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MEASURING INEFFICIENCY IN INTERNATIONAL ELECTRICITY TRADING

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Keywords Electricity trading efficiency; cross-border allocation; interconnector; market coupling; metrics.

JEL Classification : C81; F14 ; F15; Q41

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Measuring inefficiency in international electricity trading

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ABSTRACT

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KEYWORDS

Electricity trading efficiency; cross-border allocation; interconnector; market coupling; metrics.

HIGHLIGHTS

1. Measures of electricity trading inefficiency are reviewed and classified
2. New measures that are robust to market conditions are devised
3. The new measures are quantitatively assessed against existing measures
4. EU market coupling regulations have largely reduced trading inefficiency
5. The potential economic loss from market uncoupling is substantial

ABBREVIATIONS

4MMC	4M Market Coupling
ACER	Agency for the Cooperation of Energy Regulators
CWE	Central Western Europe
DA	Day-ahead
EUPHEMIA	Pan-European Hybrid Electricity Market Integration Algorithm
FAPD	Flow against price differential
FBMC	Flow Based Market Coupling
FWPD	Flow with price differential
IEM	Integrated Energy Market
MRC	Multi Region Coupling
NTC	Net transfer capacity
PCR	Price Coupling of Regions
QREEM	Quarterly Report on European Electricity Markets

1 Introduction

Interconnectors create value by enabling electricity imports from markets with lower prices as an alternative to higher-priced indigenous generation. This reduces the overall cost of supplying electricity across the two systems and would be expected to reduce consumer prices in the importing country and increase consumer welfare there. In the future, interconnectors could become increasingly valuable as electricity generation becomes more variable due to higher renewable generation. In response, countries are investing extensively in interconnectors. Imports might be expected primarily during periods of high residual demand, while exporting surplus renewable electricity helps avoid curtailment.

While interconnectors have been used in Europe for decades, the EU's Integrated Electricity Market (IEM) was established in 2014 to allow electricity to be traded freely between member states, with markets coupled to improve the economic efficiency of the interconnector flows (ACER, 2015). This means that all coupled markets are cleared simultaneously with transmission capacity allocated so that electricity flows from lower to higher priced zones until either prices equalise or interconnector capacity is fully used (ACER, 2017). By 2019, 23 European countries had coupled markets,[1] with algorithms used to ensure that the total consumer and producer surplus is maximised. This has led to more efficient coordination of trading over multiple electricity systems, and substantial welfare gains (Newbery *et al.*, 2016). Welfare gains[2] between markets depend on the price differential between the two connected markets as well as the efficiency of electricity trading (Ochoa and van Ackere, 2015).

In this paper, we systematically evaluate various metrics of day-ahead trading inefficiency for the first time. Based on this analysis, two new measures of trading inefficiency are proposed, and evaluated against existing metrics using a series of trading patterns and historical trading data. Historical measures of trading inefficiency do not incorporate valuable information about direction of flows or transfer capacity, so we devise new measures that improve on existing ones.

We also explore the potential economic losses of market uncoupling, investigating its impact on net electricity imports, price differentials, trading inefficiency, and the private and social value of the interconnectors to France and The Netherlands. The UK's foreseen withdrawal from the European Union is expected to result in Great Britain uncoupling from Continental electricity markets, with cross-border markets set to operate at different times. Understanding the impact of market uncoupling on the efficiency of cross-border trade is required to design policies that minimise likely welfare losses. This analysis will allow us to evaluate the reduction in efficiency from post-Brexit market uncoupling and provide valuable insights on the potential impact of uncoupling on cross-border trade.

The paper:

1. classifies the current measures of day-ahead trading inefficiency;
2. reviews the literature on trading inefficiencies and related measures;
3. devises new measures of inefficiency that improve over existing ones;
4. quantitatively assesses these new measures against existing measures; and
5. assesses the potential economic losses from market uncoupling.

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[1] Nineteen via Multi Regional Coupling (MRC) and four via 4M Market Coupling (4MMC) covering the Czech-Slovak-Hungarian-Romanian market areas.

[2] For more information about approaches to estimating welfare gains, including a summary of advantages and disadvantages is given in Appendix G.1

2 Electricity trading via interconnectors

Most EU and EEA interconnectors offer capacity in forward and day-ahead auctions. These allow traders the opportunity to profit from differences in electricity prices between connected markets. It also allows traders the opportunity to hedge existing physical positions. For example, a trader who purchased electricity in France and sold electricity in Great Britain can forward-buy interconnector capacity from France to Great Britain, to hedge unexpected uncertainty from day-ahead price differentials.

Day-ahead capacity is nominated and scheduled at around midday on the day prior to delivery. Traders subsequently have an opportunity to buy and nominate capacity in the intra-day market typically until a few hours before flow. The intra-day nomination can increase, reduce or even reverse the day-ahead scheduled flow. For this reason, if 1,500 MW of the 2,000 MW capacity from France to Great Britain has been scheduled, it is possible in the intra-day market to nominate an additional 500 MW from France to Great Britain, or to nominate as much as 3,500 MW from Great Britain to France.

Nominated flow positions are netted against physical purchases and sales in the individual markets. These products can be entered into in bilateral forward markets, on day-ahead exchanges, or intra-day either bilaterally or on exchanges. A trader's net position in each market is settled via balancing mechanisms, which can be highly volatile, hence most traders will seek to ensure they are balanced in each market before the delivery period.

2.1 Market coupling

Historically, national electricity markets were “uncoupled”, which meant interconnector capacity scheduling and purchasing/selling electricity in each market took place separately. Trading in uncoupled markets leads to inefficient outcomes characterised by a proportion of electricity flows from higher to lower priced regions, known as Flows Against the Price Differential (FAPD) (ACER, 2012). These are caused by information asymmetry, for example from markets closing at different times.

To avoid this, a number of European day-ahead markets introduced coupling in 2014 using a shared algorithm known as EUPHEMIA (ACER, 2017). EUPHEMIA uses bids and offers for electricity in each market, along with interconnector constraints, and generates optimal flows. Under this algorithm, interconnector flows will be directed from low to high price regions, until either the price differential is eliminated or the interconnector reaches full capacity. Day-ahead markets are now coupled across continental Europe, while the British-Irish interconnectors were coupled in October 2018. Intra-day coupling became available in 2018 for some European markets (although not for the GB market), while balancing market coupling is still at an early stage in Europe (ACER, 2017). A description of trading in coupled and uncoupled electricity markets is provided in Appendix F2.

2.2 Benefits of reducing trading inefficiency through market coupling

Inefficient use of interconnector capacity implies a missed opportunity to increase total welfare by buying electricity in the lower-priced market, flowing and selling in the higher-priced market. The size of the gains from coupling is more challenging to estimate, as it depends on estimates of the frequency and impact of suboptimal flow, which change over time. Moreover, the gains reduce with additional interconnector capacity, but increase with more variable generation.

Newbery *et al.* (2016) estimated the potential benefit to the EU of coupling interconnectors to increase the efficiency of trading day-ahead, intra-day and sharing balancing services efficiently across borders. They find that further gains are possible by eliminating unscheduled flows and avoiding the curtailment of renewables, with short-run gains potentially as high as €3.3bn/yr more than the then current gains from trade. The authors also find that one-third of these benefits comes from day-ahead coupling and another third from shared balancing. Newbery *et al.* (2013) reviewed the literature on the quantitative benefits of market integration. More recent evidence surveyed by Pollitt (2018) concludes that measurable benefits of the Integrated Electricity Market are likely to be small in total in part because there has been a large rise in subsidised renewable generation that has not been efficiently allocated across member states.

3 Measures of trading inefficiency

This paper focuses on trading efficiency based on the day-ahead market. It considers metrics of cross-zonal capacity utilisation inefficiency, which are measures that determine how inefficiently transmission capacity is used over interconnectors linking two price zones. The economic inefficiency of interconnector flows is the percentage of interconnector capacity that is not allocated such that electricity flows from lower to higher priced zones until either prices in each zone equalise. If interconnector capacity is fully used and flows are in the efficient direction then the capacity is efficiently used.

