certificates and the cost savings, in terms of renewable energy production, do not outweighed higher electricity import costs. In this numerical analysis, welfare decreases in Portugal, an importer of both electricity and certificates, and in France, an exporter of electricity and certificates (in the TYNDP scenario).

While the overall European-wide benefit of cooperation increases if countries are better interconnected (Table 7), the effect of interconnector extensions on the welfare change is ambiguous on the country level. In Germany, the benefit of cooperation is larger if the TYNDP is realized and certificates can be imported at a comparatively low price. In contrast, in Poland, the benefit of cooperation is larger without interconnector extensions because, in this case, the European certificate price is higher and higher revenues from certificate exports can be gained.

In the following, we discuss how the introduction of cross-border trading of green certificates influences prices, consumer rents and producer profits in the different European countries.

Effects of cooperation on price changes

Unteutsch (2014) shows that cross-border trading of green certificates leads to an increase (decrease) of green certificate prices in countries with comparatively low (high) RES-E generation costs, while opposite price effects occur on the regional wholesale electricity markets. Table 9 depicts green certificate prices and wholesale electricity prices in 2020 for both the cooperative and the national RES-E support scenarios in selected European countries.

[9]In these countries, cumulated welfare up to 2020 decreases; however, cumulated welfare up to the end of the modeled period

Table 9: Green certificate prices and wholesale electricity prices in 2020 (with national and with cooperative RES-E support), [EUR_{2010}/MWh]

	TYNDP						w/o TYNDP					
	Certificate price			**Wholesale electr. price**			**Certificate price**			**Wholesale electr. price**		
Certificate importers	Nat	Coop	Diff.	Nat	Coop	Diff.	Nat	Coop	Diff.	Nat	Coop	Diff.
FI	36.9	47.4	10.5	47.8	46.9	-0.9	35.0	52.1	17.1	47.4	46.7	-0.7
DE	87.6	47.4	-40.1	46.6	49.5	3.0	87.6	52.1	-35.5	46.3	49.5	3.2
GR	44.7	47.4	2.7	50.5	53.4	2.7	45.6	52.1	6.5	51.1	52.7	1.7
IT	40.7	47.4	6.7	56.8	58.4	1.6	42.4	52.1	9.7	55.4	56.7	1.3
PT	34.3	47.4	13.1	54.5	52.6	-1.9	34.2	52.1	17.9	55.8	52.6	-3.1
SE	61.9	47.4	-14.4	46.4	43.8	-2.6	64.7	52.1	-12.6	45.2	41.5	-3.7
UK	113.7	47.4	-66.3	49.4	50.7	1.3	110.0	52.1	-58.0	50.5	52.4	1.9
Certificate exporters												
CZ	14.3	47.4	33.2	45.9	47.8	1.9	13.6	52.1	38.5	46.1	47.3	1.2
DK	0.0	47.4	47.4	46.6	44.0	-2.6	0.0	52.1	52.1	46.2	42.5	-3.7
FR	14.7	47.4	32.7	45.7	46.1	0.4	16.2	52.1	35.9	44.8	45.1	0.4
IE	0.0	47.4	47.4	51.7	48.2	-3.4	4.6	52.1	47.4	53.6	46.2	-7.4
NO	0.0	47.4	47.4	46.0	40.6	-5.4	0.0	52.1	52.1	45.6	36.5	-9.0
PL	0.0	47.4	47.4	47.2	48.8	1.6	0.0	52.1	52.1	47.1	47.9	0.9
ES	23.8	47.4	23.7	52.2	51.0	-1.2	22.1	52.1	30.0	54.2	49.6	-4.6

In all certificate exporting countries, green certificate prices increase with cooperation, while the opposite generally holds true in the certificate importing countries. However, in some certificate importing countries, the green certificate price *in 2020* also increases (FI, PT, IT, GR). In these countries, the certificate prices in the period post 2020 decrease given cooperation. Therefore, from a dynamic perspective, for these countries it is cost-efficient to import certificates. Note that the range of certificate price changes is identical in many exporting countries (NO, PL, DK and IE in the 'TYNDP' case). In these countries, the national certificate price is zero because the national target is not binding. The certificate price changes thus correspond to the different certificate prices occurring with cooperation (see Table 7). The largest certificate price change occurs in the United Kingdom. As shown in Table 7, the amount of certificates imported is comparatively low (3% and 5% without and with the realization of the TYNDP, respectively). However, the high certificate price in the national RES-E scenarios shows that it is very costly to reach the national target completely by domestic production.

The wholesale electricity price increases in most certificate importing countries. Exceptions occur in Portugal, Finland and Sweden. In these countries, the wholesale electricity prices decrease because the RES-E generation in neighboring countries increases (Spain and Norway). In most certificate exporting countries,

increases. In order to account for long amortization and lifetimes of power plants, the optimization model runs up to 2040.

wholesale electricity prices are lower with cooperation (DK, IE, NO, ES). In other certificate exporting countries, which today are already well interconnected with certificate importing countries, wholesale electricity prices increase (CZ, FR and PL).

In general, it can be seen that, in most countries, the change in the green certificate price far exceeds the change in the wholesale electricity price. Unteutsch (2014) shows that, in general, the change in green certificate prices is larger than the change in wholesale electricity prices but affects a smaller quantity than the change in the wholesale electricity price. Thus, the net effect of cross-border cooperation on consumer rents and total producer profits per country is theoretically unclear and needs to be determined by numerical analyses.

