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Coordinating cross-border electricity interconnection investments and trade in market coupled regions

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ABSTRACT

Investments in cross-border electricity interconnections are key for the integration of the European energy market. To analyze policy frameworks for these decisions, we model two settings for the expansion of transmission capacity between two regions, where the volume of investment is agreed upon through either Nash-Coase or Nash bargaining. For each setting we provide fair share cost allocation solutions, respectively with and without compensations. Each region has its own TSO, maximizing social welfare within its geography, and the markets are modeled with linear supply and demand curves, with trade enabled by the interconnection. The results of the application of the models to the Iberian market suggest their ability to estimate realistic values for the capacity of cross-border interconnection between two regions.

1. Introduction

1.1. Background

The European Union (EU) sees the integration of its national electricity transmission networks into a single European energy market as a key enabler of competition and in general of the long-term improvement of social welfare in the Eurozone. Taking a resolute step in this direction was already the objective in 2002, when the Barcelona European Council set a target for the installed interconnection capacity in 2005 of 10% of the existing production capacity, even across borders where congestion was not a concern at the time [1].

It has been argued in several fora that this policy target has failed to be met. Until recently, most European countries still featured low interconnection capacities, regardless of the capacity of their internal electricity transmission networks: the cross-border transmission bottlenecks that existed in 1996 were still present in 2007; up to 2004, only 4% of the electricity transmission investment was being directed to interconnections; and an interconnection priority project presented by the European Commission largely underestimated the required investments [2]. In the EU, the most important bottlenecks have been four regions whose interconnection capacity with mainland Europe is clearly insufficient: the Baltic States, the Iberian Peninsula, Italy, and Great Britain and Ireland. These “electric peninsulas” have a high renewable generation development potential, which will be constrained in the long-term if interconnection capacity is not increased up to 10 times, in the case of the Iberian Peninsula’s connection to mainland Europe, or at least doubled, in the other regions [3].

The interdependencies between national energy markets and Transmission System Operators (TSOs) in the EU have increased significantly in recent years, for the most part due to the significant development of renewable energy sources and the ongoing efforts to liberalize the EU electricity market. Cross-border power flow growth can only be appropriately supported if an adequate electricity interconnection structure is in place [4].

The management of cross-border flows can be implemented through the auctioning of transmission rights, although Joskow and Tirole [6] have shown that this mechanism results in a higher market power for generation in the importer. The EU started by using non-market-based methods to manage cross-border congestion, such as access limitation, priority listing, and pro-rata rationing. Currently, prices are set implicitly through market coupling. Market-based methods have the advantage of providing reliable economic signs of the need for interconnection expansions [5].

Market coupling allows interconnection flows to be managed in a joint regional Power Exchange (PX) that dispatches power based on demand and available interconnection capacity. In the EU, seven PXs have joined efforts to launch the Price Coupling of Regions (PCR)

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initiative, with the objective of devising a single price coupling solution to define electricity prices and manage cross-border capacity in Europe. The most important step in this direction was the launch of the North-Western Europe Day Ahead (NWE DA) initiative, a day ahead market coupling implementation that went live in February 2014, accounting for more than 75% of the total electricity consumption in Europe. This initiative was supported by the European Network of Transmission System Operators for Electricity (ENTSO-E) and coordinates the TSOs and PXs of Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Great Britain, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland and Sweden. A few months later, in May 2014, an additional step was given, with the extension of the initiative to Portugal and Spain, enabled by the interconnection between France and Spain.

The reinforcement of interconnection infrastructures requires neighboring TSOs to reach an agreement and commit to a single interconnection investment solution capable of delivering benefits to all parties involved. This single solution can be reached either through a centrally regulated and coordinated process, voluntary local agreements, or a combination of both [7].

As the EU power system evolves into a truly trans-European infrastructure, and especially considering the recently implemented price coupling initiatives, cross-border interconnection management is becoming increasingly important, and thus warranting increased attention from both researchers and practitioners.

1.2. Interconnection expansion in market coupled regions

In this paper we introduce the Interconnection Transmission Expansion Problem for Market Coupled Regions (I-TEP-MCR), which can be regarded as a particular case of the more general Transmission Network Expansion Problem. It considers the decision to invest in a single electricity transmission corridor to establish or reinforce cross-border electricity transfer between two regions that are part of a single coupled market. Each region has its own TSO, which we assume to seek only social welfare maximization within its own geography, and to be unable to place any additional artificial constraints on transmission capacity.

Cooperative game theory provides an adequate framework to analyse I-TEP-MCR, as the modelling of bilateral negotiations allows balancing conflicting design objectives, i.e., the optimal interconnection capacity, between the two regions [35], and allows regions to improve their individual conditions [34], as measured herein through variations in net social welfare.

Optimal interconnection investment policies for settings with and without compensations, i.e., where the volume of investment is agreed upon through either Nash-Coase or Nash bargaining, respectively, are illustrated with a study of cross-border investment between Portugal and Spain, using detailed data on the buy and sell bids in the Iberian market throughout the year of 2013. The region and time frame were chosen due to the full availability of raw data for the bids.

1.3. Structure

The remainder of the paper is structured as follows: in the following section, we review prior relevant contributions to the literature; in Section 3, we present I-TEP-MCR, and describe a case application focusing on the Iberian market; optimal interconnection investment policies are illustrated for the case application in Section 4; Section 5 closes the paper, with conclusions, policy implications, and suggestions for future work.

2. Literature review

In restructured energy markets, the supply and transmission businesses have been unbundled to foster increased competition among electricity producers, that stand on equal footing to access the transmission network. Historically, however, the number of operating electricity companies has mostly remained low [14,15], and insufficient unbundling has been suggested as one of the key reasons for the difficulties in increasing interconnection capacity in the EU [16]. A low level of interconnection capacity limits electricity trade and contributes to price differentials across regions, burdening social welfare with congestion costs.

An additional important benefit of international power flows is the ability to improve the matching between uncertain generation and uncertain demand, allowing a reduction of the total level of resources required to guarantee an appropriate operation of energy markets [17]. The desired increment in competition remains challenged and so does the possibility of accessing cheaper sources, as well as larger shares of renewable sources [18].

It has also been argued that TSOs do not act independently of the political sphere [2], with national goals interfering with the investments towards an interconnected EU. With interconnections and trade, *ceteris paribus*, the prices in at least one of the connected countries must rise, even if social welfare rises in all countries, i.e., the consumer surplus may decrease even if the consumer and producer surplus increases in total [19]. In the exporting regions, generation increases, prices increase, and both consumer surplus and demand decrease. The opposite happens in the importing regions, where consumer surplus increases due to a decrease in electricity prices, but producer surplus decreases. This pattern of variations is a source of disagreement that may lead to politics interfering with the investment decision process. Parisio and Bosco [20] identify these variations as volume effects, and in addition point out an important bid-level effect related to the impact of a higher trade on generator dispatch strategies. In the exporting regions, generators with higher marginal dispatch costs will bid higher quantities and those with lower marginal costs will bid lower quantities, the opposite happening in the importing regions. Whereas by the former mechanism price differentials will always decrease, the bid-level effect can in fact lead to variations in any direction.

