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On International Renewable Cooperation Mechanisms: the Impact of National RES-E Support Schemes

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Abstract

The deployment of renewable cooperation mechanisms within the European Union (via statistical transfers, joint support schemes and joint projects) is expected to increase in the near future. Such cooperation mechanisms can significantly reduce the compliance cost for meeting renewable energy targets. Nevertheless, as it is known that ill-designed national support instruments distort renewable investment and production decisions, it can also be expected that these impact the performance of cooperation mechanisms. In this paper, we develop a bi-level two-country competitive equilibrium model that analyzes the impact of national RES-E support instruments on the performance of renewable cooperation mechanisms. Furthermore, we assess the efficiency of two international cooperation mechanisms (statistical transfers and joint support schemes) and compare it to the situation without renewable cooperation. Based on an analytical derivation and a numerical example, we first confirm that fixed feed-in premiums are the globally most efficient instrument, given production-based quotas (in MWh). Other national instruments (feed-in tariffs and capacity-based subsidies) can distort renewable investment decisions, and are sub-optimal. Second, the employment of statistical transfers always outperforms the no-renewable cooperation case, independent of the national support instruments. Third, statistical transfers are preferred over joint support schemes when employing sub-optimal national policy instruments. In fact, it even is possible that sub-optimal joint support schemes (i.e. not based on the fixed feed-in premium) perform worse than no renewable cooperation at all. Finally, we also consider the country-level distributional effects and conclude that country-level incentives for renewable cooperation may not align with the global optimum, i.e. national policy makers might be incentivized to constrain their cooperation levels.

Keywords: Energy policy, Renewable electricity, Integrated markets, Renewable cooperation mechanisms

1. Introduction

Growing climate change concerns have led to a strong promotion of renewable energy. The European Union, for example, is committed to reach a 20% share for renewables in final energy consumption in 2020. To achieve this, the European Council has adopted mandatory differentiated national targets for each of the Member States (EU, 2009). These national targets were only loosely based on a Member State's renewable potential (D'haeseleer et al., 2017), implying that the compliance cost for meeting these national targets can be substantially reduced by allowing renewable energy trade. This statement has already been extensively validated in the academic literature (Voogt and Uyterlinde, 2006; Ragwitz et al., 2007; Capros et al., 2011; Aune et al., 2012; Jägemann et al., 2013; Unteutsch and Lindenberger, 2014; Saguan and Meeus, 2014; Green et al., 2016; Perez et al., 2016). For instance, Aune et al. (2012) estimate that the additional energy

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system cost (due to the renewable target) could be reduced by 70%. Similarly, Unteutsch and Lindenberger (2014) calculate a 41% to 45% reduction of the additional electricity system cost under perfect renewable cooperation.

The European Union acknowledged this issue from the outset, and has introduced a legal framework for the use of cooperation mechanisms (EU, 2009; Klessmann et al., 2014). More specifically, Member States can employ statistical transfers, implement joint projects (also with third countries) and set up joint support schemes. Under statistical transfers, renewable energy (RES) produced in one Member State is virtually transferred to the RES statistics of another Member state. The over-complying Member State typically is financially compensated by the RES-importing Member State. Joint projects are developed under framework conditions set by the participating Member States (e.g. creating an allocation rule of the generated renewable energy) and are expected to contribute to promoting off-shore wind energy. Finally, by setting up joint support schemes, Member States can merge or coordinate their RES support policies. The participating Member States then jointly define the allocation of renewable energy produced under the joint support scheme to their national targets.

Despite the significant benefits of renewable cooperation mechanisms, their deployment has been fairly limited. Current implementations are, to the authors' knowledge, restricted to the joint tradable green certificate (TGC) market between Norway and Sweden, statistical transfers flowing from both Estonia and Lithuania towards Luxembourg, and auctions for photovoltaics (PV) capacity open to investors in Denmark and Germany (Caldés et al., 2018). Both Klessmann et al. (2014) and Klinge Jacobsen et al. (2014) discuss the rationale behind this and enlist several cooperation barriers (i.a. public acceptance, uncertainty on meeting domestic RES-targets, etc.). Caldés et al. (2018) rank the importance of these barriers based on a dedicated survey. Verhaegen et al. (2009) show that harmonizing support schemes (as is necessary for some of the cooperation mechanisms) can be challenging by unveiling key differences between the four TGC systems implemented in Belgium. Furthermore, it has been shown that the efficient use of cooperation mechanisms asks for addressing the impacts of different regulatory conditions (Ecofys and eclareon, 2018). Finally, Unteutsch (2014) analyses distributional effects from cooperation under a common TGC market and concludes that engaging in renewable cooperation can decrease a country's welfare (although global welfare can only increase). We will generalize this final result to include multiple national support instruments.

Although cooperation mechanisms thus are not without challenges, it is expected that their deployment will increase in the future. Indeed, some of the Member States are not likely to achieve their national quota by 2020 (e.g. the Netherlands and France), whilst others have already exceeded their target (e.g. Sweden and Estonia) (Eurostat, 2017). Cooperation mechanisms (and especially statistical transfers) can be employed to partly cancel these RES shortages and excesses towards 2020. Moreover, the renewed 2030 EU renewable energy framework has increased the focus on renewable cooperation mechanisms, thereby allowing two additional possibilities: the Union renewable development platform (URDP) and the Union renewable energy financing mechanism (EU, 2018a,b). The URDP basically resembles a centralized market for statistical transfers, whereas up till now only bilateral agreements were possible (EU, 2018b). The renewable energy financing mechanism collects voluntary contributions from individual Member States used to tender support for new renewable energy projects in the entire Union (EU, 2018a). The renewable energy generated by installations financed by this mechanism will be statistically attributed to the participating Member states, reflecting their relative payments. In addition, the Commission may be introducing an obligation for the use of cooperation mechanisms as of 2023, thereby alleviating the concern that cooperation mechanisms currently remain underused (EU, 2018b).

In this paper, we will focus on the power sector and analyze the impact of national renewable electricity (RES-E) support schemes on cooperation mechanisms. Historically, renewable electricity has been steadily incentivized by national support schemes (see e.g. Haas et al. (2011) for an overview). Frequently adopted RES-E support policies include the feed-in tariff, fixed feed-in premium[1] and sliding feed-in premium. Under a feed-in tariff, renewable generators are remunerated a fixed price per MWh RES-E generation, fully decoupled from the electricity price. A fixed feed-in premium is a constant premium, granted to renewable

[1]We will not include tradable green certificate (TGC) systems in this paper as, in our context, a TGC system will yield the same outcome as a fixed feed-in premium (see below).

generators, on top of the electricity price. Under a sliding feed-in premium, the premium paid on top of the electricity price varies (e.g. monthly) and is calculated as the difference between a fixed strike price and the average electricity price (typically calculated ex-post based on historical electricity prices). Additionally, we also include capacity-based subsidies in our analysis. Under this policy, renewable generators are fully exposed to the electricity price (i.e. no premium in EUR/MWh), but receive an investment offset based on the amount of capacity installed (EUR/MW).

The performance of RES-E support policies within one single country in autarky has already been thoroughly investigated. Basically, the efficiency of any support scheme strongly depends on the goal that policy makers aim to achieve. In the European context, countries are subject to quota obligations defined as a share of total energy consumption. This artificially imposes production-based externalities, i.e. renewable electricity production (in MWh) has a value outside the electricity market (namely a contribution towards achieving the national quota). In contrast, several authors have claimed that, in the EU, such production-based externalities actually do not exist as promoting renewable electricity under an emission-trading system does not displace carbon emissions. Newbery (2012) argues that all benefits from renewable electricity (referring to learning effects) are derived from the original investment, rather than the subsequent operation of the renewable generator, suggesting that subsidies should be granted based on investment, not on production. Andor and Voss (2016) also show that, if renewable electricity externalities originate from capacity, rather than production, capacity-subsidies are superior. Indeed, since renewable investors receiving a capacity-based subsidy are fully exposed to the electricity price, they aim to maximize the value of renewables within the electricity market (Rosnes, 2014; Winkler et al., 2016; Huntington et al., 2017; Newbery et al., 2017).

In this paper, we adhere to the European context (in which national RES-E production-based externalities are created by imposing quota requirements). In this setting, capacity-based subsidies are not the most efficient option. Although renewable investors under capacity-based subsidies do maximize the value of renewable production in the electricity market, they neglect the value of RES-E generation outside the electricity market (Pahle et al., 2016). More specifically, renewable investors will opt for technologies whose output correlates best with high electricity prices, regardless of their total energy yield (and their contribution towards the national quota). Capacity based subsidies thus only are optimal to correct for capacity-based externalities (in MW). On the other side of the spectrum, a feed-in tariff only considers the external value of RES-E, but neglects the value of RES-E generation inside the electricity market (as the tariff is fully decoupled from the electricity price). It has been shown that the fixed feed-in premium presents the optimal trade-off and incentivizes renewable generators to select investments which maximize the total value, i.e. the value within the electricity market plus the contribution towards achieving the quota (Höfling et al., 2015; May, 2017). Put differently, fixed feed-in premiums are optimal to correct for production-based externalities (in MWh). The performance of the sliding feed-in premium lays somewhere in between the feed-in tariff and fixed feed-in premium (see e.g. Huntington et al. (2017)).

It is worth noting that these conclusions are only valid if (at least) the following two conditions are fulfilled. First, the electricity price represents the marginal cost of production, and the marginal value of consumption. Put differently, incorrect price signals likely distort investment decisions, also under the most efficient RES-E support policy. For instance, Bjørnebye et al. (2018), Obermüller (2017) and Pechan (2017) present this inefficiency under a zonal versus nodal pricing regime. Similarly, Pahle et al. (2016) compare a fixed retail price and real time pricing, while Hitaj (2015) assesses the situation in which carbon damages are not properly internalized in the electricity price. Second, all actors have perfect information. If this would not be the case, relatively risk-free support policies (e.g. feed-in tariffs) may outperform feed-in premiums as the absence of electricity price risk may imply a lower cost of capital (Woodman and Mitchell, 2011). In this context, both Held et al. (2014) and Hiroux and Saguan (2010) argue for a trade-off between increasing market compatibility and limiting investment risk. To focus our analysis, we will assume that both conditions are fulfilled (i.e. price signals are undistorted and all actors have perfect information).

