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TIGHT VOLUME COUPLING: ANALYTICAL MODEL, ADVERSE FLOW CAUSALITY AND POTENTIAL IMPROVEMENTS

Tanguy Janssen, Yann Rebours and Philippe Dessante

EUROPEAN UNIVERSITY INSTITUTE, FLORENCE
ROBERT SCHUMAN CENTRE FOR ADVANCED STUDIES
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TANGUY JANSSEN, YANN REBOURS AND PHILIPPE DESSANTE

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For further information
Loyola de Palacio Energy Policy Chair
Nicole Ahner (scientific coordinator)
Email contact: Nicole.Ahner@eui.eu
Robert Schuman Centre for Advanced Studies
European University Institute
Via delle Fontanelle, 19
I-50016 San Domenico di Fiesole (FI)
Fax: +39055 4685755
http://www.loyola-de-palacio-chair.eu

TIGHT VOLUME COUPLING: ANALYTICAL MODEL, ADVERSE FLOW CAUSALITY AND POTENTIAL IMPROVEMENTS

T. JANSSEN, Y. REBOURS, AND PH. DESSANTE

Abstract. The European Market Coupling Company (EMCC) operates an interim tight volume coupling (ITVC) that implicitly allocates the interconnection capacities between Central West European (CWE) and Nordic (Nordpool) day-ahead electricity spot markets. Though it is to be replaced by a single price coupling in the near future, the volume coupling principle can still inspire pragmatic solutions for future challenges in other situations.

In order to learn from the current experience, this paper offers elements of understanding on the interim volume coupling run by the EMCC that are not highlighted in the documents already available. In particular, a new analytical model of the tight volume coupling is developed to show that the ITVC principle would not generate any inefficiencies under three assumptions. This analysis thus offers a new perspective on the causality of adverse flow events. Furthermore, this model could be used to study other tight volume coupling mechanisms because it can be applied with minor modifications to any number of areas, other kinds of traded products or areas using a flow-based method.

Learning from the ITVC experience, this paper proposes an example of improvement of the tight volume coupling method based on a stronger coordination between the numerical solvers. This improved mechanism could serve as an interim solution if a price coupling numerical solver does not provide satisfactory results because of the optimisation problem size or complexity. In this case, the proposed solution is expected to be a satisfactory implicit allocation method from both technical and governance points of view.

1. Introduction to the EMCC interim tight volume coupling

First, this introduction explains the concept of tight volume coupling in the European power system. The next part describes the European Market Coupling Company (EMCC) action in the day-ahead markets, followed by a discussion on the reasons given by the EMCC to explain the appearance of adverse flow events. Finally, the aim and content of this paper are exposed.

1.1. **The EMCC volume coupling is the result of key choices in the European market design.** As widely acknowledged, the electricity market design can be seen as a sequence of forward and real-time markets and mechanisms [1]. In this sequence, since the EMCC volume is taking place among the day-ahead markets, this paper focuses on the day-ahead time horizon. The following paragraphs gather the key choices of market design leading to the EMCC's Interim Tight Volume Coupling (ITVC) solution.

Key words and phrases. Volume coupling; market coupling; implicit allocation.

1.1.1. *What kind of method for cross-border capacity allocation in zonal pricing?* The European electricity day-ahead markets are currently based on zonal pricing, meaning that the markets are organized in rather broad zones with a homogeneous price for each electricity product in each zone. At each border between two zones that are physically connected, there is a possibility for cross-border trade as long as the power transmission capacity are not congested. Therefore, an efficient method of capacity allocation shall be in place to allow cross-border trade while preventing congestions on the network.

It is agreed within the European Union that a market-based allocation method shall be used [2].

1.1.2. *Implicit or explicit capacity allocations?* The various market-based methods are gathered in two sets. On the one hand, explicit auctions requires that stakeholders participate in an auction dedicated to interconnection capacity that they shall hold nominatively. On the other hand, implicit allocation is performed based on the bids and offers formulated in a set of interconnected markets [3]. The current implicit methods consist in coupling the interconnected markets while taking into account the cross-border transmission capacities as constraints in an optimization problem as described in section 2.

Implicit allocation is currently preferred to explicit auctions by a wide consensus of European stakeholders [4].

1.1.3. *Price coupling or volume coupling?* Implicit allocation is performed based on the offers and bids sent to some day-ahead market platforms. An objective of this allocation is to make the most efficient use of the interconnectors while offers and bids are matched optimally.

In a so-called price coupling, the optimization is serving at the same time both the allocation and the matching objectives. Volume coupling is another form of implicit allocation which has a more humble objective than price coupling. Indeed, it only fixes the cross-border flows on a set of interconnectors between various areas that can cover one or more zones. It thus only serve the allocation objective for a set of interconnectors. In this case, new mechanisms, which can be price couplings, are required to serve the matching objective as well as the allocation objective on the other interconnectors.

The preference for single price coupling solution is strong in Europe and it is for instance the choice made in the framework guidelines on capacity allocation by the Agency for the Cooperation of Energy Regulators (ACER) [4]. Nevertheless, as shown in section 5 about the perspectives, there may still be some room for volume coupling solutions. In practice, a single price coupling solution called Price Coupling of Regions (PCR) is currently discussed in Europe [5]. However, this option has not been implemented yet on the cables linking the Nordic market and the CWE region. This might be explained by a lack of harmonization or governance issues between the two areas [6]. Until then, the implicit volume coupling solution has empirically proved to be able to handle these hindrances with limited drawbacks, including those discussed in section 1.3. Volume coupling is thus the current functioning option, taking explicitly the name of “interim” solution.