Analyses of trading efficiency in the different time frames (day-ahead and intra-day) involve several approaches and varying degrees of complexity. Metrics for trading inefficiency are categorised based on the data used by these measures and include: (i) price-based; (ii) flow-based; and, (iii) price- and flow-based metrics. Detailed discussions of these metrics are provided in the next three subsections, and the associated studies is given in Table 1.

Method	Data	Report/Author	Metric description/method
Historical analysis	*Price*	ACER (2011)	Percentage of hours when hourly day-ahead (DA) prices were equal.
		ACER (2012)	Categorised (low, medium, high) DA price convergence.
		EU Commission (2012-Q3)	Weekly ratio of price convergence.
		EU Commission (2012-Q2)	Percentage of hours with price convergence below 1%.
	Flow	ACER (2012)	Indexed annual aggregation of hourly NTC values.
		ACER (2012)	Capacity utilisation ratio.
		ACER (2017)	Absolute sum of net nominations.
	Price and flow	Montoya *et al.* (2019)	Unweighted Inefficient Interconnector Utilisation (UIIU) – Eq.4*
		Montoya *et al.* (2019)	Price-Weighted Inefficient Interconnector Utilisation (PWIIU) – Eq.5*
		ACER (2012)	Percentage of hours with day-ahead nominations against price differentials.
		ACER (2018)	Percentage of the available NTC used in the correct economic direction.
		ACER (2012)	Loss in Social welfare.
		EU Commission (2010-Q3)	Unweighted Flows Against Price Differential (UFAPD, or FAPD).
		EU Commission (2010-Q3)	Split of flows against price difference by subcategory of pre-established intervals of price differentials.
		EU Commission (2010-Q3)	Monetary value of energy exchanged in inefficient flow regime.
		EU Commission (2010-Q3)	Sum of hourly values of absolute price differentials multiplied by net cross border flows.
		Newbery *et al.* (2019)	Value Destruction.
		Newbery *et al.* (2019)	Percentage of potential congestion revenue.
		Meeus (2011)	Test on unused capacity times price differential.
Simulation-based analysis		ACER (2011)	Measures of social welfare.
		De Jong *et al.* (2007)	
		Newbery *et al.* (2016)	

Table 1. Classification of measurements used for measuring market coupling. The shaded area denotes measures of cross-zonal capacity utilisation efficiency. * indicates the present study.

To understand how existing metrics are affected under various market conditions, we consider possible combinations and magnitudes of price and flow differentials between pairs of markets. We focus on price-and-flow-based metrics because these are the most widely used and informative, since they employ more information on market allocations compared to metrics based on prices alone or flows alone. We describe in more detail the most commonly used metrics, including FAPD and related metrics of economic inefficiency. (A full description of price-based metrics and flow-based metrics, including their advantages and disadvantages, is provided in Appendix F.3.)

Price-based metrics mainly include mean or median price differentials and econometric methods to assess prices, including correlation and co-integration analyses (Castagneto Gissey *et al.*, 2014; ACER, 2015, 2017). Flow-based metrics include: Indexed annual aggregation of hourly NTC values; Capacity utilisation ratio; and Absolute sum of net nominations per year (ACER, 2012; 2018). Here we focus on price-and-flow based metrics, which include more information about trades and are most commonly used for policy.

3.1 Price-and-flow-based metrics

Flows Against the Price Differential (*FAPD*)*.* This measures the number of times in which electricity flows from lower to higher priced zones (EU Commission, 2010). In any time period, the *FAPD*, is the total number of inefficient imports (and exports) N^{-} divided by the total number of flows *N* and is defined by the following metric:

$$FAPD = UFAPD = I_1 = \frac{N^{-}}{N}\,. \tag{1}$$

Since the magnitude of the price differential is not reflected in the *FAPD*, we refer to this as the Unweighted FAPD or *UFAPD* in this paper. *UFAPD* values between 2% and 6% have been found by Newbery *et al.* (2016), representing the imperfect coupling in European day-ahead markets over interconnectors between Germany, Denmark, Spain and France before 2014.

The simplicity of *UFAPD* is attractive due to its ease of implementation and interpretation. Yet it lacks information regarding the quantity of electricity traded unprofitably and the price differentials at which these trades occurred. For example, the 0.01% inefficient flows for Belgium-Netherlands lead to 53% of the potentially valuable trade being exchanged during inefficient flows (Figure 2). Hence judging the inefficiency of an interconnector utilisation based solely on *UFAPD* could be highly misleading.

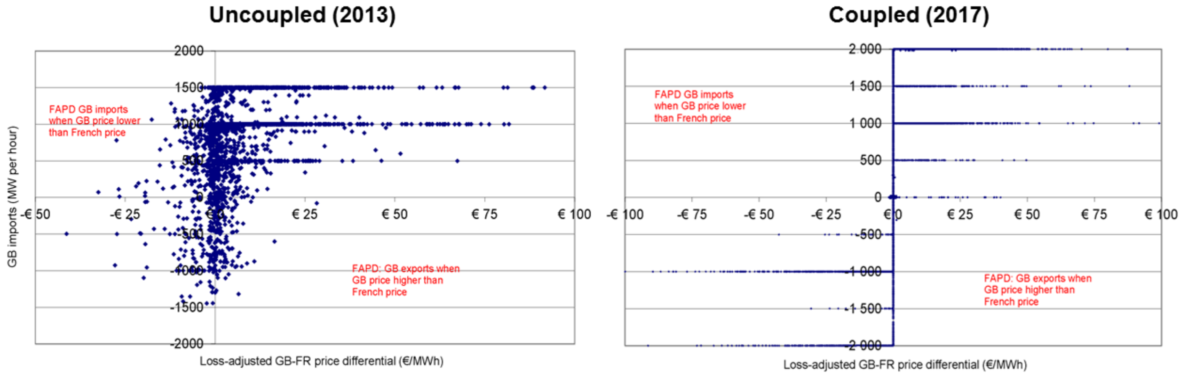

Figure 1. GB scheduled net imports vs price differentials on the IFA interconnector between GB and France before and after the 2014 implementation of the EUPHEMIA market coupling algorithm. For additional related graphs see also Appendix B.

Figure 1 shows the combinations of net scheduled imports and transmission loss-adjusted price differentials relating to trades over the IFA interconnector between GB and France in two years, before and after the 2014 coupling. The figure, which we refer to as the 'S-curve', presents the raw scheduled commercial exchanges, so it does not account for the possibility of unplanned outages or unscheduled maintenance. There are horizontal bands of observations at multiples of 500 MW because of periodic partial de-rating of one or more cables (IFA constitutes four 500-MW cables). Note the absence of costly imports and low-priced exports in the coupled period, where electricity flowed in the efficient economic direction. In this case the S-curve suggests *UFAPDs* close to zero.

The pre-2014 situation is quite different and clearly shows strong deviations from the perfect trading described earlier. There are persistent price differentials even with no capacity restrictions, which suggests that trading was not fully efficient, with numerous periods with electricity flowing in the wrong direction. Possible reasons for inefficient use were investigated by various authors (Bunn and Zachmann, 2010; Ehrenmann and Smeers, 2005; Geske *et al.*, 2018), and include: uncertainty from the separate energy and transmission markets; system operators being required to schedule cross-border flows for congestion and system balancing; and strategic trading by generators with market power. Here, the S-curve is highly dispersed, indicating severely inefficient trading.

Weighted FAPD (*WFAPD*). The Weighted FAPD, *WFAPD,* (EU Commission, 2010) accounts for the monetary value of the uneconomic flows and is defined as:

$$WFAPD = I_2 = \frac{\sum_h^{N^-} |\tilde{f}_h^- * x_h^-|}{\sum_h^{N^-} |\tilde{f}_h^- * x_h^-| + \sum_h^{N^+} |\tilde{f}_h^+ * x_h^+|}, \tag{2}$$

where – and + denote 'wrong' (inefficient) and 'correct' (efficient) direction; $\tilde{f}$ are flows during hour h at a corresponding spread of x, or price differential; and $|\tilde{f} * x|$ is the absolute value of $\tilde{f} * x$. The EU Commission (2010) denotes "welfare loss" and "mark-up" as the numerator and denominator respectively. Figure 2 shows the inefficient flows for the Belgian-Dutch and Austrian-Italian markets, with the numbers in brackets indicating (in order) the Unweighted FAPD and Weighted FAPD, illustrating the differences between the metrics.