Following Held et al. (2014), Member States' support instruments appear to display a convergence towards sliding feed-in premiums for which the remuneration levels are set by a competitive procedure, i.e. an auctioning system. Compared to determining the support level by administrative procedures, auctioning systems generally allow to better control policy costs and to achieve more cost-effective support levels. In this paper, however, we solely focus on the impact of policy instruments and not on the procedure to determine support levels. As we will assume a perfectly competitive setting (including perfect information), determining the remuneration by administrative procedures would yield identical support levels as an auctioning system (given the same instrument). Furthermore, we will only consider the feed-in tariff, the fixed feed-in premium and capacity-based subsidies. As mentioned above, the fixed feed-in premium should correspond to the optimum, whilst the other two instruments represent rather extreme cases.

The contribution of this paper is threefold. First, we analyze the impact of varying national RES-E support policies on the efficiency of renewable cooperation mechanisms. As described above, the performance of these support policies within a single country is relatively well-known. Since literature on the efficiency of RES-E support schemes is somewhat fragmented, however, we will first use our numerical results to briefly compile these established conclusions. We will then compare how the benefits of cooperation change, depending on the national support schemes implemented by the different countries. In this regard, the work of del Río et al. (2017) is closest to our study. The authors quantitatively analyze the impact of different degrees of harmonization and varying support instruments on renewable generation costs, also in an European context. We add to their work by representing the electricity sector in greater detail, thereby aiming to illustrate the underlying mechanisms triggering potential efficiency losses. Second, we analyze the efficiency of two international cooperation mechanisms (statistical transfers and a joint support scheme) and compare it to the situation without renewable cooperation. In our modeling framework, the URDP and the Union renewable energy financing mechanism (i.e. the new cooperation possibilities) will yield identical outcomes as statistical transfers and a joint support scheme, respectively. We find that joint support schemes can never outperform renewable cooperation based on an optimal amount of statistical transfers. Third, instead of solely focusing on global efficiency, we will also consider the country-level distributional effects. For instance, we find that national incentives for renewable cooperation are not necessarily aligned with the global optimum, i.e. countries may be incentivized to limit their cooperation levels below the global optimum. Note that the main goal of this paper is to qualitatively reveal these effects, backed by an analytical derivation and a numerical case study. It should be mentioned that all these effects are very case-specific. As such, a case-by-case analysis is warranted to assess whether such effects will actually manifest, and to quantify the potential efficiency losses.

The remainder of this paper is structured as follows. In Section 2, we present the formulation of our two-country model. Based on the model formulation, Section 3 derives general analytical results concerning the optimal renewable cooperation level, and Section 4 presents a numerical case study. Section 5 concludes this paper.

2. Model

In what follows, we formulate a bi-level, two-country model to analyze the cross-border effects of national RES-E support schemes. The formulation is based on the work of Saguan and Meeus (2014), and extended to account for varying national support schemes and different implementations of renewable cooperation mechanisms. The cases that will be considered are presented in Table 1. We analyze three national RES-E support schemes: a feed-in tariff (FIT), fixed feed-in premium (FIP), and capacity-based subsidies (CAP). Furthermore, we consider three international cooperation cases: no renewable cooperation, statistical transfers and a joint support scheme. For the cases with statistical transfers and without renewable cooperation, national support policies need not be the same, leading to 9 policy-combinations each (e.g. the first country implements a FIT, while the second country utilizes a FIP). Under a joint support scheme, national RES-E support policies must be harmonized. Put differently, the countries employ the same support scheme with uniform support levels (e.g. a feed-in tariff of 80 EUR/MWh), resulting in 3 additional cases. Note that each model run corresponds to a cooperation scheme and a set of national support policies. The model thus does not optimize the choice of cooperation or support schemes, merely the levels thereof.

The model is formulated as a mathematical program with equilibrium constraints (MPEC) to represent the incentives of renewable investors under varying support schemes. The upper level comprises the policy makers of both countries, which are assumed to be fully collaborative (i.e. the policy makers are modeled as a single entity aiming to maximize total welfare, regardless of the distributional consequences). Both

Table 1: Overview of the cases considered in this paper (legend: x = considered scenario; \= combination not possible).

Support policy		Cooperation mechanism		
Country 1	Country 2	No cooperation	Statistical transfers	Joint support scheme
FIT	FIT	x	x	x
	FIP	x	x	\
	CAP	x	x	\
FIP	FIT	x	x	\
	FIP	x	x	x
	CAP	x	x	\
CAP	FIT	x	x	\
	FIP	x	x	\
	CAP	x	x	x

governments are subject to a renewable generation target and optimize (i) the RES-E support levels and (ii) the amount of renewable (statistical) transfers between both countries. Note that the governments anticipate the reaction of the lower level agents. The lower level comprises conventional generators, renewable investors and the market operator. All agents aim to maximize profit and are assumed to behave perfectly competitive. Furthermore, we assume that all agents have perfect information and that price-signals are correct (Section 1).

For clarity, we will denote parameters by upper case letters, while denoting variables by lower case and Greek letters. The nomenclature is presented in Appendix C.

2.1. Conventional generation

The conventional generation portfolio remains fixed, implying that conventional generators can make production decisions only. It can be shown that this assumption eases the discussion, whilst not changing the main qualitative results put forth in Sections 3 and 4. Moreover, this assumption best reflects the current situation of overcapacity within the EU power market. Technical power plant limitations such as ramping rates, minimum down times, operating ranges, etc. are neglected. Conventional generators thus bid their marginal costs and follow the merit-order curve:

$$MC_{n,s} + \lambda^c_{n,s,t} - p^e_{n,t} \geq 0 \perp y_{n,s,t} \geq 0 \qquad \forall n, s, t \qquad (1)$$

$$\bar{Y}_{n,s} - y_{n,s,t} \geq 0 \perp \lambda^c_{n,s,t} \geq 0 \qquad \forall n, s, t \qquad (2)$$

Eq. 1 ensures that, for every time step t, conventional power plant s in country n only produces when the electricity price ($p^e_{n,t}$) covers their marginal cost ($MC_{n,s}$). Eq. 2 guarantees that the power output of conventional generator s in country n ($y_{n,s,t}$) can never exceed the fixed capacity limit ($\bar{Y}_{n,s}$). Combined, Eqs. 1 - 2 ensure that the electricity price can only surpass a generator's marginal cost if that generator is producing at full capacity. During these time steps, the generator is able to accumulate inframarginal rents ($\lambda^c_{n,s,t} > 0$). Note also that the electricity price will equal the marginal cost of the marginal generator.

2.2. Renewable generation and investment

In contrast to conventional plants, renewable investment is not fixed and typically depends on the national RES-E support policies. Furthermore, we only consider uniform support levels. Within a country, every renewable generator is thus eligible for the same RES-E support. Across countries, the governments are allowed to set diverging support levels (except under a joint support scheme, see below). Finally, we assume that renewable generators have zero marginal production costs.

The following condition remains valid regardless of the national RES-E support-schemes:

$$A_{n,i,t} \cdot \bar{x}_{n,i} - x_{n,i,t} \geq 0 \perp \lambda^r_{n,i,t} \geq 0 \qquad \forall n, i, t \qquad (3)$$

It ensures that renewable generation ($x_{n,i,t}$) cannot exceed the total amount of installed capacity ($\bar{x}_{n,i}$), adjusted by an availability factor ($0 \leq A_{n,i,t} \leq 1$). As before, the renewable generator can only earn revenues $\lambda^r_{n,i,t}$ when producing at capacity. The revenue ($\lambda^r_{n,i,t}$) a renewable generator receives depends on the national promotion scheme (see below).

2.2.1. Feed-in tariff

Under a feed-in tariff, renewable generators are remunerated a fixed price (fit_n), set by the governments, per MWh electricity produced:

$$-fit_n + \delta_{n,t} + \lambda^r_{n,i,t} \geq 0 \perp x_{n,i,t} \geq 0 \qquad \forall n,i,t \tag{4}$$

$$p^e_{n,t} + \delta_{n,t} \geq 0 \perp \delta_{n,t} \geq 0 \qquad \forall n,t \tag{5}$$

Eqs. 4 - 5 link the revenues of the generator ($\lambda^r_{n,i,t}$) to the tariff level (fit_n). We included the auxiliary variable $\delta_{n,t}$ to induce a minimum amount of market-responsiveness from renewable generators. Eq. 5 imposes that $\delta_{n,t}$ is equal to zero when electricity prices are positive, and is equal to the absolute value of the electricity price when these are negative. Combined with Eqs. 3 and 4, this ensures that renewable generators are willing to curtail electricity if the price drops to $-fit_n$ ($\lambda^r_{n,i,t} = 0$). Under fixed feed-in tariffs and capacity-based subsidies, renewable generators will automatically start curtailing if the electricity price falls below a certain threshold (see below), therefore not requiring this auxiliary variable. Omitting this additional variable under a feed-in tariff would lead to infeasible solutions, especially for higher renewable quotas. The market equilibrium would then typically be violated by the unwillingness of renewable generators to curtail electricity. Multiple countries have implemented variants to this feed-in tariff scheme, e.g. Germany does not grant tariffs during at least six consecutive hours of negative electricity prices (Bundesministeriums der Justiz und für Verbraucherschutz, 2017).

The following constraint represents the investment condition:

$$C^r_{n,i} - \sum_t A_{n,i,t} \cdot \lambda^r_{n,i,t} \cdot L_t \geq 0 \perp \bar{x}_{n,i} \geq 0 \quad \forall n,i \tag{6}$$

Eq. 6 ensures that renewable generators will only invest in technology i ($\bar{x}_{n,i} > 0$) if they can recover the annualized investment costs ($C^r_{n,i}$). L_t is a parameter representing the length (or weight) of time step t. We could also impose a maximum capacity limit for each renewable technology (reflecting the scarcity of favorable locations), but omit this constraint to keep the discussion focused[2].

2.2.2. Fixed feed-in premium

Under a fixed feed-in premium, renewable generators receive a constant premium, set by the governments, on top of the electricity price:

$$-fip_n - p^e_{n,t} + \lambda^r_{n,i,t} \geq 0 \perp x_{n,i,t} \geq 0 \quad \forall n,i,t \tag{7}$$

Note that renewable generators are automatically willing to curtail electricity if the electricity price drops to $-fip_n$. The auxiliary variable required for the feed-in tariff thus is not necessary here.