Apart from the complexity of permission procedures, reaching an agreement between the TSOs is arguably the other major difficulty that is faced in this context [21]. In general, TSOs will have different preferences regarding the desired level of interconnection capacity, but a single volume of investment and allocation of transmission investment costs will have to be agreed upon, satisfying all regions. This decision can be made centrally by a supraregional planner, independently by each regional planner, or cooperatively between the regional planners.

Buijs et al. [22] propose two models for this problem, based on the first and second approaches outlined above. One is a Mathematical Program with Equilibrium Constraints, in which all the planners accept the decisions that maximize the total social welfare, as if a supraregional planner existed, and the transmission planner acts as a Stackelberg leader, preceding the market dispatching decisions. In the other model, the planners act individually, with responsibility only for the parts of the interconnection lines that are located in their own territories, seeking to maximize the social welfare of their own regions but taking into account the decisions of the other planners. The problem is formulated as an Equilibrium Problem with Equilibrium Constraints, with a non-cooperative Nash equilibrium solution. In equilibrium, the capacity of each interconnection is the minimum among the levels desired by each region that it connects, as this would become the bottleneck. Circumstances in which all the planners might benefit from a different split of the investments costs, e.g., with one region covering part of the costs of another, are not considered, possibly leading to solutions with lower levels of investment.

Without a regulatory framework capable of leading the planners to consider the total social welfare, if such solution does not provide economic benefits to all planners it is extremely unlikely that it will be accepted by those unfavored. Motivated by this concern, Buijs and Belmans [23] suggest another approach that considers only the solutions to the supranational model for which the social welfare of each region is not reduced, even if the consumer surplus, producer surplus, and congestion rents mix changes. In this case the benefits may accrue to only a subset of regions, which suggests the need to devise a welfare transfer mechanism.

Saguan and Meeus [24] analyze the impact of the regulatory framework on the optimality of the investments in transmission and the costs of renewable energy, comparing no trade and perfect trade settings, as well as national and supranational transmission investment plans. Their model features a single market two-region network, with a three-stage decision process in which the transmission capacity investment decisions precede the generation investment decisions, which in turn precede the market supply and demand decisions. The study concludes that the benefits from trade outweigh investment costs.

Hobbs et al. [25] study the effect of market coupling on market power, using the model proposed by Jing-Yuan and Smeers [26], including individual electricity producers that maximize profit from the sale of power and consider the existence of other producers, an arbitrager that buys and sells power at the different nodes, and a TSO that guarantees the power flows. The prices are obtained using a Cournot-Nash approach. The model is applied to the Belgian and Dutch markets and considers power flows from Germany and France. The analysis shows that even though market power is still present when the two countries are market coupled, undesired effects are significantly reduced. The impact of an increase in interconnection capacity on market power is studied, with an application to the EU20, by Lise et al. [27], who conclude that market power is mitigated and price differences tend to decrease as trade increases, even though prices may increase slightly for some countries.

Bargaining models have had prior application in transmission planning. Haurie and Zaccour [28] present and discuss a model for power exchange between interconnected power utilities, seeking to minimize the costs of investment in exchange capacity, investment in generation capacity, and generation. Bai et al. [29] study a model for open access electricity transmission, in which the utilities establish quantity and price contracts for transmission. Zhou et al. [30] apply Nash bargaining to the negotiation between a renewable generation company and a transmission company that share the net benefits of the investment in a new transmission line. Bargaining has also recently been used for the valuation of right-of-way costs between transmission line investors and land owners [31–33] and to determine right-of-way costs in order to compute an optimal portfolio value for investors under centralized transmission expansion planning [34]. A review of cooperative and non-cooperative game theory models with relevance for transmission expansion planning is included in Ref. [32]. Mei et al. [35] provide a broader introduction to game theory applied to power systems.

The approach presented in this paper extends prior research by focusing on the sizing of electricity interconnections in market coupled regions, while considering social welfare as an objective and allowing investment costs to be shared based on the benefits accrued to each region (the principle of allocating investment costs according to the benefits that the infrastructure provides is already considered by the European Parliament and the Council [36]).

3. Material and methods

3.1. Proposed approach

To the best of our knowledge, our I-TEP-MCR model is the first to consider (1) cooperative decision-making in cross-border electricity interconnection investments and (2) a fair share allocation of investment costs. A fair transfer of resources between two players is herein understood as one in which the percentage increase in the utility of one of the players is larger than the percentage decrease in the utility of the other. A fair share allocation is a point of equilibrium for which no additional fair transfers are possible. This point of equilibrium is the Nash bargaining solution [52].

Our model values the option to trade electricity between two regions to improve social welfare, by analysing a two-stage, two-player, two-market cooperative game. In stage one, the two regions decide jointly on the interconnection capacity investment volume, and in stage two supply and demand curve uncertainties in both regions are resolved, and both have the option to trade when deciding on their supply and demand levels, enabled and constrained by their earlier investment decision.

We adapt a single decision maker model (applicable to a reference scenario with a centralized supraregional decision maker) to a bargaining setting where two regions cooperate in the interconnection investment and accept an ex-ante fair share cost allocation. We use Karush–Kuhn–Tucker optimality conditions and relationships between the problem constraints to obtain methods to solve two variants of the model, which result from allowing or not financial compensations.

In the first variant, side payments are accepted, allowing, e.g., one player to fully cover the investment costs or even provide financial compensations to the other player to enable larger investments. As this case allows for investment externalities to be fully incorporated [8], it configures a Nash-Coase bargaining setting [37]. We propose for this setting a model with an electricity auction in the two market coupled regions, represented with linear supply and demand curves, and trade enabled and restricted by the volume of interconnection capacity agreed upon by the two regions. In line with tradition, the model considers maximization of the net social welfare variation as the objective function. Variability in the market conditions is accounted for by considering distinct operating conditions, weighted by the respective proportion within a full year of operation.

In the second variant, side payments are restricted to investment costs, and financial compensations are not allowed. Without the full incorporation of externalities, this variant configures a Nash bargaining setting [9]. We choose Nash bargaining because it is a well-known classic solution for cooperative games, and is also the particular case of the Shapley value applied to a two-player game [51]. More particular contexts of analysis might suggest different assumptions and solutions, e.g., in the form of Kalai-Smorodinsky bargaining [10], which requires monotonicity instead of the independence of irrelevant alternatives required by Nash bargaining.

We study how the social welfare variations and optimal investment evolve with the cost of interconnection capacity (a proxy for economic, regulatory, physical, technical, and other costs and difficulties), in a setting in which each region features a predominant role as either importer or exporter. The social welfare variation due to the investment in transmission capacity is chosen as the relevant metric for decision-making as it represents the overall benefit accrued to society. The model also allows us to examine the role of the bargaining power of each region in interconnection decisions and social welfare improvement, interpreting the ex-ante expected fraction of total surplus as a measure of bargaining power [11,12].