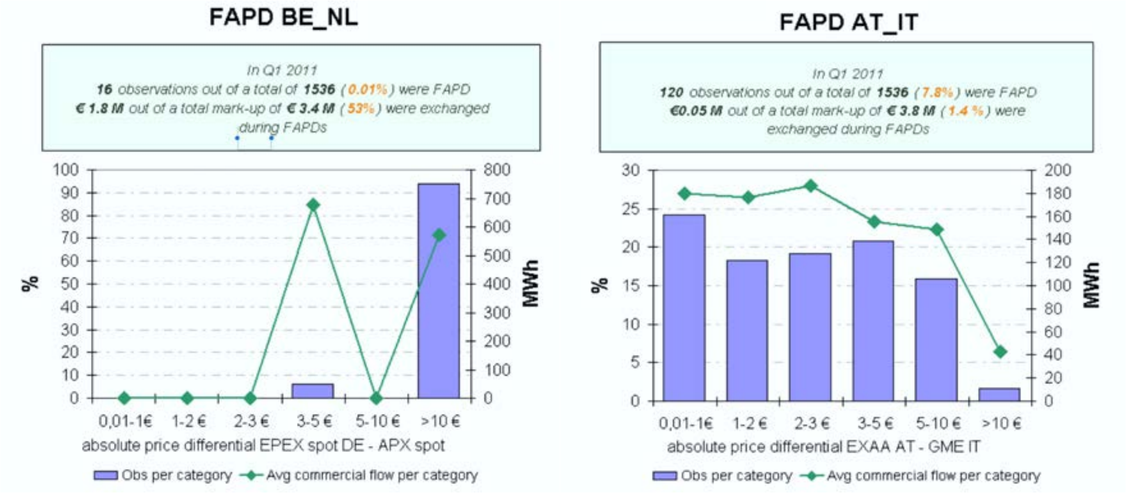

Figure 2. Chart of inefficient flows for the Belgian-Dutch and Austrian-Italian markets. Numbers in brackets indicate Unweighted FAPD (FAPD) and Weighted FAPD (WFAPD). Source: European Commission (2011-Q1).

The 53% value calculated using the *WFAPD* metric improves on this by addressing these two shortcomings but still fails to offer a complete and reliable description of interconnector inefficiency because it does not take account of the Net Transfer Capacity (NTC) actually available. In addition, during periods without inefficient flows, both measures indicate zero inefficiency so do not account for any inefficiencies resulting from underutilised NTC during efficient import or export periods. That is, if all flows were Flows With the Price Differentials (FWPD), it would not adjust accordingly in the case where, for example, only 50% or 25% of the available capacity was utilised when price differences remained.

Share of capacity used in the correct economic direction (*SCURED*)*.* Another measure of market coupling derives the share of capacity used in the correct economic direction and is illustrated in Figure 3. We reproduce this metric from ACER (2018) as:

$$SCURED^* = I_3^* = \frac{\sum_h^{N^+}\sum_i^B M_{i,x(h)>k}^+}{\sum_h^{N^+}\sum_i^B NTC_{i,x(h)>k}^+}. \tag{3}$$

Here N^+ represents the number of hourly (h) nominations (M) that occurred across a given border (B) in the efficient economic direction $(+)$ with the available capacity(NTC); k denotes a threshold (normally set to €1/MWh) to represent the level below which price differential (x) observations are excluded from the calculation. ACER (2018) uses this to derive the share of capacity used in the efficient direction relative to the price differential.

The advantage of *SCURED* is that it indicates how much of the capacity is used to flow electricity associated with a favourable price differential, but like *UFAPD* it lacks information about the price differential at which these flows occurred.[3] Another shortcoming is that the presence of flows against the price differential does not impact the metric at all and, as such, its accuracy diminishes as the number of inefficient flows increases.

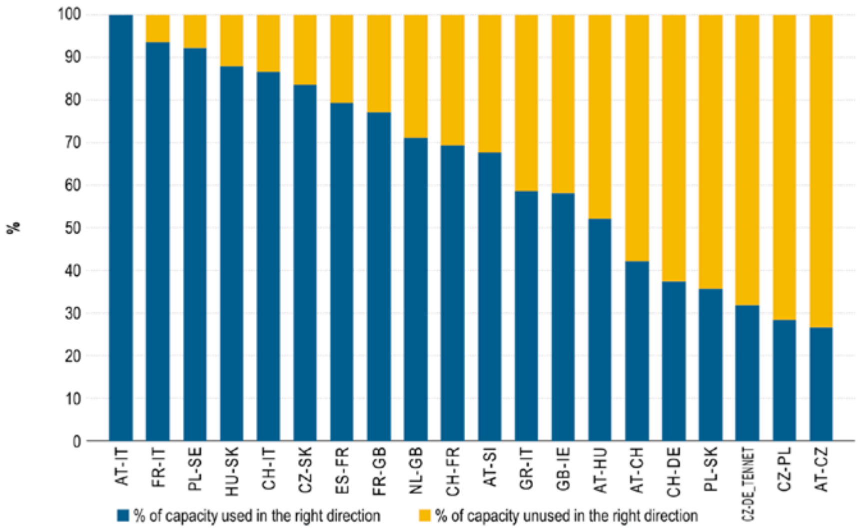

Figure 3. Percentage of NTC used in the correct economic direction for a selection of EU borders in 2011. Note that this was prior to coupling through EUPHEMIA. Source: ACER (2012).

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[3] Apart from these having occurred above the predetermined significant price differential threshold.

Inefficiency based on nominal capacity. If prices are materially different, interconnector capacity should be fully used, while it should be underused only if prices are essentially the same. This metric indicates the percentage of potential congestion revenue. For example, the BritNed interconnector has a capacity of 1,000 MW. From 2015–18 this measure of efficiency is 95% (€12,276/hr vs €13,378/hr), yielding €107 million/yr (Newbery *et al.*, 2019), assuming the interconnector is available at full capacity throughout each year. This is equivalent to 5% inefficiency. Its main advantage is that it is simple to estimate given the day-ahead market prices in each country and the nominal capacity of the interconnector, but its drawback is that full capacity may not be available for technical or other reasons, and so overstates what could actually be earned.

Value destruction. This is calculated as the physical flow times the price differential for flows against the price differential (FAPDs), indicating the amount of value that could have been generated by the interconnector but was not due to inefficient flows. Newbery *et al.* (2019) compute value destruction on the IFA interconnector before the 2014 coupling of GB and France. Value destruction in 2013 was 14% of the total value of €231m/yr at €31.9m/yr.

Several studies have calculated social welfare, but these can hardly be considered metrics as they typically depend on models of the underlying electricity system. With numerous assumptions varying across models and studies, this makes comparisons difficult. More information about measures of social welfare is given in Appendix F.4.

3.2 Defining an ideal metric for interconnector trading efficiency

The ideal metric should provide the highest degree of accuracy irrespectively of whether two markets are coupled or not. To ensure transparency, it should use information that is readily available to the public and not rely on proprietary data, which would restrict use. The underlying algorithm should ideally be simple to implement with commonly used software. These properties ensure reproducibility and auditability, but generally exclude the use of models.

As interconnectors have different capacities, the metric should facilitate comparisons of trade inefficiency, so absolute valued metrics (whether in currency or energy units) would make this difficult. An index ranging, for example, between 0% and 100% is easier to interpret.

3.3 Interconnector utilisation inefficiency metrics

We have developed two new metrics that uniquely include information not only on the direction of flows (both efficient and inefficient) and the price differential level, but also on the percentage of net transfer capacity used during the cross-zonal exchange. Our new metrics similarly have values ranging from zero to unity.