We do not explicitly model tradable green certificates since the resulting equilibrium would be identical to the one obtained by employing a fixed feed-in premium (assuming a TGC system with consumers obligations). For the latter, the quota is imposed on the government, which sets the FIP to maximize welfare. For the former, the quota obligation is imposed on the lower-level agents. The agents' utility maximization behavior, along with the green certificate market clearing, will then lead to the TGC price. Since (i) we are considering a perfectly competitive setting (including perfect information), and (ii) both support-schemes grant a constant premium on top of the electricity price, the TGC price will equal the FIP and correspondingly, both equilibria will coincide.

The investment condition under a fixed feed-in premium is the same as in the feed-in tariff case (Eq. 6):

$$C^r_{n,i} - \sum_t A_{n,i,t} \cdot \lambda^r_{n,i,t} \cdot L_t \geq 0 \perp \bar{x}_{n,i} \geq 0 \quad \forall n,i \tag{8}$$

[2]Including this extension would add complexity without providing additional insights.

2.2.3. Capacity subsidies

Under capacity subsidies, renewable generators are fully exposed to the electricity price:

$$-p^e_{n,t} + \lambda^r_{n,i,t} \geq 0 \perp x_{n,i,t} \geq 0 \quad \forall n, i, t \tag{9}$$

From Eq. 9, it can be seen that renewable generators are willing to curtail electricity if the electricity price drops to zero, i.e. prices cannot become negative under a capacity-based support scheme (recall that technical constraints of conventional generators are not being considered).

Since the revenues from the electricity market typically do not cover their investment costs, the government partly offsets these initial expenses by a lump-sum capacity subsidy (σ_n). Consequently, the investment condition now yields:

$$C^r_{n,i} - \sigma_n - \sum_t A_{n,i,t} \cdot \lambda^r_{n,i,t} \cdot L_t \geq 0 \perp \bar{x}_{n,i} \geq 0 \quad \forall n, i, t \tag{10}$$

2.3. Market operator

The market operator sets, for every time step t, the electricity price ($p^e_{n,t}$) such that demand and supply are in equilibrium. Intra-country transmission constraints are assumed to be non-binding. Furthermore, we will consider an inelastic electricity demand ($D_{n,t}$).

$$\sum_i x_{n,i,t} + \sum_s y_{n,s,t} - D_{n,t} + (-1)^n \cdot f^e_t = 0 \quad \forall n, t \tag{11}$$

f^e_t represents the electricity flow between both countries and is positive (negative) if country 1 exports (imports) electricity. We assume that the market operator perfectly arbitrates between both zones, while respecting the transmission capacity $T^{e,cap}$:

$$T^{e,cap} - f^e_t \geq 0 \perp \epsilon^+_t \geq 0 \quad \forall t \tag{12}$$

$$T^{e,cap} + f^e_t \geq 0 \perp \epsilon^-_t \geq 0 \quad \forall t \tag{13}$$

$$p^e_{1,t} + \epsilon^+_t = p^e_{2,t} + \epsilon^-_t \quad \forall t \tag{14}$$

2.4. Policy makers

The policy makers fully collaborate and aim to maximize total welfare by selecting the support levels and the amount of renewable (statistical) transfers. As such, the model allows us to assess the impact of national RES-E support policies on the optimal level of renewable transfers.

For each country, we impose a minimum renewable production target expressed as a share (S_n) of total electricity consumption:

$$\sum_{i,t} x_{n,i,t} \cdot L_t - S_n \cdot \sum_t D_{n,t} \cdot L_t + (-1)^n \cdot f^r \geq 0 \quad \forall n \tag{15}$$

f^r represents the flow of renewable transfers between both countries and is positive (negative) if country 1 exports (imports) statistical transfers, thereby overachieving (underachieving) their national target. Furthermore, we impose a limit on the maximum amount of inter-country renewable trade, which allows us to model the different international cooperation schemes:

$$-T^{r,cap} \leq f^r \leq T^{r,cap} \tag{16}$$

Without international renewable cooperation, the parameter $T^{r,cap}$ is set to zero, implying that both quota's must be achieved nationally. For both statistical transfers and joint support schemes, the parameter is set to a non-binding value.

Finally, the governments aim to maximize total welfare, or to minimize total cost (electricity demand is considered inelastic). The total cost comprises conventional production costs and renewable investment costs for both countries (note that investment costs related to existing capacity are assumed sunk):

$$min \quad TC = \sum_{n,s,t} MC_{n,s} \cdot y_{n,s,t} \cdot L_t + \sum_{n,i} C^r_{n,i} \cdot \bar{x}_{n,i} \tag{17}$$

This base model is valid for both the case without renewable cooperation ($T^{r,cap} = 0$) and with cooperation based on statistical transfers ($T^{r,cap}$ set to a non-binding value). Under a joint support scheme, the national RES-E policies must be harmonized and thus, we also impose equal support levels (e.g. $fit_1 = fit_2$ for the joint feed-in tariff). Again, the flow of renewable transfers is set to a non-binding value.

2.5. Distributional effects

As mentioned before, the model results allow to assess the impact of renewable policy choice on global efficiency. Furthermore, we also assess distributional effects on the individual country level. Since demand is assumed to be inelastic, we calculate a country's total cost to fulfill their electricity demand and their renewable quota, adjusted for transfers occurring between both countries:

$$CC_n = \sum_{s,t} MC_{n,s} \cdot y_{n,s,t} \cdot L_t + \sum_{i} C^r_{n,i} \cdot \bar{x}_{n,i} - ER^e_n - CR^e_n - ER^r_n - CR^r_n \tag{18}$$

The first two terms represent the conventional production cost and renewable investment cost in country n. ER^e_n represents the total export revenues in the electricity market:

$$ER^e_n = -(-1)^n \sum_t L_t \cdot p^e_{n,t} \cdot f^e_t \tag{19}$$

Conventionally, we assume that congestion revenues (CR^e_n) in the electricity market are shared equally among both countries:

$$CR^e_n = \frac{T^{e,cap}}{2} \sum_t L_t \cdot |p^e_{1,t} - p^e_{2,t}| \tag{20}$$

To determine the monetary transfers associated with renewable trade, we must determine a price (p^r_n) on which this trade is based. Analogous to electricity trade[3], we assume that p^r_n equals the marginal support cost (MSC), i.e. the additional cost, for country n, to produce one additional unit of renewable electricity over the time horizon. A similar pricing scheme has been brought forward in a case study on statistical transfers between Estonia and Luxembourg (Ten Donkelaar et al., 2014). A country's marginal support cost expression can be derived analytically and depends on the national support scheme (see Appendix A for the derivation):

$$p^{r,fit}_n = fit_n - \sum_{i,t} L_t \cdot p^e_{n,t} \cdot \frac{\partial x_{n,i,t}}{\partial f^r} \tag{21}$$

$$p^{r,fip}_n = fip_n \tag{22}$$

$$p^{r,cap}_n = \sigma \cdot \sum_i \frac{\partial \bar{x}_{n,i}}{\partial f^r} \tag{23}$$

$\frac{\partial x_{i,t}}{\partial f^r}$ and $\frac{\partial \bar{x}_i}{\partial f^r}$ are defined as the change in renewable production and capacity of generator i respectively, if the renewable quota constraint of the country is increased by 1 MWh (i.e. $\sum_{i,t} L_t \cdot \frac{\partial x_{n,i,t}}{\partial f^r} = 1$). Consider for

[3]The electricity price represents the marginal production cost.

instance the marginal support cost under a feed-in tariff scheme. Imposing one additional unit of renewable electricity generation will increase the country's total cost by the feed-in-tariff level (the additional renewable investment cost, see Appendix A) minus the avoided conventional production costs (or avoided electricity import expenses). As will be shown, the marginal support cost is a core concept which drives renewable electricity trade. We will occasionally hint towards the analogy with the electricity market in which marginal electricity production costs (i.e. electricity prices) drive physical electricity trade.

Unfortunately, the partial derivatives in Eqs. 21 - 23 are not readily available from the model output. As a solution, we rerun the model twice, once per country. In the rerun, the renewable quota constraint of the country in consideration is increased by 1 MWh. Furthermore, we only allow the renewable technologies located in the considered country to vary (with respect to the original model solution). Conventional production is allowed to vary in both countries. Comparing production quantities and installed capacities from the original model with the rerun then allows approximating the partial derivatives. This approach proved to be sufficiently accurate[4]. Note that the marginal support costs thus are endogenously determined variables.

Returning to the country-level components in Eq. 18, export revenues (ER_n^r) and congestion revenues[5] (CR_n^r) in the renewable electricity market can be defined as before. Congestion revenues again are assumed to be split equally among both countries:

$$ER_n^r = -(-1)^n \cdot p_n^r \cdot f^r \tag{24}$$

$$CR_n^r = \frac{f^r}{2} \cdot (p_2^r - p_1^r) \tag{25}$$

To better illustrate the analogy with the electricity market, consider the following three cases. In the first case, there is no renewable energy trade ($f^r = 0$) and consequently, both components equal zero ($ER_n^r = CR_n^r = 0$). This would correspond to a lack of transmission capacity between both countries in the electricity market ($ER_n^e = CR_n^e = 0$). In the second case, renewable trade is unconstrained, undistorted and as such, prices will converge ($p_1^r = p_2^r$). Consequently, there only are export revenues (and import expenses), but no congestion revenues ($ER_n^r \neq 0$, $CR_n^r = 0$). This would correspond to uncongested trade in the electricity market ($ER_n^e \neq 0$, $CR_n^e = 0$). In the third case, an intermediate situation emerges. Renewable trade occurs, but not sufficiently to harmonize the marginal support costs in both countries. As such, both components are nonzero ($ER_n^r \neq 0$, $CR_n^r \neq 0$). This situation would correspond to congested trade in the electricity market ($ER_n^e \neq 0$, $CR_n^e \neq 0$). The occurrence of this final case in the renewable energy market can have multiple rationales. Although this requires looking ahead towards the main conclusions of this paper, an exemplification is warranted here (both rationales will become clear in Section 3). Under statistical transfers, policy makers might be incentivized to constrain the amount of trade in order to maximize their country-level welfare (Section 4.4). Under a joint support scheme, sub-optimal national policies (i.e. not the fixed feed-in premium) can distort renewable energy trade as well (Section 4.3). As such, all three cases are relevant in this paper. The first for the no-cooperation case, the second for analyzing the optimal amount of statistical transfers, and the third for analyzing the effects of sub-optimal joint support schemes[6].