To increase tractability, our model is simplified and deliberately focused on the economics of the problem. Nevertheless, it still features enough detail, e.g., through the inclusion of operating conditions, to be able to accommodate a rich set of empirical data and yield analysis results with higher relevance to practice. We do not model explicitly the electricity transmission networks, which may be regarded as absence of losses and absence of internal congestion in the networks. We also do not consider wheeling, which may be interpreted as the existence of restrictions, e.g., geographic, that make it impossible for a secondary region to be used for power transfer. Finally, we do not consider a distinction between consumer surplus and producer surplus, with the decisions focusing solely on the total increase in social welfare.

Markets are modeled considering perfect competition. Even though perfect competition is a strong assumption, market coupling settings allow market power to be significantly mitigated [25,38]. This is further reinforced when expansions in the interconnections are possible [27]. Küpper et al. [39] also note that even if the interconnections are not congested, they will still represent a competitive threat. We would expect the introduction of imperfect competition, à la Cournot, to have a marginal impact on interconnection investments.

Similarly to the majority of the literature on game-theoretic capacity expansion models, the timing of the decisions of the players is relevant [40]. In our model we consider a stationary setting, with a single decision agreed by the two players, and a single year divided into distinct operating conditions for the forecasts of supply and demand.

Emphasizing the novelty of our approach, while aware of its assumptions and simplifications, we consider it to be a useful first iteration on top of which further developments may contribute realism and increase practical applicability.

3.2. Centralized interconnection planning

Trade between two regions is desired as long as there is a price differential between them. We consider the linear inverse demand function (1) and the linear inverse supply function (2) for two regions, and the corresponding demand function and supply function, for operating condition $s \in \mathscr{S}$,

$$P_{s,i} = \alpha_{s,i} - \beta_{s,i} D_{s,i} \tag{1}$$

$$P_{s,i} = -\gamma_{s,i} + \delta_{s,i} G_{s,i}. \tag{2}$$

The constant $\alpha_{s,i}$ and the constant $\gamma_{s,i}$ are the intercepts, and the positive constant $\beta_{s,i}$ and the positive constant $\delta_{s,i}$ are the slopes, of the demand and supply curves for region $i \in \{M, X\}$ in operating condition s, with M and X denoting the importing region and the exporting region, respectively.

We can write the variation in social welfare (Appendix A) based on the flows f_s from the exporting to the importing region as

$$\Delta \text{sw}_{s,X} = \left(\frac{b_{s,M}}{a_{s,M}} - \frac{b_{s,X}}{a_{s,X}}\right) f_s - \frac{1}{2}\left(\frac{2}{a_{s,M}} + \frac{1}{a_{s,X}}\right) f_s^2, \quad \forall\, s \in \mathscr{S} \tag{3}$$

$$\Delta \text{sw}_{s,M} = \frac{1}{2a_{s,M}} f_s^2, \quad \forall\, s \in \mathscr{S}, \tag{4}$$

where

$$a_{s,i} = \left(\frac{1}{\beta_{s,i}} + \frac{1}{\delta_{s,i}}\right) \tag{5}$$

$$b_{s,i} = \left(\frac{\alpha_{s,i}}{\beta_{s,i}} - \frac{\gamma_{s,i}}{\delta_{s,i}}\right), \tag{6}$$

and

$$f_s = \min\{f_s^{\text{FT}}, K\}, \tag{7}$$

with

$$f_s^{\text{FT}} = \frac{a_{s,X} b_{s,M} - a_{s,M} b_{s,X}}{a_{s,X} + a_{s,M}}. \tag{8}$$

The optimal value for the interconnection capacity K^*, from the perspective of a supraregional transmission planner, can be obtained from the following mathematical model:

$$\max \quad \textstyle\sum_{s \in \mathscr{S}} h_s (\Delta \text{sw}_{s,X} + \Delta \text{sw}_{s,M}) - I \tag{9}$$

$$\text{s. t.} \quad I = c(K) \tag{10}$$

$$f_s = \min\{f_s^{\text{FT}}, K\}, \quad \forall\, s \in \mathscr{S} \tag{11}$$

$$\Delta \text{sw}_{s,X} = \left(\frac{b_{s,M}}{a_{s,M}} - \frac{b_{s,X}}{a_{s,X}}\right) f_s - \frac{1}{2}\left(\frac{2}{a_{s,M}} + \frac{1}{a_{s,X}}\right) f_s^2, \quad \forall\, s \in \mathscr{S} \tag{12}$$

$$\Delta \text{sw}_{s,M} = \frac{1}{2a_{s,M}} f_s^2, \quad \forall\, s \in \mathscr{S}. \tag{13}$$

The supraregional transmission planner maximizes, with Eq. (9), a weighted sum of the increments in the total social welfare subtracted by the annualized interconnection investment cost I, considering a weight h_s for operating conditions $s \in \mathscr{S}$. Weights h_s represent the number of hours for a particular operating condition s in a year. Investment costs are described in Eq. (10) by an arbitrary cost function $c(K)$ of the interconnection capacity K. It should be noted that based on the current model the only variable controlled by the transmission planner is the amount of transmission capacity K to be built. All other variables can be obtained from K.

Market dispatch is resolved with Eq. (11) considering free-trade flows f_s^{FT}, capped by the available transmission capacity K. Variations in social welfare due to electricity trade result from the previously obtained Eqs. (12) and (13). In this particular formulation, we assume that a region either always imports or always exports, but the model can be generalized by having (12) and (13) change in preprocessing depending on the roles of the regions based on free-trade quantity values f_s^{FT}. We adopt this formulation for the sake of simplicity, and in line with the fact that the roles of the two regions do not change in the case that we consider later in the paper.

Convexity is proven in Appendix B, allowing us to conclude that the solution is the unique and global optimum.

3.3. Decentralized interconnection planning with compensations

Using Nash-Coase bargaining to adapt the previous model to a game where two regions agree on the level of investment in interconnection capacity, we introduce the requirement that the variation in social welfare for each of the two regions compensates its part of the investment, defined for each region as I_X and I_M:

$$\max \quad \left(\sum_{s \in \mathscr{S}} h_s \Delta \text{sw}_{s,X} - I_X\right)\left(\sum_{s \in \mathscr{S}} h_s \Delta \text{sw}_{s,M} - I_M\right) \tag{14}$$

$$\text{s. t.} \quad I_X + I_M = c(K), \quad :\lambda_I \tag{15}$$

$$f_s = \min\{f_s^{\text{FT}}, K\}, \quad \forall\, s \in \mathscr{S} \tag{16}$$

$$\Delta \text{sw}_{s,X} = \left(\frac{b_{s,M}}{a_{s,M}} - \frac{b_{s,X}}{a_{s,X}}\right) f_s - \frac{1}{2}\left(\frac{2}{a_{s,M}} + \frac{1}{a_{s,X}}\right) f_s^2, \quad \forall\, s \in \mathscr{S} \tag{17}$$

$$\Delta \text{sw}_{s,M} = \frac{1}{2a_{s,M}} f_s^2, \quad \forall\, s \in \mathscr{S} \tag{18}$$

$$I_X \leqslant \sum_{s \in \mathscr{S}} h_s \Delta \text{sw}_{s,X}, \quad :\mu_X \tag{19}$$

$$I_M \leqslant \sum_{s \in \mathscr{S}} h_s \Delta \text{sw}_{s,M}, \quad :\mu_M. \tag{20}$$

To model the bargaining decision, we adapt the objective function, Eq. (14), to split the individual benefits for each of the two regions, which are then multiplied [9]. The investment costs are also separated (15) and constraints (19) and (20) model the requirements for benefits in each region.