Considering a sample size *N*, of hourly *price differential* and *flow* combinations, we define the *Unweighted Inefficient Interconnector Utilisation*[4] (UIIU) metric as:

$$\begin{aligned} UIIU = I_4 = \left(\frac{N^-}{N}\right)\left(\frac{1}{N^-}\right)\sum_h^{N^-}\frac{(1+|f_h^-|)}{2} + \left(\frac{N^+}{N}\right)\left(\frac{1}{N^+}\right)\sum_h^{N^+}\frac{(1-|f_h^+|)}{1} \\ + \left(\frac{N^0}{N}\right)\left(\frac{1}{N^0}\right)\sum_h^{N^0}\frac{\left(1-\left|f_h^0\right|\right)}{1} \end{aligned} \tag{4}$$

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[4] A detailed derivation can be found in the Appendix A. A simplistic interpretation of Equation (1) is the average flow-distance from the S-curve weighted by the proportion of FAPDs (or FWPDs) observed in the corresponding (efficient or inefficient) region.

where

$$
\begin{aligned}
N &= N^- + N^+ + N^0 \\
F &= f^- + f^+ + f^0 \\
|f| &= absolute\ value\ of\ f \\
f_h &= \frac{\tilde{f}_h}{NTC_h}
\end{aligned}
$$

with the superscripts '-', '+', and *'0'*[5], denoting inefficient-*flow*[6], efficient-*flow* and *no-flow,*[7] respectively. *NTC* stands for Net Transfer Capacity, while $\tilde{f}_h$ is the hourly flow. *UIUU* is an index of trading *inefficiency* ranging from 0 to 1, with a value of 0 indicating no inefficiency (or 100% efficiency), and a value of 1 indicating maximum inefficiency (0% efficiency). This means that the level of *efficiency* can be extrapolated by simply subtracting the index from 1.

Consider two inefficient flows occurring at distinct price differentials: inefficient flow #1 occurs at 900 MW, at a price differential of €200/MWh; and inefficient flow #2 occurs at 900 MW, but at a €2/MWh price differential. Everything else being equal, inefficient flow #1 should be more inefficient than inefficient flow #2 due to the larger congestion rent loss. As the flows in Equation 4 already adjust by NTC, we adjust further by the price differential dimension (in an analogous fashion as *WFAPD* adjusted *UFAPD*) leading to the *Price-Weighted Inefficient Interconnector Utilisation* (PWIIU) metric.

$$PWIIU = I_5 = \sum_{h}^{N^-} w_h \frac{(1+|f_h^-|)}{2} + \sum_{h}^{N^+} w_h (1-|f_h^+|) + \sum_{h}^{N^0} w_h \tag{5}$$

where

$$w_h = \frac{|x_h|}{\sum |x_h|}$$

and x is the price differential. As *UIIU* is a measure between 0 and 1, we choose the weighting scheme w_h for *PWIIU* in such a way as to preserve these same bounds. Similarly, PWIIU is also an index ranging from 0 to 1, with a value of 0 indicating no inefficiency (or 100% efficiency), and a value of 1 indicating maximum inefficiency (0% efficiency).

Equation 4 is deliberately specified[8] to blend existing metrics (*UFPAD* and *SCURED**) in the special case of dealing with only one border and when NTC_h is constant over the sampled period. We can summarise Equation 4 as:

$$UIIU = (UFAPD)(\zeta) + \left(\frac{N^+}{N}\right)(1 - SCURED^*) + \left(\frac{N^0}{N}\right) \tag{6}$$

A Microsoft Excel formula is provided as an attachment to this paper to facilitate estimation. See Appendix C.

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[5] By definition, $f_h^0 = 0$.

[6] An inefficient flow is one against the price differential (FAPD).

[7] A no-flow is the event of zero IC utilisation given that a non-zero price differential occurred.

[8] The denominators of 1 and 2 emphasise the maximal flow distance of any point from the S-curve, where the S-curve is given by the price differential-flow combination e.g. in Figure 1, with flows divided by available capacity. The closer the combinations to the S-curve, the more efficient is interconnector trading.

4 Methodology

We benchmark our metrics against *UFAPD*, *WFAPD*, and *SCURED**[9]*,* as these are regularly used in official market reports (e.g. ACER, 2016; 2017; and EU Commission, 2015-Q1). First, we use a series of hypothetical trading scenarios, which represent extreme cases of interconnector utilisation, to test the robustness of the metrics. Second, we assess variations between metrics using historical data for the IFA interconnector between Great Britain and France for the years 2013 to 2018.

4.1 Testing the inefficiency metrics

4.1.1 Stress data

We construct a total of eleven scenarios to represent extreme market conditions that can be experienced by coupled and uncoupled markets with the aim of stress-testing the metrics.[10] The scenarios are classified as follows:

- *Scenarios 1 to 4* span the combination of high price differentials (for both profitable and unprofitable flows) with varying interconnector efficiency utilisation;
- *Scenarios 5 and 6* represent periods of zero and 100% unprofitable flows.
- *Scenarios 7 and 8* represent a very low number of extreme price differentials in instances of profitable and unprofitable flows.
- *Scenario 9* contains only a single profitable flow at a low price differential that is captured at 90% of available NTC.
- *Scenarios 10 and 11* contain 100% profitable flows and differ in the degree to which the large price differentials are captured with interconnector use.

These scenarios are graphed in Section 5.1.1.

4.1.2 Historical data

Historical data for the IFA and BritNed interconnectors covers the timeframe 1 Jan 2013 to 31 Dec 2018 in order to include periods in which markets were coupled and uncoupled. Forecasted NTCs for the day-ahead market are available from the ENTSO-E Transparency Platform (TP) and are used as a proxy for NTC. Day-ahead GB prices are sourced from Nord Pool N2EX prices. French and Dutch power prices for the period 2013–2015 are from EPEX Spot; for 2015–2018 they are from the ENTSO-E TP. The flow data is the RTE (day-ahead) commercial forecast for IFA; for BritNed, scheduled commercial exchanges are from ENTSO-E in the first period (2013-2014) and simulated[11] in the second (2015-2018). In the calculations, we ignore samples where the price differential is equal to zero and cap[12] the flow series by the corresponding NTC. Table 2 reports the data sources by time period.

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[9] As SCURED* is an efficiency measure, we define SCURED = 1-SCURED* as the inefficiency measure.

[10] We assume a constant NTC of 2,000 MWh, which is equivalent to full capacity on the IFA interconnector.

[11] Due to data unavailability, we used the same simulation as Guo *et al.* (2019).

[12] If a flow of 1,665 MW occurred when NTC was only 1,500 MW, we reset the flow to 1,500 MW.

Data	2013–2015	2015–2018
FR prices	EPEX	ENTSO-E
NL prices	EPEX	ENTSO-E
GB prices	Nord Pool N2EX	Nord Pool N2EX
IFA flows	RTE	RTE
BritNed flows	ENTSO-E	Simulated
IFA NTC	ENTSO-E	ENTSO-E
BritNed NTC	ENTSO-E	ENTSO-E

Table 2. Data sources by time series and historical period.

4.2 Econometric analysis of market coupling

We use an econometric model for the purpose to define the annual average degree of utilisation inefficiency of the interconnectors between Great Britain and France (through IFA) between 2014 and 2019,[13] as well as between Great Britain and the Netherlands (through BritNed) between 2015 and 2018,[14] by assuming the presence or absence of market coupling.

We simulate a situation, during the period 2014-2019, where GB is assumed uncoupled from France and the Netherlands and compare our results with actual data where markets are coupled. This will also allow us to obtain valuable insights on the potential economic impact of market uncoupling, and thereforehence on the potential impact of a no-deal Brexit on cross-border trade. We investigate potential economic losses by considering how uncoupling is likely to impact net electricity imports, price differentials, trading inefficiency, and the private and social value of GB's two main interconnectors in this period, IFA and BritNed. In this analysis, using the estimated parameters from Guo *et al.* (2019),[15] we also simulate the cases where the GB Carbon Price Support (CPS) is removed. This will be useful to understand the impacts of market uncoupling in the case where Britain's carbon tax, the Carbon Price Support, is abolished or extended to other EU countries. Details of the methodology used in this part of the paper are provided in Appendix D.

