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Redistribution effects resulting from cross-border cooperation in support for renewable energy[☆]

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Abstract

It has been shown that international cooperation in achieving renewable energy targets, e.g., via a common tradable green certificate market, increases overall welfare. However, cooperation in the support of electricity from renewable energy sources also leads to regional price effects, from which some groups benefit while others lose. On a regional level, the introduction of cross-border cooperation in RES-E support generally has an opposite effect on support expenditures and wholesale electricity prices, as long as grid congestion between the different regions exists. In this paper, a theoretical model is used to analyze under which conditions different groups benefit or suffer from the introduction of cooperation. Findings of the analysis include that effects on consumers and total producers per country can only be clearly determined if no grid congestions between the countries exist. If bottlenecks in the transmission system exist, the relationship between the slopes of the renewable and the non-renewable marginal generation cost curves for electricity generation as well as the level of the RES-E target essentially determine whether these groups benefit or lose from the introduction of green certificate trading. In contrast, system-wide welfare always increases once cooperation in RES-E support is introduced. Similarly, welfare on the country level always increases (compared to a situation without RES-E cooperation) if the countries are perfectly or not at all physically interconnected. In the case of congested interconnectors, each country always at least potentially benefits from the introduction of certificate trade, taking into account possible distributions of congestion rents between the countries.

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

JEL classification: Q40, F19, Q48, Q28

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1. Introduction and background

International trade increases overall welfare. However, trade also results in redistribution effects such that different groups may be better or worse off with or without trade. These general findings of international trade theory (see, e.g., Krugman and Obstfeld (2009) or Bhagwati et al. (1998)) also apply to cross-border cooperation in achieving political targets for electricity generation from renewable energy sources (RES-E). Due to favorable meteorological conditions (e.g., high wind speeds or high solar radiation) or large resource availabilities (e.g., of hydro reservoirs), some regions have cost advantages in RES-E generation. Political targets for RES-E generation are, however, often not linked to the resource potential of a region. Cooperation between regions with different supply functions of RES-E generation thus increases system-wide welfare because less costly generation options can be used. However, this cooperation also leads to regional price effects from which some groups (e.g., consumers or producers in a particular region) benefit while other groups lose compared to a situation without cooperation. While the effect of increasing welfare resulting from cooperation in RES-E support has been studied quite extensively (e.g., by Ragwitz et al. (2007), EWI (2010) and Aune et al. (2012)), the associated redistribution effects have received little attention in literature thus far. This is intriguing as redistribution effects seem to be one of the main reasons that cooperation in RES-E support among member states of the European Union has been impeded thus far (Fürsch and Lindenberger (2013)).

With this paper, we try to fill the existing gap in literature. We analyze redistribution effects resulting from cooperation in a theoretical two-country electricity system model in which RES-E support is implemented via a tradable green certificate system. In a green certificate system, consumers or distributors of electricity are obliged to present an amount of 'green certificates' corresponding to a politically-defined percentage share of their electricity demand. Thereby, a market for the 'green value' of RES-E generation is created (see Section 3). The green certificate market is closely linked to the wholesale electricity market for two reasons. First, the certificate price is paid on top of the wholesale electricity price, such that the RES-E investor has two sources of incomes from which he covers his costs. Therefore, if the electricity price level is high, the investor will bid at low prices on the certificate market and vice versa. Second, an increase in renewable-based electricity generation leads to a decrease in non-renewable-based electricity generation (ceteris paribus). Therefore, as long as grid congestions between different regions exist, varying regional allocations of RES-E also affect regional wholesale electricity markets. Consequently, welfare and redistribution effects resulting from RES-E cooperation are significantly influenced by the degree of physical interconnection between different regional power systems. In this paper, we explicitly distinguish between different grid interconnections, in analyzing under which conditions different groups benefit or lose from the introduction of cooperation.

Main findings of this analysis include that the effects on consumers and total producers per country resulting from cooperation can only be clearly determined if no grid congestions between the countries exist. If bottlenecks in the transmission system exist, the relationship between the slopes of the renewable and the non-renewable marginal generation cost curves for electricity generation as well as the level of the RES-E target essentially determine whether these groups benefit or lose from the introduction of cross-border trading in green certificates. In contrast, system-wide welfare always increases once cooperation in RES-E support is introduced. Similarly, welfare on the country level always increases (compared to a situation without RES-E cooperation) if the countries are perfectly or not at all physically interconnected. In the case of congested interconnectors, the sum of producer and consumer rents in a country may also decrease under certain conditions. However, in this case the level of congestion rents is also influenced by the introduction of RES-E cooperation. Therefore, in this case, there always exists a possible distribution of congestion rents between the countries which ensures that each country benefits from the introduction of certificate trade.

The remainder of the article is structured as follows: In Section 2, an overview of the related literature and the contribution of the current work is presented. In particular, the relationship between cooperation in RES-E support and international trade theory is highlighted. Section 3 covers the theoretical analysis of redistribution effects. In Section 4, we draw conclusions and provide an outlook for further research.

2. Related literature and contribution of the current work

To our knowledge, the redistribution effects resulting from RES-E cooperation have not yet been analyzed in a theoretical framework. However, our analysis is related to two strands of literature. First, as pointed out in the introduction, the question of welfare and redistribution effects resulting from RES-E cooperation is closely related to international trade theory. Second, our analysis builds on the literature on the interaction between renewable support and the competitive wholesale market for electricity. A part of the latter literature also includes an investigation of cross-border cooperation in RES-E support, however, these investigations do not analyze redistribution effects.

2.1. Relation to international trade theory

International trade theory shows that trade between different regions increases welfare for two main reasons: First, because differences between the regions (e.g., in terms of different resource availabilities) can be exploited and second, because trade enables economies of scale to be achieved (Krugman and Obstfeld

(2009)). The classical and neoclassical trade theory (Smith, Ricardo, Heckscher and Ohlin) is founded on differences between the countries, whereas the new trade theory focuses on reasons for trade between similar countries, e.g., on the achievement of economies of scale and the reinforcement of competition through increasing market sizes (Mejía (2011)). The analysis presented in this paper can be best related to classical and neoclassical trade theory, as cooperation in our model occurs between regions with different RES-E generation costs.

In 1776, Adam Smith showed that trade between regions with an absolute cost advantage in the production of different goods increases overall welfare. The Ricardian model (developed by David Ricardo in 1817) states that trade increases welfare even if a region has higher production costs for all goods. In the Ricardian model, countries specialize in the production of the good in which they have a comparative advantage (Krugman and Obstfeld (2009)). In both the models of Smith and Ricardo, labor is the only production factor and trade occurs due to differences in regional labor productivities. Trade is beneficial for both countries, which reach higher aggregate consumption levels than in autarky. In addition, trade is beneficial for all individuals within the countries because productivities and real wages increase in both countries (Mejía (2011)).[1] Redistribution effects resulting from trade were first addressed in the context of the Heckscher-Ohlin model. Heckscher and Ohlin analyze trade between regions with different factor endowments. Their model consists of two countries, two output goods and - in contrast to Smith and Ricardo´s model - two input factors. Each of the output goods is intensive in one of the input factors (i.e., it requires more of one of the input factors than of the other) and each of the input factors is relatively abundant in one of the two countries. The Heckscher and Ohlin model states that countries specialize in the production of the good that is intensive in the input factor that is relatively abundant in the specific country. As in the models of Smith and Ricardo, trade increases overall consumption and, thus, welfare in both countries (Krugman and Obstfeld (2009)). However, as shown in the Stolper-Samuelson theorem, changes in the output price, induced by trade, also affect the relative factor prices in both countries, such that owners of the relatively abundant factor, benefit from trade, whereas owners of the relatively scarce factor, lose compared to the pre-trade situation (see, e.g., Zweifel and Heller (1992)).

Our analysis of cooperation in RES-E support is closest related to the theory of Heckscher and Ohlin. The motivation for cooperation in RES-E, e.g., implemented as a cross-border green certificate trading scheme, is that regions have different resource availabilities, such as sites with high wind speeds, hydro reservoirs or lignite mines. Furthermore, as will be shown in Section 3, cross-border green certificate trading

[1] Note that the Ricardian model assumes free and costless mobility of labor between the sectors within a country. Also, the productivity of all workers in a country is assumed to be identical.

leads to regional price effects which in turn lead to income distribution effects between different groups within a country. A difference between the analysis in this paper and the models of Smith, Ricardo and Heckscher-Ohlin is that our model covers only the electricity system (partial equilibrium model) and not the economy as a whole (general equilibrium model). In addition, the general equilibrium models of Smith, Ricardo and Heckscher and Ohlin assume that all factors are fully used, both before and after trade (which implies, e.g., that no unemployment exists). Therefore, no country will export or import both goods. An export of both goods would simply not be possible and an import of both goods would lead to unused resources and, thus, to inefficiencies. In our partial equilibrium model of the electricity system, it is not assumed that all input factors are fully used.[2] Therefore, it is possible that a country is an importer or an exporter of both green certificates and electricity. As will be shown in Section 3, in this case, and under the additional condition that the interconnector between the two countries is congested, it is possible that the sum of consumer rents and producer profits in a country decreases once cooperation is introduced. However, if interconenctors are congested, cooperation not only affects the welfare of producers and consumers, but also impacts congestion rents. Including changes of the congestion rents, we find that, analogous to general trade theory, overall international system-wide welfare always increases when trade is possible. Moreover, similar to the Heckscher-Ohlin model, in which trade is beneficial for all countries, we find that there always exists a possible redistribution of congestion rents between the countries which ensures that sectoral welfare in the electricity systems of all countries increases.