We should note that Eqs. (11) and (16) make both the centralized and decentralized problems bilevel [53]. They can be reformulated as Mathematical Problems with Equilibrium Constraints by substituting each constraint by those presented in Appendix C.

We define Lagrange multipliers λ_I, μ_X and μ_M, and develop the following Karush–Kuhn–Tucker optimality conditions to establish a relationship between the benefits for each region:

$$\frac{\partial \mathscr{L}}{\partial I_X} = \textstyle\sum_{s \in \mathscr{S}} h_s \Delta \text{sw}_{s,M} - I_M - \lambda_I + \mu_X = 0 \tag{21}$$

$$\frac{\partial \mathscr{L}}{\partial I_M} = \sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,X} - I_X - \lambda_I + \mu_M = 0 \tag{22}$$

$$\mu_X\left(\sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,X} - I_X\right) = 0 \tag{23}$$

$$\mu_M\left(\sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,M} - I_M\right) = 0. \tag{24}$$

Using the above conditions we write the equality

$$\frac{\partial \mathscr{L}}{\partial I_X} = \frac{\partial \mathscr{L}}{\partial I_M} \Leftrightarrow \sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,M} - I_M + \mu_X = \sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,X} - I_X + \mu_M, \tag{25}$$

and by considering Appendix D we show that $\mu_X = \mu_M$, allowing the simplification

$$\sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,M} - I_M = \sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,X} - I_X. \tag{26}$$

In Appendix E we show that the solutions to the centralized and Nash-Coase decentralized problems are the same. The optimal solution is such that the net changes in social welfare, i.e., the social welfare variations subtracted by investment costs, are equal for both players. It follows that solving the original model is sufficient to obtain the global optimal solution for any unrestricted bargaining situation when we consider Eq. (26) and define $I = I_X + I_M$.

3.4. Decentralized interconnection planning without compensations

In the previous setting it is possible for one of the partial investment costs I_X or I_M to be higher than the total investment cost I, while the other partial cost becomes negative. This represents a situation where a compensation between players takes place. We now consider a setting without compensations, in order to be able to compare the solutions obtained for both settings and understand the impact of this constraint. We implement this setting by adding $I_X \geqslant 0$ and $I_M \geqslant 0$ to the bargaining model defined by Eqs. (14)–(20).

Considering that I_X and I_M are bounded by

$$0 \leqslant I_X \leqslant \sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,X}, \tag{27}$$

$$0 \leqslant I_M \leqslant \sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,M}, \tag{28}$$

we can characterize different combinations of results for the variables I_X and I_M. An optimal solution with null investment costs features no trade and hence no increase in either social welfare, resulting in a null objective function value. If each player faces investment costs that are equal to the social welfare benefits, the objective function value is again null and the solution is indifferent to making no investment. When for an optimal solution the above constraints become strict inequalities, the non-negativity constraints for investment costs are unnecessary and the decisions with or without compensations are the same. When a compensation takes place, one of the players finances all the investment, leading to a reduction in the agreed upon investment in transmission capacity, as we will see later.

Given that the model is non-linear, but all other variables are a function only of K, we carry out a sensitivity analysis for K between 0 and the highest f_s^{FT} to identify the globally optimal solution.

3.5. Case application

With an implementation of the model in MATLAB, using CVX, a package for specifying and solving convex programs [41,42], we apply it to the case of the Iberian market, to estimate the required level of interconnection capacity between Portugal and Spain.

In November 2001, Portugal and Spain signed the collaboration protocol for the creation of MIBEL, the Iberian Electricity Market, aiming at guaranteeing conditions of objectivity, transparency and equality to all participations in this market. Later, in 2004, a new agreement was signed to enable the creation of a regulatory council to supervise the development of MIBEL. With additional agreements in 2007 and 2008, a capacity payment mechanism was introduced, as well as a methodology to identify agents acting as dominant operators, and harmonized procedures to allow consumers to change suppliers.

The day-ahead market was initially established in Spain, in January 1998, with Portugal joining only almost a decade later, in July 2007. In this market, power producers and distribution companies bid for the purchase and sale of electricity to be delivered in the following day, in a process that leads to the settling of power exchanges at a single marginal price that results from the matching of the bids. An additional market was created to bridge the differences between the day-ahead forecasts and the actual values of supply and demand, operating six times a day in individual time blocks of four hours.

With the establishment of MIBEL, Portugal and Spain would be supposed to operate under a single electricity price. As long as the interconnection capacity between the two regions is sufficient to allow the transmission of power without curtailment, this single market price holds. This, however, is not always the case. In certain hours of operation, the interconnection capacity may not be sufficient, and the prices in each region may then diverge, leading to a market split. Price differences, enabling transmission owners to obtain congestion rents, are powerful signs of the need for further investment in interconnections. The evidence for the pivotal role of the creation of MIBEL in the suppression of transmission investment needs is clear. The average difference between prices in Iberia, calculated as the difference between the Portuguese and Spanish prices, was 10 €/MWh in 2007. The difference decreased significantly in the meantime to less than 1 €/MWh, and in 2014 there even was a slight difference of −0.26 €/MWh.

We use daily bid data retrieved from OMIE, the daily and intraday Iberian electricity market operator[1], for the whole year of 2013, with approximately 15.7 million buy and sell bids. The bids are separated for Portugal and Spain, and for the sake of simplicity all bids from France and Morocco are assumed to be from Spain.

For each hourly slot throughout the year, we sort the bids by price and quantity to obtain hourly supply and demand curves, as well as points of equilibrium. These data are then grouped in a total of 168 distinct operating conditions for different months, weekdays and peak/off-peak periods (the peak occurs between 9 a.m. and 10 p.m.).

For each operating condition, we obtain linear regressions for supply and demand from all the points in the supply and demand curves, respectively, constrained to pass through the average of the equilibrium points of all the operating conditions' hourly slots. This allows us to avoid, for instance, negative equilibrium points, which may result from considering independent supply and demand regressions. All these data operations were performed in R. We should note that the importer and exporter roles do not change, Portugal is the importer and Spain is the exporter, in all 168 operating conditions. Fig. 1 shows an operating condition for the Spanish market, with the results of the linear regression, and the results of the constrained linear regression.

Figs. 2 and 3 present the constrained linear regression parameters for the different operating conditions. Demands in both regions show similar and wide variations in the constant α, suggesting that the different operating conditions represent a fair diversity of power needs. The slopes of demand in Spain are mostly stable at around 1 €/MWh, whereas in Portugal they vary in a range of values 3 to 7 times higher. Even if elasticity is not linear, *ceteris paribus*, demand in Portugal is more inelastic than in Spain. On the other hand, generation in Spain is

[1] http://www.omie.es/.