Effects on consumers rents and producer profits

Results of the numerical analysis in terms of consumer rents and producer profits per country are depicted in Table 10. The upper part of the table depicts the change of discounted, cumulated consumer rents and producer profits up to 2020 that result from cross-border green certificate trading. Percentage changes are depicted in the lower part of the table.[10] Consumer rents are only affected by cooperation via changes in the green certificate prices and in the wholesale electricity prices, assuming an inelastic demand. Producer profits, in contrast, are affected by cooperation via price and quantity effects as the amount of electricity produced and/or the electricity mix within a country also changes.

[10]Due to the assumption of an inelastic electricity demand, absolute values for consumer rents with either national or cooperative RES-E support cannot be determined. Thus, the percentage change of consumer rents between cooperative and national RES-E support can also not be determined. While absolute differences in the expenditures of consumers in meeting their electricity demand (multiplied with -1) correspond to absolute difference in consumer rents, percentage changes cannot be determined. Thus, the lower part of Table 10 depicts the percentage change in expenditures of consumers as well as the percentage changes of producer profits between cooperative and national RES-E support.

Table 10: Differences in consumer rents and producer profits between cooperative and national RES-E support, cumulated up to 2020 and discounted by 5% [bn. EUR_{2010} and %-changes]

changes in bn. $\mathbf{EUR_{2010}}$				
	TYNDP		w/o TYNDP	
Certificate importing countries	Consumer rent changes (Coop-Nat)	Changes of producer profits (Coop-Nat)	Consumer rent changes (Coop-Nat)	Changes of producer profits (Coop-Nat)
FI	-1.0	1.2	-1.9	2.2
DE	20.0	-14.7	18.1	-13.8
GR	-0.4	0.5	-0.6	0.6
IT	-4.2	4.3	-3.8	3.9
PT	-1.1	1.1	-1.5	1.6
SE	5.2	-4.8	5.4	-5.4
UK	20.8	-20.8	18.2	-18.1
Certificate exporting countries				
CZ	-1.7	2.5	-1.5	2.5
DK	-2.6	2.7	-2.8	2.9
FR	-13.0	13.3	-14.9	15.1
IE	-1.7	1.6	-1.3	1.4
NO	-13.9	14.5	-13.7	13.7
PL	-5.6	6.3	-5.2	6.2
ES	-13.6	14.8	-14.6	14.9
% changes				
Certificate importing countries countries	Changes in consumer expenditures (Coop-Nat)	Changes of producer profits (Coop-Nat)	Changes in consumer expenditures (Coop-Nat)	Changes of producer profits (Coop-Nat)
FI	2.4	7.9	4.5	14.9
DE	-7.3	-13.5	-6.6	-12.7
GR	1.3	4.3	1.9	5.2
IT	2.3	7.5	2.1	7.0
PT	3.6	9.5	5.0	13.1
SE	-6.3	-7.5	-6.5	-8.6
UK	-11.3	-36.3	-9.9	-31.5
Certificate exporting countries				
CZ	5.8	17.7	5.1	17.2
DK	17.1	42	18.3	45
FR	5.0	9.2	6.0	11.2
IE	13.5	85	10.1	78
NO	34.3	38	34.2	37
PL	9.3	60	8.6	59
ES	8.6	28	9.2	28

Positive (negative) values indicate that consumer rents, consumer expenditures or producer profits are higher (lower) once cooperation is introduced.

It can be seen that, in those countries which are exporters of certificates, consumer rents decrease and producer rents increase when changing from a national to a cooperative support system. Results for countries that are importers of certificates are more ambiguous. In some certificate importing countries, the effect of the change in the certificate price overcompensates for the effect of the change in the wholesale electricity price (e.g., in DE, GB and SE), such that consumer rents increase and producer profits decrease. However, in other certificate importing countries, the wholesale electricity price effect dominates such that producers make higher profits (especially from the utilization of existing conventional plants) and consumers are worse off with cooperation (e.g., PT). In Italy and Greece, both the certificate and the wholesale electricity price in 2020 increase such that consumers rents decrease and producer profits increase.

The largest effects of cooperation on consumer rents (in terms of percentage changes) occur in Norway, Denmark, Ireland and the United Kingdom. In these countries, the certificate price effect resulting from cooperation is very large and, in addition, the RES-E targets are comparatively high, such that the change in the certificate price has a large influence on the electricity bill of end consumers. Regarding the change in producer profits, cooperation substantially increases profits in Ireland, Poland, Denmark and Norway. These countries export large amounts of certificates and are characterized by high changes in the certificate prices. Moreover, it can be seen that redistribution effects are generally large compared to the overall welfare gain resulting from cooperation on the European level. For example, the changes in consumer rents and producer profits in the United Kingdom, Germany, Spain, Norway and France far exceed the overall change in European-wide welfare (see Table 7).

Comparing changes in consumer rents and producer profits in the scenarios with and without the realization of the TYNDP, it can be seen that the effects of cooperation are of a similar order of magnitude in both settings. Even in Norway, which exports certificates corresponding to 51 TWh RES-E generation when the TYNDP is realized and less than half as much when interconnectors are not enforced, the effect of cooperation on consumer rents and producer profits hardly differs. Consumer rents are not directly affected by the amount of certificates traded but only by the changes in prices. In Norway, the combined effect of cooperation on the wholesale electricity price and the certificate price are of the same order of magnitude with and without realization of the TYNDP. In addition, due to the assumed high RES-E target in Norway, both price changes affect nearly the same amount of electricity for consumers. Moreover, the effect of cooperation on producer profits is hardly influenced by different grid extensions because (as discussed in more detail in the following) producer profits in Norway mainly increase with cooperation as the incomes of existing hydro plants increase. Additional incomes from those capacities that are only built to export green certificates (in the cooperative support scenarios), in contrast, are comparatively low.