2.2. Interaction between RES-E support and the competitive wholesale electricity market

The influence of RES-E support on the wholesale electricity market, i.e., in terms of wholesale electricity prices, has been studied e.g., by Amundsen and Mortensen (2001), Jensen and Skytte (2002) and Fischer (2010). These authors either use one-country models or models with electricity trading, in which, however, RES-E is only supported in one country. Models with a common support scheme for renewable energies in two or more countries are investigated by e.g., Bye (2003), Amundsen and Nese (2009), Sun (2012), Aune et al. (2012) and Laffont and Sand-Zantman (2012). Except for Laffont and Sand-Zantman (2012), all authors study the effects of RES-E support via a green certificate market. Bye (2003) studies volume and price effects of an increasing RES-E percentage requirement in a model under autarky, a model with only electricity trading and a model with both electricity and green certificate trading. Amundsen and Nese (2009) investigate the impact of the RES-E percentage requirement and CO_2 emission prices on RES-E

[2] In a partial equilibrium model, such an assumption would not be sensible. For example, agricultural land can be used either for producing energy crops or for producing food. As the food sector is not included in the model of the electricity system, it would not be reasonable to assume that all available production sites are fully used for producing energy crops.

generation and total electricity production, both under autarky and with cross-border certificate trading. Aune et al. (2012) show that a common certificate market ensures the cost-efficient allocation of production across countries as long as the countries aim to increase their share of renewable energy in aggregate energy consumption. Sun (2012) builds on the two-country model presented in Aune et al. (2012) and investigates welfare effects of a socially-optimal RES-E percentage requirement under a joint renewable support system. Laffont and Sand-Zantman (2012) study the optimal degree of coordination in RES-E support in a two-country model with potentially limited transmission capacity. Their key finding is that the optimal degree of coordination depends on the level of transmission capacity.

In summary, while theoretical two-country models with common renewable promotion systems have been studied by several authors, these analyses do not include redistribution effects.[3] Our contribution to literature is thus to theoretically determine the redistribution effects resulting from cooperation in RES-E support, which to the best of our knowledge has not yet been performed.

3. Theoretical analysis

In analyzing the redistribution effects resulting from cooperation in RES-E support, we use a theoretical two-country model with a wholesale electricity market and a market for green certificates. A system of tradable green certificates (TGC) is a support mechanism for RES-E generation that is currently implemented in e.g., Poland, Great Britain, Norway and Sweden.[4] Of course, other support mechanisms also exist (see www.res-legal.eu for an overview of current RES-E support mechanisms across Europe) and cooperation in RES-E support is not restricted to a common TGC market. In this analysis, we chose to focus on the TGC system because, as outlined in Section 2, most literature that theoretically analyze RES-E support mechanisms, focus on this support mechanism.

In the model, producers sell electricity from renewable and non-renewable energy sources on the wholesale electricity market. Most renewable electricity sources are currently not competitive with non-renewable electricity sources. It is assumed that a certain RES-E target is decided politically and expressed as a percentage share of electricity demand, and that RES-E generation is incentivized by a green certificate system. In a green certificate system, the electricity consumer, or the electricity utility providing the consumer with electricity, is usually obliged to present a certain amount of certificates per unit of electricity

[3]The paper of Aune et al. (2012) also includes a numerical analysis in which welfare effects of cooperation on country levels are shown. However, redistribution effects between different groups within the countries are analyzed neither in their theoretical nor in their numerical model.

[4]The term 'tradable' generally does not refer to trade between different countries, but simply to the fact that green certificates can be traded between different market actors and often also across different time periods.

demand. Producers of renewable energy usually receive green certificates for each generated unit of RES-E (from the regulatory body). Thus, they sell their produced electricity on the wholesale electricity market and the 'green value' of the electricity on the green certificate market. Therefore, producers of renewable energy have two sources of income and - in competitive markets - will offer green certificates at a price which compensates for the additional costs of renewable generation compared to the wholesale electricity price. For more information on the functioning of TGCs, the interested reader is referred to, e.g., Amundsen and Mortensen (2001), Menanteau et al. (2003) and Agnolucci (2007).

The RES-E percentage requirements in the model are set on the national level and may or may not be identical in the two countries. Without cooperation in renewable support between the two countries, the national RES-E targets have to be achieved by domestic RES-E production only. With cooperation, implemented in our analysis as a cross-border green certificate trading system, imported green certificates can also contribute to national target achievement. Note that cross-border trade in green certificates is also possible without electricity trading because the green value, and not necessarily the green electricity itself, is traded across borders. In the following, we analyze the welfare effects of introducing a cross-border green certificate trading scheme in two cases. In the first case, we assume that the grid connection between the two countries is unlimited ('copper plate'). Neglecting transmission losses, the two countries in this case have a common wholesale price of electricity that is not affected by the regional distribution of RES-E generation.[5] In the second case, we assume that the interconnector linking the two countries is congested or that, in the extreme case, the two countries are not at all physically connected ('limited grid'). Therefore, in this case, the regional distribution of RES-E generation affects regional wholesale electricity markets.

In Section 3.1, we present the theoretical model. In Sections 3.2 and 3.3 we discuss welfare and redistribution effects resulting from cross-border green certificate trading for the case of a copper plate and the case of limited grid connection, respectively. In Section 3.4, the determinants for the results in the 'limited grid' case are discussed in more detail and in Section 3.5, we present numerical examples to illustrate how different assumptions (e.g., on the supply curves) influence welfare and redistribution effects shown in the theoretical model.

[5] Note that the (common) wholesale price for electricity could be affected by a different regional distribution of RES-E generation if the impact of the demand *structure* is taken into account. Assume, for example, that the introduction of cross-border green certificate trading leads to a reduction of photovoltaic generation in country A, which is then replaced by a higher wind generation in country B. In this case, the total amount of RES-E generation remains unchanged; however the structure of the renewable infeed has changed. A possible influence on the wholesale electricity market resulting from a different renewable energy mix is neglected in this analysis.

3.1. The theoretical model

As a starting point for our analysis, we take the model presented in Amundsen and Nese (2009), which is a theoretical two-country model with a wholesale electricity market and a green certificate market. However, the research question of this paper is completely different to the one of Amundsen and Nese (2009). Amundsen and Nese (2009) use the model to investigate whether it is possible to derive clear results on the level of RES-E generation resulting from a) an increase in the RES-E percentage requirement and of b) an increase in the CO_2 -price. We use the model to investigate welfare effects of cross-border green certificate trading, under different assumptions about the physical interconnection between different regions. In contrast to Amundsen and Nese (2009), we do not consider the market for CO_2 emissions and assume that electricity demand is inelastic. Unlike in other markets, demand in electricity markets is characterized by a relatively low elasticity, especially in the short term (Erdmann and Zweifel (2008)).[6] Thus, we believe that, for our research question, the assumption of a perfectly inelastic demand is appropriate as an approximation for a low demand elasticity.[7]

Table 1 presents the parameters and variables of the two-country model, where the index i denotes the country i $\in \{A, B\}$ (and where i´ is an alias of i).

[6]An overview of electricity demand estimations is, e.g., provided by Simmons-Süer et al. (2011) and Liejesen (2007). In general, electricity demand of industrial consumers is more elastic than of household customers. Furthermore, electricity demand is more elastic in the long term than in the short term. Simmons-Süer et al. (2011) determine average household electricity demand elasticities to be -0.2 in the short term (up to one year) and -0.6 in the long term (ten years or more), based on a literature review. Real-time price elasticity of electricity demand is estimated to be close to zero (Liejesen (2007)).

[7]In contrast, the main finding of Amundsen and Nese (2009), namely that the effect of an increasing percentage requirement on RES-E generation is indeterminate, relies on the assumption of an elastic electricity demand. With elastic electricity demand, an increasing percentage requirement can lead to a decreasing electricity demand such that the percentage requirement can also be achieved without an increase in RES-E generation.

Table 1: Notation of the theoretical model (partly based on Amundsen and Nese (2009))

s_i	price of green certificate
q_i	wholesale price of electricity
x_i	total consumption of electricity
y_i	production of conventional electricity
g_i	production of renewable electricity
α_i	RES-E percentage requirement
z_i	national RES-E target [with $z_i = \alpha_i \cdot x_i$]
$C_i(y_i)$	costs for conventional electricity with $\frac{\partial C}{\partial y} > 0; \frac{\partial C^2}{\partial y^2} \geq 0$
$h_i(g_i)$	costs for RES-E with $\frac{\partial h}{\partial g} > 0; \frac{\partial h^2}{\partial g^2} \geq 0$
π_i	profit function of all producers
π_i^R	profit function of renewable electricity producers
π_i^C	profit function of conventional electricity producers
CR_i	consumer rent
CE_i	consumer expenditures (expenditures for meeting electricity demand)
W_i	welfare
$T_{i,i'}$	traded green certificates
$M_{i,i'}$	interconnector capacity
$E_{i,i'}$	congestion rent

We assume that country B has a large potential of RES-E generation options with comparatively lower costs than country A (e.g., due to favorable meteorological conditions). More specific, we assume that in the market equilibrium without certificate trading, the price of green certificates in country B (at the certificate demand level corresponding to the national RES-E target z_B) is lower than in country A. Technologies and resource availabilities for the generation of non-renewable electricity may or may not be identical in both countries. Analogous to Amundsen and Nese (2009), we assume perfect competition in all markets.