1.1.4. *Tight or loose volume coupling?* A volume coupling can be applied with more or less accuracy as a consequence of, among other factors, a lack of compatibility between the products on the coupled markets. The term tight is used when the volume coupling "uses full information on the bids and offers submitted in each constituent market and fully replicates the individual matching rules" [3]. On the contrary, a loose volume coupling misses at least one of these conditions.

The EMCC runs a tight volume coupling. Pragmatically, it means that the optimization problem handled by the EMCC volume coupling replicates constraints and objective functions of the price couplings performed in the areas it is coupling. Unless specified explicitly, the term tight volume coupling shall be referred in this paper simply as volume coupling.

1.2. **Description of the EMCC action in the day-ahead markets.** The objective of the volume coupling is to allocate the interconnection capacities between market areas using independent price coupling algorithms. In the case of the EMCC, two day-ahead market couplings using zonal pricing are connected, namely (see figure 1):

- The synchronous Central West Europe (CWE) region, covering Belgium (BE), France (FR), Germany (DE), the Luxembourg (LU) and the Netherlands (NL);
- The Nordic market covering Denmark[1] (DK), Estonia (EE), Finland (FI), Norway (NO) and Sweden (SE).

Both market platforms offer the possibility to submit block bids, i.e., bids linking several hours together. This kind of bids shall introduce dynamic constraints in the optimization process described in section 2 and they are a key element in the explanation of adverse flow events given by EMCC, as summarized in section 1.3.

In practice, the process can be described with three chronological steps (see figure 2, using notations that are introduced in sections 2 and 3):

(1) The power exchanges (PXs) operating day-ahead market platforms collect selling and purchasing bids in each of the two areas, while the TSOs calculate the available commercial capacities. The PXs receive the TSOs data while all data are sent to EMCC.
(2) EMCC fixes the interconnection flows between both areas, which are represented in plain lines in figure 1.
(3) Two independent price couplings are performed in the Nordic market and the CWE region taking into account the interconnection flows through specific bids and offers.

Step (2) and (3) are performed within a limited period of time which must also include the time to send the information in step (1). This period starts with what is known as the gate closure for submitting offers and bids in the day-ahead market and it ends with the market clearings, i.e., the decision of accepting or rejecting offers and bids that are sent to the market players. It is agreed that the duration of this calculation period shall be kept as low as possible. Indeed, the sooner the market players are informed of the market results, the better they can handle other tasks requiring this information, such as the optimization of the

[1]The Western Denmark zone is synchronous with the CWE area but it is included in the Nordpool spot market.

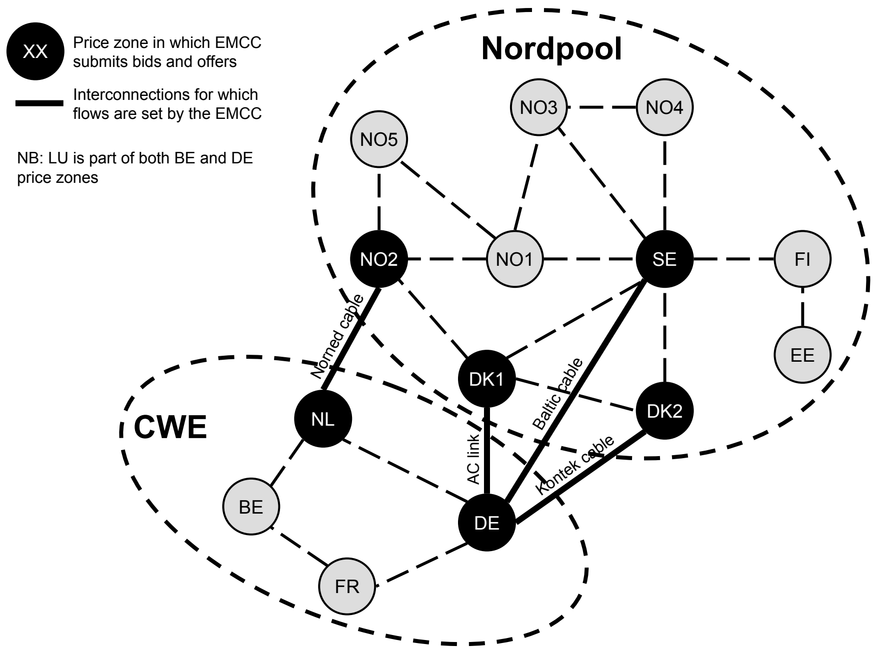

FIGURE 1. Overview of the geographical situation of EMCC's ITVC as in September 2011

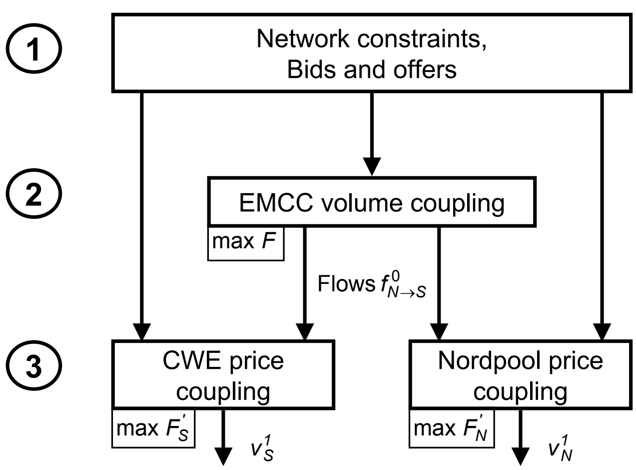

FIGURE 2. Overview of the ITVC process as in September 2011

generation portfolios. Therefore, there is in principle a maximum duration for each optimization numerical solver.