A closer look on producer profits

Tables 11 through 13 present a closer look on changes in producer profits. Table 11 depicts differences in producer profits between the national and the cooperative support scenarios by fuel type and Tables 12 and 13 highlight effects of cooperation in RES-E support on producer profits per country for conventional power plants and renewable energy plants, respectively. In all three tables, only changes in producer profits realized using plants from the currently existing European power plant fleet are shown. Thus, to be specific, producer *rents* (and not *profits*) of existing plants are depicted because investment costs of existing power plants are considered as stranded costs.

Examining the changes in producer rents of the existing power plant fleet is interesting for two main reasons. First, in contrast to new power plant investments, existing plants are not mobile. Investment decisions for the existing power plant fleet have been made in the past without anticipating European-wide cooperation (and possibly also without anticipating a strong RES-E expansion in general). If producer rents realized by these plants would decrease due to a shift in politics towards more cooperation in RES-E support, cooperation plans would presumably face strong opposition from the respective plant owners.[11] Second, it may be questioned as to whether it is appropriate to determine country-wise producer profits in light of international capital markets. While this question also concerns the existing power plant fleet, since large international stock companies generate a large part of electricity in many countries, this question becomes even more important for new investments. While the current ownership structure of the European power plant fleet is known, it is unclear which companies would build new capacities. Furthermore, in some countries, the state owns a large part of the existing power plant fleet.

Table 11 shows that, on a European level, producer rents gained from electricity generation by existing lignite, coal, gas and hydro plants are larger with cooperative than with national RES-E support. In contrast, rents gained from generation by existing biomass, offshore wind and photovoltaic plants decrease once cooperation is introduced. Rents gained from existing nuclear plants are larger with cooperative RES-E support if the TYNDP is realized but lower with national RES-E support if interconnectors are not enforced. The owners of existing onshore wind plants, in contrast, benefit in sum (on a European level) from cooperation if interconnectors are not enforced but are worse off in the cooperation case if the TYNDP

[11] In fact, Portugal, for example, states in its National Renewable Energy Action Plan (NREAP) that it would be interested in surpassing its own target and make use of cooperation mechanisms, given that the interconnector between Spain and France is expanded. Without a stronger interconnection of the Iberian Peninsula to Central Europe, the impact of a higher RES-E share on the existing conventional power plant fleet in Portugal would be strong (see Portuguese Republic (2010) and Fürsch and Lindenberger (2013)).

is realized.

Producer rents realized with lignite-based, gas-based and coal-based electricity generation increase because wholesale electricity prices in those countries, in which large capacities of lignite, gas and coal plants are located, increase once cooperation is introduced. Large lignite plants exist in Germany, Poland and the Czech Republic. Lignite production in these countries is hardly affected by the introduction of cooperation in RES-E support, whereas wholesale electricity prices in these three countries increase (Table 9). Producer rents of existing coal plants mainly increase because wholesale electricity prices in Germany and Italy increase. Producer rents realized by existing gas plants increase mainly due to increased generation and electricity prices in Germany, the United Kingdom, Italy and - especially in the TYNDP case - the Netherlands.

The effect of cooperation on producer rents gained from electricity generation by existing nuclear plants is rather small because generation levels are hardly affected by the introduction of cooperation. In addition, existing nuclear plants are located both in countries in which the wholesale electricity price increases with cooperation (e.g., FR) and in countries where the wholesale electricity price decreases (e.g., ES and FI). Therefore, the net effect on overall producer rents from existing nuclear plants on the European level is small.

Hydro rents are substantially larger with cooperative RES-E support because most hydro power plants are competitive without support payments. For example, the national green certificate price (without cooperation) is zero in Norway, where large hydro power resources are located. Thus, a shift towards a cooperative RES-E support system, in which hydro power producers gain revenues from selling green certificates at the European certificate prices, increases hydro rents substantially.[12] The increase in hydro rents is larger if the TYNDP is not realized because, in this case, the European certificate price is higher.

Producer rents realized using existing biomass plants, offshore wind plants and photovoltaic systems decrease once cooperation is introduced because a large part of these plants were built in countries that are importers of certificates if cooperation is possible (e.g., Germany, Finland, Sweden, United Kingdom, Italy). In most of these countries, the certificate price is lower with cooperation than with national RES-E support.

Existing onshore wind capacities are mainly located in Germany and Spain. While the certificate price in Germany decreases once cooperation is introduced, the opposite price effect resulting from cooperation is observed for Spain. If the TYNDP is realized, onshore rents on a European level decrease because the effect of lower rents gained in Germany is dominant. In contrast, if interconnectors are not enforced, the

[12]Of course, hydro may also be excluded from the support system, depending on the specific support design. For example, in Germany, large hydro power plants are currently excluded from the RES-E support system.

increase in the certificate price resulting from cooperation in Spain is higher than if the TYNDP is realized and onshore wind rents increase on a European level.

Table 11: Differences in producer rents gained from electricity generation of existing power plants (by fuel type) between cooperative and national RES-E support, cumulated up to 2020 and discounted by 5% [bn. EUR_{2010} and %-changes]

	TYNDP		w/o TYNDP	
	bn. EUR_{2010}	%	bn. EUR_{2010}	%
Nuclear	1.1	0.6	-0.8	-0.5
Lignite	1.4	4.6	0.6	2.0
Coal	4.8	12.2	4.2	10.5
Gas	3.3	8.3	0.6	1.4
Storage	0.2	3877.4	0.5	-337.5
Hydro	23.7	9.4	31.3	12.5
Biomass	-3.6	-74.4	-1.9	-42.1
Onshore Wind	-0.9	-1.7	0.7	1.4
Offshore Wind	-0.5	-18.6	-0.3	-12.1
Photovoltaics	-1.0	-6.1	-0.7	-4.3

Positive (negative) values indicate that producer rents are higher (lower) once cooperation is introduced.