3.2. Welfare effects with unlimited grid connection ('copper plate')

In the case of unlimited grid connection between countries A and B, the introduction of cross-border green certificate trading only affects the certificate market and not the wholesale electricity market. In the absence of grid congestions non-renewable power generation is optimally distributed between countries A and B even if green certificate trading is not possible and the regional distribution of RES-E generation is not optimal. Neglecting grid losses, a change in the regional distribution of renewable energy generation has no influence on the optimal regional distribution of non-renewable generation. Thus, the outcome of the wholesale electricity market (in terms of the common power price q and the regional levels of conventional electricity generation y_i) is not affected by the trading of green certificates.[8] With the possibility to trade

[8] In addition, as explained in footnote 5, this proposition relies on the assumption that the cost function for non-renewable electricity generation C_i only depends on the level of non-renewable electricity generation and thus only on the level of demand minus the level of RES-E infeed. The possible influence of a different structure of RES-E infeed, which may result from

green certificates, country A (with comparatively higher generation costs of RES-E) will import an amount T of certificates instead of fulfilling the national renewable target (z_A) using only local RES-E production. In country B, a higher RES-E generation is generated than needed to fulfill domestic demand for certificates (z_B), such that an amount T of certificates can be exported to country A. Equation (1) shows the profit function of conventional electricity producers in countries A and B. Equations (2) and (3) show the profit functions of renewable electricity producers in countries A and B, respectively.

$$\pi_i^C = q \cdot y_i - C(y_i); \quad i \in \{A, B\} \tag{1}$$

$$\pi_A^R = [q + s_A][z_A - T] - h_A(z_A - T) \tag{2}$$

$$\pi_B^R = [q + s_B][z_B + T] - h_B(z_B + T) \tag{3}$$

Analogous to Billette de Villemeur and Pineau (2010), who analyze the impact of a marginal increase in cross-border *electricity* trade on producer profits, consumer rents and total welfare, we analyze the welfare effects of a marginal increase in cross-border *certificate* trade T from country B to country A. The case $T = 0$ corresponds to the case where trading of green certificates is not allowed. In this case, by assumption, the price of green certificates in country A is larger than in country B ($s_A(z_A) > s_B(z_B)$). In the market equilibrium without certificate trading, the price of green certificates in each country corresponds to the additional marginal costs of renewable energy production, associated with a RES-E production of $g_i = z_i$, compared to the wholesale electricity price: $s_i = h_i'(z_i) - q$.[9] If green certificate trading is allowed, T is increased until the prices of green certificates in both countries converge ($s_A = s_B$). As the wholesale electricity price is identical in both countries and not affected by trading green certificates (meaning that q and y_i are independent of T), the convergence of green certificate prices is reached when the marginal costs of RES-E generation in both countries are equal ($h_A^{'}(z_A - T) = h_B^{'}(z_B + T)$). Thus, the optimal certificate trade T* is reached when $s_A = h_A^{'}(z_A - T^*) - q = h_B^{'}(z_B + T^*) - q = s_B$, and arbitrage is no longer possible.

Lemma 1 states that an increase in the trading of green certificates increases welfare in both countries, as long as $0 < T < T^*$ (implying $h_A^{'} > h_B^{'}$) and under the condition that the interconnector is not congested. While consumers in country A benefit from trading, producers of renewable electricity are worse off.

certificate trading, is neglected. Furthermore, wholesale electricity price effects can occur if the RES-E quota in country B is not binding. In this case, overall RES-E production in countries A and B would be lower than without the possibility of certificate trading. This case is discussed via a numerical example in Section 3.5.

[9]The equilibrium condition in the certificate market (i.e., the certificate price corresponds to the marginal generation costs of RES-E minus the wholesale electricity price) results from differentiating the profit function of RES-E producers with regard to RES-E production g_i (i.e., to the first-order condition of profit maximization of the RES-E producers) (see Amundsen and Nese (2009)).

Contrarily, RES-E producers in country B profit from trading, whereas consumers are worse off (for proof, see Appendix).[10] In both countries, producers of conventional electricity are not affected by cross-border certificate trading.

[10] To be precise, price effects (and thus also most redistribution and welfare effects) on country-levels are only non-negative and not strictly positive or negative, as indicated in Lemma 1.

Lemma 1. *If $0 < T < T^*$ and M is unlimited then*

$$\frac{dCR_A}{dT} = -\frac{ds_A}{dT} \cdot \alpha_A x_A = -\frac{ds_A}{dT} \cdot z_A \geq 0 \tag{4}$$

$$\frac{d\pi_A^R}{dT} = \frac{ds_A}{dT} \cdot [z_A - T] \leq 0 \tag{5}$$

$$\frac{d\pi_A^C}{dT} = 0 \tag{6}$$

$$\frac{dW_A}{dT} = -\frac{ds_A}{dT} \cdot T \geq 0 \tag{7}$$

$$\textit{with} \quad \frac{ds_A}{dT} = -h_A^{''}(z_A - T) \leq 0 \tag{8}$$

$$\frac{dCR_B}{dT} = -\frac{ds_B}{dT} \cdot \alpha_B x_B = -\frac{ds_B}{dT} \cdot z_B \leq 0 \tag{9}$$

$$\frac{d\pi_B^R}{dT} = \frac{ds_B}{dT} \cdot [z_B + T] \geq 0 \tag{10}$$

$$\frac{d\pi_B^C}{dT} = 0 \tag{11}$$

$$\frac{dW_B}{dT} = \frac{ds_B}{dT} \cdot T \geq 0 \tag{12}$$

$$\textit{with} \quad \frac{ds_B}{dT} = h_B^{''}(z_B + T) \geq 0 \tag{13}$$

$$\frac{dW}{dT} = \frac{dW_A}{dT} + \frac{dW_B}{dT} = [-\frac{ds_A}{dT} + \frac{ds_B}{dT}] \cdot T \geq 0 \tag{14}$$

In country A, the trading of green certificates leads to a decreasing price in green certificates (Eq. (8)), which is beneficial for consumers (Eq. (4)) and worse for RES-E producers compared to a situation without trade (Eq. (5)). The price decrease refers to the quantity z_A for the consumers, but only to the quantity $(z_A - T)$ for the RES-E producers. Producers of conventional electricity are not affected by certificate trade (Eq. (6)). Thus, total welfare in country A increases (Eq. (7)). In country B, in contrast, the trade in green certificates leads to an increasing price in green certificates (Eq. (13)), which is beneficial for RES-E producers (Eq. (10)) and worse for consumers compared to a situation without trade (Eq. (9)). In this case, the price increase refers to the quantity $(z_B + T)$ for the RES-E producers, but only to the quantity z_B for the consumers. Thus, total welfare in country B increases (Eq. (12)). The change in total system-wide welfare corresponds to the sum of the welfare changes in A and B and is therefore also positive (Eq. (14)).

Consequently, when grid connections are unlimited, it can be clearly shown that total welfare in both countries increases. Furthermore, it can be seen that in the country with a cost advantage for RES-E production (country B), producers are better and consumers are worse off than without trade. The opposite holds true in country A. The magnitude of the overall welfare and distributional effects essentially depends on the slope of the RES-E generation cost curves, which in turn determine the optimal certificate trade T^* and the changes in certificate prices.

3.3. Welfare effects with limited interconnection ('limited grid')

We now consider the case in which the electricity systems of countries A and B are not perfectly physically interconnected. Either, the interconnector between the two countries is congested, or, in the extreme case, the two regional electricity markets are not physically linked at all. Under this assumption, the different regional allocation of renewable energy generation capacities, resulting from the introduction of green certificate trading, has an influence on national wholesale electricity prices. If country A imports green certificates and thus reduces its domestic RES-E production, (inelastic) electricity demand in country A has to be met by increasing generation from conventional plants. Similarly, in country B, an increasing production of renewable energy leads to a decreasing production of electricity from conventional energy sources. This effect is the larger, the smaller electricity trading possibilities are. In the extreme case of no physical interconnection between the countries, the amount of lower (higher) RES-E generation in country A (B) has to be completely compensated by higher (lower) domestic conventional electricity generation.

The profit functions of electricity producers (for renewable and conventional electricity) in countries A and B are given by Eq. (15) - Eq. (20).[11] Equations (15) and (16) both present the profit function of conventional electricity producers in country A - once for the case that country A is an importer of electricity and once for the case that it exports electricity. Country A may be an importer both of certificates and of electricity, e.g., if countries A and B have the same production costs for conventional electricity or if country A has higher costs both for the generation of green and of conventional electricity. In contrast, if country A has a cost advantage for the generation of conventional electricity compared to country B, it may be an importer of certificates but an exporter of electricity. Similarly, Country B is an exporter of green certificates and may either be an importer or an exporter of electricity (Eq. (18) and Eq. (19)). Note that we only consider the case, when the interconnector is congested and a complete electricity price convergence between the two regional electricity markets cannot be achieved. Thus, total electricity imports or exports correspond to the interconnector capacity M. Setting M=0 corresponds to the case that the two countries are not at all interconnected.

[11] Note that the intermittent character of RES-E technologies such as wind and solar, is not taken into account in the model. This becomes apparent in Equations (15), (16), (18) and (19) as the total costs of conventional electricity generation (C_A and C_B) directly depend on the level of the residual demand (= demand - RES-E generation). Additional integration costs that occur in the conventional power system when RES-E shares increase (e.g., due to increasing balancing requirements or in ensuring security of supply during hours of low RES-E infeed) are not taken into account.

$$\pi_A^C = q_A \cdot [x_A - z_A + T - M] - C_A(x_A - z_A + T - M) \quad \text{[A imports electricity]} \tag{15}$$

$$\pi_A^C = q_A \cdot [x_A - z_A + T + M] - C_A(x_A - z_A + T + M) \quad \text{[A exports electricity]} \tag{16}$$

$$\pi_A^R = [q_A + s_A] \cdot [z_A - T] - h_A(z_A - T) \tag{17}$$

$$\pi_B^C = q_B \cdot [x_B - z_B - T + M] - C_B(x_B - z_B - T + M) \quad \text{[B exports electricity]} \tag{18}$$

$$\pi_B^C = q_B \cdot [x_B - z_B - T - M] - C_B(x_B - z_B - T - M) \quad \text{[B imports electricity]} \tag{19}$$

$$\pi_B^R = [q_B + s_B] \cdot [z_B + T] - h_B(z_B + T) \tag{20}$$

As in the 'copper plate' case, certificates are traded until certificate prices converge. However, in this case, convergence implies that the *additional* marginal generation costs of RES-E are identical in both countries ($(h_A' - C_A') = (h_B' - C_B')$). Lemma 2 defines welfare and redistribution effects resulting from the trading of green certificates (for $0 < T < T^*$; meaning that $(h_A' - C_A') > (h_B' - C_B')$), given that country A (B) is not only a certificate but also an electricity importing (exporting) country.