2.6. The set of assumptions

Some of the key assumptions were already highlighted throughout the introduction. For transparency reasons, we summarize these briefly. The results presented in the following Sections of course should only be considered valid under this assumption set.

All market participants have perfect and complete information. There are no information asymmetries among different agents (e.g. the policy maker is fully aware of the renewable energy technologies' cost and

[4]In Section 3, we derive a condition for the optimal level of statistical transfers. The marginal support costs calculated ex-post by employing this method always fulfilled the optimality condition.

[5]Note that the modulus sign in Eq. 25 is dropped. This is necessary because, as we will show below, joint support schemes might induce renewable energy to be traded in the wrong direction (the country with the highest MSC exports renewable energy). In this case, renewable congestion rents are negative.

[6]The last situation also is applicable to Figure 6 since the amount of statistical transfers than can be traded is constrained.

yield). Financial markets are complete and undistorted (i.e. no risk aversion related market failures). All agents behave perfectly competitive. As in the European context, we assume RES production-based quotas, or more generally, RES production-based externalities. Renewable electricity trade is based on the marginal support cost and follows typical electricity market conventions (i.e. sharing congestion rents equally). We assume that electricity price signals are correct (i.a. internalizing carbon damages) and that intra-country transmission constrains are non-binding. Conventional capacity remains fixed and is unconstrained by technical limitations. The policy makers of both countries are fully cooperative and aim to maximize global welfare, regardless of the distributional consequences. Finally, we focus on the renewable electricity sector, omitting the fact that other renewable energy sources contribute towards achieving the quota as well. Even within this idealized setting, we will reveal distortive effects of national RES-E policies on cooperation mechanisms. Many of these assumptions provide relevant paths for future research as these may imply additional distorting effects under renewable cooperation.

3. Analytical results

Before moving on to the case study, we first derive some general analytical results concerning the optimal renewable cooperation level. Appendix B presents a derivation of the total marginal renewable cooperation benefit, i.e. the global welfare gain (or cost savings) if one additional statistical transfer would be traded between the countries. Without loss of generality, we declare country 1 to be the exporter of renewable transfers (implying that $p^r_2 \geq p^r_1$). The global marginal renewable cooperation benefit can then be written as[7]:

$$\sum_n \frac{\partial W_n}{\partial f^r} = -\frac{\partial TC_n}{\partial f^r} = p^r_2 - p^r_1 \tag{26}$$

The total cost saving thus equals the difference between marginal renewable support costs. The expression is valid for every national support scheme set considered in this paper (Eqs. 21 - 23). Clearly, this imposes an optimality condition: marginal renewable support costs should be equal in both countries, regardless of the national support-schemes. A direct implication of Eq. 26 is that total welfare can only increase when employing statistical transfers. Thus although sub-optimal national promotion instruments may be distorting renewable investment decisions, cooperation via statistical transfers will always be globally beneficial. Note, however, that the optimality of joint support schemes is not guaranteed, e.g. for a joined feed-in tariff:

$$\frac{\partial TC_n}{\partial f^r} = fit_1 - fit_2 - \sum_{i,t} L_t \cdot p^e_{1,t} \cdot \frac{\partial x_{1,i,t}}{\partial f^r} + \sum_{i,t} L_t \cdot p^e_{2,t} \cdot \frac{\partial x_{2,i,t}}{\partial f^r} \tag{27}$$

The amount of statistical transfers traded will be set such that the feed-in tariff levels in both countries are harmonized. From Eq. 27, this does not imply that marginal support costs are equal. A country with higher electricity prices (or with renewable technologies producing proportionally more during spike-prices) should install more renewable capacity, ceteris paribus. Only a joint fixed feed-in premium (Eq. 22) will fulfill the optimality condition for renewable transfers. Joint support schemes will thus yield a higher total cost when compared to cooperation based on the optimal amount of statistical transfers. The exception is the joint fixed feed-in premium, for which the equilibrium will coincide with the one obtained by employing statistical transfers.

In Appendix B, an individual country's marginal cooperation benefit is derived as well. Following the conventions defined above (i.a. country 1 exports statistical transfers):

$$\frac{\partial CC_1}{\partial f^r} = \frac{1}{2} \cdot (p^r_1 - p^r_2) - \sum_t \frac{f^e_t}{2} \cdot L_t \cdot (\frac{\partial p^e_{1,t}}{\partial f^r} + \frac{\partial p^e_{2,t}}{\partial f^r}) - \frac{f^r}{2} \cdot (\frac{\partial p^r_1}{\partial f^r} + \frac{\partial p^r_2}{\partial f^r}) \tag{28}$$

$$\frac{\partial CC_2}{\partial f^r} = \frac{1}{2} \cdot (p^r_1 - p^r_2) + \sum_t \frac{f^e_t}{2} \cdot L_t \cdot (\frac{\partial p^e_{1,t}}{\partial f^r} + \frac{\partial p^e_{2,t}}{\partial f^r}) + \frac{f^r}{2} \cdot (\frac{\partial p^r_1}{\partial f^r} + \frac{\partial p^r_2}{\partial f^r}) \tag{29}$$

[7]Note the analogy with electricity trade.

The first term in Eqs. 28 - 29 represents the global cost reductions due to increased renewable trade, which, due to our assumptions, are shared equally among both countries. Country 1 (2) must increase (decrease) renewable production by 1 MWh, thereby increasing (decreasing) their cost by p_1^r (p_2^r), i.e. the definition of the marginal support cost. In return, country 1 (2) receives (pays) the average marginal support cost $\frac{1}{2}(p_1^r + p_2^r)$[8]. The sum of both effects yield the first term in Eqs. 28 - 29.

Interestingly, the second and third term in Eqs. 28 - 29 represent transfers between both countries. The second term results from changes in terms of trade in the electricity market. Altering renewable cooperation likely impacts the electricity prices, and e.g. increasing average electricity prices benefit the electricity-exporting country at the expense of the importing country. The interpretation of the third term is analogous for the renewable energy market. Our analysis provides a generalization of the results obtained by Unteutsch (2014): she has reached a similar conclusion under a system of tradable green certificates.

The major implication is that national incentives for renewable cooperation are not necessarily aligned with the global optimum (compare Eq. 26 with Eqs. 28 - 29). A country indeed might benefit from restricting renewable cooperation (e.g. to keep the average marginal support cost high, or to influence electricity prices). Likewise, it is not necessarily true that countries are better off when participating in renewable cooperation. Whether this actually is the case or not cannot be assessed analytically as it depends on the relative magnitudes of the terms in Eqs. 28 - 29. The country-level distributional effects of renewable cooperation will be further discussed in Section 4.4.

Of course, whenever there are gains of cooperation between two countries, there is a way to share these gains such that both countries are better off. Before engaging in cooperation, countries may have a bargaining phase where they agree on additional transfers compensating for potential country-level welfare losses. The exact allocation of the gain will depend on the bargaining position of both countries. In this paper, however, we adhere to typical competitive electricity market rules and conventions (e.g. sharing congestion rents equally) to allocate the cooperation gains. As a consequence, it likely is overly optimistic to assume fully collaborative governments. Nevertheless, the remainder of this paper will focus on the effects of different policy schemes under this assumption. An analysis under non-cooperative governments is an interesting path for future research.

4. Numerical simulation

We analyze the effect of three national RES-E support instruments (feed-in tariff, feed-in premium and capacity-based subsidies) on statistical transfers, joint support schemes, and the case without renewable cooperation (see Table 1). In total, there thus are 21 cases which allow to (i) assess the impact of national support schemes on cooperation mechanisms, (ii) compare the design of cooperation mechanisms (e.g. statistical transfers versus joint support schemes), and (iii) investigate country-level distributional effects.

In what follows, we first introduce the data employed in the case study (Section 4.1). The three main model outcomes are presented subsequently. Section 4.2 serves as an introductory discussion and presents the optimal outcome with and without renewable cooperation. Section 4.3 analyzes the impact of national policies and cooperation mechanism designs on global efficiency. Finally, the country-level distributional effects of cooperation are presented in Section 4.4.

In the remainder of this Section, we denote the set of national policy instruments by S1/S2, in which S1 and S2 refer to the instrument implemented in country 1 and country 2, respectively. For instance, CAP/FIP implies that country 1 employs capacity-based subsidies whilst country 2 implements a fixed feed-in premium.

4.1. Data

For the numerical example, we employ a temporal coverage of one year. Demand is equal in both countries and modeled by the following load duration curve: $d_h = 22,000 - 1.37H$ (H being the number of hours between 0 and 8760). The same duration curve was used by Joskow (2008) and Saguan and Meeus

[8] $ER_n^r + CR_n^r = -(-1)^n \cdot p_n^r \cdot f^r + \frac{f^r}{2} \cdot (p_2^r - p_1^r) = -(-1)^n \cdot \frac{f^r}{2} \cdot (p_1^r + p_2^r)$

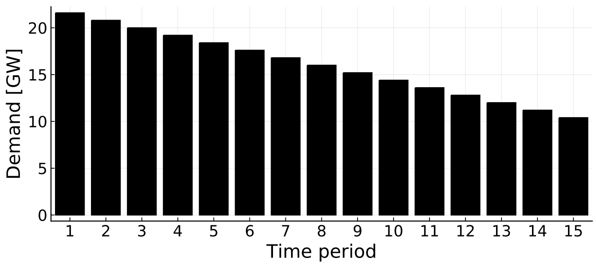


Figure 1: Load duration curve used for both countries.