Finally, some additional informations on the optimization problem solver are interesting for the perspectives given in section 5:

- The optimization problem, described in section 2, can be expressed by Mixed Integer Linear Programming (MILP). Indeed, the problem can be modeled with continuous and binary optimization variables and a linear objective function.
- The numerical solver run by EMCC uses a branch and cut method [7].

The most interesting characteristic of this problem is the complexity added by binary variables which are here to model the bids with dynamic constraints. Moreover, when the number of the these binary variables is multiplied by two, the calculation time to solve the problem can be much more than twice longer. This explains that despite the great current potential of the numerical solvers, the duration constraints introduced in the previous paragraph may prevent from finding every times the optimum solution of the problem.

1.3. **Pragmatic reasons explaining adverse flow events.** In practice, the outcome of the independent price couplings, i.e., step three of the process described in section 1.2, may differ from the ITVC's outcome. From the EMCC's efficiency point of view, this is a problem especially when independent price couplings result in adverse flows on the cables between the two areas, i.e., when energy flows in the opposite direction of the price spread (exchange from an expensive price zone to a cheaper one). A report [8] gathers the result of tests about the occurrence of these adverse flows and a presentation [9] lists four explanations of this effect:

- rounding procedures;
- currency conversion;
- differing price caps in each area;
- block bid selection.

The two first reasons have both a "low impact" [9] and there are perspectives of improvement. Indeed, as stated in [9] "EMCC has already implemented an 'intelligent' rounding which respects the flow direction and which reduces adverse flows significantly". In addition, the three optimization algorithms could agree on values and mechanisms they use to handle the currency conversion issue.

The price cap is a meaningful parameter from a regulatory point of view, but this does not prevent the regulators and PXs from negotiating a common value. Anyhow, the present paper shows that the use of different price caps should not be an issue as soon as these constraints are correctly implemented within the EMCC optimization problem.

Concerning the fourth reason, it is not difficult to imagine that the block bid selection can have an impact if the algorithms used in step two and three differ. However, it is stated in presentation [9] that "differences in block bid selection, which may result in adverse flows, are considered as inherent to volume coupling". Furthermore, report [8] also states more generally that "[adverse flows] are inherent to a volume market coupling". The present paper shows that in theory adverse flows are not inherent to block bid selection, but they are likely to appear in practice for reasons described above and in section 3.4.

1.4. **Aim and content.** This paper introduces in section 2 an analytical model that helps understanding some EMCC's volume coupling principles. Based on this model, a mathematical argumentation in section 3 shows that if the numerical solvers were always converging to an optimum, then the volume coupling could in theory handle block bids and differing price caps in one area without adverse flow events. This supports that the volume coupling is not so inherently limited and section 4 illustrates how this conclusion can be generalized to other cases. Last, section 5 put an improved tight volume coupling solution forwards.

2. Analytical model of the EMCC's optimizer and price coupling objective functions

This section introduces a general formulation of the EMCC optimization problem, built from the information given in [10].

2.1. **Objective function and optimization variables.** Let the optimization variables of the EMCC's objective function F be gathered in three vectors:

- $\boldsymbol{v_N}$ as the vector of all variables strictly in the northern area, including the zonal prices, the internal flows, the accepted bids, etc.; and
- $\boldsymbol{v_S}$ as the similar vector in the southern area;
- $\boldsymbol{f_{N\to S}}$ as the vector of the flows on the interconnectors between the northern and the southern area; the positive flows are set by convention going from North to South and these are the only optimization variables involved in both areas.

The objective function to maximize is "the generated social welfare summed over all areas and hours, and bid types" [10]. In practice, this generated welfare is the sum of two kinds of surplus [11].

- the transaction surplus for every accepted selling or purchasing bids calculated with reference to the market price in each price zone;
- the congestion surplus between two zones with differing prices.

In fact, the congestion surplus can be expressed as financial flows for the respectively importing or exporting zones as described in the EMCC optimizer [10]. The volume coupling's objective function can thus be expressed as a sum over the zones and over the hours of the aggregated sells and imports minus the aggregated purchases and exports in monetary value. Let $F_N(\boldsymbol{v_N}, \boldsymbol{f_{N\to S}})$ be the sum of these surpluses over the zones of the northern area. This function as expressed above does not depend on any variables included in $\boldsymbol{v_S}$. Similarly, $F_S(\boldsymbol{v_S}, \boldsymbol{f_{N\to S}})$ is defined as the sum of surpluses over the zones of the southern area. Then the EMCC objective function F can be expressed as:

$$F(\boldsymbol{v_N}, \boldsymbol{v_S}, \boldsymbol{f_{N\to S}}) = F_N(\boldsymbol{v_N}, \boldsymbol{f_{N\to S}}) + F_S(\boldsymbol{v_S}, \boldsymbol{f_{N\to S}}) \tag{2.1}$$

2.2. **Constraints.** The optimization problem includes various constraints such as bid usage[2], demand-supply balance in each zone, transmission capacities or the transmission flow ramp rates[3]. The constraints involving variables concerning both

[2]For instance, paradoxically rejected blocks are allowed and paradoxically accepted blocks are forbidden as described in [12].