Lemma 2. *If $0 < T < T^*$, $M > 0$ but limited and A (B) is an electricity importer (exporter), then:*

$$\frac{dCR_A}{dT} = \underbrace{-\frac{ds_A}{dT} \cdot z_A}_{\geq 0} \underbrace{-\frac{dq_A}{dT} \cdot x_A}_{\leq 0} \tag{21}$$

$$\frac{d\pi_A}{dT} = \underbrace{\frac{ds_A}{dT} \cdot [z_A - T]}_{\leq 0} + \underbrace{\frac{dq_A}{dT} \cdot [x_A - M]}_{\geq 0} \tag{22}$$

$$\frac{d\pi_A^R}{dT} = [\frac{ds_A}{dT} + \frac{dq_A}{dT}] \cdot [z_A - T] \leq 0 \tag{23}$$

$$\frac{d\pi_A^C}{dT} = \frac{dq_A}{dT} \cdot [x_A - z_A + T - M] \geq 0 \tag{24}$$

$$dW_A = \underbrace{-\frac{ds_A}{dT} \cdot T}_{\geq 0} \underbrace{-\frac{dq_A}{dT} \cdot M}_{\leq 0} \tag{25}$$

$$\textit{with} \quad \frac{ds_A}{dT} = -h_A^{''}(z_A - T) - C_A^{''}(x_A - z_A + T - M) \leq 0 \tag{26}$$

$$\textit{and} \quad \frac{dq_A}{dT} = C_A^{''}(x_A - z_A + T - M) \geq 0 \tag{27}$$

$$\frac{dCR_B}{dT} = -\frac{dCE_B}{dT} = \underbrace{-\frac{ds_B}{dT} \cdot z_B}_{\leq 0} \underbrace{-\frac{dq_B}{dT} \cdot x_B}_{\geq 0} \tag{28}$$

$$\frac{d\pi_B}{dT} = \underbrace{\frac{ds_B}{dT} \cdot [z_B + T]}_{\geq 0} + \underbrace{\frac{dq_B}{dT} \cdot [x_B + M]}_{\leq 0} \tag{29}$$

$$\frac{d\pi_B^R}{dT} = [\frac{ds_B}{dT} + \frac{dq_B}{dT}] \cdot [z_B + T] \geq 0 \tag{30}$$

$$\frac{d\pi_B^C}{dT} = \frac{dq_B}{dT} \cdot [x_B - z_B - T + M] \leq 0 \tag{31}$$

$$\frac{dW_B}{dT} = \frac{d\pi_B}{dT} + \frac{dCR_B}{dT} = \underbrace{\frac{ds_B}{dT} \cdot T}_{\geq 0} + \underbrace{\frac{dq_B}{dT} \cdot M}_{\leq 0} \tag{32}$$

$$\textit{with} \quad \frac{ds_B}{dT} = h_B^{''}(z_B + T) + C_B^{''}(x_B - z_B - T + M) \geq 0 \tag{33}$$

$$\textit{and} \quad \frac{dq_B}{dT} = -C_B^{''}(x_B - z_B - T + M) \leq 0 \tag{34}$$

$$\frac{dE_{A,B}}{dT} = [\frac{dq_A}{dT} - \frac{dq_B}{dT}] \cdot M \geq 0 \tag{35}$$

$$\frac{dW}{dT} = \frac{dW_A}{dT} + \frac{dW_B}{dT} + \frac{dE_{A,B}}{dT} = [-\frac{ds_A}{dT} + \frac{ds_B}{dT}] \cdot T \geq 0 \tag{36}$$

In country A, the trading of green certificates leads to a decreasing price of green certificates (Eq. (26))

but to an increasing wholesale electricity price (Eq. (27)). The change in the wholesale electricity price is always (in absolute values) smaller than, or equal to, the change in the green certificate price. Thus, profits of renewable electricity producers decrease (Eq. (23)) and profits of conventional electricity producers increase (Eq. (24)). However, effects on consumer rents and on total producer profits cannot be clearly determined without making further assumptions. With regard to consumer rents, the smaller change in the wholesale electricity price refers to total electricity demand (x_A), while the larger change in the green certificate price only affects a fraction of electricity demand (namely ($z_A = x_A \cdot \alpha_A$)). With regard to producer profits, the change in the wholesale electricity price refers to ($x_A - M$), which is likely to be larger than the quantity ($z_A - T$) that is affected by the change in the certificate price.[12]

In country B, the trading of green certificates leads to an increasing price of green certificates (Eq. (33)) but to a decreasing wholesale electricity price (Eq. (34)). Thus, profits of renewable electricity producers increase (Eq. (30)), while profits of conventional electricity producers decrease (Eq. (31)). However, as in country A, the effects on consumer rents and on total producer profits are not clear. Again, the change in the wholesale electricity price (in absolute values) is smaller than, or equal to, the change in the green certificate price and affects total electricity demand (x_B) for consumers and ($x_B + M$) for producers. The change in the certificate price, in contrast, affects only ($z_B = x_B \cdot \alpha_B$) for consumers and ($z_B + T$) for producers.

The change in total welfare in countries A and B depends on the change in the green certificate price and, in contrast to the 'copper plate' case, also on the change in the wholesale electricity price (Eq. (25) and Eq. (32)). If country A is an electricity exporter and the wholesale electricity price increases once cooperation is introduced, consumers pay a higher wholesale electricity price for their total demand (x_A), while producers only profit from the higher price for the quantity ($x_A - M$). Therefore, the welfare change in country A, defined as the sum of changes in producer profits and consumer rents, depends on ($\frac{ds_A}{dT} \cdot T$) and on ($\frac{dq_A}{dT} \cdot M$), and can without further assumptions on the slopes of the marginal generation cost curves only be clearly determined if either one of the price effects is zero or if $T > M$.[13] Similarly, if country B is an electricity exporting country, the decreasing wholesale electricity price affects producers to a larger extent ($x_B + M$) than consumers (x_B), such that it is unclear, whether total welfare in country B increases or decreases.

In contrast, if either the two countries are not at all interconnected (M=0) or if country A (B) is an

[12] As ($x_A > z_A$), M would need to be substantially larger than T in oder to let ($x_A - M$) be smaller than ($z_A - T$). At the same time, when assuming that the interconnector is congested, it is unlikely that M is substantially larger than T.

[13] As $|\frac{ds_A}{dT}| > |\frac{dq_A}{dT}|$, it follows that, if $T > M$, $|\frac{ds_A}{dT} \cdot T| > |\frac{dq_A}{dT} \cdot M|$ (independent of the slopes of the marginal cost curves).

electricity exporting (importing) country, the welfare changes in A and B are always positive. In the latter case, Equation (25) is transformed to $\frac{dW_A}{dT} = -\frac{ds_A}{dT} \cdot T + \frac{dq_A}{dT} \cdot M$ and Equation (32) to $\frac{dW_B}{dT} = \frac{ds_B}{dT} \cdot T - \frac{dq_B}{dT} \cdot M$. These equations are always non-negative.

The change in total system-wide welfare corresponds to the sum of the welfare changes in countries A and B and to the change in the congestion rents. If the interconnector between A and B is congested, the changes in the regional wholesale electricity prices affect the price difference between the countries and thus, in turn, the congestion rents. If country A is an electricity importing country (and correspondingly, country B is an electricity exporting country), the price difference between A and B increases when certificate trade is possible (Eq. (35)). In contrast, if country A (B) is an electricity exporting (importing) country, then the difference in the wholesale electricity price between A and B decreases with an increasing T, since the wholesale electricity price in A is lower than in B without certificate trading. In both cases, total system-wide welfare increases in T. If country A (B) imports (exports) electricity, then the increasing congestion rents compensate for the negative components in $\frac{dW_A}{dT}$ and $\frac{dW_B}{dT}$ (Eq. (36)). If country A (B) exports (imports) electricity, the decreasing congestion rent compensates for the additional welfare increasing effects in A and B based on the changing wholesale electricity prices (see Appendix). Thus, the change in total system-wide welfare always only depends on the change in the certificate price in both countries and on T, and is always positive. Therefore, even if the welfare in one country, defined as the sum of consumer rents and producer profits, decreases in T, congestion rents can always be redistributed in a way that all countries benefit from certificate trading. In fact, in the European Union congestion rents have to be used for one or several of the three following purposes: (1) guaranteeing the actual availability of the allocated capacity, (2) for network investments maintaining or increasing interconnector capacities or (3) for reducing network tariffs (Art. 6 of the Regulation (EC) 1228/2003; see also Kapff and Pelkmans (2010)). Therefore, if congestion rents are used for purposes (2) or (3), increasing congestion rents have a welfare increasing effect on the country level. If interconnector capacities are increased, ceteris paribus, the welfare in both countries increases - either because of increasing producer profits that overcompensate decreasing consumer rents or, vice versa, because increasing consumer rents dominate (e.g., Kapff and Pelkmans (2010)). If network tariffs are reduced, endconsumer electricity prices decrease and consumer rents increase, which also has a welfare increasing effect. Therefore, if for example congestion rents are used for a network tariff reduction, there exist possible distributions of the network tariff reduction between the two countries, which ensure that welfare in both countries increases once certificate trade is introduced.