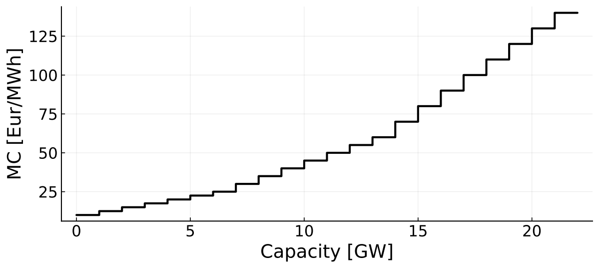
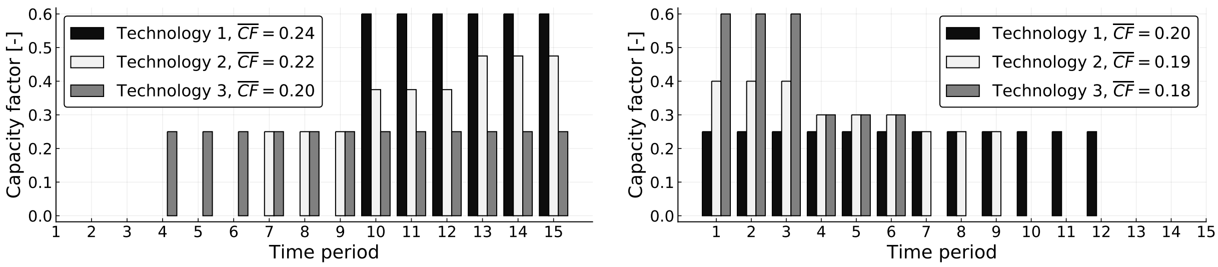


Figure 2: Conventional portfolio used for both countries.



(a) Country 1

(b) Country 2

Figure 3: Capacity factors of the three different technologies for both countries.

(2014). In this paper, the curve is approximated by 15 periods of equal length (i.e. 584 hours per period) as shown in Figure 1. As mentioned before, the conventional portfolio is fixed. Both countries have an identical set of conventional power plants for which the merit-order curve is illustrated in Figure 2. The typical convex shape of a merit-order curve is approximated by three linear segments, and discretized such that each power plant has a maximum capacity of 1,000 MW. Transmission capacity between both countries is fixed at 4,000 MW. We model three renewable technologies per country, all having the same annualized investment cost of 125,000 EUR/MWy. The capacity factors of the technologies for both countries are shown in Figure 3. Generally, the average capacity factors of the technologies within country 1 are higher, but the generation profiles of the technologies in country 2 correlate better with demand. In addition, within each country, the average capacity factor decreases when moving from technology 1 to technology 3 (as shown in Figure 3). The technologies with lower capacity factors generate proportionally more during periods of higher demand. Finally, both countries are subject to a renewable share of 35% based on total electricity demand. The model was linearized using big-M constraints, implemented in the Julia/Jump language and solved by the Gurobi-solver to optimality (MIP gap equals 0).

This situation is highly hypothetical, and basically designed to reveal the inefficiencies of sub-optimal national instruments, along with their impact on cooperation mechanisms. As such, the magnitude of the efficiency losses presented in the following Sections is inconsequential, but the fact that these efficiency losses can actually occur is not. The advantage of this specific case study is that it allows to qualitatively present all notable effects at once. Although all results thus are very case specific (see Section 1), a generalization will be provided in Section 5. The analytical results derived in Section 3 (i.e. statistical transfers are always beneficial; a joint support scheme can never outperform statistical transfers, given the same national support instruments, etc.) of course are generally valid.

4.2. The optimal outcome: fixed feed-in premiums

As stated by i.a. Pahle et al. (2016), a fixed feed-in premium yields the optimal outcome when considering a single country in autarky, given production-based quotas. A feed-in tariff does minimize the renewable generation cost (i.e. renewable investors select technologies that minimize the cost per unit of renewable production (EUR/MWh)), yet, since the remuneration is fully decoupled from electricity prices,

Table 2: Model cost outcomes for the FIP/FIP case under varying cooperation mechanisms. Cost savings relative to the case without renewable cooperation are presented between brackets.

	No cooperation	Statistical transfers	Joint support scheme
Total cost [M EUR/y]	11,726	11,604 (1.04%)	11,604 (1.04%)
Cost country 1 [M EUR/y]	6,249	6,139 (1.76%)	6,139 (1.76%)
Cost country 2 [M EUR/y]	5,477	5,465 (0.22%)	5,465 (0.22%)
MSC country 1 [EUR/MWh]	34.07	28.30	28.30
MSC country 2 [EUR/MWh]	21.86	28.30	28.30

a feed-in tariff neglects the value of renewable generation inside the electricity market. Correspondingly, renewable investors are not incentivized to adjust their investment decisions to system needs, implying larger conventional production costs. In our case study, this creates a bias towards technology 1 in both countries. On the other side of the spectrum, renewable generators receiving capacity-based subsidies are fully exposed to the electricity price (not distorted by a production-based subsidy) and will aim to maximize the value of renewable generation in the electricity market (thereby minimizing conventional production costs). This, however, creates a bias in favor of technologies whose output correlates best with electricity demand, regardless of their total energy yield (and their contribution towards the national quota), implying higher renewable investment costs. Put differently, capacity-based subsidies neglect the value of renewable generation outside the electricity market. In our case study, this generally creates a bias towards technology 3 in both countries. The fixed feed-in premium provides the optimal trade-off and minimizes the sum of renewable and conventional generation costs, i.e. the total system cost.

This framework can be extended to a two-country setting. Based on the work of Aune et al. (2012), one can indeed conclude that the FIP/FIP combination will yield the most optimal outcome, for any given cooperation mechanism[9]. In fact, the FIP/FIP equilibrium aligns with the one that would be obtained if policy makers had full control over investment decisions (i.e. the centralized optimum), regardless of the cooperation mechanism.

In Section 3, we showed that cooperation via an unconstrained amount of statistical transfers will always be beneficial as this leads to a convergence of the marginal support costs. The model outcomes verify this result and are presented in Table 2. The total system cost comprises conventional production costs and renewable investment costs in both countries (Eq. 17), whilst the country-level costs also consider the transfers between both countries (Eq. 18). Without renewable cooperation, the marginal support cost in country 2 is lower than that of country 1 and thus, despite the higher average capacity factors in country 1, the renewable capacity within country 2 is less costly because of the higher correlation between renewable generation and demand. This also is reflected in the lower cost for country 2 (note that both countries only differ in the capacity factors of their renewable technologies, Figure 3). A better optimum can only be achieved by engaging in renewable cooperation. The optimum entails a yearly flow of 17.92 TWh (corresponding to a share of 13% based on a country's total electricity demand) statistical transfers from country 2 to country 1. The marginal support costs of both countries converge, accompanied by a global cost decrease of 122 M EUR/y. Note, however, the unequal allocation of this gain: country 1 decreases it's cost by 110 M EUR/y, whilst country 2 only appropriates 12 M EUR/y. The explanation for these country-level distributional effects was already provided in Section 3, and will be further discussed in Section 4.4.

Finally, note that the equilibrium under the optimal amount of statistical transfers, and the one obtained by a joint fixed feed-in premium yield identical cost outcomes. As stated before (Section 3), the

[9] The authors do not directly present this result, mostly since they employ a single-period model (thereby, implicitly assuming that the electricity price remains constant over the year). In such a setting, the feed-in premium and the feed-in tariff (but not necessarily capacity-based instruments) yield identical outcomes. Nevertheless, our statement can be verified by extending their analytical model to include multiple time steps. We do not provide the proof in this work, but refer to the numerical results presented in Section 4.3 (and note that the optimality of the FIP/FIP combination is generally true under production-based quotas).

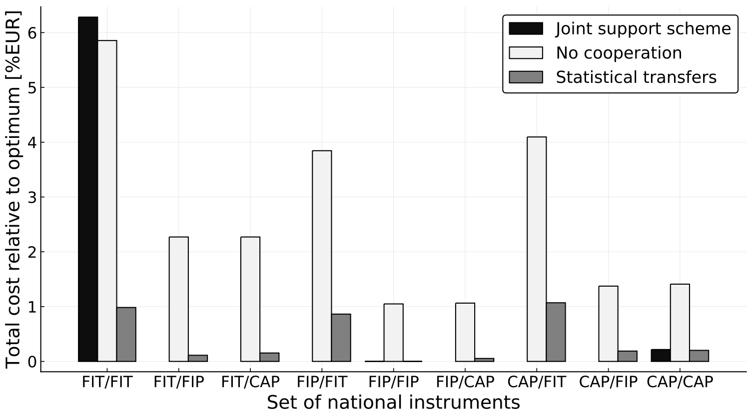


Figure 4: Impact of national support instruments and cooperation mechanism design on total system cost (percentages are cost increases relative to the optimum).

Table 3: Installed renewable capacities (in GW) for selected national policy instrument combinations. For each national policy combination, all relevant cooperation mechanisms are presented (None = no renewable cooperation, Stat = statistical transfers, Joint = joint support scheme).

GW		FIP/FIP			FIT/FIT			FIP/FIT		CAP/FIP	
Country	Technology	None	Stat	Joint	None	Stat	Joint	None	Stat	None	Stat
1	1	11.3	11.5	11.5	23.3	8.0	24.0	5.3	5.3	4.7	7.0
1	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	3	14.4	4.0	4.0	0.0	0.0	0.0	21.6	4.8	22.4	8.8
2	1	0.0	13.3	13.3	28.0	46.4	27.2	28.0	44.8	0.6	17.6
2	2	29.5	26.3	26.3	0.0	0.0	0.0	0.0	0.0	25.7	22.3
2	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	0.0

optimal amount of renewable cooperation requires a convergence of marginal support costs. Additionally, the marginal support cost under a fixed feed-in premium simply equals the premium level (Eq. 22). It thus does not matter which cooperation mechanism is chosen when employing the optimal promotion instrument. Indeed, setting the amount of statistical transfers to harmonize feed-in premium levels, or creating a joint feed-in premium (and forcing identical premium levels), yields the same equilibrium.

4.3. The impact on global efficiency

Figure 4 presents the total system cost of the considered cases, relative to the optimum. As stated in Section 4.2, both a joint fixed feed-in premium, and the FIP/FIP case with an optimal amount of statistical transfers correspond to this optimum. Furthermore, the figure presents three noteworthy findings.