5 Results of metrics testing

5.1 Stress dataset

Figures 4-6 show the different scenarios. The first four scenarios are illustrated below, followed by Table 3, which summarises the performance of all scenarios under the different metrics.

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[13] Electricity years run from 1 April to 31 March.

[14] Due to data availability issues, we use the simulated the day-ahead scheduled commercial exchange for BritNed from Guo *et al.* (2019).

[15] In particular, the partial effects of interconnector flows on the GB-FR(NL) price differential, and the partial effects of the CPS on the GB-FR(NL) price differential.

5.1.1 Scenarios 1–4 (Low number of inefficient flows)

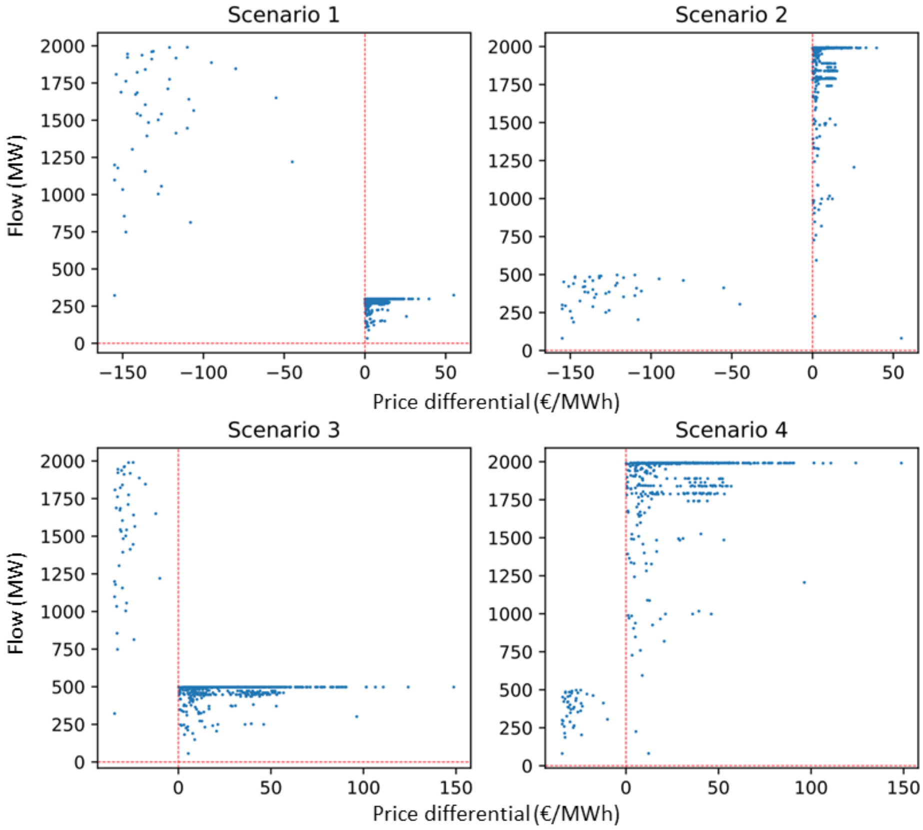

Figure 4. Scenarios 1–4: Low number of inefficient flows.

Scenario	N+	N-	UFAPD	WFAPD	SCURED	UIIU	PWIIU
1	699	45	6.1%	84.7%	85.7%	85.8%	86.6%
2	699	45	6.1%	17.4%	4.8%	8.1%	32.7%
3	699	45	6.1%	16.60%	76.2%	76.9%	76.5%
4	699	45	6.1%	1.3%	4.8%	8.1%	6.7%
5	744	0	0.0%	0.0%	4.8%	4.8%	4.1%
6	0	744	100%	100%	UND	97.6%	97.9%
7	729	15	2.0%	69.6%	85.6%	85.6%	84.7%
8	15	729	98.0%	30.4%	32.1%	56.7%	49.5%
9	1	743	99.9%	99.9%	10%	97.5%	97.8%
10	168	0	0.0%	0.0%	33.8%	33.8%	36.9%
11	168	0	0.0%	0.0%	33.8%	33.8%	34.1%

Table 3. Results using stress data for each of the metrics based on price differentials and flows. UND=Undefined. N^+, N^-, and N^0 indicate flows in the correct economic direction, in the wrong economic direction, and no flows, respectively.

These first four scenarios represent a range of low inefficient flow proportions combined with varying degrees of price differentials and NTC utilisation**.** As an absolute measure of efficiency, Table 3 demonstrates the inability of the *UFAPD* index to address an interconnector's underutilisation of efficient flows in Scenario 3. *UIIU* and *PWIIU* consistently display a greater degree of inefficiency of interconnector utilisation compared to the *SCURED* index, which ignores inefficient flows. Both *WFAPD* and *PWIIU* correctly capture the subtlety in Scenario 2 where, despite the rare appearances, inefficient flows occurred at very high price differentials.

5.1.2 Scenarios 5–6 (0% and 100% inefficient flows)

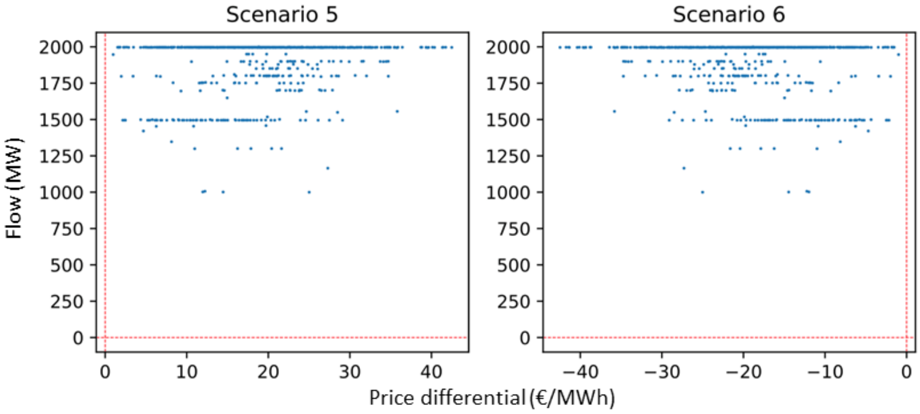

Figure 5. Scenarios 5–6: 0% and 100% inefficient flows.

UFAPD and *WFAPD* results are binary: they indicate either 0% or 100% inefficiency. *SCURED*, *UIIU* and *PWIIU* provide greater accuracy as they are relative to NTC. *SCURED* is undefined for Scenario 6 as that metric solely focuses on FWPDs. *SCURED* and *UIIU* are identical in the absence of inefficient flows (Scenario 5). *WFAPD* understates inefficiency in Scenario 5 as by design it is not rescaled by NTC.

5.1.2.1 *Scenarios 7–8 (Low NTC utilisation)*

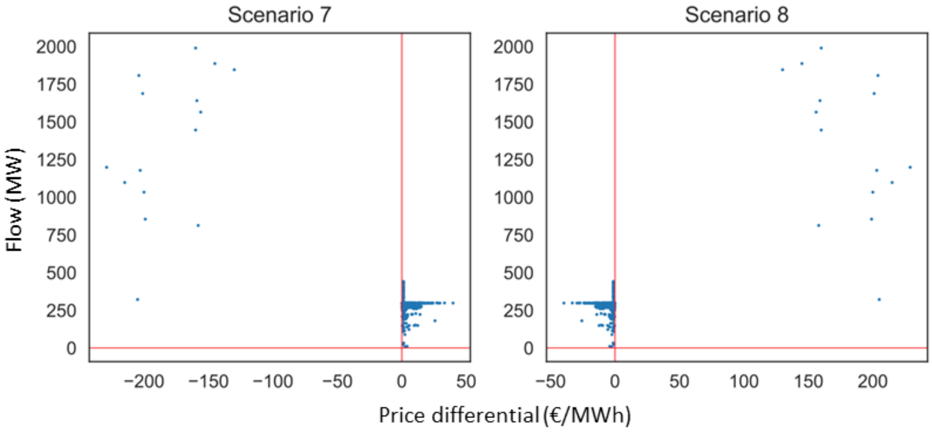

Figure 6. Scenarios 7–8: Low NTC utilisation.