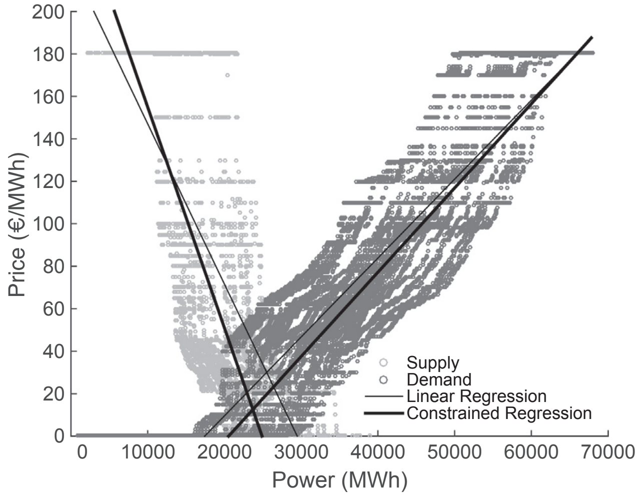

Fig. 1. Off-peak hours of Spanish Sundays of January 2013. Linear regressions and linear regressions constrained to the average of the equilibrium values.

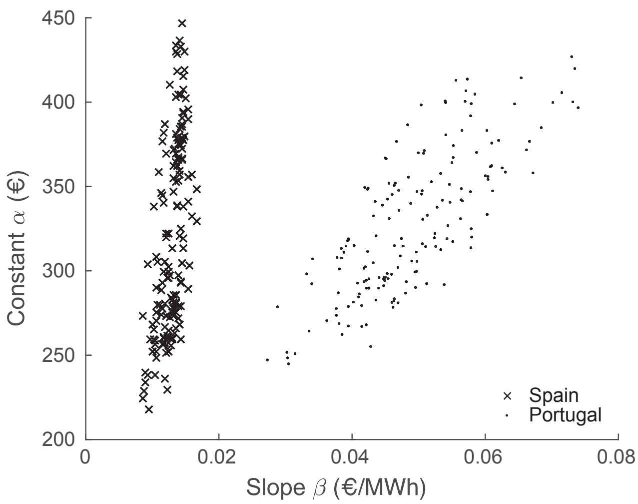

Fig. 2. Demand parameters obtained using linear regression for the 168 operating conditions.

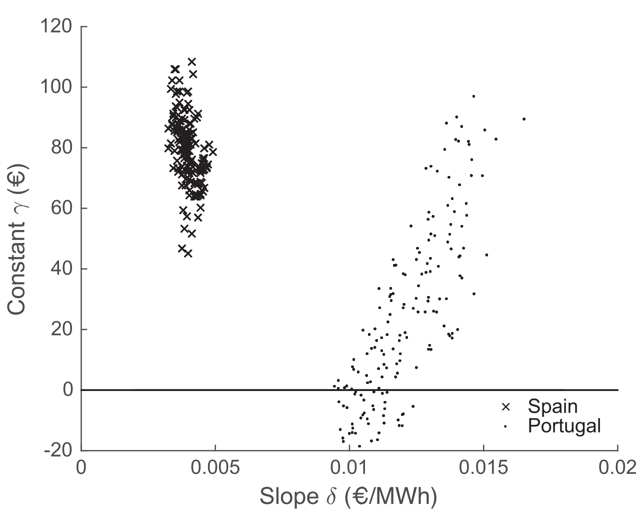

Fig. 3. Supply parameters obtained using linear regression for the 168 operating conditions.

more concentrated in both constants γ and slopes δ. The considerable reliance on variable energy resources in Portugal may explain this greater variability.

The length of the interconnection line l is assumed to be 100 km. To work with the changes in social welfare and the investment costs in the same annual time scale, we compute an annualised investment cost, considering as the economic life for the investment T the mid-term to long-term threshold in ENTSO-E's cost benefit analysis, which is 10 years [4]. The discount rate r is 6.04%, the highest cost of debt of the countries that finance the project, in this case the long term government bond yield of Portugal as of the end of 2013[2], also as suggested by ENTSO-E. For a transmission investment cost u_{ref}, the corresponding annualised investment cost u, is computed as follows [43]:

$$u_{\mathrm{ref}}\cdot l = u\left(\frac{1}{r} - \frac{1}{r(1+r)^T}\right) \Leftrightarrow u = u_{\mathrm{ref}}\cdot l\left(\frac{r(1+r)^T}{(1+r)^T - 1}\right). \quad (29)$$

4. Results and discussion

In this section we describe the results from the analysis of the case outlined in the previous section, focusing on the optimal volume of transmission capacity required between Portugal and Spain when considering a fair share allocation of investment costs.

Fig. 4 shows the optimal volume of transmission capacity investment in an interconnection between Portugal and Spain, considering a wide range of transmission capacity costs. As costs increase, the required capacity decreases non-linearly when compensations are possible, under Nash-Coase bargaining. Without compensations, and for costs between 0 and 30 thousand €/MW, investments decrease, when compared to the previous solution, and remain generally stable at around 3100 MW. The difference in investments can be significant, e.g., as high as 900 MW for lower costs. Maybe counter-intuitively, as costs increase, capacity also increases, even if slightly, for the cost range where compensations would take place. To understand this behavior, we should recall that the benefit to the importer (Portugal) consists of the increase in social welfare subtracted by the total investment, whereas for the exporter (Spain) it consists only of the improvement in social welfare. With an increase in costs, the importer has a lower benefit for any agreed upon capacity, whereas the exporter keeps the same level of benefit. This configures an increase in bargaining power of the exporter over the importer, with an agreement now only possible under a bargaining setting if the investment increases. When compensations would not naturally occur, i.e., for costs above 30 thousand €/MW, optimal capacity is the same in both settings and decreases as costs increase.

Although there is a significant uncertainty about transmission investment costs, in our analysis we used as a reference an upper-bound value u_{ref} of 3.2 thousand €/(MW-km), which is the maximum value reported by Lamy et al. [44], converted here from USD to EUR. The corresponding annualized transmission investment cost, considering a length of 100 km, has a value of approximately 40 thousand €/MW. In the case of the Iberian market, considering this cost range, according to our model, we would expect a value for cross border capacity in the 3000–4000 MW interval capped to 3100 MW in a fair share cross-border cost allocation procedure without compensations. Considering the projects for the reinforcement of the interconnection capacity between Portugal and Spain that were being developed at the time, a capacity value of 3000 MW was expected for 2016 [45]. Our results are thus in line with the current investment plans, however, as previously noted, it should be emphasized that our model does not account for real world frictions such as transmission losses or internal congestion of transmissions networks.

As the costs increase, the allocation of the total costs switches from

[2] http://ec.europa.eu/eurostat.