In summary, we find that both when the two countries are perfectly interconnected or if bottlenecks exist, system-wide welfare always increases in T (as long as $T < T^*$). Also, welfare on the country-levels always increases either if the two countries form a copper plate or if the countries are not at all interconnected. If bottlenecks exist, congestion rents can always be redistributed in a way, that both countries benefit from the introduction of certificate trading. In contrast, redistribution effects arise between different groups within the two countries, such that the introduction of certificate trade is not beneficial for all groups. Producers of renewable energy yield lower profits in country A (characterized by relative higher generation costs of renewable energy), while profits of RES-E producers in country B increase. If bottlenecks exist, the opposite holds true for producers of conventional electricity. In the copper plate case, producers of conventional electricity are not affected by the introduction of certificate trading. Effects on consumer rents and total producer profits (renewable and conventional) can, however, not be determined, except for the copper plate case. Table 2 provides an overview of the price, welfare and redistribution effects resulting from trading of green certificates.

Table 2: Price, welfare and redistribution effects resulting from cross-border trading of green certificates

	Copper plate	Limited interconnection	
		M>0 but limited	M=0
ds_A	≤ 0	≤ 0	≤ 0
ds_B	≥ 0	≥ 0	≥ 0
dq_A	$=$	≥ 0	≥ 0
dq_B	$=$	≤ 0	≤ 0
dCR_A	≥ 0	?	?
dCR_B	≤ 0	?	?
$d\pi_A^C$	$=$	≤ 0	≤ 0
$d\pi_B^C$	$=$	≥ 0	≥ 0
$d\pi_A^R$	≤ 0	?	?
$d\pi_B^R$	≥ 0	?	?
$d\pi_A$	≤ 0	?	?
$d\pi_B$	≥ 0	?	?
dW_A	≥ 0	?	≥ 0
dW_B	≥ 0	?	≥ 0
$dE_{A,B}$	$=$	?	$=$
$dW_A + dW_B + dE_{A,B}$	≥ 0	≥ 0	≥ 0

In the next section, the influence factors for those effects marked by a question mark in Table 2 are discussed.

3.4. Determinants of the redistribution effects in the case of limited interconnection

In this section, determinants of redistribution effects of cooperation, arising in the case of limited interconnection, are investigated in more detail. In the following, it will be shown that the sign of the changes of consumer rents and producer profits essentially depends on the relationship between the slopes of the generation cost curves for renewable-based and conventional electricity and on the level of the RES-E quota.

For this purpose, Equation (21), which defines the change in consumer rents in country A due to an increase in T, can be rewritten as follows:

$\frac{dCR_A}{dT} = -(-h_A''(z_A - T) - C_A''(x_A - z_A + T - M)) \cdot z_A - (C_A''(x_A - z_A + T - M) \cdot x_A)$.

Thereby, it can be seen that the change in consumer rents depends on the slopes of the generation cost curves of renewable and non-renewable electricity generation (h_A'' and C_A'') and on the RES-E percentage requirement (z_A). While the slopes of the supply curves determine the magnitude of the price effects (resulting from cooperation) on the certificate and on the wholesale electricity market, the level of the RES-E percentage requirement determines how large the part of electricity demand is that is affected by the change in the green certificate price. If the slopes of the two marginal generation cost curves are identical (in the relevant areas) and the RES-E quota is exactly 50%, then the effect of the change in the certificate price exactly compensates for the effect of the change in the wholesale electricity price. In this case, consumer rents are not affected by certificate trading. The upper part of Table 3 shows how consumer rents in country A change in T, depending on the relationship between the slopes of the two marginal generation cost curves and the level of the RES-E quota. Generally, consumers in country A benefit from certificate trading, if the RES-E marginal generation cost curve is relatively steep compared to the conventional one ($h_A'' \geq C_A''$) and/or the RES-E quota is high.

Table 3: Changes in consumer rents and producer profits in country A (case II, 'limited grid') depending on the slopes of the marginal generation cost curves and the level of the RES-E quota

$\mathbf{dCR_A/dT}$			
	$h_A'' = C_A''$	$h_A'' > C_A''$	$h_A'' < C_A''$
$z_A = 0.5x_A$	0	> 0	< 0
$z_A < 0.5x_A$	< 0	?	< 0
$z_A > 0.5x_A$	> 0	> 0	?
$\mathbf{d\pi_A/dT}$			
	$h_A'' = C_A''$	$h_A'' > C_A''$	$h_A'' < C_A''$
$z_A = 0.5(x_A - M)$	> 0	?	> 0
$z_A < 0.5(x_A - M)$	> 0	?	> 0
$z_A > 0.5(x_A - M)$	?	?	?

The lower part of Table 3 shows how the change in total producer profits in country A depends on the slopes of the marginal generation cost curves, on the RES-E quota and on the size of the interconnector capacity.[14] As defined in Equation (23), the change in the certificate price refers to the quantity $(z_A - T)$ for the producers. Thus, the change in total producer profits shown in Table 3 cannot be determined in many cases because the level of T is also necessary to determine whether the sum of producers benefit or lose from certificate trading. Generally, if the slope of the marginal generation cost curve for conventional electricity is relatively steep and the RES-E target is low, the wholesale electricity price effect is likely to be dominant, implying that producers in country A benefit from certificate trading.

Table 4 depicts the changes in consumer rents and total producer profits in country B depending on the slopes of the renewable and the conventional marginal generation cost curves and the level of the RES-E quota. The effects shown in Table 4 mirror the ones depicted in Table 3: Under the same conditions as in country A, either the certificate price effect or the wholesale electricity price effect is dominant. However, as price effects in country A and B are opposite, a dominant certificate price effect implies increasing consumer rents in country A and decreasing consumer rents in country B.[15]

Table 4: Changes in consumer rents and producer profits in country B (case II, 'limited grid') depending on the slopes of the marginal generation cost curves and the level of the RES-E quota

$\mathbf{dCR_B/dT}$			
	$h''_B = C''_B$	$h''_B > C''_B$	$h''_B < C''_B$
$z_B = 0.5x_B$	0	< 0	> 0
$z_B < 0.5x_B$	> 0	?	> 0
$z_B > 0.5x_B$	< 0	< 0	?
$\mathbf{d\pi_A/dT}$			
	$h''_B = C''_B$	$h''_B > C''_B$	$h''_B < C''_B$
$z_B = 0.5(x_B + M)$	> 0	> 0	?
$z_B < 0.5(x_B + M)$	?	?	?
$z_B > 0.5(x_B + M)$	> 0	> 0	?

Table 5 shows under which conditions (i.e., the slopes of the marginal cost curves and the relation between T and M) welfare in country A decreases or increases, given that A is an importer both of certificates and of electricity.[16] Generally, if the amount of certificates traded is large compared to the amount of electricity traded, and if the marginal cost curves of RES-E are relatively steep compared to the marginal cost curves of conventional electricity, then welfare on the country level increases. In contrast, if the amount of certificates

[14] Note that the depicted changes in producer profits correspond to the case that country A is not only a certificate but also an electricity importing country. If A is an electricity exporting country, $(x_A - M)$ has to be replaced by $(x_A + M)$.

[15] Note that the depicted changes in producer profits correspond to the case that country B is not only a certificate but also an electricity exporting country. If B is an electricity importing country, $(x_B + M)$ has to be replaced by $(x_B - M)$.

[16] Note that the welfare effects in country B are identical to the ones depicted in Table 5 when h''_A is replaced by h''_B and C''_A by C''_B.

traded is relatively small and the conventional marginal generation cost curves are relatively steep, then the wholesale electricity price effect dominates and welfare, defined as the sum of producer profits and consumer rents, decreases. Remember however, that, as explained in Section 3.3, congestion rents increase in T if A is electricity importer. These congestion rents can be distributed between A and B in a way which ensures that welfare in both countries always increases in T.

Table 5: Change in welfare in country A (case II, M>0, but limited) depending on the slopes of the marginal generation cost curves and the relation between certificate and electricity trading

$\mathbf{dW_A/dT}$			
	$h''_A = C''_A$	$h''_A > C''_A$	$h''_A < C''_A$
$T = 0.5M$	0	> 0	< 0
$T < 0.5M$	< 0	?	< 0
$T > 0.5M$	> 0	> 0	?
$T > M$	> 0	> 0	> 0

Summarizing, the relation between the slopes of the RES-E supply curve and the supply curve for conventional electricity has a high influence on welfare and redistribution effects resulting from cooperation. Whether in real-world power systems the supply curve of RES-E is steeper or flatter than the one of non-renewable-based electricity cannot be generally said and depends, for example, on available country-specific potentials for different power plant types. For this reason, a determination of redistribution effects in real-world power systems needs to be based on quantitative modeling analyses and is an important subject for future research. In the next section, the role of the supply curves´ slopes and the RES-E percentage requirement is further demonstrated, using numerical examples.

3.5. Numerical examples

In this section, we construct two simple numerical examples in order to highlight the effect of the degree of physical interconnection between the two countries, the slopes of the RES-E and the conventional supply curves and the RES-E quota requirement on welfare and redistribution effects induced by cooperation in RES-E support. Table 6 provides an overview of the assumptions made in the two numerical examples.