Tables 12 and 13 depict changes in producer rents on the country level. The changes in producer rents gained from generation by existing conventional power plants (Table 12) mostly reflect the changes in wholesale electricity prices (see Table 9). An exception is Spain, where producer rents increase despite of decreasing wholesale electricity prices in 2020. However, the wholesale electricity price in 2015 is higher given cooperative rather than national RES-E support. The largest benefit (in absolute values) from cooperation in terms of producer rents of existing conventional power plants is realized in Germany (+ 5.1 bn. EUR_{2010} in the TYNDP scenario), followed by Spain (+ 1.9 bn. EUR_{2010}) and United Kingdom (+ 1.3 bn. EUR_{2010}).

Table 12: Differences in producer rents gained from electricity generation by existing conventional power plants (per country) between cooperative and national RES-E support, cumulated up to 2020 and discounted by 5% [bn. EUR_{2010} and %-changes]

	TYNDP		w/o TYNDP	
Certificate importing countries	bn. EUR_{2010}	%	bn. EUR_{2010}	%
Finland (FI)	0.1	0.7	0.0	0.1
Germany (DE)	5.1	14.1	4.3	12.0
Greece (GR)	0.1	1.9	0.1	1.5
Italy (IT)	0.7	8.2	0.1	1.8
Portugal (PT)	-0.1	-2.9	-0.1	-2.8
Sweden (SE)	-0.6	-3.8	-1.0	-6.7
United Kingdom (UK)	1.3	9.5	1.1	7.1
Certificate exporting countries				
Czech Republic (CZ)	0.6	4.3	0.2	1.6
Denmark (DK)	-0.1	-2.3	-0.1	-2.3
France (FR)	-1.0	-0.9	-1.1	-1.1
Ireland (IE)	0.1	35.3	0.1	103.9
Norway (NO)	0.0	23.4	0.0	135.7
Poland (PL)	0.5	4.4	-0.1	-0.6
Spain (ES)	1.9	7.4	1.1	4.4

Positive (negative) values indicate that producer rents are higher (lower) once cooperation is introduced.

Existing RES-E plants make up approximately one third of the currently existing European power plant capacity. Producer rents realized up to 2020 using currently existing RES-E plants are higher given cooperative RES-E support, in particular, in countries that are characterized by large hydro power resources and in which, in addition, the certificate price increases once cooperation is introduced (NO, FR, ES, IT). Lower producer rents under cooperative RES-E support are mainly realized in Germany and the United Kingdom, where the certificate price decreases with cooperation. In many other European countries, very few RES-E capacities currently exist.

Table 13: Differences in producer rents gained from electricity generation by existing RES-E plants (per country) between cooperative and national RES-E support, cumulated up to 2020 and discounted by 5% [bn. EUR_{2010} and %-changes]

	TYNDP		w/o TYNDP	
Certificate importing countries	bn. EUR_{2010}	%	bn. EUR_{2010}	%
Finland (FI)	0.7	11.7	1.3	21.3
Germany (DE)	-14.5	-23.0	-12.8	-20.3
Greece (GR)	0.1	1.9	0.2	4.0
Italy (IT)	1.8	5.0	3.8	10.0
Portugal (PT)	0.7	8.0	1.0	10.9
Sweden (SE)	-4.3	-9.3	-4.5	-9.8
United Kingdom (UK)	-6.2	-34.7	-5.3	-30.3
Certificate exporting countries				
Czech Republic (CZ)	1.0	94.0	1.1	104.2
Denmark (DK)	1.5	93.8	1.8	120.0
France (FR)	5.8	17.9	6.7	21.8
Ireland (IE)	0.4	35.9	0.4	30.4
Norway (NO)	15.8	38.1	18.6	44.4
Poland (PL)	0.6	77.5	0.7	84.5
Spain (ES)	6.4	22.6	7.7	27.5

Positive (negative) values indicate that producer rents are higher (lower) once cooperation is introduced.

3.3.2. Sensitivity Analysis: The influence of CO_2 emission prices and RES-E investment cost developments on welfare and redistribution effects

As shown by Unteutsch (2014), the slopes of the electricity supply curves (for RES-E and conventional electricity) determine the magnitude of the price changes and thereby also the magnitude of redistribution effects induced by certificate trade. Therefore, we run sensitivities with regard to three parameters that influence the slopes of the supply curves and investigate whether findings of the main scenarios are robust to these changes. We run sensitivities for the development of the CO_2 emission price, photovoltaic investment costs and offshore wind investment costs, which are all subject to great uncertainty. In the sensitivity analysis, we assume that the CO_2 emission price in 2020 is higher (by 10 EUR/t) and that photovoltaic and offshore wind investment costs in 2020 are lower (by 10% each) compared to the assumptions made in the main scenarios.

An increasing CO_2 emission price and decreasing RES-E investment costs have a common impact on the electricity system: Generation cost differences between RES-E plants and conventional plants decrease. Thus, the costs of achieving RES-E targets also decrease - both on a national level and under cooperation. The overall European system-wide benefit of cooperation decreases ('lower photovoltaic costs') or increases ('lower offshore costs' and 'higher CO_2 price'), depending on whether costs in the national or in the cooperative RES-E support scenarios are more affected by an increasing CO_2 emission price/decreasing RES-E investment costs. Table 14 provides an overview of European-wide welfare effects and the European green certificate price in the 'reference' case, corresponding to the 'TYNDP' scenario of the main scenarios, as well as in the sensitivity scenarios. In addition, certificate trade streams, price changes, redistribution and welfare effects in selected countries are presented.