[3]These flow ramp rates limit the variation of the flows between successive time periods [10].

the northern area (Nordpool) and the southern area (CWE) are only the transmission constraints involving exclusively the transmission flows on the cables between these two areas.

The set of constraints $\{C\}$ is introduced as the set of all constraints of the volume coupling optimization problem. This set includes the three following subsets[4]:

- $\{C_I\}$ the subset of constraints involving only optimization variables included in the vector $\boldsymbol{f_{N\rightarrow S}}$;
- $\{C_N\}$ the subset of constraints involving at least an optimization variable included in the vector $\boldsymbol{v_N}$;
- $\{C_S\}$ the subset of constraints involving at least an optimization variable included in the vector $\boldsymbol{v_S}$.

2.3. **Relation between price and volume coupling objective functions.** The objective functions of the price couplings sum the same kind of surpluses as the objective function of the volume coupling F described in section 2.1. Nevertheless, there are two differences:

- the congestion surplus on the interconnectors handled by the volume coupling is no more part of the objective function of the price couplings;
- the way the flows are fixed by EMCC can add new offers and bids in the price coupling objective functions.

Based on this observation, the section aims at expressing the objective function of the price coupling in the northern area F'_N as a function of F_N which is the objective function of the volume coupling restricted to the northern area as introduced in section 2.1.

First, let $\{I_{N\rightarrow S}\}$ be the set of interconnection flows which are corresponding to the elements of $\boldsymbol{f_{N\rightarrow S}}$ so that each $i \in I_{N\rightarrow S}$ refers to a given interconnector and a given time period where $f_{N\rightarrow S,i}$ is the amount of power flowing.

Each interconnection flow is physically attached to a northern price zone and a southern price zone, and it is related to a single time period. Then, let $\boldsymbol{x_N(v_N)}$ be the vector of zone prices such as $\forall i \in \{I_{N\rightarrow S}\}$, the element $x_{N,i}(\boldsymbol{v_N})$ is the zone price in the northern area related to the element $f_{N\rightarrow S,i}$. The function x_N thus allows to exhibit the prices related to congestion surpluses.

The EMCC objective function F includes the congestion surplus between the northern and southern areas, which is equal to $(\boldsymbol{x_S(v_S)}-\boldsymbol{x_N(v_N)})\cdot\boldsymbol{f_{N\rightarrow S}}$. Therefore, let $F_{f,N}(\boldsymbol{v_N},\boldsymbol{f_{N\rightarrow S}})$ be the surplus that shall be subtracted from F_N because it has become external to the optimization problem related to F'_N:

$$F_{f,N}(\boldsymbol{v_N},\boldsymbol{f_{N\rightarrow S}}) = -\boldsymbol{x_N(v_N)}\cdot\boldsymbol{f_{N\rightarrow S}} = -\sum_{i\in\{I_{N\rightarrow S}\}}(x_{N,i}(\boldsymbol{v_N})\cdot f_{N\rightarrow S,i}) \quad (2.2)$$

Second, the bids and offers created in order to fix the flows between the two areas are now included in the objective functions of the price couplings. As described for example in [13], the inter-area transmission flows that are the solution of the volume coupling optimization are fixed in practice by unlimited bids included in

[4]These three subsets happens to form a partition of $\{C\}$, i.e., the union of the subsets is equal to $\{C\}$ and the subsets do not intersect each other. In particular, there is no constraints in the EMCC description involving at the same time an optimization variable included in the vector $\boldsymbol{v_N}$ and one in $\boldsymbol{v_S}$. Nevertheless, this property shall not be used in section 3.

the price coupling of each area. The surplus $F_{b,N}$ to be added for the northern price coupling is given in the following paragraphs.

Let $P_{min,N}$ and $P_{max,N}$ be the price caps in this area, i.e., respectively the minimum and maximum bid prices authorized by the regulation, the PXs and used by the algorithm in case of curtailment in a price zone. In order to exchanges the quantities $\boldsymbol{f^0_{N\to S}}$ calculated through the volume coupling, purchasing bids at the price $P_{max,N}$ are included in the exporting zone (these extra purchases are exported), while selling bids at the price $P_{min,N}$ are defined in the importing zone (these extra sells are imported). This way, the bids and offers are to be activated in the northern price coupling.

Let $F_{b,N}(\boldsymbol{v_N}, \boldsymbol{f^0_{N\to S}})$ be the additional producer or consumer surplus associated to the unlimited bids and offers, which quantities are determined by $\boldsymbol{f^0_{N\to S}}$. The case of the exporting and importing interconnectors shall be differentiated in $\{I_{N,exp}\}$ and $\{I_{N,imp}\}$ forming a partition of $\{I_{N\to S}\}$.

$$\{I_{N,exp}\} = \{i \in \{I_{N\to S}\}, f^0_{N\to S,i} \geq 0\} \tag{2.3}$$

$$\{I_{N,imp}\} = \{i \in \{I_{N\to S}\}, f^0_{N\to S,i} < 0\} \tag{2.4}$$

The surplus $F_{b,N}$ is thus an addition of purchasing and selling surpluses from the exporting (purchases at any price) and importing (sells at any price) zones, respectively. Note that the 'minus' sign in the second term is added to translate the negative flows from North to South into a positive surplus.