Scenario 7 represents very low inefficient NTC utilisation with a low number of inefficient flows that occur at extreme price differentials, whereas Scenario 8 represents very low inefficient NTC utilisation with a low number of FWPDs that occur at extreme price differentials. *UFAPD* provides an unrealistically low inefficiency in Scenario 7 since it only focuses on the low number of inefficient flows. *WFAPD* provides underestimates in both scenarios because it is not weighted by available NTC. In both scenarios, *SCURED* is lower than both *UIIU* and *PWIIU* as it does not account for inefficient flows.

In general, *SCURED* converges to *UIIU* as inefficient-flows and no-flows decrease and will, in practice, occasionally exceed *UIIU* as shown in Scenario 7.[16]

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[16] See Figure A3 in the SI. Results of metrics by year and by hour of the day for selected years are reported in Figure A4 and Figure A5 of the SI, respectively.

5.1.3 Scenarios 9–11 (1 inefficient flow and 0% inefficient flows)

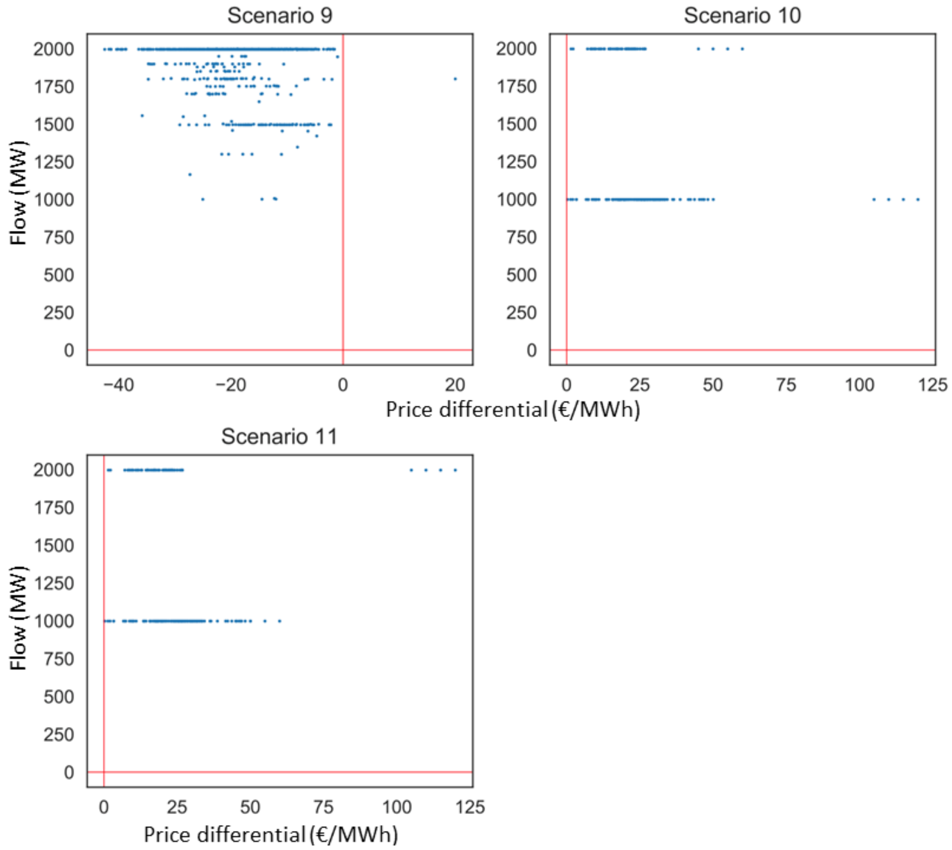

Figure 7. Scenarios 9–11: 1 inefficient flow and 0% inefficient flows.

Scenario 9 has just one efficient flow at 90%, yet *SCURED* estimates only 10% inefficiency. All of the other examined metrics are able to detect the extremely high numbers of inefficient flows at large volumes. In this scenario, *UFAPD* and *WFAPD* are very similar to *UIIU* and *PWIIU* as a substantial number of inefficient flows occurred at a high percentage of NTC. The four large favourable price differentials (>€105) in Scenario 10 are only captured at 50% NTC but they are captured at 100% NTC in Scenario 11[17]. As *PWIIU* is weighted by price, it is the only metric between Scenarios 10 and 11 that detects a change (from 36.9% to 34.1%) whereas the other metrics retain their respective values.

5.2 Historical dataset

Table 4 reports the results for the examined metrics based on historical data ranging between 2013 and 2018 in relation to IFA and BritNed. Annual results based on ENTSO-E IFA cross-border physical flows are in Appendix Table A1.

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[17] See Figure A6 in the SI.

A. IFA									
Year	**N**	**N+**	**N-**	**N0**	**UFAPD**	**WFAPD**	**SCURED**	**UIIU**	**PWIIU**
2013	8,760	7669	1090	1	12.4%	1.7%	8.1%	17.2%	5.2%
2014	8,760	8395	360	5	4.1%	0.2%	0.8%	4.2%	0.4%
2015	8,759	8017	737	5	8.4%	0.3%	1.4%	8.4%	0.5%
2016	8,783	8572	141	70	1.6%	0%	6.7%	9.3%	1%
2017	8,759	8623	20	116	0.2%	0%	8.3%	9.7%	1.4%
2018	8,760	8604	27	129	0.3%	0%	6.8%	8.0%	0.7%

B. BritNed									
Year	**N**	**N+**	**N-**	**N0**	**UFAPD**	**WFAPD**	**SCURED**	**UIIU**	**PWIIU**
2013	8,760	7068	1541	151	15.9%	2.7%	14.2%	24.8%	11.0%
2014	8,760	6758	781	1221	5.1%	0.5%	2.1%	19.8%	16.0%
2015	8,760	8122	505	133	5.8%	0.2%	4.6%	10.1%	2.6%
2016	8,784	8493	185	106	2.1%	0.08%	5.3%	8.0%	4.8%
2017	8,760	8418	234	108	2.7%	0.2%	8.4%	11.3%	3%
2018	8,760	8283	347	130	4.0%	0.3%	12%	15.8%	3.9%

Table 4. Annual historical dataset results (Panel A. IFA; Panel B. BritNed) for the examined metrics. EUPHEMIA day-ahead market coupling was implemented in early 2014. Results are reported up to 1 significant figure. N^+, N^-, and N^0 indicate flows in the correct economic direction, in the wrong economic direction, and no flows, respectively.

5.2.1 Years 2013–2016

All metrics show a general decrease in inefficiency between the years before market coupling (2013-2014) and the years after coupling (2014-2018). Although the level of inefficiency could only be compared to a single pre-coupling year, a general decrease in inefficient interconnector use was observed between GB and both France and the Netherlands after day-ahead coupling went live in 2014.

Interestingly, there was a slight deterioration in 2014-2015. In 2016, *SCURED*, *UIIU* and *PWIIU* see an increase in inefficiency. This is due to the underutilisation of NTC by inefficient flows compared to the previous year. *PWIIU* compounds the 2016 underutilisation with the corresponding large price differentials.[18] The average % NTC utilisation decreases in 2015 and 2016. Finally, the increase in the number of no-flows (N^0) is only recorded by the new metrics *UIIU* and *PWIIU*, and not by others.

This might be explained by the fact that coupling not always results in a decrease in flows against the price differential, which was observed when the Italian market was price-coupled with France, Austria and Slovenia. (See European Commission, QREEM Q1-2015, Section 4.4.). During this period, there was a shift from price coupling to flow-based market coupling, which might explain these results, since the new coupling process is predominantly based on flows as opposed to both flows and prices (Van den Bergh *et al.*, 2016).