Table 14: The influence of the CO_2 price and RES-E investment cost developments on model results [[bn. EUR_{2010}], cumulated 2010-2020 and discounted by 5 %; [EUR_{2010}/MWh] in 2020 or [TWh] in 2020]

		Reference	Higher CO_2 price	Lower wind offshore costs	Lower photovoltaic costs
Overall welfare gain [bn. EUR_{2010}]		12	13.4	12.4	11.3
European certificate price [EUR_{2010}/MWh]		47.4	34.2	45.6	42.4
Results for selected countries					
Certificate price change [EUR_{2010}/MWh] and (wholesale electricity price change)	DE	- 40.1 (+ 2.9)	- 30.8 (+ 1.4)	- 42 (+ 3.2)	- 33.6 (+ 3.4)
	DK	+ 47.4 (- 2.6)	+ 34.2 (- 2.5)	+ 45.6 (- 3.7)	+ 42.4 (- 0.8)
	ES	+ 23.7 (- 1.2)	+ 15.1 (- 2.2)	+ 21.9 (- 0.5)	+ 16.0 (+ 0.2)
	IE	+ 47.4 (- 3.4)	+ 34.2 (- 3.3)	+ 45.6 (- 4.2)	+ 42.4 (- 2.9)
	IT	+ 6.7 (+ 1.6)	- 2.8 (+ 0.3)	+ 4.9 (+ 1.7)	+ 10 (+ 1.6)
	NO	+ 47.4 (- 5.4)	+ 34.2 (- 5.5)	+ 45.6 (- 5.5)	+ 42.4 (- 3.9)
	PL	+ 47.4 (+ 1.6)	+ 34.2 (- 0.8)	+ 45.6 (+ 1.8)	+ 42.4 (+ 1.9)
Certificate trade [TWh]	DE	-91	-91	-91	-91
	DK	28	21	34	21
	ES	23	20	19	36
	IE	7	7	9	7
	IT	-9	-9	-9	3
	NO	51	50	51	51
	PL	19	17	19	17
Consumer rent change [bn. EUR_{2010}] and (changes in producer profits [bn. EUR_{2010}])	DE	+ 20.0 (- 14.7)	+ 19.9 (- 9.8)	+ 20.6 (- 15.5)	+ 15.4 (- 8.8)
	DK	- 2.6 (+ 2.7)	- 1.8 (+ 1.6)	- 2.4 (+ 2.4)	- 2.5 (+ 2.5)
	ES	- 13.6 (+ 14.8)	- 6.8 (+ 7.5)	- 12.9 (+ 14.3)	- 9.9 (+ 10.4)
	IE	- 1.7 (+ 1.6)	- 1.1 (+ 1.3)	- 1.6 (+ 1.5)	- 1.5 (+ 1.3)
	IT	- 4.2 (+ 4.3)	+ 1.4 (- 0.7)	- 4.1 (+ 4.2)	- 5.4 (+ 5.1)
	NO	- 13.9 (+ 14.5)	- 9.5 (+ 8.9)	- 13.3 (+ 14.3)	- 12.7 (+ 12.7)
	PL	- 5.6 (+ 6.3)	- 2.4 (+ 3.4)	- 5.5 (+ 6.1)	- 5.1 (+ 5.7)
Changes in country-wise welfare [bn. EUR_{2010}]	DE	5.3	7.1	5	6.7
	DK	0.1	-0.2	0	0
	ES	1.3	0.7	1.4	0.5
	IE	-0.1	0.2	-0.2	-0.2
	IT	0.1	0.7	0.1	-0.4
	NO	0.6	-0.7	1	0
	PL	0.7	1	0.6	0.6

In many countries, the amount of certificates traded is not sensitive to changes in the CO_2 emission price or RES-E investment costs. For example, the amount of certificates traded by Germany and by Norway is (approximately) the same in the reference and all sensitivity scenarios. In the case of lower investment costs for offshore wind plants, Denmark and Ireland export a higher amount of certificates, while exports from Spain decrease compared to the 'reference' case. In the case of lower photovoltaic costs, countries in the Mediterranean region (Spain and Italy) produce more RES-E, while offshore wind generation in the North

Sea region is reduced. In fact, Italy is a certificate importing country in all scenarios except for the 'lower photovoltaic' sensitivity scenario. A higher CO_2 price reduces the overall amount of traded certificates in Europe by around 10%. Due to a higher CO_2 price, the relative costs of generating power and heat in geothermal plants compared to the costs of generating heat and power in hard coal CHP plants decrease in some countries. Therefore, in some countries which are certificate importers in the 'reference' scenario, the optimal amount of domestic RES-E production increases.

Furthermore, the sign of the redistribution effects determined in the main scenarios is, in most countries, robust to changes in the supply curves assumed in the sensitivity scenarios. In most certificate importing countries, such as Germany, the certificate price decreases and the wholesale electricity price increases. In addition, in most certificate importing countries, the certificate price effect overcompensates for the wholesale electricity price effect such that consumers are better and producers are worse off than in a situation with purely national RES-E support systems. The opposite holds true for most certificate exporting countries, such as Norway and Ireland.