Table 6: Assumptions made in the numerical examples

	Example 1	Example 2
Demand		
x_A	10	10
x_B	10	10
RES-E target		
z_A	5	4
z_B	5	4
Cost curves		
C_A	$0.5y_A^2$	$0.75y_A^2 + 2y_A$
C_B	$0.5y_B^2$	$0.5y_B^2$
h_A	$2g_A^2$	$0.75g_A^2 + 5g_A$
h_B	g_B^2	$0.5g_B^2 + 3g_B$

In the first numerical example, a 50% RES-E share of electricity demand has to be reached in both countries and costs for conventional electricity generation are identical in both countries. In contrast, country B has a cost advantage in the production of renewable-based electricity compared to country A. Furthermore, in both countries, the slope of the RES-E supply curve is steeper than the slope of the conventional supply curve ($h''_A(g_A) = 4 > C''_A(y_A) = 1$ and $h''_B(g_B) = 2 > C''_B(y_B) = 1$).

Table 7 shows the results of this first numerical example for three different interconnector settings: M=0 ('no grid'), M=1 ('limited grid') and M unlimited ('copper plate'). It can be seen that the optimal amount of certificate trade (T*) increases with an increasing level of interconnection between the two countries and that the common certificate price with certificate trading (s*) decreases when M increases. Furthermore, overall welfare gains of certificate trading ($W_A + W_B + E_{A,B}$) increase when M, and therefore T*, increases.

Table 7: Effects of cooperation in RES-E support:Results from numerical example 1

		M = 0 ('no grid')			M = 1 ('limited grid')			M unlimited ('copper plate')		
	T*		1.25			1.5			1.67	
	s*		8.75			8.5			8.33	
		T=0	**T=T***	**diff.**	**T=0**	**T=T***	**diff.**	**T=0**	**T=T***	**diff.**
A	s_A	15.00	8.75	-6.25	15.00	8.50	-6.50	15.00	8.33	-6.67
	q_A	5.00	6.25	1.25	5.00	5.50	0.50	5.00	5.00	0.00
	π_A^R	50.00	28.12	-21.88	50.00	24.50	-25.50	50.00	22.22	-27.78
	π_A^C	12.50	19.53	7.03	12.50	15.13	2.63	12.50	12.50	0.00
	π_A	62.50	47.66	-14.84	62.50	39.63	-22.88	62.50	34.72	-27.78
	CE_A	125.00	106.25	-18.75	125.00	97.50	-27.50	125.00	91.67	-33.33
	CR_A			18.75			27.50			33.33
	W_A			3.91			4.63			5.55
B	s_B	5.00	8.75	3.75	5.00	8.50	3.50	5.00	8.33	3.33
	q_B	5.00	3.75	-1.25	5.00	4.50	-0.50	5.00	5.00	0.00
	π_B^R	25.00	39.06	14.06	25.00	42.25	17.25	25.00	44.44	19.44
	π_B^C	12.50	7.03	-5.47	12.50	10.13	-2.38	12.50	12.50	0.00
	π_B	37.50	46.09	8.59	37.50	52.38	14.88	37.50	56.94	19.44
	CE_B	75.00	81.25	6.25	75.00	87.50	12.50	75.00	91.67	16.67
	CR_B			-6.25			-12.50			-16.67
	W_B			2.34			2.38			2.77
	$E_{A,B}$	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00
	$W_A + W_B + E_{A,B}$			6.25			8.00			8.32

Note that, due to the assumption of an inelastic electricity demand, no absolute values for consumer rents and welfare levels can be calculated. However, the differences in expenditures that consumers pay for meeting their electricity demand (CE) (multiplied by (-1)) correspond to the change in consumer rents (CR).

Regardless of the size of the interconnector capacity M, the certificate price effect is always dominant in this example. Therefore, consumers in country A and total producers in country B benefit from certificate trading, while consumers in country B and total producers in country A are worse off than without certificate trading. On the country level, the change in welfare is positive in A and B. However, trade gains are unequally distributed between the two countries. In all three interconnector settings, the welfare increase in country A is larger than in country B. When the two countries form a copper plate, the welfare gain in country A makes up even two thirds of the overall welfare gain. The reason is, that, as shown in Lemma 2, the welfare change on the country-level depends on the changes in the green certificate and in the wholesale electricity price ($dW = |\frac{ds}{dT} \cdot T| + |\frac{dq}{dT} \cdot M|$). As the slopes of the conventional electricity supply curves are the same in both countries, it follows that $|\frac{dq_A}{dT}| = |\frac{dq_B}{dT}|$. In contrast, the RES-E supply curve is steeper in A than in B, such that the certificate price effect in A is larger than in B ($|\frac{ds_A}{dT}| > |\frac{ds_B}{dT}|$). Consequently, the welfare change in A is larger than in B ($\frac{dW_A}{dT} > \frac{dW_B}{dT}$).

In the second example, it is assumed that countries A and B have different cost curves for RES-E as well as for conventional electricity generation. In contrast to the first example, the slopes of the RES-E and the conventional supply curves in each country are identical ($h''_A(g_A) = C''_A(y_A) = 1.5$ and $h''_B(g_B) = C''_B(y_B) = 1$). Moreover, in contrast to the first example, the RES-E quotas in both countries are assumed to be 40% instead of 50%.

Table 8 shows price, welfare and redistribution effects occurring in this second example due to certificate trading. First of all, it needs to be noted that under the assumptions made in this example, country A is not always a certificate importing country. When M=0 and certificate trading is not possible, the certificate price in A is lower than in country B. The reason is that country A has higher costs for RES-E *and* conventional electricity generation compared to country B. Therefore, the certificate price in country A is lower than in B, due to a high wholesale electricity price. When electricity trading is possible (M=1 or M unlimited), country A is an electricity importing country, both when certificate trade is and is not possible. Therefore, the wholesale electricity price in country A is lower than without the possibility of electricity trading and the pre-certificate trading certificate price is higher in country A than in B. Thus, when M=1 or when M is unlimited, country A imports electricity and green certificates.

Table 8: Effects of cooperation in RES-E support:Results from numerical example 2

		M = 0 ('no grid')			**M = 1** ('limited grid')			**M unlimited** ('copper plate')		
	T*	0.2			0.3			1.6		
	s*	0.6			0.6			0.6		
		T=0	**T=T***	**diff.**	**T=0**	**T=T***	**diff.**	**T=0**	**T=T***	**diff.**
A	s_A	0.00	0.60	0.60	1.50	0.60	-0.90	3.38	0.60	-2.78
	q_A	11.00	10.70	-0.30	9.50	9.95	0.45	7.63	8.00	0.38
	π_A^R	12.00	13.23	1.23	12.00	10.27	-1.73	12.00	4.32	-7.68
	π_A^C	27.00	25.23	-1.77	18.75	21.07	2.32	10.55	12.00	1.45
	π_A	39.00	38.46	-0.54	30.75	31.34	0.59	22.55	16.32	-6.23
	CE_A	110.00	109.40	-0.60	101.00	101.90	0.90	89.75	82.40	-7.35
	CR_A			0.60			-0.90			7.35
	W_A			0.06			-0.32			1.12
B	s_B	1.00	0.60	-0.40	0.00	0.60	0.60	0.00	0.60	0.60
	q_B	6.00	6.20	0.20	7.00	6.70	-0.30	7.63	8.00	0.38
	π_B^R	8.00	7.22	-0.78	8.00	9.25	1.25	10.69	15.68	4.99
	π_B^C	18.00	19.22	1.22	24.50	22.45	-2.06	29.07	32.00	2.93
	π_B	26.00	26.44	0.44	32.50	31.69	-0.81	39.76	47.68	7.92
	CE_B	64.00	64.40	0.40	70.00	69.40	-0.60	76.25	82.40	6.15
	CR_B			-0.40			0.60			-6.15
	W_B			0.04			-0.21			1.77
	$E_{A,B}$	0.00	0.00	0.00	2.50	3.25	0.75	0.00	0.00	0.00
	$W_A + W_B + E_{A,B}$			0.10			0.22			2.89

As in the first example, the optimal amount of certificates traded and the welfare gains increase with an increasing interconnection between the two countries.[17] In contrast to the first example, however, the

[17]Note that the overall welfare gain is significantly higher when M is unlimited compared to the case when M=1, as shown in

common certificate price when certificate trading is possible (s*) does not vary with different levels of M. As shown in Lemma 2, the certificate price effect depends on the slopes of the RES-E and the conventional electricity supply curve. On the one hand, an increase in M leads to an increase in T* and therefore, ceteris paribus, to an increasing certificate price effect. On the other hand, the larger the interconnector capacity is, the smaller the wholesale electricity price effect becomes. As the change in the wholesale electricity price reinforces the certificate price effect, a larger interconnector capacity also has a decreasing effect on changes in the certificate price. Under the assumptions of equal slopes of the two supply curves, these two effects exactly compensate for each other.

Regarding redistribution effects, the certificate price effect in this example clearly dominates if M is unlimited. In contrast, it can be seen that if M=1, the wholesale electricity price effect is dominant both with regard to changes in consumer rents and with regard to changes in producer profits in the two countries. As the slopes of the RES-E and the conventional electricity supply curves are identical in this example, the change in the certificate price is twice as high as the change in the wholesale electricity price in both countries. However, as the RES-E quota is lower than 50%, the wholesale electricity price effect dominates.

Regarding welfare effects on the country-level, it can be seen that welfare in countries A and B decreases if M=1. As stated in Table 5, welfare on the country level decreases if the slopes of the RES-E and the conventional supply curves are identical and if $T < 0.5M$, which is satisfied in this example. In this case, the increase in the wholesale electricity price in country A leads to increasing end-consumer electricity prices for all consumers in country A, while producers in country A only partly benefit from this price increase because a part of the consumed electricity is imported. Similarly in country B, the decrease in the wholesale electricity price affects producers to a larger extent than consumers because electricity generation is higher than electricity demand due to exports. However, if M=1, congestion rents increase by 0.75 once cooperation is introduced and consequently, welfare on the system-level increases. Moreover, in this case, e.g., an equal distribution of the additional congestion rents between the two countries would ensure that both countries benefit from the introduction of certificate trade.

the third column of Table 8. The reason is that without certificate trading the RES-E quota in country B is not binding (i.e., the certificate price would be negative when producing only 4 units of RES-E). Thus, the overall amount of RES-E produced is lower when certificate trading is possible because a part of the certificates traded from country B to country A corresponds to RES-E generation that exceeds the RES-E quota even without certificate trade. Consequently, some of the traded certificates do not induce extra costs in country B. Moreover, for this reason, the wholesale electricity price increases both in countries A and B when certificate trading is possible.