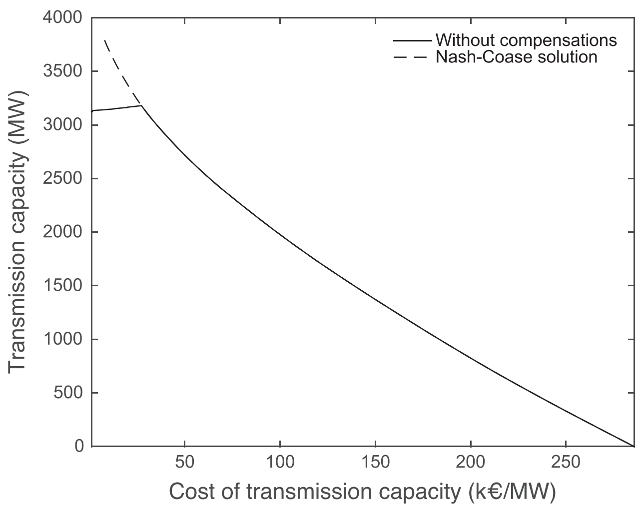

Fig. 4. Representation of the desired total investment in transmission capacity considering different transmission costs.

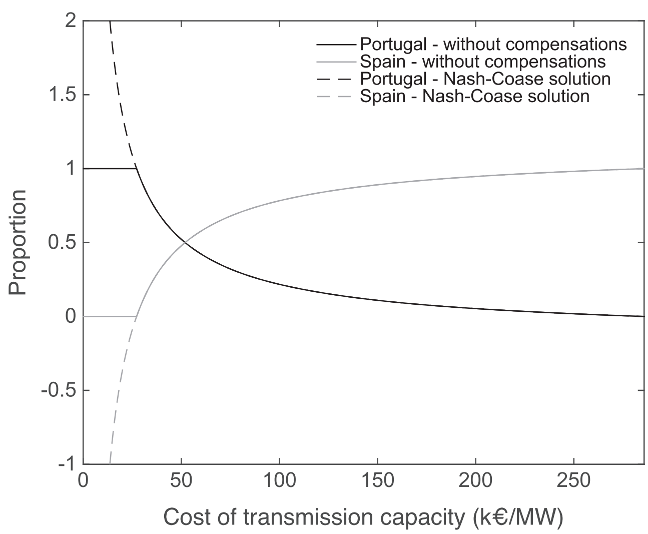

Fig. 5. Share of investments between Portugal and Spain considering different transmission costs.

the importing region to the exporting region, as is clearly visible in Fig. 5. For costs in the range below 30 thousand €/MW, the proportion of the total cost allocation for Portugal is higher than 100%, which means that the country should pay for the whole interconnection, on both sides of the border, and should in addition provide some form of economic compensation to the other country, for it to accept the desired level of interconnection capacity. Without financial compensations, investment costs cannot exceed the total and are thus capped at 100%. When the costs rise to 50 thousand €/MW, the total costs are equally shared by both countries. For higher costs, the exporting country (Spain) receives a higher allocation of the total costs, which asymptotically approaches 100%. It should be noted that only the importing region can face a situation that implies an economic compensation to the other region.

Fig. 6 shows the impact of costs on social welfare variation for the setting without compensations. Considering the importing region (Portugal), the analysis of the behavior of social welfare variation should distinguish between cost ranges for which the costs are or are not binding. In the first interval, between 0 and 30 thousand €/ MW, social welfare variation is high and increases slightly to a maximum with increasing costs. Between 30 and 300 thousand €/ MW, increasing costs lead to a non-linear decrease in social welfare variation. For the

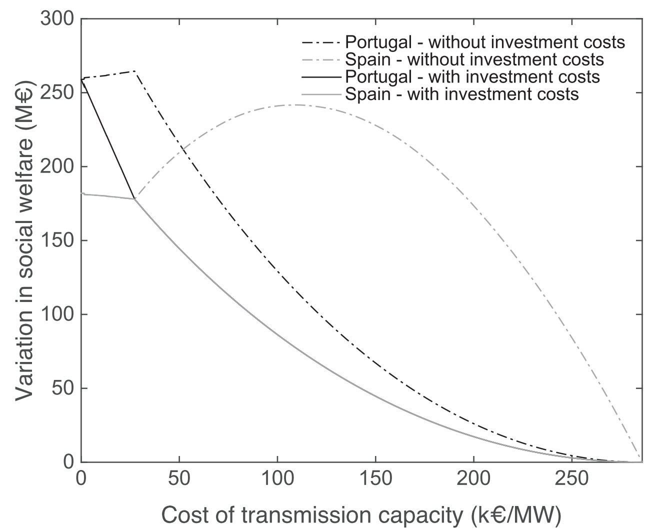

Fig. 6. Variation in social welfare without compensations considering different transmission costs.

exporting region Spain, for the same interval, between 0 and 30 thousand €/ MW, the variation in social welfare is slightly decreasing. For costs that would not lead to compensations, up to 100 thousand €/ MW the variation in social welfare increases due to a curtailment in traded power that leads to an increase in the price differential between regions. Above 100 thousand €/ MW transmission capacity is highly curtailed and even with rising price differentials, the social welfare variation decreases. Subtracting the investment costs, for costs between 0 and 30 thousand €/ MW, the net social welfare variation in the exporting region is the same as its social welfare variation, as the importer supports all the investment and its net social welfare variation decreases. Net social welfare variations converge at 30 thousand €/ MW, and for higher transmission investment costs always decrease non-linearly and are the same for Nash-Coase and Nash bargaining settings.

Assuming perfect competition, a centralized decision setting and a voluntary agreement setting will lead to the same level of investment in interconnection capacity in market coupled regions, when compensations are not restricted or needed. The outcome of the interconnection expansion planning models with a single decision maker may thus be a useful reference for the desirable level of interconnection capacity for transmission costs higher than 30 thousand €/ MW, the range where we can assume Nash-Coase bargaining.

At lower costs, the importer supports the whole investment and possibly additional compensations to the exporter, if they are allowed. At higher costs, the exporter supports a higher share of the investment, asymptotically approaching the total investment. The social welfare variation and the investment in interconnection capacity decrease when the costs increase and are such that compensations would not be needed. At the lowest costs, where compensations could be required to maximize the social welfare variation of both regions, their restriction leads to a slight increase in transmission capacity investments with costs, due to an increase in the exporter's bargaining power.

For costs above the range where compensations are needed, the importer, but not the exporter, sees an inverse U-shaped behavior in social welfare variation. These results can also be regarded as the evolution of social welfare variation and interconnection capacity investment with a decreasing social welfare "contribution margin", i.e., decreasing price-elasticities of demand and/or supply. Our models could also accommodate the analysis of the impact of the level of market uncertainties and correlations [13].

In our analysis, we have used historical data to estimate the benefits to social welfare from investments in interconnection capacity, and our models do not explicitly consider the possibility of an adjustment of generation bidding strategies. For this reason, we will be overestimating the revenues from trade, which are expected to decrease in the long term [46], and underestimating the reduction in market power for the producers of the importing region [47]. Still, given all the limitations and simplifications in the I-TEP-MCR models, with proper parametrization we were able to obtain realistic results that are in line with the current expectations for these investments in our case application. Many of these limitations may be addressed in future work, but these models are nevertheless useful as fast screening models, capable of providing reliable approximations to optimal interconnection capacities.