In contrast, the magnitude of price and redistribution effects highly depends on the assumptions varied in the sensitivity scenarios. The European certificate price is lower by around 28% when assuming a CO_2 price of 30 EUR/t (instead of 20 EUR/t). A decrease in offshore wind investment costs (photovoltaic costs) by 10% reduces the European green certificate price by around 4% (11%) compared to the 'reference case'. In countries where the national RES-E target is not binding, the European certificate price directly corresponds to the certificate price change resulting from cooperation (e.g., in Ireland and Norway). In these countries, a lower European certificate price reduces the benefit of cooperation for producers and attenuates the effect of decreasing consumer rents. For example, in the sensitivity scenario 'higher CO_2 price', the benefit that producers receive from cooperation decreases compared to the 'reference' case by 32% in Norway (19% in Ireland). Furthermore, the effect of increasing expenditures for consumers to meet their electricity demand decreases compared to the 'reference' case (-32% in Norway, -35% in Ireland). In other countries, the change in the certificate price depends on the relation between the national and the European certificate price, which both depend on changes in CO_2 emission prices and/or RES-E investment costs. For example, in Germany, lower photovoltaic costs have a larger impact on the national than on the European certificate price. Thus, both the benefit consumers have from cooperation and the negative impact cooperation has on producer profits substantially decrease compared to the reference case (by 23% for consumers, by 40% for producers). Moreover, the effect that lower photovoltaic costs have on the redistribution effects between individual groups within the countries is significantly larger than the effect of lower photovoltaic costs on the total system-wide welfare change resulting from cooperation (- 6% compared to the reference case).

In summary, the sensitivity analysis shows that the sign of the redistribution effects of cooperation and the magnitude of the overall European-wide welfare effect are quite robust to different assumptions which influence the slope of the electricity supply curves. However, the magnitude of price changes and thus also of redistribution effects is sensitive to different developments of RES-E investment costs and the CO_2 emission price.

3.4. Critical discussion of the numerical results

This paper numerically analyzes welfare and redistribution effects potentially resulting from the introduction of cooperation in European RES-E support. While the modeling represents the European power system by including European data about e.g., electricity demand, resource potentials, wind speed and the existing power plant fleet, some important differences between the current real-world European power system and the modeled situation exist. Therefore, in this section we discuss which model specifics have to be kept in mind when drawing conclusions from the model results presented in Section 3.3.

Probably the largest difference between the modeled scenarios and the real-world European power system stems from the assumption of technology-neutral RES-E support in all countries, both in the cases with and without cross-border cooperation. As stated in the introduction of this section, currently a variety of country-specific RES-E support systems exists in Europe and many countries have implemented technology-specific support systems, generally not leading to a cost-optimal generation mix. This current real-world situation is not taken into account in the analysis presented in Section 3.3. Therefore, in this paper, we do not quantify welfare and redistribution effects induced by a change from the currently implemented country-specific RES-E support systems to a RES-E support system with European-wide cooperation. Instead, we analyze the effects of introducing European-wide cooperation starting from a (hypothetical) situation of country-specific technology-neutral RES-E support. Thereby, we explicitly determine the separate welfare and redistribution effects of cooperation and exclude the effects which could also be achieved by optimizing national RES-E policies.

Note also that a complete change from purely national RES-E support to European-wide cooperation represents an extreme shift of politics that is very unlikely to occur before 2020. A first step towards European-wide cooperation would be the use of bilateral and multilateral cooperation mechanisms. Our analysis shows that especially Germany would have a large benefit from cooperation - even under the assumption of a cost-efficient domestic RES-E generation mix. Also, the analysis identifies potential cooperation partners such as Poland or Spain. However, the magnitude of redistribution effects resulting from different bilateral or multilateral engagements would have to be calculated in separate model analyses as the magnitude of price effects would be different compared to the case when changing from purely national support to complete European-wide cooperation. Nevertheless, this analysis shows that in the European power system effects of cooperation arising in the RES-E market would in most countries (such as Germany) be dominant compared to effects in the electricity market and that the sign of redistribution effects is in most countries very robust. Therefore, the results from this analysis provide a general idea of the impact different cooperation agreements would have on individual groups within the participating countries.

In addition, the magnitude of redistribution effects would in reality also depend on a variety of additional political decisions. For example, grandfathering rules could apply for existing renewable energy power plants. In this case, owners of existing RES-E plants would not be affected by the introduction of cooperation and consumers in countries with comparatively expensive existing RES-E plants would benefit to a smaller extent from cooperation. Moreover, as stated in footnote 12, renewable energies which are competitive without subsidies, such as large hydro power plants, might be excluded from the RES-E support system. In this case, countries with large hydro power resources would benefit less from cooperation.

In summary, the exact magnitude of redistribution effects resulting from different cooperation mechanisms in reality depends on many design specifics of the RES-E support systems and the cooperation mechanisms themselves. Conclusions which can be drawn from this analysis for the European electricity system are presented in the next section and include that the effects of cooperation in the RES-E market overcompensate in most countries for the effects occurring in the wholesale electricity market - even if interconnectors are not further extended compared to today.

4. Conclusion

Due to different meteorological conditions and resource availabilities across Europe, cooperation in the support of renewable energies would increase overall welfare in the European electricity sector. However, just like international trade in general, cooperation in the achievement of national RES-E targets, e.g., via cross-border green certificate trading, is not beneficial for all groups but creates winners and losers.

We find that in the European electricity system, effects of the change in the certificate price in most countries would overcompensate for the effects of the change in the wholesale electricity price. Thus, in most countries with comparatively high (low) generation costs for renewable energies, consumer rents increase (decrease) due to cooperation and producers yield lower (higher) profits. In addition, we find that the magnitude of redistribution effects between the individual groups is quite large: In some countries, the change in consumer rents or producer profits resulting from cooperation is nearly twice as high as the overall welfare effect of cooperation in the whole European electricity system. Moreover, the benefit different countries have from cooperation varies substantially. In our analysis, we find that Germany would by far have the largest (absolute) benefit of cooperation, achieved by significant reductions of RES-E target compliance costs via certificate imports. Finally, we find that the sign of redistribution effects is quite robust to different developments of interconnector extensions, the CO_2 price and RES-E investment costs. The magnitude of redistribution effects, in contrast, is in some countries sensitive to these assumptions (especially with regard to the assumption on the CO_2 price).