4. Conclusion

As shown in neoclassical trade theory, trade between regions characterized by different resource availabilities increases overall welfare. However, due to trade-induced changes in prices, some individuals benefit from trade while others are worse off compared to a situation in autarky. This paper is motivated by findings of trade theory and analyzes cooperation in RES-E support between regions that are characterized by different supply functions of RES-E generation. The paper shows that cooperation in RES-E support also increases overall welfare and creates winners and losers compared to a situation in which each country achieves its RES-E target by local production only.

Our analysis shows that, due to opposing price effects of cooperation on the wholesale electricity market and on the green certificate market, the determination of winners and losers of cooperation is not straightforward as long as the different regions are not perfectly physically interconnected. Whether consumers or producers in a country benefit or are worse off essentially depends on the relation between the slopes of the RES-E and the conventional electricity supply curves as well as on the level of the RES-E target and on the degree of physical interconnection between the different countries. In contrast, system-wide welfare always increases once cooperation in RES-E support is introduced. Similarly, welfare on the country level always increases (compared to a situation without RES-E cooperation) if the countries are perfectly or not at all physically interconnected. In the case of congested interconnectors, the sum of producer and consumer rents in a country may also decrease under certain conditions. However, in this case the level of congestion rents is also influenced by the introduction of RES-E cooperation. Therefore, in this case, there always exists a possible distribution of congestion rents between the countries which ensures that each country benefits from the introduction of certificate trade.

Redistribution effects have a high relevance in political decisions surrounding the implementation of cooperation in RES-E support. In most real-world electricity systems, bottlenecks in the transmission lines between different countries exist currently. Our analysis shows that, in this case, the determination of redistribution effects is not straightforward and needs to be based on thorough quantitative analyses of real-world electricity systems. In particular, the interaction between the support for renewable energy and the wholesale electricity market needs to be taken into account. Moreover, important influence factors of redistribution effects can change over time, e.g., when interconnectors are expanded, when the RES-E targets increase over time or when cost degressions of different technologies lead to changing supply curves.

It is also important to take these considerations into account when discussing the sharing of costs and benefits of cooperation mechanisms. In this context, two important questions arise: First, who should or would need to be compensated in order to enhance cooperation between different regions? And second, how should compensation payments be determined? Regarding the first question, our analysis shows that in most cases cooperation increases welfare on the country level. Thus, compensation mechanisms on the country level would be hardly needed if countries are not concerned about domestic redistribution effects or unequally high benefits among participating countries. However, while the analysis includes effects resulting form cooperation on RES-E support expenditures and on the wholesale electricity market, effects on regional grid enhancement costs and other integration costs are neglected. Furthermore, the theoretical model assumes that producer profits are clearly allocated to the country in which the electricity is produced. For example, in the European electricity system, large international companies operating in several countries play an important role in electricity production. Thus, a clear association between producer profits and countries can be difficult in practice.

Regarding the second question, direct and indirect costs and benefits of cooperation have already been assessed in literature, e.g., by Klessmann et al. (2010) and Pade et al. (2012). These costs and benefits include, e.g., a reduction of RES-E target compliance costs, grid reinforcement and grid expansion costs, power market effects, effects on the technological development of power plants, employment effects and regional environmental effects. In particular, Pade et al. (2012) state that compensation mechanisms should include power market effects and that barriers to cooperation between countries with a common electricity market are lower because, in this case, RES-E deployment leads to similar power market effects in the cooperating countries. Our analysis confirms that power market effects can have a significant influence on redistribution effects resulting from cooperation. However, thorough quantitative analysis based on real-world data is needed to determine the magnitude of these power market effects. In summary, further research, is needed to further investigate redistribution effects and possible measures to enhance cooperation.

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Appendix

Proof of Welfare effects in case 1 ('copper plate')

In the first case, it is assumed that the two countries form a copper plate, implying that the common wholesale electricity market price is not affected by cross-border trading of green certificates.

Country A (certificate importing country):

- Effects on producers:

  Producer profits are defined as:

$$\pi_A^C = q \cdot y_A - C(y_A) \tag{37}$$

$$\pi_A^R = [q + s_A][z_A - T] - h_A(z_A - T) \tag{38}$$

  A marginal increase of T changes producer profits as follows:

$$\frac{d\pi_A^C}{dT} = 0 \tag{39}$$

$$\frac{d\pi_A^R}{dT} = \frac{ds_A}{dT}[z_A - T] - q - s_A + h'_A(z_A - T) \tag{40}$$

  The first order condition of profit maximization of RES-E producers ($\frac{d\pi_A^R}{dg_A}$ with $g_A = z_A - T$) implies that the certificate price corresponds to the additional marginal costs of renewable energy compared to the wholesale electricity price (see also Amundsen and Nese (2009)) $s_A = h'_A(z_A - T) - q$. It follows that:

$$\frac{d\pi_A^R}{dT} = \frac{ds_A}{dT} \cdot [z_A - T] \leq 0 \tag{41}$$

$$\text{with} \quad \frac{ds_A}{dT} = -h''_A(z_A - T) \leq 0 \tag{42}$$

- Effects on consumers:

Due to the assumption of an inelastic electricity demand, changes in consumer rents correspond to the changes in expenses for consumers in meeting their electricity demand (eq. (43)), multiplied by (-1). Thus, the effects of cross-border trading of green certificates on consumer rents is defined by Equation (44).

$$\text{Consumer expeditures} = CE_A = q \cdot x_A + s_A \cdot \alpha_A \cdot x_A \tag{43}$$

$$\frac{dCR_A}{dT} = -\frac{dCE_A}{dT} = -\frac{ds_A}{dT} \cdot \alpha_A x_A = -\frac{ds_A}{dT} \cdot z_A \geq 0 \tag{44}$$

- Effects on total welfare in country A:

$$\frac{dW_A}{dT} = \frac{d\pi_A}{dT} + \frac{dCR_A}{dT} = -\frac{ds_A}{dT} \cdot T \geq 0 \tag{45}$$

Country B (certificate exporting country):

- Effects on producers:

  Producer profits are defined as:

$$\pi_B^C = q \cdot y_B - C(y_B) \tag{46}$$

$$\pi_B^R = [q + s_B][z_B + T] - h_B(z_B + T) \tag{47}$$

A marginal increase in T changes producer profits as follows:

$$\frac{d\pi_B^C}{dT} = 0 \tag{48}$$

$$\frac{d\pi_B^R}{dT} = \frac{ds_B}{dT}[z_B + T] + q + s_B - h'_B(z_B + T) \tag{49}$$

Using $s_B = h'_B(z_B + T) - q$, changes in producer profits correspond to:

$$\frac{d\pi_B^R}{dT} = \frac{ds_B}{dT} \cdot [z_B + T] \geq 0 \tag{50}$$

$$\text{with} \quad \frac{ds_B}{dT} = h_B^{''}(z_B + T) \geq 0 \tag{51}$$

- Effects on consumers:

$$CE_B = q \cdot x_B + s_B \cdot \alpha_B \cdot x_B \tag{52}$$

$$\frac{dCR_B}{dT} = -\frac{dCE_B}{dT} = -\frac{ds_B}{dT} \cdot \alpha_B x_B = -\frac{ds_B}{dT} \cdot z_B \leq 0 \tag{53}$$

- Effects on total welfare in country B:

$$\frac{dW_B}{dT} = \frac{d\pi_B}{dT} + \frac{dCR_B}{dT} = \frac{ds_B}{dT} \cdot T \geq 0 \tag{54}$$

Proof of Welfare effects in case 2 ('limited interconnection')

In the second case, it is assumed that the two countries are not perfectly physically interconnected. Either, an interconnector exists which is congested, or the two regional electricity systems are not physically interconnected at all. In both cases, the trading of green certificates also influences the regional wholesale electricity markets. Note that setting the interconnector capacity M=0 corresponds to the case of no interconnection.

Country A (certificate importing country):

In the following, it is first assumed that country A is not only a certificate, but also an electricity importing country.