First, consider the case without renewable cooperation. Figure 4 shows the optimality of the FIP/FIP case, along with the distortions of sub-optimal national instrument choice. The behavior of renewable investors under sub-optimal national instruments already was explained in Section 4.2. Furthermore, Table 3 exemplifies these distortions by presenting the installed renewable capacity for selected sets of national instruments. An interesting nuance is that, because of cross-border electricity trade, investment decisions in the separate countries will affect each other. Support policies including the electricity price will enforce some complementary in renewable investment decisions, i.e. investors are indirectly incentivized to select technologies whose generation profiles are less correlated with each other (even in separate countries). An example can be found in Table 3 (e.g. compare the installed capacity in country 1 under the FIP/FIP and FIP/FIT autarky cases).

Second, Figure 4 illustrates that employing statistical transfers will always be beneficial from a global perspective, independent on the set of national support instruments. As proven in Section 3, statistical

Table 4: The optimal amount of statistical transfers (in TWh per year) under different national policy combinations.

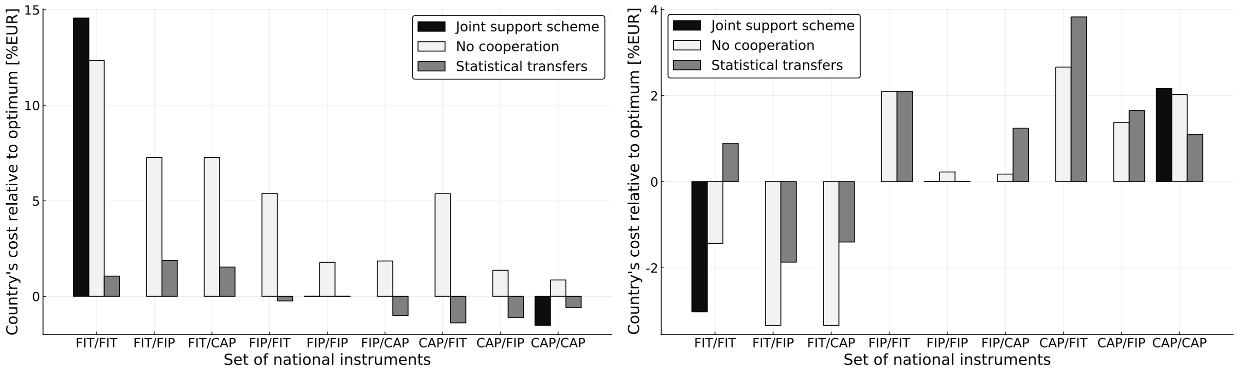
Country 1 / Country 2	FIT	FIP	CAP
FIT	32.24	20.32	19.62
FIP	29.43	17.92	19.10
CAP	26.63	18.92	19.62

Table 5: Model outcomes for the FIT/FIT case under varying cooperation mechanisms. Cost savings relative to the case without renewable cooperation are presented between brackets.

	No cooperation	Statistical transfers	Joint support scheme
Total cost [M EUR/y]	12,284	11,718 (4.61%)	12,333 (-0.40%)
Tariff level country 1 [EUR/MWh]	59.46	59.46	71.35
Tariff level country 2 [EUR/MWh]	71.35	71.35	71.35
MSC 1 [EUR/MWh]	44.87	29.89	59.26
MSC 2 [EUR/MWh]	10.10	29.89	9.26
Renewable transfers [TWh/y]	0	-32.24	1.40

transfers allow mitigating cross-border renewable investment inefficiencies by harmonizing the marginal support costs. In addition, as national policy choice has an impact on the marginal support cost, the optimal amount of statistical transfers varies accordingly. In our simulations, the yearly amount of statistical transfers always flow from country 2 towards country 1, but differ in magnitude (as shown in Table 4). From this numerical example, no general rule can be deduced. Yet, this likely is an artifact from the small-scale and highly aggregated set-up. We expect that, for realistic cases, sub-optimal national instruments imply larger marginal support costs (compared to the FIP). Correspondingly, the country with the more efficient support scheme will export more (or import less) statistical transfers when compared to the FIP/FIP case. In other words, renewable capacity will, for the optimal amount of statistical transfers, be biased towards the country with the more efficient support policy, ceteris paribus. Note, however, that this effect will probably only change the magnitude of the optimal amount of statistical transfers, and not the direction as renewable potential considerations are an important driver as well.

Third, Figure 4 also presents the global cost effects of joint support schemes. Despite the optimality of joint fixed feed-in premiums, a joint feed-in tariff or a joint capacity-based subsidy yield sub-optimal outcomes with a higher global cost than cooperation based on statistical transfers, given the same national policy combinations (see Section 3). The total cost deficiency of a joint capacity-based subsidy is, in this numerical example, relatively small compared to the CAP/CAP combination employing the optimal amount of statistical transfers (2.2 M EUR/y in absolute terms). For a joint FIT, the effects are more pronounced, and the joint support scheme even performs worse than no renewable cooperation at al. Table 5 zooms in on the FIT/FIT cases to illustrate the rationale behind this poor performance. Without renewable cooperation, country 2 needs to set a higher feed-in tariff, a direct consequence of the lower average capacity factor for renewable technologies in country 2 (i.e. a higher investment cost per unit of renewable generation). The marginal support cost, however, is lower in country 2. The marginal support cost is the additional renewable investment cost (= FIT which is higher in country 2) minus saved conventional generation costs (Eq. 21). As in country 2, higher cost conventional power plants are displaced, this second effect outweighs the first, resulting in lower MSC in country 2 compared to country 1. Thus from a system perspective, renewable capacity in country 2 is less costly because of the higher correlation between their generation profile and demand. With statistical transfers, the total cost can thus be reduced by shifting renewable capacity towards country 2 (Table 3), thereby harmonizing the marginal support costs in both countries. A joint feed-in tariff does, in this case, the exact opposite and biases renewable capacity towards country 1 because (i) FITs do not consider the value within the electricity market, and (ii) country 1 has a higher average capacity factor. Put differently, renewable transfers flow in the wrong direction. For any joint tariff level, renewable investors



(a) Country 1 (b) Country 2

Figure 5: Impact of national support instruments and cooperation mechanism design on an individual country's cost.

will indeed invest in technology 1 within country 1 as the average capacity factor is highest (and since all technologies have identical investment costs). Actually, the only reason that capacity also is being build in country 2 (Table 3) is because generators do not earn any revenues if renewables are being curtailed (see Eq. 5). Indeed, installing one additional MW of any technology in country 1 would entail curtailment in the final period (see Figures 1 and 3), thereby effectively decreasing the capacity factors of all technologies within that country. The next best investment then becomes the first technology of country 2.

In summary, joint support schemes based on sub-optimal instruments will always be outperformed by renewable cooperation via statistical transfers. This arises because, under a joint support scheme, policy makers are no longer able to set diverging support levels, as it is the marginal support cost—and not the support level—that should be harmonized.

4.4. Country-level distributional effects

Both countries' total costs (calculated by Eq. 18) are shown in Figure 5 for all considered cases. As before, these are presented relative to the countries' cost under the global optimum (i.e. the FIP/FIP instrument combination with unrestricted renewable cooperation). Although these effects proved case-specific, and thus influenced by our small-scale set-up, we infer two general results.

First, a country's national policy choice influences the welfare of interconnected countries, also without renewable cooperation. In Section 4.3, we already illustrated the interaction between both countries' renewable investment decisions via the electricity price. Figure 5 presents the consequences on the country-level costs. For instance, the total cost of country 2 (Figure 5b) clearly is impacted by the national instrument implemented in country 1, being lower (higher) when country 1 implements the FIT (CAP). Conversely, the total cost of country 1 will always be lowest when implementing a capacity-based subsidy, at least for the cases without renewable cooperation. Indeed, regardless of the national policy implemented in country 2, country 1 can minimize their total cost by implementing a capacity based mechanism (see Figure 5a). Put differently, countries may have incentives to implement sub-optimal instruments, thereby extracting rents from neighboring countries at the cost of global welfare. Of course, this remains a highly stylized numerical example and whether this occurs (or even is possible) in reality can be questioned.

The second result concerns the impact of cooperation mechanisms on a country's individual cost. Figure 5a shows that the impact of cooperation mechanisms on country 1's cost mostly aligns with the impact on the global cost (Figure 4), i.e. statistical transfers are always beneficial. The results are different for country 2 (see Figure 5b). Indeed, for most sets of national support instruments, country 2 is better off without renewable cooperation (compared to the globally optimal amount of statistical transfers). The explanation can be found in Section 3, in which we argued that although global renewable cooperation benefits are shared equally among both countries, the occurrence of additional transfers between the countries may differentiate the total country-level effects. For most cases in our example, country 2 vastly exports electricity. Additionally, renewable cooperation here decreases the average electricity price, impairing the

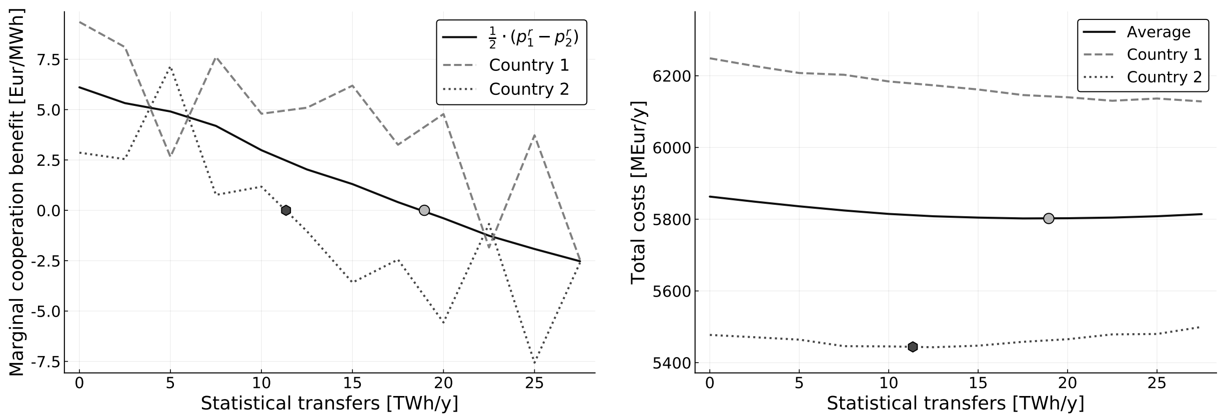


Figure 6: Impact of the amount of statistical transfers traded on the marginal cooperation benefit (left) and total costs (right) for the FIP/FIP case.

net exporter. The second term of Eqs. 28 and 29 thus is relatively large, and this transfer benefits country 1 at the expense of country 2.