Our bargaining solution provides a fair share cost allocation, dependent on the uneven increments in social welfare that might accrue to each region from trade, which is useful to address the 'user pays', 'beneficiary pays' and 'tax payer pays' principles that the European Commission has proposed to apply in establishing appropriate financing frameworks for infrastructure development [48].

The models, however, provide only a *ceteris paribus* valuation of the benefits from electricity trade made possible by investments in the interconnection between two regions. Power consumption may increase as trade is fostered by investments in interconnections between regions, and generation companies may adjust the location and technology of their new generation investments and thus reduce the negative impact of imports in the social welfare in the long term. Populations may have a higher difficulty in adjusting to increasing electricity prices but if, also in this case, generation adjusts to the new operating conditions and increases capacity, the price increase may be mitigated through an increase in competition. Nevertheless, if these adjustments are insufficient or too slow, and no other wealth transfer mechanisms are put into place, public opinion may present a significant opposition to further steps towards integration and the creation of a single European electricity market.

5. Conclusions

In this paper we present an interconnection investment model that considers bargaining between market coupled regions, together with solutions for fair share cost allocation of investment costs in settings with and without compensations.

With a case study to the Iberian Peninsula, using market data of 2013, we show different patterns of cost allocation, depending on transmission investment costs. At very low costs, the importing country (Portugal) fully supports the investment and if allowed would provide an economic compensation to the exporting country (Spain). As the costs increase, the allocation switches from the importing country to the exporting country. In both models, an increase in the overall social welfare comes at the expense of the consumers from the exporting region, who will pay a higher price for electricity, and the producers of the importing country, who may have difficulty in dispatching their most expensive generators. Policy makers must be aware of these trade-offs.

The results of the I-TEP-MCR models suggest their ability to estimate realistic values for cross-border interconnection investments between two regions. In the case of the Iberian market, the results are in the 3000 to 4000 MW interconnection capacity range, when compensations are allowed, and up to 3100 MW when these are restricted. Both these results nevertheless contain the projected value for 2016.

Iberia is currently one of the few "electric peninsulas" in Europe [3], and the interconnection between Spain and France may be one of the interconnections to deserve a larger expansion, to allow the European market to take advantage of the high electricity export capacity in Iberia, enabled by the recent investments in renewable energy. If both parties, Iberia and France, were to benefit from the expansion of the interconnection between Spain and France, a solution through bargaining would come naturally.

Our analysis suggests that, as a possible outcome of decentralized negotiations for interconnection expansion, a fair share cost allocation might yield a negative proportion, i.e., a direct economic compensation, for one of the regions. To realize these investments, however, the expansion of the interconnection would benefit from financial support from the European Union, through the Connecting Europe Facility initiative, the Structural Funds, or the European Fund for Strategic Investment, as well as the European Investment Bank [49]. An intervention from a supraregional decision-maker, such as the European Union, in the form of a financial support such that uneven benefits accrue to the regions, would be a possible way to implement compensations.

Modelling and analysing these scenarios would be a natural next step for the research presented in this paper. Further improvements to the models may increase their usefulness: independent consideration of consumer and producer surpluses in each region would allow the analysis of different policy preferences, namely from the Rawlsian perspective, requiring "that inequalities benefit all persons", as opposed to the utilitarian perspective, requiring that "only (…) the general interest be served" [50]; modelling supply and demand as non-linear curves or sets of bids would improve the representation of electricity markets; explicit modelling of transmission networks would allow assessing investments in different interconnection corridors, as well as accounting for wheeling effects, and identifying relevant internal transmission investments necessary to relieve regional congestion, as needed for trade; explicit inclusion of long-term uncertainties would improve the relevance of the model, due to the long construction time and lifespan of these projects; other objectives, such as risk-aversion or environmental impact, would also improve its relevance to practice; additionally, the analysis of different mechanisms to implement the compensations between regions would also be of high relevance under circumstances where benefits from trade are significantly uneven.

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Appendix A. Social welfare constraints

The identification of the importing region and the exporting region roles is based on the comparison of the autarkic prices of the two regions, i.e., the equilibrium prices when trade is not possible, at the intersection of the demand curve (1) and the supply curve (2). The exporting region is the one featuring the lower autarkic price.

Substituting $D_{s,i}$ and $G_{s,i}$ by the autarkic quantity $q_{s,i}^{\text{aut}}$, we obtain

$$\alpha_{s,i}-\beta_{s,i}q_{s,i}^{\text{aut}} = -\gamma_{s,i} + \delta_{s,i}q_{s,i}^{\text{aut}} \Leftrightarrow q_{s,i}^{\text{aut}} = \frac{\alpha_{s,i} + \gamma_{s,i}}{\beta_{s,i} + \delta_{s,i}}. \tag{30}$$

The autarkic price $p_{s,i}^{\text{aut}}$, obtained by substituting $q_{s,i}^{\text{aut}}$ in (2), is

$$p_{s,i}^{\text{aut}} = \alpha_{s,i} - \beta_{s,i}\frac{\alpha_{s,i}+\gamma_{s,i}}{\beta_{s,i}+\delta_{s,i}} = \frac{\alpha_{s,i}\delta_{s,i}-\gamma_{s,i}\beta_{s,i}}{\beta_{s,i}+\delta_{s,i}} = \frac{b_{s,i}}{a_{s,i}}, \tag{31}$$

with $a_{s,i}$ and $b_{s,i}$ defined in (5) and (6).

Introducing trade, we consider a same imported and exported F_s quantity:

$$F_s = G_{s,X} - D_{s,X} = D_{s,M} - G_{s,M} \Leftrightarrow \tag{32}$$

$$\Leftrightarrow \frac{P_{s,X}+\gamma_{s,X}}{\delta_{s,X}} - \frac{\alpha_{s,X}-P_{s,X}}{\beta_{s,X}} = -\frac{P_{s,M}+\gamma_{s,M}}{\delta_{s,M}} + \frac{\alpha_{s,M}-P_{s,M}}{\beta_{s,M}} \Leftrightarrow \tag{33}$$

$$\Leftrightarrow a_{s,X}P_{s,X} - b_{s,X} = -a_{s,M}P_{s,M} + b_{s,M}. \tag{34}$$

Assuming free trade, the traded quantity f_s^{FT} is such that the price differential is eliminated, and the single free trade price p_s^{FT} is given by:

$$a_{s,X}p_s^{\text{FT}} - b_{s,X} = -a_{s,M}p_s^{\text{FT}} + b_{s,M} \Leftrightarrow p_s^{\text{FT}} = \frac{b_{s,X}+b_{s,M}}{a_{s,X}+a_{s,M}}. \tag{35}$$