$$\begin{aligned} F_{b,N}(\boldsymbol{v_N}, \boldsymbol{f^0_{N\to S}}) = &\sum_{i\in\{I_{N,exp}\}} (P_{max,N} - x_{N,i}(\boldsymbol{v_N})) \cdot f^0_{N\to S,i} \\ &+ \sum_{i\in\{I_{N,imp}\}} (x_{N,i}(\boldsymbol{v_N}) - P_{min,N}) \cdot (-f^0_{N\to S,i}) \\ &= -\boldsymbol{x_N(v_N)} \cdot \boldsymbol{f^0_{N\to S}} + \sum_{i\in I_{N,exp}} P_{max,N} * f^0_{N\to S,i} \\ &+ \sum_{i\in I_{N,imp}} P_{min,N} \cdot f^0_{N\to S,i} \end{aligned} \tag{2.5}$$

From equations (2.2) and (2.5), the objective function F'_N for the price coupling of the northern area can be rewritten in (2.6) as a function of the volume coupling objective function F_N.

$$\begin{aligned} F'_N(\boldsymbol{v_N}, \boldsymbol{f^0_{N\to S}}) &= F_N(\boldsymbol{v_N}, \boldsymbol{f^0_{N\to S}}) - F_{f,N}(\boldsymbol{v_N}, \boldsymbol{f^0_{N\to S}}) + F_{b,N}(\boldsymbol{v_N}, \boldsymbol{f^0_{N\to S}}) \\ &= F_N(\boldsymbol{v_N}, \boldsymbol{f^0_{N\to S}}) \\ &+ \sum_{i\in\{I_{N,exp}\}} P_{max,N} \cdot f^0_{N\to S,i} + \sum_{i\in\{I_{N,imp}\}} P_{min,N} \cdot f^0_{N\to S,i} \end{aligned} \tag{2.6}$$

Therefore, the new objective function F'_N is equal to F_N plus $\Delta F_N(\boldsymbol{f^0_{N\to S}})$ which is a constant expressed in (2.7).

$$\Delta F_N(\boldsymbol{f^0_{N\to S}}) = \sum_{i\in\{I_{N,exp}\}} P_{max,N} \cdot f^0_{N\to S,i} + \sum_{i\in\{I_{N,imp}\}} P_{min,N} \cdot f^0_{N\to S,i} \tag{2.7}$$

Obviously, the situation is similar in the southern region, with $P_{min,S}$ and $P_{max,S}$ as the price caps. The new objective function F'_S is equal to F_S plus a constant $\Delta F_S(\boldsymbol{f^0_{N\to S}})$:

$$\Delta F_S(\boldsymbol{f^0_{N\to S}}) = -\sum_{i\in\{I_{N,imp}\}} P_{max,S}\cdot f^0_{N\to S,i} - \sum_{i\in\{I_{N,exp}\}} P_{min,S}\cdot f^0_{N\to S,i} \tag{2.8}$$

3. Relations between the optimization solutions and conclusion about adverse flow events

3.1. **Assumptions.** First, it is assumed that price couplings in the northern area (respectively the southern area) use the set of constraints $\{C_N\}$ (respectively $\{C_S\}$), i.e., the three optimizations EMCC, CWE and Nordpool market couplings work with similar constraints. This assumption is reasonably acceptable if the volume coupling and the price couplings share a common network model.

Second, it is assumed the solution of the volume coupling is unique. In fact, it is conceivable that two differing solutions may provide the same surplus. In this case, it is also conceivable that an additional step in the three algorithms use a common discriminatory process to select one of the optimal outcomes. With this additional step the solution can be made unique.

Third, it is assumed that the three numerical solvers converge to the optimal solution within the period allocated to them. This is the main assumption, given the complexity of the non-convex Mixed-Integer Linear Programming (MILP) problem induced by the introduction of block bids [14].

3.2. **Mathematical intuition.** The idea is that when the interconnection capacities are fixed by the volume coupling, the space of possibilities of the optimization problem is reduced. This could lead to adverse flows if the optimal point was not included in the new optimization problems.

However, since the variables are fixed with the results of the optimization, the reduced space of possibilities still include the first optimal solution. Therefore, there should not be any adverse flows as shown in the following paragraph.

3.3. **Mathematical proof.** Let $(\boldsymbol{v^0_N}, \boldsymbol{v^0_S}, \boldsymbol{f^0_{N\to S}})$ be the result of the volume coupling, i.e., the optimal solution of the optimization problem (3.1).

$$\max_{\boldsymbol{v_N},\boldsymbol{v_S},\boldsymbol{f_{N\to S}}} F(\boldsymbol{v_N}, \boldsymbol{v_S}, \boldsymbol{f_{N\to S}}),\ \text{subject to } \{C\} \tag{3.1}$$

Following this first optimization, $\boldsymbol{f^0_{N\to S}}$ is fixed and the two price couplings are performed separately. For example, the optimization problem for the northern area is given in (3.2). The additional term $\Delta F_N(\boldsymbol{f^0_{N\to S}})$, introduced in equation (2.7), does not impact the optimum point of the price coupling optimization because it is a constant. Therefore, it can be removed from the optimization problem.