Note, however, that this conclusion should be qualified due to the limitations in our modeling framework. We only model extreme renewable cooperation mechanisms (the optimal amount of statistical transfers, no cooperation at all, and joint support schemes) and thus, it only is possible to compare a country's cost for these extreme cases. In reality, the amount of statistical transfers may vary from 0 TWh/y (no renewable cooperation) up to the optimal amount. Knowing this, it remains possible that there is an optimal amount of cooperation, for each country, which maximizes their individual welfare. Thus although Figure 5b suggests that country 2 loses when engaging in cooperation mechanisms for most national policy combinations, there may exist a certain amount of statistical transfers (in between the extreme cases) for which the country becomes better off relative to the case without renewable cooperation. Figure 6 illustrates this for the FIP/FIP case, in which we imposed a fixed amount of statistical transfers flowing from country 2 towards country 1 (in steps of 2.5 TWh/y). The left panel illustrates the marginal cooperation benefit for both countries (calculated as the negative of Eqs. 28 and 29) along with half of the global cooperation benefit, i.e. the part that each country appropriates (Eq. 26). The right panel presents the corresponding impact on total (average) cost, and on a country's individual cost. One can see that the global cooperation benefit is positive up to about 18 TWh/y statistical transfers (17,92 TWh/y to be exact, see Section 4.2) and correspondingly, the total cost reaches a minimum for this amount. This is the optimal amount of statistical transfers required to harmonize the marginal support costs of both countries. The left panel of Figure 6 also presents each country's individual marginal cooperation benefit, and thus the impact of the transfer-terms in Eqs. 28 and 29. For a small amount of statistical transfers, both countries have a positive marginal benefit because of the relatively large global marginal benefit. Yet, the marginal cooperation benefit for country 2 becomes negative as of roughly 12 TWh/y statistical transfers (thereby reaching a minimum for that country's cost). A country can thus be incentivized to limit the amount of statistical transfers traded below the global optimum[10].

5. Conclusion and policy implications

As stated in prior studies, an EU-wide green certificate market, or a common fixed feed-in premium, yields the globally most efficient outcome (see e.g. Aune et al. (2012)). Our study contributes to the literature by comparing the efficiency of different renewable cooperation mechanisms (statistical transfers

[10]Note again the analogy with electricity trade and transmission investment (e.g. Buijs and Belmans (2012) and Saguan and Meeus (2014)).

and joint support schemes) and by assessing the impact of national support instruments on these cooperation mechanisms.

Regardless of the renewable cooperation mechanisms (no cooperation, statistical transfers and joint support schemes), the fixed feed-in premium remains the globally most efficient policy instrument to promote renewable electricity. Feed-in tariffs imply excessive conventional generation costs as the renewable investors do not consider their value within the electricity market. Capacity-based subsidies lead to excessive renewable investment costs as investors do not consider their value outside the electricity market. We again stress the sensitivity of these conclusions towards the policy maker's goals. The fixed feed-in premium will only be optimal if renewable production-based externalities are assumed (as currently is the case in the European context, due to production-based quotas). If, as suggested by several authors (see Section 1), renewables must be promoted to correct for capacity-based externalities, subsidies should be granted based on capacity. This asks for careful consideration from EU governance as to what types of externalities must actually be corrected. Indeed, imposing production-based quotas will bias national instrument choice towards production-based subsidies (e.g. the FIP). Consequently, establishing production-based quotas to correct for capacity- or investment-based externalities clearly is sub-optimal.

Secondly, we find that employing statistical transfers will always outperform the no-renewable cooperation case, independent of the choice of national support instruments. These national support instruments do have an impact on the optimal amount of statistical transfers, as renewable capacity will, for the optimal amount of statistical transfers, likely be biased towards countries with the more efficient support policy, ceteris paribus. Additionally, we find that statistical transfers are preferred over joint support schemes. The exception is a joint feed-in premium, which would yield the socially most optimal outcome (under production-based quotas). Enforcing equal support policy levels does not guarantee the harmonization of marginal support costs, which, as we have shown, is an optimality condition. In fact, it is not excluded that a sub-optimal joint support scheme performs worse than no renewable cooperation at all. National policy makers should thus only consider joint support schemes based on the most efficient instrument. If not, it is better to keep national support schemes decoupled, whilst employing a correction via statistical transfers. This conclusion also directly impact the design of one of the EU's new cooperation possibilities: the European renewable energy financing mechanism. To maximize efficiency, EU-wide auctions should be designed based on a premium on top of the electricity price and not on, for instance, a contract for difference system (which basically resembles a feed-in tariff).

Finally, we also considered country-level distribution effects. We have shown that it is possible that a country can be worse-off after engaging in renewable cooperation mechanisms. We also illustrated that country-level incentives for renewable cooperation may not align with the global optimum, and that countries may be incentivized to constrain their cooperation levels. When Member States are planning to engage in renewable cooperation, they should not only consider the gains in the renewable energy market, but also the impact on the electricity market. Since this latter effect is the major driver of redistributive effects, any quantification of renewable cooperation gains should be taking this complication into account. Moreover, the country-level distribution effects will act as an additional barrier for renewable cooperation, which especially is true for the most recent cooperation possibilities (the URDP and the Union renewable energy financing mechanism). Indeed, the Commission will be in charge of implementing these new mechanisms, making it difficult for Member States to estimate their benefits and costs of engaging in such a system a priori. As our modeling framework does not allow to further investigate these concerns, we suggest an analysis assuming no-cooperative national policy makers as an interesting path for future work. Additionally, we assumed that the price of statistical transfers is based on the marginal support cost. Future work might explore more innovative schemes which would better align a country's individual benefit with the global gains.

We mentioned that the stylized example merely serves to illustrate what type of effects might occur. Whether or not these findings will actually transpire can only be assessed by a more comprehensive modeling framework and a case study based on actual historical data, again warranting further research. If would i.a. be interesting to reveal which conditions actually trigger cross-border distributive effects of renewable cooperation. Finally, we again note that our work is based on several strong assumptions, summarized in Section 2.6. Investigating the impact of any of these assumptions on our results also provide relevant paths for future research as these may imply additional distorting effects under renewable cooperation.

Appendix A. Derivation: marginal support cost

In this section, the marginal support cost will be derived for the feed-in-tariff. The marginal support cost derivation for the two other support policies is analogous. As a simplification, we only consider one single country in autarky (the extension to two countries is presented in Appendix B). The total cost to fulfill electricity demand and the renewable quota then can be written as:

$$TC = \sum_{s,t} MC_s \cdot y_{s,t} \cdot L_t + \sum_i C_i^r \cdot \bar{x}_i \tag{A.1}$$

Denoting $\frac{\partial x}{\partial f^r}$ as the effect on x when increasing the renewable quota requirement by 1 MWh, yields:

$$\frac{\partial TC}{\partial f^r} = \sum_{s,t} MC_s \cdot \frac{\partial y_{s,t}}{\partial f^r} \cdot L_t + \sum_i C_i^r \cdot \frac{\partial \bar{x}_i}{\partial f^r} \tag{A.2}$$

From the conventional generation decisions (Eqs. 1 - 2), it can be seen that only the marginal generators are able to change production during a specific time-step, i.e. $\frac{\partial y_{s,t}}{\partial f^r} < 0$ only if $0 < y_{s,t} \leq \bar{Y}_s$. Therefore, the first term in Eq. A.2 can be rewritten as:

$$\sum_{s,t} MC_s \cdot \frac{\partial y_{s,t}}{\partial f^r} \cdot L_t = \sum_{s,t} p_t^e \cdot \frac{\partial y_{s,t}}{\partial f^r} \cdot L_t \tag{A.3}$$

Since demand is inelastic, and the market clearing must be fulfilled at every time-step, the following condition can be derived from Eq. 11:

$$\sum_s \frac{\partial y_{s,t}}{\partial f^r} + \sum_i \frac{\partial x_{i,t}}{\partial f^r} = 0 \quad \forall t \tag{A.4}$$

Consequently, the first term in Eq. A.2 represents the avoided conventional production costs and can be rewritten as:

$$\sum_{s,t} MC_s \cdot \frac{\partial y_{s,t}}{\partial f^r} \cdot L_t = -\sum_{i,t} p_t^e \cdot \frac{\partial x_{i,t}}{\partial f^r} \cdot L_t \tag{A.5}$$

From the renewable investment decision (Eq. 6), it can be seen that investment in renewable generation can only alter for those technologies actually being installed, i.e. $\frac{\partial \bar{x}_i}{\partial f^r} \neq 0$ only if $\bar{x}_i > 0$. Consequently, the second term in Eq. A.2 can be written as:

$$\sum_i C_i^r \cdot \frac{\partial \bar{x}_i}{\partial f^r} = \sum_{i,t} A_{i,t} \cdot \lambda_{i,t}^r \cdot L_t \cdot \frac{\partial \bar{x}_i}{\partial f^r} \tag{A.6}$$

Inserting Eq. 3 yields:

$$\sum_i C_i^r \cdot \frac{\partial \bar{x}_i}{\partial f^r} = \sum_{i,t} \lambda_{i,t}^r \cdot L_t \cdot \frac{\partial x_{i,t}}{\partial f^r} \tag{A.7}$$

For the feed-in-tariff, we know that $\lambda_{i,t}^r = fit - \delta_t$ (Eq. 4). Furthermore, we know that renewable electricity is curtailed if $\delta_t > 0$, and thus (from the electricity market clearing): $\delta_t \cdot \frac{\partial x_{i,t}}{\partial f^r} = 0$. The second term in Eq. A.2 thus represents the increase in renewable investment costs to generate one additional unit of renewable electricity and can be rewritten as:

$$\sum_i C_i^r \cdot \frac{\partial \bar{x}_i}{\partial f^r} = \sum_{i,t} fit \cdot L_t \cdot \frac{\partial x_{i,t}}{\partial f^r} = fit \tag{A.8}$$

The latter expression follows from the fact that $\sum_{i,t} L_t \cdot \frac{\partial x_{i,t}}{\partial f^r} = 1$.