5.2.2 Market coupling during years 2016–2018

Most indices for IFA measure more efficient interconnector trading in 2018 compared to 2017 and 2016.[19] *UFAPD* and *WFAPD* show a near-zero level of inefficiency in 2018 that the other metrics do not exhibit, as they are over-reliant on inefficient flows and ignore NTC utilisation inefficiency. An understanding of the reasons behind this improvement requires additional

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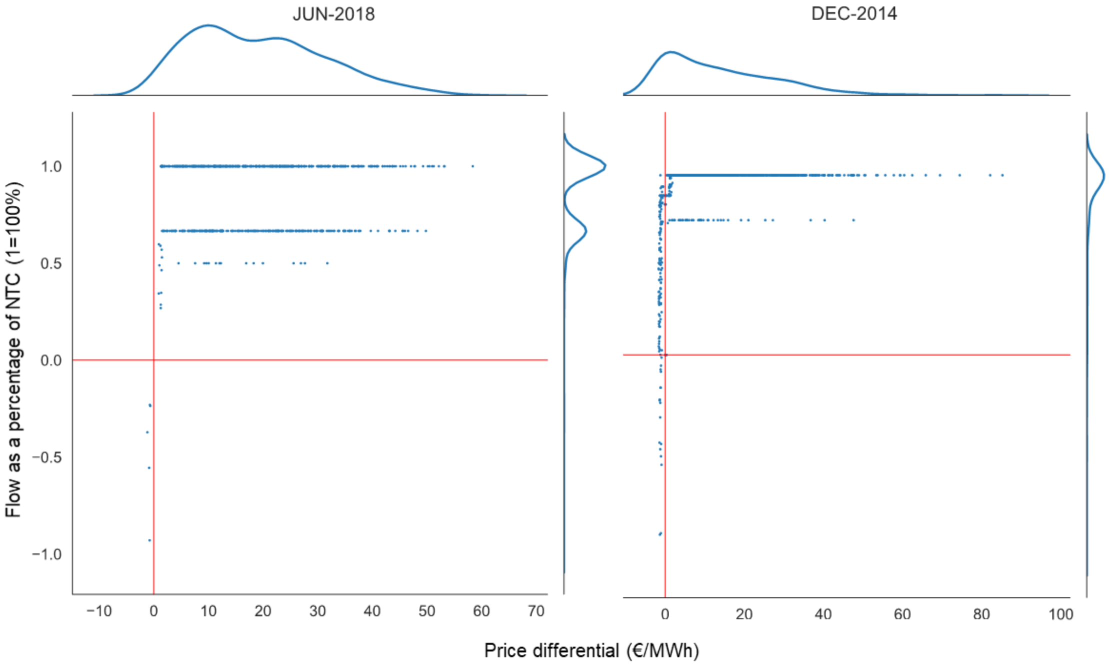
[18] In a similar fashion to scenario 10.

[19] Not for BritNed as the data is simulated under the assumption of perfect market coupling (after taking the Mid Channel loss factor into consideration).

analysis, potentially using our metrics as explanatory variables in regression analysis. The markets are perfectly coupled after adjusting loss factor for IFA of 1.17% and for BritNed of 3%. The reason for non-zero FAPDs and *WFAPDs* is simply because: (1) using the unadjusted price differential; and (2) publicly available data from ENTSO-E and RTE data contains several reporting issues. It is also possible for part of this to be a result of improvements through learning-by-doing in electricity trading after the implementation of market coupling rules in 2014.

5.2.3 Market coupling analysis using monthly intervals

At monthly intervals, the historical data produced periods similar to our stress data in which the existing metrics failed to fully incorporate the interconnector utilisation information (NTC, flow direction, price differential) and, when compared to either of the new metrics, varied substantially. In these instances, the two new metrics, *UIIU* and *PWIIU*, provide greater accuracy. Plots of these occurrences and an excerpt from Appendix Tables A9 and A10 displaying high discrepancies are provided in Figure 8 for IFA.



Year	Month	N^+	N^-	N^0	*UFAPD*	*WFAPD*	*SCURED*	*UIIU*	*PWIIU*
2014	12	622	119	3	16%	0.7%	4%	16%	2%
2018	6	720	0	0	0%	0%	14%	13%	12%

Figure 8. Plots of interconnector utilisation patterns for selected months when the examined metrics differed significantly from the new metrics here introduced. N^+, N^-, and N^0 indicate flows in the correct economic direction, in the wrong economic direction, and no flows, respectively. Results are reported up to 1 significant figure.

We highlight the following results from Appendix Table A9:

1. *SCURED* and *UIIU* coincide in the absence of inefficient flows and no-flows (Jan 2018);
2. *UFAPD* and *WFAPD* understate the degree of interconnector inefficiency (Jun 2018);
3. The occurrence in April 2018 when *UIIU*<*PWIIU*, where despite all flows being efficient, available NTC was not fully utilised during high price differentials.[20]

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[20] See Figure A8 in the SI.

6 Trading inefficiency and market coupling

The results relating to the impact of market coupling on trading inefficiency, price differentials, net import, congestion revenue, and infra-marginal surplus are reported in detail in Appendix E. Here, we provide a summary in relation to IFA and BritNed.

6.1.1 IFA

Among our main findings, market coupling led the price differential between GB and France to fall by €0.40/MWh (2.9%), net imports into GB to increase by 3.27 TWh (or by 34.4%), congestion income to increase by €23.4 million (or by 10.6%), and infra-marginal surplus to increase by €3.8 million (or 30.4%).

We compare the inefficiency of the coupled and uncoupled markets using the examined trading inefficiency metrics, with results shown in Table A16. Market coupling reduced the inefficiency of cross-border trading. On average, during 2014-2019, the share of FAPDs fell from 13.3% to a negligible 2.8%, and the Weighted FAPDs (*WFAPDs*) from 1.5% to only 0.1%. *PWIIU*, *UIIU*, and *SCURED* also considerably decreased.

We also simulated the cases where the GB Carbon Price Support (CPS) is removed, finding that when GB and French day-ahead prices are reasonably close (in 2016-2018), and when markets are uncoupled, all metrics of inefficiency would be significantly higher than the cases where the CPS has been implemented and the GB price is much greater than the French price. This is because when prices are closer together, it is much more difficult to accurately forecast the sign of a price differential between two markets, hence the direction of flows, resulting in greater trading inefficiency.

Without the CPS, average differences in prices (€/MWh), net imports (TWh), congestion income (million €), and infra-marginal surplus (million €) for coupled and uncoupled trading over IFA between 2016-2018 are reported in the last three rows of Appendix Table A12. The impact of uncoupling on congestion income and infra-marginal surplus would have been slightly higher than with the CPS. This is, again, because the comparable price levels bring more uncertainty towards the sign of the price differentials as well as the efficient direction of the flows. Specifically, with uncoupling, congestion income would on average have fallen by €26.7m/yr without the CPS, compared to €23.4m/yr with the CPS, a difference of 1.4% of the coupled congestion income, and the difference in the loss of infra-marginal surplus is less than 1% of coupled congestion income.

6.1.2 BritNed

We assess the impact of market coupling on BritNed, with results shown in Table A16. Similarly to IFA, market coupling facilitates price convergence, and raises congestion revenue and infra-marginal surplus. GB also imported more because the GB price was almost always greater than the Dutch price during 2015-2018.

On average, market coupling reduced the price differential between GB and the Netherlands by €0.28/MWh (by 1.8%), increased net imports into GB by 1.03 TWh/yr (by 14.9%), raised congestion income by €6.7 m/yr (by 5.4%), and boosted infra-marginal surplus by €1.8 m/yr (by 18.8% of uncoupled infra-marginal surplus). The impact of market coupling on BritNed is smaller than that on IFA. This is not only because of BritNed's lower capacity, but also because the price differential between GB and the Netherlands is much larger than that between GB and France, meaning there is less uncertainty on the sign of the GB-NL price differential. Relative to IFA, uncoupling BritNed would have a lower impact on FAPDs as well as congestion income and infra-marginal surplus.