For the free trade quantity:

$$f_s^{\text{FT}} = a_{s,X}p_s^{\text{FT}} - b_{s,X} = \frac{a_{s,X}b_{s,M}-a_{s,M}b_{s,X}}{a_{s,X}+a_{s,M}}. \tag{36}$$

With trade capped by the transmission capacity of the interconnection K,

$$f_s = \min\{f_s^{\text{FT}}, K\}. \tag{37}$$

The social welfare, $\text{sw}_{s,i}$, is defined as the sum of the consumer surplus and the producer surplus, i.e., the area under the demand curve and to the left of the demand in equilibrium $d_{s,i}$, subtracted of the area under the supply curve and to the left of the supply in equilibrium $g_{s,i}$. To account for trade, its profits and costs, i.e., the traded quantity multiplied by the price in the importing region, are also considered:

$$\text{sw}_{s,X} = \int_0^{d_{s,X}} P_{s,X}\,\text{d}D_{s,X} - \int_0^{g_{s,X}} P_{s,X}\,\text{d}G_{s,X} + p_{s,M}f_s \tag{38}$$

$$\text{sw}_{s,M} = \int_0^{d_{s,M}} P_{s,M}\,\text{d}D_{s,M} - \int_0^{g_{s,M}} P_{s,M}\,\text{d}G_{s,M} - p_{s,M}f_s. \tag{39}$$

Using appropriate substitutions and integrating we obtain:

$$\text{sw}_{s,X} = \frac{1}{2}\left(\frac{\alpha_{s,X}^2}{\beta_{s,X}} + \frac{\gamma_{s,X}^2}{\delta_{s,X}} - \frac{b_{s,X}^2}{a_{s,X}}\right) + \left(\frac{b_{s,M}}{a_{s,M}} - \frac{b_{s,X}}{a_{s,X}}\right)f_s - \frac{1}{2}\left(\frac{2}{a_{s,M}} + \frac{1}{a_{s,X}}\right)f_s^2 \tag{40}$$

$$\text{sw}_{s,M} = \frac{1}{2}\left(\frac{\alpha_{s,M}^2}{\beta_{s,M}} + \frac{\gamma_{s,M}^2}{\delta_{s,M}} - \frac{b_{s,M}^2}{a_{s,M}}\right) + \frac{1}{2a_{s,M}}f_s^2. \tag{41}$$

Appendix B. Convexity of the quadratic programming model

Considering Eqs. (12) and (13), we can rewrite objective function (9) in the form $v^{\top}Mv + v^{\top}b$. Vector v has f_s, I and K as elements, in this sequence, and matrix M and vector b are

$$[M_{j_1 j_2}] = \begin{cases} h_{j_1}\frac{1}{2}\left(\frac{1}{a_{j_1,M}} + \frac{1}{a_{j_1,X}}\right), & j_1 = j_2 \quad \forall\, j_1, j_2 \in \mathscr{S} \\ 0, & \text{otherwise} \end{cases} \tag{42}$$

$$[b_j] = \begin{cases} -h_j\left(\frac{b_{j,M}}{a_{j,M}} - \frac{b_{j,X}}{a_{j,X}}\right), & \forall\, j \in \mathscr{S} \\ 1, & j = \max(\mathscr{S}) + 1 \\ 0, & j = \max(\mathscr{S}) + 2. \end{cases} \tag{43}$$

The objective function is convex if M is positive semi-definite, i.e.,

$$v^{\top}Mv = \sum_{s\in\mathscr{S}} h_s\frac{1}{2}\left(\frac{1}{a_{s,M}} + \frac{1}{a_{s,X}}\right)f_s^2 \geqslant 0, \tag{44}$$

which is verified, since h_s is positive and so is $a_{s,i}$, as the sum of the inverses of $\beta_{s,i}$ and $\delta_{s,i}$, positive by definition.

Appendix C. Flow constraints

We prove that $f_s \leqslant K$ is sufficient to model the second level problem $f_s = \min\{f_s^{\text{FT}}, K\}$ (11).

By substituting $\Delta\text{sw}_{s,X}$ and $\Delta\text{sw}_{s,M}$ in Eq. (9) using Eqs. (12) and (13), we obtain the relevant KKT optimality conditions

$$\frac{\partial \mathscr{L}}{\partial I_X} = h_s\left[\left(\frac{b_{s,M}}{a_{s,M}} - \frac{b_{s,X}}{a_{s,X}}\right) - \left(\frac{1}{a_{s,M}} + \frac{1}{a_{s,X}}\right)f_s\right] = \mu_{K,s} \tag{45}$$

$$0 \leqslant \mu_{K,s} \perp K - f_s \geqslant 0, \tag{46}$$

where $\mu_{K,s}$ is the Lagrangian multiplier. With $\mu_{K,s} > 0$, it follows from (46) that $f_s = K$. With $\mu_{K,s} = 0$, it follows from (45) that $f_s = \frac{a_{s,X} b_{s,M} - a_{s,M} b_{s,X}}{a_{s,X} + a_{s,M}} = f_s^{\mathrm{FT}}$. Based on the result of Appendix E this also applies to Eq. (16).

Appendix D. Equality of μ_X and μ_M

μ_X and μ_M, in (25), are Lagrange multipliers of inequalities, and thus non-negative. We next consider combinations of null or positive values for the two multipliers.

With $\mu_X > 0$ and $\mu_M > 0$, from (23) $\sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,X} = I_X$, and from (24) $\sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,M} = I_M$. From (21) and (22) $\mu_X = \lambda_I = \mu_M$.

With $\mu_M > 0$, from (24) $\sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,M} = I_M$, and from (21) $\lambda_I = \mu_X$. If $\mu_X = 0$, $\lambda_I = 0$, and from (23) $\sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,X} - I_X = -\mu_M$, whereas from (22) $\sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,X} - I_X \geqslant 0$, which are in contradiction. A similar result is obtained for $\mu_X > 0$ and $\mu_M = 0$.

Considering the above and also the case when $\mu_X = \mu_M = 0$, $\mu_X = \mu_M$, allowing the simplification of (25).

Appendix E. Equality of the Nash-Coase bargaining and centralized interconnection planning model solutions

We define

$$\tau = \sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,M} - I_M = \sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,X} - I_X. \tag{47}$$

Objective function (14) can be rewritten as $\max \tau^2$. With (19) and (20), $\tau \geqslant 0$ and the same results are obtained using $\max \tau$ or

$$\begin{aligned} \max 2\tau &= \max \sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,M} - I_M + \sum_{s\in\mathscr{S}} h_s \Delta \mathrm{sw}_{s,X} - I_X \\ &= \max \sum_{s\in\mathscr{S}} h_s (\Delta \mathrm{sw}_{s,M} \Delta \mathrm{sw}_{s,X}) - I, \end{aligned} \tag{48}$$

where $I = I_X + I_M$.

Eqs. (19) and (20) are redundant as $I = 0 \Rightarrow \Delta \mathrm{sw}_{s,i} = 0, \forall\, s \in \mathscr{S}, i \in \{X, M\}$, the objective value is zero and maximizing the objective function always results in a non-negative value.

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