- Effects on producers:

  Producer profits are defined as:

$$\pi_A^C = q_A \cdot [x_A - z_A + T - M] - C_A(x_A - z_A + T - M) \tag{55}$$

$$\pi_A^R = [q_A + s_A] \cdot [z_A - T] - h_A(z_A - T) \tag{56}$$

  A marginal increase in T changes producer profits as follows:

$$\frac{d\pi_A^C}{dT} = \frac{dq_A}{dT} \cdot [x_A - z_A + T - M] + q_A - C_A^{'}(x_A - z_A + T - M) \tag{57}$$

$$\frac{d\pi_A^R}{dT} = \frac{dq_A}{dT} \cdot [z_A - T] + \frac{ds_A}{dT} \cdot [z_A - T] - q_A - s_A + h_A^{'}(z_A - T) \tag{58}$$

  Again, the certificate price corresponds to the additional marginal costs of renewable energy compared to the wholesale electricity price ($s_A = h'_A(z_A - T) - q_A$) and the wholesale electricity price corresponds to the marginal costs of meeting residual demand (=total electricity demand - RES-E production - electricity imports) with electricity from conventional energy sources ($C_A^{'}(x_A - z_A + T - M) = q_A$). It follows that:

$$\frac{d\pi_A^C}{dT} = \frac{dq_A}{dT} \cdot [x_A - z_A + T - M] \geq 0 \tag{59}$$

$$\frac{d\pi_A^R}{dT} = [\frac{ds_A}{dT} + \frac{dq_A}{dT}] \cdot [z_A - T] \leq 0 \tag{60}$$

$$\frac{d\pi_A}{dT} = \underbrace{\frac{ds_A}{dT} \cdot [z_A - T]}_{\leq 0} + \underbrace{\frac{dq_A}{dT} \cdot [x_A - M]}_{\geq 0} \tag{61}$$

$$\text{with} \quad \frac{ds_A}{dT} = - h_A^{''}(z_A - T) - C_A^{''}(x_A - z_A + T - M) \leq 0 \tag{62}$$

$$\text{and} \quad \frac{dq_A}{dT} = C_A^{''}(x_A - z_A + T - M) \geq 0 \tag{63}$$

- Effects on consumers:

$$CE_A = q_A \cdot x_A + s_A \cdot \alpha_A \cdot x_A \tag{64}$$

$$\frac{dCR_A}{dT} = -\frac{dCE_A}{dT} = \underbrace{-\frac{ds_A}{dT} \cdot z_A}_{\geq 0} \underbrace{- \frac{dq_A}{dT} \cdot x_A}_{\leq 0} \tag{65}$$

- Effects on total welfare in country A:

$$\frac{dW_A}{dT} = \frac{d\pi_A}{dT} + \frac{dCR_A}{dT} = \underbrace{-\frac{ds_A}{dT} \cdot T}_{\geq 0} \underbrace{- \frac{dq_A}{dT} \cdot M}_{\leq 0} \tag{66}$$

If country A is a certificate *importing* as well as an electricity *exporting* country, the profits gained from conventional generation and total producer profits in country A change as follows:

$$\pi_A^C = q_A \cdot [x_A - z_A + T + M] - C_A(x_A - z_A + T + M) \tag{67}$$

$$\frac{d\pi_A^C}{dT} = \frac{dq_A}{dT} \cdot [x_A - z_A + T + M] \geq 0 \tag{68}$$

$$\frac{d\pi_A}{dT} = \underbrace{\frac{ds_A}{dT} \cdot [z_A - T]}_{\leq 0} + \underbrace{\frac{dq_A}{dT} \cdot [x_A + M]}_{\geq 0} \tag{69}$$

Thus, if country A is a certificate importing as well as an electricity exporting country, welfare in country A changes as follows:

$$\frac{dW_A}{dT} = -\frac{ds_A}{dT} \cdot T + \frac{dq_A}{dT} \cdot M \geq 0 \tag{70}$$

Country B (certificate exporting country):

In the following, it is first assumed that country B is not only a certificate but also an electricity exporting country.

- Effects on producers:

  Producer profits are defined as:

$$\pi_B^C = q_B \cdot [x_B - z_B - T + M] - C_B(x_B - z_B - T + M) \tag{71}$$

$$\pi_B^R = [q_B + s_B] \cdot [z_B + T] - h_B(z_B + T) \tag{72}$$

A marginal increase in T changes producer profits as follows:

$$\frac{d\pi_B^C}{dT} = \frac{dq_B}{dT} \cdot [x_B - z_B - T + M] - q_B + C_B^{'}(x_B - z_B - T + M) \tag{73}$$

$$\frac{d\pi_B^R}{dT} = \frac{dq_B}{dT}(z_B + T) + \frac{ds_B}{dT}(z_B + T) + q_B + s_B - h_B^{'}(z_B + T) \tag{74}$$

Using that $s_B = h'_B(z_B - T) - q_B$ and $C_B^{'}(x_B - z_B - T + M) = q_B$, we find that:

$$\frac{d\pi_B^C}{dT} = \frac{dq_B}{dT} \cdot [x_B - z_B - T + M] \leq 0 \tag{75}$$

$$\frac{d\pi_B^R}{dT} = [\frac{ds_B}{dT} + \frac{dq_B}{dT}] \cdot [z_B + T] \geq 0 \tag{76}$$

$$\frac{d\pi_B}{dT} = \underbrace{\frac{ds_B}{dT} \cdot [z_B + T]}_{\geq 0} + \underbrace{\frac{dq_B}{dT} \cdot [x_B + M]}_{\leq 0} \tag{77}$$

$$\text{with} \quad \frac{ds_B}{dT} = h_B^{''}(z_B + T) + C_B^{''}(x_B - z_B - T + M) \geq 0 \tag{78}$$

$$\text{and} \quad \frac{dq_B}{dT} = -C_B^{''}(x_B - z_B - T + M) \leq 0 \tag{79}$$

- Effects on consumers:

$$CE_B = q_B \cdot x_A + s_B \cdot \alpha_B \cdot x_B \tag{80}$$

$$\frac{dCR_B}{dT} = -\frac{dCE_B}{dT} = \underbrace{-\frac{ds_B}{dT} \cdot z_B}_{\leq 0} \underbrace{-\frac{dq_B}{dT} \cdot x_B}_{\geq 0} \tag{81}$$

- Effects on total welfare in country B:

$$\frac{dW_B}{dT} = \frac{d\pi_B}{dT} + \frac{dCR_B}{dT} = \underbrace{\frac{ds_B}{dT} \cdot T}_{\geq 0} + \underbrace{\frac{dq_B}{dT} \cdot M}_{\leq 0} \tag{82}$$

If country B is a certificate *exporting* as well as an electricity *importing* country, the profits which can gained from conventional generation and total producer profits in country B change as follows:

$$\pi_B^C = q_B \cdot [x_B - z_B - T - M] - C_B(x_B - z_B - T - M) \tag{83}$$

$$\frac{d\pi_B^C}{dT} = \frac{dq_B}{dT} \cdot [x_B - z_B - T - M] \leq 0 \tag{84}$$

$$\frac{d\pi_B}{dT} = \underbrace{\frac{ds_B}{dT} \cdot [z_B + T]}_{\geq 0} + \underbrace{\frac{dq_B}{dT} \cdot [x_B - M]}_{\leq 0} \tag{85}$$

$$\tag{86}$$

Thus, if country B is a certificate exporting as well as an electricity importing country, welfare in country B changes as follows:

$$\frac{dW_B}{dT} = \frac{ds_B}{dT} \cdot T - \frac{dq_B}{dT} \cdot M \geq 0 \tag{87}$$

Congestion rents:

If the interconnector is congested, congestion rents, corresponding to the price difference between the two regions multiplied by the amount of electricity traded, are also affected by certificate trading.

- If country A is an electricity importing country and country B an electricity exporting country, congestion rents increase in T. Country A (B) imports (exports) electricity (even in the absence of certificate trading) if the wholesale electricity price in A is higher than in B. With an increasing T, the wholesale electricity price in A increases further, while the wholesale electricity price in B decreases. Thus, the price difference, and thereby the congestion rent, increases. If electricity trades are zero in the absence of certificate trading, congestion rents are also zero. In this case, the price difference also increases once certificate trading is introduced and congestion rents increase from zero to a positive value.

$$\frac{dE_{A,B}}{dT} = [\frac{dq_A}{dT} - \frac{dq_B}{dT}] \cdot M \geq 0 \tag{88}$$

- If country A is an electricity exporting country and country B an electricity importing country, congestion rents decrease in T. Country A exports electricity if the wholesale electricity price in A is lower than in B. When certificate trading is possible and wholesale electricity prices in A (B) increase (decrease), the price difference decreases.

$$\frac{dE_{A,B}}{dT} = [\frac{dq_B}{dT} - \frac{dq_A}{dT}] \cdot M \leq 0 \tag{89}$$

Overall welfare:

- If country A is an electricity importing country and country B an electricity exporting country, the increasing congestion rent compensates exactly for the sum of the negative components in the change in welfare in countries A and B, such that system-wide welfare increases and only depends on the changes in certificate prices.

$$\begin{aligned} \frac{dW}{dT} = \frac{dW_A}{dT} + \frac{dW_B}{dT} + \frac{dE_{A,B}}{dT} &= \underbrace{-\frac{ds_A}{dT} \cdot T}_{\geq 0} \underbrace{-\frac{dq_A}{dT} \cdot M}_{\leq 0} + \underbrace{\frac{ds_B}{dT} \cdot T}_{\geq 0} \\ \underbrace{+\frac{dq_B}{dT} \cdot M}_{\leq 0} + \underbrace{[\frac{dq_A}{dT} - \frac{dq_B}{dT}] \cdot M}_{\geq 0} &= [-\frac{ds_A}{dT} + \frac{ds_B}{dT}] \cdot T \geq 0 \end{aligned} \tag{90}$$

- If country A is an electricity exporting country and country B an electricity importing country, the decreasing congestion rent compensates exactly for the sum of the wholesale price effects in the changes in welfare of country A and B (which in this case are positive).

$$\frac{dW}{dT} = \frac{dW_A}{dT} + \frac{dW_B}{dT} + \frac{dE_{A,B}}{dT} = \underbrace{-\frac{ds_A}{dT} \cdot T}_{\geq 0} + \underbrace{\frac{dq_A}{dT} \cdot M}_{\geq 0} + \underbrace{\frac{ds_B}{dT} \cdot T}_{\geq 0} \tag{91}$$

$$\underbrace{-\frac{dq_B}{dT} \cdot M}_{\geq 0} + \underbrace{[\frac{dq_B}{dT} - \frac{dq_A}{dT}] \cdot M}_{\leq 0} = [-\frac{ds_A}{dT} + \frac{ds_B}{dT}] \cdot T \geq 0$$