$$\begin{aligned} &\max_{\boldsymbol{v_N}} F'_N(\boldsymbol{v_N}, \boldsymbol{f^0_{N\to S}}),\ \text{s.t. } \{C_N\} \\ \Leftrightarrow &\max_{\boldsymbol{v_N}} F_N(\boldsymbol{v_N}, \boldsymbol{f^0_{N\to S}}) + \Delta F_N(\boldsymbol{f^0_{N\to S}})\ \text{s.t. } \{C_N\} \\ \Leftrightarrow &\max_{\boldsymbol{v_N}} F_N(\boldsymbol{v_N}, \boldsymbol{f^0_{N\to S}})\ \text{s.t. } \{C_N\} \end{aligned} \tag{3.2}$$

Similarly, the optimization problem for the southern region is equivalent to:

$$\max_{\boldsymbol{v_S}} F_S(\boldsymbol{v_S}, \boldsymbol{f^0_{N\to S}}) \text{ s.t. } \{C_S\} \tag{3.3}$$

Let v_N^1 and v_S^1 be the optimal solutions to problems (3.2) and (3.3), respectively, and:

$$F_N^0 = F_N(v_N^0, f_{N\to S}^0) \tag{3.4}$$

$$F_N^1 = F_N(v_N^1, f_{N\to S}^0) \tag{3.5}$$

$$F_S^0 = F_S(v_S^0, f_{N\to S}^0) \tag{3.6}$$

$$F_S^1 = F_S(v_S^1, f_{N\to S}^0) \tag{3.7}$$

On both sides of the border, the new optimization can at least achieve the same value for F_N and F_S. Indeed, the EMCC solution is included in the space of possibilities, i.e., $\boldsymbol{v^0_N}$ and $\boldsymbol{v^0_S}$ are still possible outcomes. Therefore:

$$F_N^1 \geq F_N^0 \tag{3.8}$$

$$F_S^1 \geq F_S^0 \tag{3.9}$$

Summing term by term leads to the new relation (3.10).

$$\begin{aligned} & F_N^1 + F_S^1 \geq F_N^0 + F_S^0 \\ \Leftrightarrow & F_N^1 + F_S^1 \geq F^0 \end{aligned} \tag{3.10}$$

From relation (3.10), it is obvious that the outcomes of price couplings cannot be different from the volume coupling.

Proof. Since the point $(\boldsymbol{v^1_N}, \boldsymbol{v^1_S}, \boldsymbol{f^0_{N\to S}})$ is fulfilling the constraints $\{C\}$ of the EMCC optimizer, and since it results in a solution at least as optimal as the EMCC optimization as shown in (3.10), then $(\boldsymbol{v^1_N}, \boldsymbol{v^1_S}, \boldsymbol{f^0_{N\to S}})$ shall be equal to $(\boldsymbol{v^0_N}, \boldsymbol{v^0_S}, \boldsymbol{f^0_{N\to S}})$. □

Thus there shall not be any adverse flow, and the volume coupling solution is as optimal as the result of a single price coupling, except that the duration of the process between the gate closure and the clearing time may be longer with the volume coupling solution.

3.4. **Conclusion on the explanation of adverse flow events.** The mathematical argumentation given in section 3.3 proves that adverse flows should only appear if at least one of the three assumptions made in section 3.1 is not fulfilled.

The first assumption is not fully met as highlighted in the EMCC's communication summarized in section 1.3. Nevertheless, these issues can be solved with a reasonable level of coordination. Similarly, the second assumption can be fulfilled with a coordinated selection process to discriminate two solutions offering the same outcome.

Last, adverse flows can also appear if the third assumption is not met, i.e., if the numerical solvers provide an acceptable solution which is not necessary the optimum. In practice, this issue appears with block bids and other sophisticated products, which introduce binary variables in the optimisation problem [12].

This demonstration brings a new theoretical insight completing the pragmatic explanation of adverse flow events given in reference [9].

4. Potential application of this analytical model in more general cases

Before the next section presenting an improved interim tight volume coupling solution, this section points at three other cases that can be studied with the model developed in section 2 for the EMCC case. The aim is to illustrate that the conclusion of section 3.4 can also be valid for another interim tight volume coupling solution with differing conditions, including at least the conditions listed in this section.

4.1. **Generalization to more than two areas.** The model used in this paper could be easily generalized to numerous regions. The results of this paper would thus apply to a volume coupling handling interconnectors between more than two regions.

4.2. **Generalization to other products.** A market platform in one or more areas covered by a tight volume coupling might be willing to offer standard products differing from the one considered in the EMCC's case. The conclusions of this paper would remain valid if these products fit in the model described in section 2 without any modification.

4.3. **Compliant with flow-based.** The current market coupling frameworks in Europe use so-called ATC-based[5] transmission capacity values in the algorithm. A flow-based solution is expected to calculate more optimally the physical transmission capacities and the TSOs of the CWE region intend to implement it [3].

For example, in the model described in section 2, the flow-based implementation in the northern area would lead to the change of $\{C_N\}$ to $\{C_N^{flow-based}\}$, a new subset of constraints. The new transmission constraints have a more complex expression, but they can be kept linear. Therefore, if flow-based capacity calculation is applied independently in one or both areas, the model used in this paper is still valid assuming that the EMCC updates its algorithm to manage it similarly, meaning it would work with the new set of constraints $\{C^{flow-based}\} = \{C_N^{flow-based}\} \cup \{C_S\} \cup \{C_I\}$.