Therefore, this analysis shows that cooperation indeed has a significant influence on the welfare of different groups and thereby sheds further light to the question why it has been difficult to implement cooperation mechanisms thus far. Although on a country level the benefit of cooperation is generally positive, large inner-country redistribution effects may occur and those groups which potentially are worse off once cooperation is introduced may have a large influence on political decisions about the implementation of cooperation. The question, how these redistribution effects should be dealt with, however, is not straightforward. According to international trade theory, winners of trade can always compensate losers such that no group is worse off than without trade. However, in reality such compensation mechanisms can be complicated to design. First, it would need to be clarified who should be compensated by whom. Considering only consumers, cross-country compensation mechanisms could be implemented between those consumers who benefit from trade and those who pay higher prices once cooperation is introduced. But which group would, for example, compensate owners of conventional power plants in a country where the power price decreases once cooperation is introduced? Implementing compensation mechanisms for producers is especially difficult because many companies in the electricity sector operate in several countries and may therefore in some countries benefit from cooperation and lose revenues in other countries. Moreover, companies may also own both conventional and renewable power plants. Finally, even a clear distinction between producers and consumers can be difficult in practice, e.g., in the field of household photovoltaic installations. Second, the quantification of adequate compensation payments can be difficult ex-ante to the implementation of cooperation. As shown in this analysis, the exact magnitude of redistribution effects is specific to economic and technological developments in the power system, which are often subject to uncertainty. Finally, many other policies in the European power sector also induce redistribution effects, for which no compensation mechanisms exist. Examples are the European CO_2 emission trading system, the initial implementation of RES-E targets and the plan to create a single European electricity market. Thus, the question of welfare and redistribution effects resulting from cooperation in RES-E support comes back to the general question of trade and cooperation: To what extent should individual groups be protected and how far should overall welfare be increased?

This analysis has several shortcomings which could be addressed by future research. First, no sensitivities regarding the particular design of (national and cooperative) RES-E support systems have been made. This, for example, includes the question of how welfare and redistribution effects of cooperation depend on a technology-neutral (versus a technology-specific) and a quantity-based (versus a price-based) support. Moreover, in this analysis, we neglected that in practice grandfathering rules may apply for existing RES-E technologies. Second, in this analysis, we aggregated producer profits and consumer rents on country levels. While this seems appropriate for consumers as well as for some electricity producers, this procedure may be questioned for many electricity producers that are large international stock companies, operating in several countries. Further research analyzing the impact of cooperation on firm levels may be interesting. Third, this analysis is based on a purely deterministic approach and neglects, e.g., the stochastic nature of wind and solar in-feed. Nagl et al. (2013) show that including weather uncertainties in optimization models influences the value of different power plant types. In particular, Nagl et al. (2013) find that the value of fluctuating renewables such as wind decreases compared to deterministic modeling approaches. Consequently, including weather uncertainties would also affect the optimal generation mixes both when cooperation is and when it is not possible. Including stochastics therefore would lead to a more accurate determination of welfare and redistribution effects. Fourth, in this analysis, only the impact of an EU-wide cooperation in comparison to pure national RES-E support systems is analyzed. A first step towards European-wide cooperation would be the use of cooperation mechanisms between two or more countries via a common support system, joint projects or statistical transfers. Our analysis shows that in all scenarios the benefit of cooperation would be particularly large for Germany. Therefore, an engagement in bilateral or multilateral cooperation mechanisms would be an important measure to increase cost-efficiency in German RES-E support. The analysis of welfare and redistribution effects resulting from cooperation between Germany and different potential cooperation partners would be an interesting subject for further research.

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Appendix

Assumptions

Table A.1 shows the conversion efficiencies, the technical availability, the capacity factor (which is assumed to be securely available at peak demand) and the technical lifetime of power plants (taken from EWI and energynautics (2011)). Note that the technical availability of renewable energy plants varies significantly between different hours and regions and is thus not shown in Table A.1.

Table A.1: Technical parameters of power plants

Technologies	η (gen) [%]	η (load) [%]	avail [%]	secured capacity [%]	lifetime [a]
Nuclear	33	-	84.5	84.5	60
Hard coal	46	-	83.75	83.75	45
Hard coal innovative	50	-	83.75	83.75	45
Hard coal - CHP	22.5	-	83.75	83.75	45
Lignite	43	-	86.25	86.25	45
Lignite innovative	46.5	-	86.25	86.25	45
OCGT	40	-	84.5	84.5	25
CCGT	60	-	84.5	84.5	30
CCGT-CHP	36	-	84.5	84.5	30
Pump storage	87	83	95	95	100
Hydro storage	87	-	90	90	100
CAES	86	81	95	95	40
Biomass gas	40	-	85	85	30
Biomass gas - CHP	30	-	85	85	30
Biomass solid	30	-	85	85	30
Biomass solid - CHP	22.5	-	85	85	30
Geothermal (hot dry rock)	22.5	-	85	85	30
Geothermal (high enthalpy)	22.5	-	85	85	30
PV ground	-	-	-	0	25
PV roof	-	-	-	0	25
Concentrated solar power	-	-	-	40	25
Wind onshore	-	-	-	5	25
Wind offshore (shallow)	-	-	-	5	25
Wind offshore (deep)	-	-	-	5	25
Run-of-river hydropower	-	-	-	50	100

Table A.2 depicts investment costs and fixed operation and maintenance costs in 2020, taken from Fürsch and Lindenberger (2013).