The marginal support cost thus simplifies to:

$$\frac{\partial TC}{\partial f^r} = \sum_{s,t} MC_s \cdot \frac{\partial y_{s,t}}{\partial f^r} \cdot L_t + \sum_i C_i^r \cdot \frac{\partial \bar{x}_i}{\partial f^r}$$
$$= fit - \sum_{i,t} p_t^e \cdot \frac{\partial x_{i,t}}{\partial f^r} \cdot L_t \tag{A.9}$$

A similar derivation yields the marginal support costs for the two other support policies (Eqs. 22 - 23).

Appendix B. Derivation: a country's marginal renewable cooperation benefit

In this section, a country's marginal benefit of renewable cooperation will be derived. More specifically, we consider the effect on a country's total cost (adjusted for occurring transfers, see Eq. 18), when one additional unit of renewable electricity is traded between both countries ($\frac{\partial f^r}{\partial f^r} = 1$). We assume that the renewable production target (Eq. 15) is binding and, without loss of generality, we declare country 1 to be the exporter of renewable transfers. This implies that $\sum_{i,t} L_t \frac{\partial x_{n,i,t}}{\partial f^r} = -(-1)^n$, i.e. country 1 (2) increases (decreases) renewable generation by 1 MWh over the entire time horizon. In this section, the impact on country 1's cost is derived under a feed-in tariff support scheme (recall that this country exports electricity and renewable certificates if $f_t^e > 0$ and $f^r > 0$, respectively). Again, we note that the marginal cooperation benefit derivation for the two other national support schemes (and for the renewable-transfer importing country) is analogous.

Following Eq. 18:

$$\frac{\partial CC_1}{\partial f^r} = \sum_{s,t} MC_{1,s} \cdot \frac{\partial y_{1,s,t}}{\partial f^r} \cdot L_t + \sum_i C_{1,i}^r \cdot \frac{\partial \bar{x}_{1,i}}{\partial f^r} - \frac{\partial ER_1^e}{\partial f^r} - \frac{\partial CR_1^e}{\partial f^r} - \frac{\partial ER_1^r}{\partial f^r} - \frac{\partial CR_1^r}{\partial f^r} \tag{B.1}$$

and from Eqs. 19 - 25:

$$\frac{\partial ER_1^e}{\partial f^r} = \sum_t L_t \cdot (f_t^e \cdot \frac{\partial p_{1,t}^e}{\partial f^r} + p_{1,t}^e \cdot \frac{\partial f_t^e}{\partial f^r}) \tag{B.2}$$

$$\frac{\partial CR_1^e}{\partial f^r} = T^{e,cap} \sum_t \frac{L_t}{2} (|\frac{\partial p_{1,t}^e}{\partial f^r} - \frac{\partial p_{2,t}^e}{\partial f^r}|) \tag{B.3}$$

$$\frac{\partial ER_1^r}{\partial f^r} = p_1^r + f^r \cdot \frac{\partial p_1^r}{\partial f^r} \tag{B.4}$$

$$\frac{\partial CR_1^r}{\partial f^r} = \frac{1}{2}\big((p_1^r - p_2^r) + f^r \cdot (\frac{\partial p_2^r}{\partial f^r} - \frac{\partial p_1^r}{\partial f^r})\big) \tag{B.5}$$

The electricity market clearing (Eq. 11) implies:

$$\sum_i \frac{\partial x_{1,i,t}}{\partial f^r} + \sum_s \frac{\partial y_{1,s,t}}{\partial f^r} - \frac{\partial f_t^e}{\partial f^r} = 0 \tag{B.6}$$

Furthermore, from Appendix A, we know that:

$$\sum_i C_{1,i}^r \cdot \frac{\partial \bar{x}_{1,i}}{\partial f^r} = fit_1 \tag{B.7}$$

$$\sum_{s,t} MC_{1,s} \cdot \frac{\partial y_{1,s,t}}{\partial f^r} \cdot L_t = \sum_{s,t} p_{1,t}^e \cdot \frac{\partial y_{1,s,t}}{\partial f^r} \cdot L_t \tag{B.8}$$

Using Eqs. B.6 - B.8, we can simplify part of Expression B.1:

$$\sum_{s,t} MC_{1,s} \cdot \frac{\partial y_{1,s,t}}{\partial f^r} \cdot L_t + \sum_i C^r_{1,i} \cdot \frac{\partial \bar{x}_{1,i}}{\partial f^r} - \sum_t L_t \cdot p^e_{1,t} \cdot \frac{\partial f^e_t}{\partial f^r}$$
$$= fit_1 - \sum_{i,t} p^e_{1,t} \cdot \frac{\partial x_{1,i,t}}{\partial f^r} \cdot L_t = p^r_1 \tag{B.9}$$

The last expression results from the marginal support cost definition (and from the assumption that renewable trade is based on marginal support costs).

Furthermore, it can be shown that the following expressions always hold:

$$-\sum_t L_t \cdot f^e_t \cdot \frac{\partial p^e_{1,t}}{\partial f^r} - \sum_t L_t \cdot \frac{T^{e,cap}}{2} \left| \frac{\partial p^e_{1,t}}{\partial f^r} - \frac{\partial p^e_{2,t}}{\partial f^r} \right| = -\sum_t \frac{f^e_t}{2} \cdot L_t \cdot \left(\frac{\partial p^e_{1,t}}{\partial f^r} + \frac{\partial p^e_{2,t}}{\partial f^r}\right) \tag{B.10}$$

$$-f^r \cdot \left(\frac{\partial p^r_1}{\partial f^r} + \frac{1}{2} \cdot \left(\frac{\partial p^r_2}{\partial f^r} - \frac{\partial p^r_1}{\partial f^r}\right)\right) = -\frac{f^r}{2} \cdot \left(\frac{\partial p^r_1}{\partial f^r} + \frac{\partial p^r_2}{\partial f^r}\right) \tag{B.11}$$

Using Eqs. B.9 - B.11, we can finally rewrite Expression B.1 as:

$$\frac{\partial CC_1}{\partial f^r} = \frac{1}{2} \cdot (p^r_1 - p^r_2) - \sum_t \frac{f^e_t}{2} \cdot L_t \cdot \left(\frac{\partial p^e_{1,t}}{\partial f^r} + \frac{\partial p^e_{2,t}}{\partial f^r}\right) - \frac{f^r}{2} \cdot \left(\frac{\partial p^r_1}{\partial f^r} + \frac{\partial p^r_2}{\partial f^r}\right) \tag{B.12}$$

A similar derivation for country 2 (which imports statistical transfers) yields:

$$\frac{\partial CC_2}{\partial f^r} = \frac{1}{2} \cdot (p^r_1 - p^r_2) + \sum_t \frac{f^e_t}{2} \cdot L_t \cdot \left(\frac{\partial p^e_{1,t}}{\partial f^r} + \frac{\partial p^e_{2,t}}{\partial f^r}\right) + \frac{f^r}{2} \cdot \left(\frac{\partial p^r_1}{\partial f^r} + \frac{\partial p^r_2}{\partial f^r}\right) \tag{B.13}$$

The impact on the global welfare (cost) then reads:

$$\frac{\partial TC}{\partial f^r} = \sum_n \frac{\partial CC_n}{\partial f^r} = p^r_1 - p^r_2 \tag{B.14}$$

Although, we derived this expression based on a feed-in tariff, Eqs. B.12 - B.13 are generally valid, i.e. the marginal support cost (p^r_n) can be substituted by any of the Expressions 21 - 23, depending on the set of national support policies.

Appendix C. Nomenclature

Nomenclature

Sets

$i \in \mathcal{I}$ Types of renewable technologies

$n \in \mathcal{N}$ Countries

$s \in \mathcal{S}$ Types of conventional technologies

$t \in \mathcal{T}$ Periods

Parameters

$\bar{Y}_{n,s}$	Capacity of conventional unit s in country n	MW
$A_{n,i,t}$	Availability factor of renewable technology i during period t in country n	MW/MW
$C^r_{n,i}$	Annual capacity investment cost for renewable technology i in country n	EUR/MWy
$D_{n,t}$	Demand in country n at period t	MW
L_t	Duration (weight) of period t	h/y
$MC_{n,s}$	Marginal cost of conventional unit s in country n	EUR/MWh
S_n	Renewable production share imposed on country n	$-$
$T^{e,cap}$	Inter-country transmission capacity	MW
$T^{r,cap}$	Inter-country renewable trade limit	MWh
Variables		
$\bar{x}_{n,i}$	Installed renewable capacity of technology i in country n	MW
$\delta_{n,t}$	Auxiliary variable for waiving FIT-subsidy revenues if curtailment is necessary	EUR/MWh
ϵ^+_t	Dual variable related to the positive transmission flow constraint	EUR/MWh
ϵ^-_t	Dual variable related to the negative transmission flow constraint	EUR/MWh
$\lambda^c_{n,s,t}$	Inframarginal rents of conventional unit s during period t in country n	EUR/MWh
$\lambda^r_{n,i,t}$	Revenues of renewable technology i during period t in country n	EUR/MWh
σ_n	Capacity subsidy level in country n (only applicable under a CAP)	EUR/MW
f^e_t	Inter-country power flow during period t	MW
f^r	Renewable (statistical) transfers between both countries	MWh/y
fip_n	Feed-in premium level in country n (only applicable under a FIP)	EUR/MWh
fit_n	Feed-in tariff level in country n (only applicable under a FIT)	EUR/MWh
$p^e_{n,t}$	Electricity price in country n during period t	EUR/MWh
$x_{n,i,t}$	Power generation of renewable technology i during period t in country n	MW
$y_{n,s,t}$	Power generation of conventional unit s during period t in country n	MW
Output variables		
CC_n	Total cost of country n, adjusted for occurring transfers	EUR/y
CR^e_n	Congestion revenues in the electricity market for country n	EUR/y
CR^r_n	Congestion revenues in the renewable energy market for country n	EUR/y
ER^e_n	Export revenues in the electricity market for country n	EUR/y
ER^r_n	Export revenues in the renewable energy market for country n	EUR/y
p^r_n	Marginal renewable electricity support cost	EUR/MWh
TC	Total cost (sum of both countries) to fullfill electricity demand and renewable quotas	EUR/y
W_n	Welfare of country n	EUR/y

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