As a result, the flow-based capacity calculation in one area would not prevent inherently the implementation of a volume coupling with another area. This result can also be found in a technical report about flow-based implementation in the CWE area [15].

5. Perspectives for an improved interim tight volume coupling

If a single price coupling solution proves to be fairly efficient, it is agreed that it should be preferred to a tight volume coupling solution. As stated in the introduction, the EMCC runs an interim solution that shall be replaced sooner or later. Moreover, the difficulties encountered with the first experiments on the Kontek cable between Germany and Denmark may have limited the enthusiasm for the volume coupling solution [6], while a European price coupling solution is progressing [16], supported by potential improvements of the algorithms [17].

[5]Where ATC stands for Available Transmission Capacity.

Nevertheless, this section intends to show that the door should be kept open for improved interim tight volume coupling solutions in specific cases as in the example described in section 5.2.

5.1. **Criteria for a good coupling of day-ahead electricity markets.** The three following criteria shall be used to assess the quality of a coupling between two or more day-ahead markets:

- the distance to the optimum solution, which can be evaluated afterwards;
- the duration of the process between the day-ahead market gate closures and the market clearings;
- the capacity to handle complex electricity products.

The acceptability of a new solution depends not only on these criteria but also on the initial situation and on the expected visible improvements. In particular, the acceptability of a volume coupling depends on a low occurrence of adverse flows, i.e., low visible inefficiencies.

5.2. **An improved tight volume coupling if a single price coupling solution fails to obtain acceptable results.** If the implementation study of a single price coupling solution does not bring satisfactory results[6], the following interim solution might be more acceptable, while offering better outcomes than explicit allocation. Compared to the classical volume coupling, the proposed solution should improve cross-border allocation between areas, while preserving the market efficiency in the coupled areas.

The improvements are based on additional coordination between the volume and price coupling numerical solvers:

- The first improvement can be assimilated to a hot start, a method used in various optimisation processes [18]. The principle is that some additional output data from the first numerical solver may be useful to accelerate the calculation of the price coupling solutions. It should result in a more efficient utilisation of the duration allocated to the market coupling process.
- The second improvement is to allow a progressive evolution toward a single price coupling within a stable market coupling organisation for the market players.

The resulting mechanism is shown in figure 3 based on the notation used in section 2. Let t_0 be the gate closure of the day-ahead market couplings and let $(t_{max} - t_0)$ be the maximum duration given to the whole coupling process.

(1) The volume coupling is operated with the algorithm built as if it were to be used as a single price coupling. This optimization is performed between t_0 and a time t_1 with $t_1 < t_{max}$.
(2) At t_1, the cross-border flows are fixed (as $\boldsymbol{f^0_{N\to S}}$) and the numerical solver is copied *in its current state* in each of the two areas. In the northern area, the variable $\boldsymbol{v_S}$ is fixed at $\boldsymbol{v^0_S}$ while in the southern area $\boldsymbol{v_N}$ is fixed at $\boldsymbol{v^0_N}$. Though this operation can be performed reasonably quickly in theory, operational procedures should be designed carefully to reduce this duration as much as possible.

[6]Such a situation may appear while applying market coupling to other time horizons or geographical areas, resulting in a too large or too complex optimization problem.

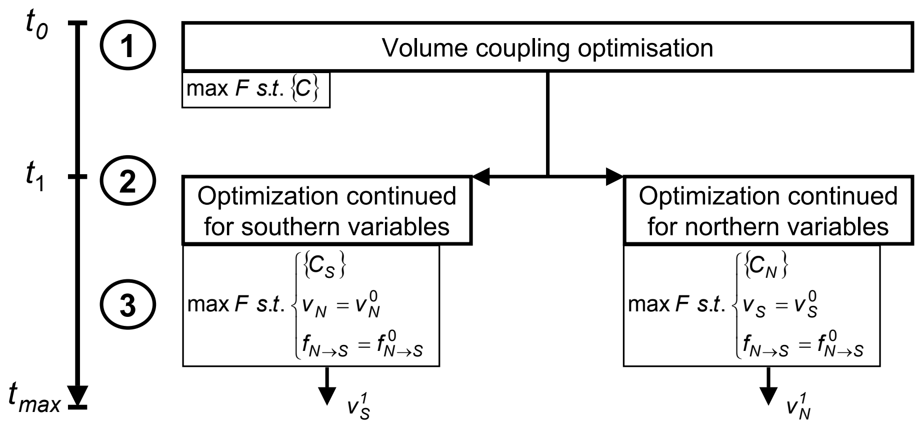

FIGURE 3. Scheme of the proposed improved volume coupling with price couplings taking over the same optimization process.

(3) Between t_1 and t_{max}, the two new problems with their reduced number of optimization variables are run in parallel. They start exactly where the volume coupling stopped with all that has been "learned" by the algorithm between t_0 and t_1.

At the end, even if $\boldsymbol{f^0_{N\to S}}$ is fixed at a not-so-optimal state, the hope is that the overall solution $(\boldsymbol{v^1_N}, \boldsymbol{v^1_S}, \boldsymbol{f^0_{N\to S}})$ might be better than the one the single price coupling would have found. The potential benefits lies in the fact that the problem is transformed into two smaller sub-problems run in parallel between t_1 and t_{max} in the improved volume coupling solution. These two sub-problems are solved with a reduced number of variables and constraints, while benefiting from the learning made between t_0 and t_1.