Table A.2: Investment costs and fixed operation and maintenance costs in 2020 [$€_{2010}/kW$]

	invest. costs	FOM		invest. cost	FOM
Nuclear	3,157	97	Biomass gas	2,398	120
Nuclear Retrofit	300	97	Biomass gas - CHP	2,597	130
Hard Coal	1,500	36	Biomass solid	3,297	165
Hard Coal - innov.	2,250	36	Biomass solid - CHP	3,497	175
Hard Coal - innov. CHP	2,650	55	Geothermal (hot dry rock)	10,504	300
Lignite	1,850	43	Geothermal (high enthalpy)	1,050	30
Lignite - innov.	1,950	43	PV ground	1,440	15
OCGT	700	17	PV roof	1,600	17
CCGT	1,250	28	Concentrated solar power	3,423	120
CCGT - CHP	1,500	40	Wind onshore	1,221	41
			Wind offshore (shallow)	2,615	128
Pump storage	-	12	Wind offshore (deep)	3,105	152
Hydro storage	-	12	Run-of-river hydropower	-	12
CAES	850	9			

Table A.3: Generation and capacity differences between cooperative and national RES-E support in the year 2020 [TWh and GW] in the largest certificate importing countries (in the TYNDP and in the 'w/o TYNDP' scenario)

		Generation differences		Capacity differences	
		TYNDP	w/o TYNDP	TYNDP	w/o TYNDP
FI	non RES-E	-4.3	-0.3	0.9	0.1
	biomass	-3.5	0.1	-0.5	0.0
	onshore wind	-4.9	-4.9	-2.6	-2.6
	offshore wind	0.0	0.0	0.0	0.0
	pv/csp	0.0	0.0	0.0	0.0
DE	non RES-E	40.1	49.3	-0.1	-0.6
	biomass	-30.5	-30.5	-4.1	-4.1
	onshore wind	-26.0	-26.0	-15.1	-15.1
	offshore wind	-32.2	-32.2	-10.0	-10.0
	pv/csp	0.0	0.0	0.0	0.0
GR	non RES-E	5.1	3.0	0.5	0.3
	biomass	-0.4	0.0	-0.1	0.0
	onshore wind	-0.7	-0.7	-0.4	-0.4
	offshore wind	0.0	0.0	0.0	0.0
	pv/csp	-4.8	-1.2	-2.8	-0.3
IT	non RES-E	12.8	8.3	0.0	0.9
	biomass	0.0	0.0	0.0	0.0
	onshore wind	-0.2	-0.2	-0.1	-0.1
	offshore wind	0.0	0.0	0.0	0.0
	pv/csp	-8.8	-8.8	-6.1	-6.1
SE	non RES-E	2.2	1.8	0.8	0.7
	biomass	-7.6	-7.1	-0.5	-0.5
	onshore wind	-0.7	-0.7	-0.3	-0.3
	offshore wind	0.0	0.0	0.0	0.0
	pv/csp	0.0	0.0	0.0	0.0
UK	non RES-E	-1.4	3.5	0.3	0.0
	biomass	-0.6	-0.5	0.0	0.0
	onshore wind	0.0	0.0	0.0	0.0
	offshore wind	-3.4	-3.4	-0.9	-0.9
	pv/csp	0.0	0.0	0.0	0.0

Positive (negative) values indicate that generation levels or capacities are higher (lower) once cooperation is introduced.

Table A.4: Generation and capacity differences between cooperative and national RES-E support in the year 2020 [TWh and GW] in the largest certificate exporting countries (in the TYNDP and in the 'w/o TYNDP' scenario)

		Generation differences		Capacity differences	
		TYNDP	w/o TYNDP	TYNDP	w/o TYNDP
CZ	non RES-E	-0.6	0.4	0.2	0.2
	biomass	1.0	1.4	0.0	0.0
	onshore wind	8.2	7.8	3.8	3.6
	offshore wind	0.0	0.0	0.0	0.0
	pv/csp	0.0	0.0	0.0	0.0
DK	non RES-E	0.0	0.0	-0.3	0.0
	biomass	2.0	1.8	0.0	0.0
	onshore wind	0.0	0.0	0.0	0.0
	offshore wind	19.2	2.8	4.5	0.6
	pv/csp	0.0	0.0	0.0	0.0
IE	non RES-E	-2.2	-5.5	-0.2	-0.5
	biomass	0.0	0.0	0.0	0.0
	onshore wind	6.4	6.1	2.5	2.7
	offshore wind	0.0	0.0	0.0	0.0
	pv/csp	0.0	0.0	0.0	0.0
NO	non RES-E	-0.1	-1.1	0.0	-0.1
	biomass	0.0	0.0	0.0	0.0
	onshore wind	5.9	5.9	2.4	2.4
	offshore wind	45.0	14.9	10.0	3.3
	pv/csp	0.0	0.0	0.0	0.0
PL	non RES-E	-21.6	-16.8	0.3	0.3
	biomass	2.0	2.0	0.3	0.3
	onshore wind	17.0	17.0	6.8	6.8
	offshore wind	0.0	0.0	0.0	0.0
	pv/csp	0.0	0.0	0.0	0.0
ES	non RES-E	-14.3	-29.4	-1.4	-1.7
	biomass	2.2	2.1	0.3	0.3
	onshore wind	-0.7	-1.2	-0.4	-0.6
	offshore wind	0.0	0.0	0.0	0.0
	pv/csp	21.8	34.4	9.3	17.6

Positive (negative) values indicate that generation levels or capacities are higher (lower) once cooperation is introduced.