The choice of t_1 between t_0 and t_{max} could for example be determined empirically. It can be fixed before the optimization has started or it can be linked to an indicator of convergence towards a stable solution. In the second case, an upper boundary $t_{1,max}$ can be fixed. Besides, this choice can evolve with the exogenous constraints, such as an improvement of the numerical solvers. For instance, when the numerical solvers are improved so that the benefits of a better calculation after t_1 do not compensate anymore the fact that $\boldsymbol{f^0_{N\to S}}$ is less optimal than it could be, it will be decided that t_1 is pushed further from t_0. When t_1 reached t_{max}, it means that the single price coupling solution has become the best option.

Similarly, the choice of the internal interconnectors fixed in $\boldsymbol{f^0_{N\to S}}$ can also evolve as a function of the network topology, the solver capacities, or political issues.

5.3. **Test of the proposed solution.** The stakeholders having access to the appropriate data and algorithms are well placed to test this solution if there is any interest for it.

6. Conclusion

The interim tight volume coupling run by the European Market Coupling Company is to be replaced sooner or later by another solution. Nevertheless, the volume coupling principle can still inspire pragmatic solutions for future challenges.

A new analytical model of the tight volume coupling is developped in this paper. A brief mathematical demonstration offers a new perspective on the causality of adverse flow events which completes the pragmatic reasons already described in the available documents. Furthermore, this analytical model could be applied with minor modifications to any number of areas, other kinds of traded products or areas using a flow-based method.

Learning from the ITVC experience, this paper proposes an example of improvement of the tight volume coupling method based on a stronger coordination between the numerical solvers. This improved mechanism could serve as an interim solution if a price coupling numerical solver do not provide satisfactory results because the optimisation problem is too large or too complex. In this case, the proposed solution is expected to be a satisfactory implicit allocation method from both technical and governance points of view.

7. List of symbols and abbreviations

7.1. Abbreviations.

ACER Agency for the Cooperation of Energy Regulators
ATC Available Transmission Capacity
CWE Central West Europe
EMCC European Market Coupling Company
ITVC Interim Tight Volume Coupling
MILP Mixed Integer Linear Programming
PCR Price Coupling of Regions
PX Power exchange
TSO Transmission System Operator

7.2. Symbols.

$\{C\}$ the set of constraints of the volume coupling optimization problem
$\{C_I\}$ the subset of constraints involving only optimization variables included in the vector $\boldsymbol{f_{N \to S}}$
$\{C_N\}$ the subset of constraints involving at least an optimization variable included in the vector $\boldsymbol{v_N}$
$\{C_S\}$ the subset of constraints involving at least an optimization variable included in the vector $\boldsymbol{v_S}$
ΔF_N the difference between F_N and F'_N
ΔF_S the difference between F_S and F'_S
$\boldsymbol{f_{N \to S}}$ the vector of the flows on the interconnectors between the northern and the southern area
F the objective function of the volume coupling
F_N the restriction to the northern area of the objective function of the volume coupling
F_S the restriction to the southern area of the objective function of the volume coupling

F'_N	the objective function of the northern price coupling
F'_S	the objective function of the southern price coupling
$\{I_{N\to S}\}$	the set of interconnection flows which are corresponding to the elements of $\boldsymbol{f_{N\to S}}$
$\{I_{N,exp}\}$	the subset of $\{I_{N\to S}\}$ of all interconnection flows exporting from the northern area
$\{I_{N,imp}\}$	the subset of $\{I_{N\to S}\}$ of all interconnection flows importing to the northern area
$P_{min,N}$	the minimum price in the northern area
$P_{max,N}$	the maximum price in the northern area
$\boldsymbol{v_N}$	the vector of all variables strictly in the northern area, including the zonal prices, the internal flows, the accepted bids, etc.
$\boldsymbol{v_S}$	the vector of all variables strictly in the southern area, including the zonal prices, the internal flows, the accepted bids, etc.
$\boldsymbol{x_N}$	the vector of zone prices in the northern area corresponding to the elements of $\boldsymbol{f_{N\to S}}$
t_0	the time when the improved volume coupling is launched
t_1	the time when the improved volume coupling shifts to independent price couplings
$t_{1,max}$	the maximum value for t_1
t_{max}	the maximum duration of the improved solution for market coupling

In addition, the numbers 0 and 1, placed in superscript next to a vector of variables or an objective function, refer to a result from the volume coupling and price coupling, respectively.

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(T. Janssen) PhD student at Université Paris XI, Economics Department, under the direction of J.-M. Glachant, Director of the Florence School of Regulation.

(Y. Rebours) Researcher at EDF R&D, Economy, Operation and Analysis of Energy Systems Department. Corresponding Author. Address: 1, avenue du Général de Gaulle BP 408 - 92141 Clamart, FRANCE. Email: yann.rebours@ieee.org. Phone number: +33147655730. Fax number: +33147653734.

(Ph. Dessante) Adjoint professor at Supélec, Energy Department.

Author contacts:

Tanguy Janssen and Yann Rebours

EDF R&D

1, avenue du Général de Gaulle

F-92141 CLAMART Cedex

Email : tanguy.janssen@supelec.fr

Email : yann.rebours@ieee.org

Philippe Dessante

SUPELEC

Départment d'Electrotechnique et de Systèmes d'Energie

Plateau de Moulon

3 rue Joliot Curie

91192 Gif-sur-Yvette cedex

France

Email : philippe.dessante@supelec.fr

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