Similarly to IFA, the removal of asymmetric carbon taxes would result in spot price convergence between GB and the Netherlands. As a result, uncoupling the interconnector would have slightly higher impact on both congestion income and infra-marginal surplus.

Table A16 compares trading inefficiency for BritNed, with and without market coupling during 2015-2018. Again, uncoupling increases trading inefficiency. *UFAPD* (*WFAPD*) increased from 3% (0.1%) to 10.8% (1.7%). *SCURED*, *UIUU*, and *PWIIU* also substantially increased.

It is also worth mentioning that the metrics (I_{1-5}) shown in Table A16 based on uncoupled markets during 2015-2018 are smaller than the metrics in 2013, where BritNed was also uncoupled. This is because in 2013, the average GB-NL price differential was €7.11/MWh, or much lower compared to 2015-2018, as shown in Appendix Table A16 (on average €15.2/MWh under market coupling). This confirms our earlier finding where if prices are closer together, uncoupling would have a more negative impact on trading inefficiency (although in absolute terms as the prices are closer, the gains from trade are smaller, amplifying the proportional inefficiency).

Without carbon tax asymmetries, the electricity prices between GB and both France and the Netherlands would converge. As a result, the impact of market uncoupling would lead to large changes in trade but the value of that trade would be lower. Removing carbon tax asymmetries would reduce deadweight losses and improve social welfare, demonstrating that these measures based on commercial income are not necessarily a guide to sensible decisions that should be based on social welfare.

7 Discussion

Interconnectors have provided welfare benefits to electricity systems, and these have been increased where market coupling has been introduced, at least where the connected markets are workably competitive and undistorted (Newbery *et al.*, 2019). The two new metrics we have introduced in this paper are able to compare both coupled and uncoupled markets on the same scale, and this innovation enables them to outperform metrics that are currently used to measure inefficient trading, including *UFAPD*, *WFAPD,* and *SCURED*, with the proviso that they are based on commercial incomes that may not properly measure social value.

In an uncoupled market with a very high number of inefficient flow occurrences, *SCURED* will be inaccurate as inefficient flows are not part of that metric; *UIIU* and *PWIIU* provide greater accuracy as they capture inefficient flows. Conversely in a coupled market with no inefficient flows but where electricity exchanges occurred at low utilisation levels of NTC, efficient and inefficient flows will be inaccurate as NTC is not captured by those metrics; *UIIU* and *PWIIU* will again provide a higher degree of accuracy as NTC is directly considered in *UIIU* and *PWIIU*. This consistently superior performance of *UIIU* and *PWIIU* (irrespective of the state of market coupling) should provide confidence in their use. Furthermore, the increased accuracy of *UIIU* and *PWIIU* does not incur any mathematical-complexity penalty.

7.1 Added value of new metrics

Despite their significant drawbacks, regulators are familiar with *UFAPD*, *WFAPD*, and *SCURED*, which have been widely used in measuring the implementation success of market coupling. The new measures (*UIIU* and *PWIUU*) address the shortcomings of such metrics by including the dimensions that each of those metrics lack. The similarity between the new metrics, *UFAPD,* and *SCURED*, is such that under special circumstances, *UIIU* can be described as a function of those two as in Equation (6). *UIIU* and *PWIIU* can be considered generalisations of *UFAPD, WFAPD* and *SCURED.*

If all flows are FWPDs, *UFAPD* and *WFAPD* will measure perfect interconnector utilisation by recording a value of 0% inefficiency. Yet as was shown in relation to the stress and historical datasets, this will not be the case if the capacity of the interconnector is not fully utilised. *UIIU* and *PWIIU* include available NTC as a variable in their computation and so are more accurate. Conversely, if inefficient flows are more likely, *SCURED* will underestimate the true inefficiency. Again, as *UIIU* and *PWIIU* factor inefficient flows in the calculation, they will provide a higher degree of accuracy.

The computational requirements of *UIIU* and *PWIIU* are similar to the other metrics and can be implemented in a spreadsheet using built-in functions. To simplify this process, we have included two example spreadsheets in the supporting information.

7.2 Limitations of current metrics

The most commonly used metrics to measure trading efficiency, *UFAPD* and *WFAPD*, were introduced in parallel to major market coupling initiatives that took place in the last quarter of 2010 across Europe, including price coupling in the Central-Western European (CWE) region and volume coupling in the CWE-Nordic region (EU Commission, 2010b). After these initiatives were introduced, inefficient flows largely decreased, nearly disappearing in Q1-2011 in CWE (See EU Commission, 2012-Q3; 2012-Q4). Yet we have shown that existing metrics solely based on historical information using price differentials and flows are no longer fit-for-purpose when monitoring trading efficiency during the absence of coupling as well as the progress in coupling markets.

The new metrics that we have proposed are particularly useful to measure the inefficiency of trading in uncoupled markets, since they emphasise meaningful flows against price differentials. For the UK, which is planning to leave the jurisdiction of the European Court of Justice and possibly end market coupling with neighbouring countries, the metrics could be used to accurately identify and minimise trading inefficiencies.

On the other hand, as coupled markets progress toward a state where inefficient flows are no longer observed across borders, the bias from inefficient flows that affects existing metrics limits their utility for evaluating the level of inefficiency of available cross-zonal capacity utilisation. Inefficiency should not only be a measure of inefficient flows, but also one of underutilisation of the available capacity when it is efficient to import or export electricity. Moreover, the introduction of coupling does not always result in a decrease in flows against the price differential, which was observed when the Italian market was price-coupled with France, Austria and Slovenia (See EU Commission, 2015-Q1).

The inception of the *SCURED* index (ACER/CEER, 2012) occurred after most market coupling initiatives were put in place. This measure was mainly used when inefficient flows were expected to be small, which may explain the bias on efficient flows and the verified failure of this measure in scenarios with inefficient flows. The left panel in Figure 2 suggests a situation where cross-zonal exchanges between the Belgian and Dutch markets in Q1-2011 were in the correct economic direction 99.99% of the time capturing small price differentials close to €1/MWh at 70% of the interconnector's capacity. As *SCURED* focuses on beneficial capacity utilisation, it inclines toward reporting an inefficiency of 30%, but this would be an understatement of the monetary inefficiency where 53% (€1.8m/€3.4m) were exchanged during inefficient flows (see Figure 2). The fact that this index does not address inefficient flows in such a situation is a clear flaw of the metric because it focuses on the volumetric dimension and ignores the price differential dimension.

We summarise the drawbacks of the most commonly used metrics of market coupling as:

- ***UFAPD***: fails to incorporate price differential magnitude and available NTC.
- ***WFAPD***: fails to incorporate available NTC.
- ***SCURED***: fails to incorporate inefficient flows and the price differential magnitude.

Despite their shortcomings, one key benefit of *UFAPD*, *WFAPD*, and *SCURED* is their ease of implementation, as they do not include information about the level of electricity loads or generation and as such can be replicated using simple methods and the use of publicly available price and flow data. This is in contrast to metrics from electricity system models, which estimate the impact of market coupling in terms of social costs and benefits.

7.3 Limitations of the study

The third term in Equations 4 and 5 deal with occurrences of no-flows in the presence of a non-zero price differential. There is however a discontinuity in the S-curve (see Figure A1 in the SI) when the price differential is exactly zero. From an arbitrageur's perspective it would be uneconomic[21] to import/export electricity if prices in both markets were in equilibrium and flows across interconnectors can occur for reasons other than economic profitability. We have ignored zero price differentials[22] across all of our analyses by filtering out such occurrences from our computations. With full price convergence across the IEM, the tendency is for prices across different regions to equilibrate over time and result in greater occurrences of price differentials being exactly equal to zero. While an increasing number of such occurrences will diminish the accuracy of *UIIU* and *PWIIU*, such situations are highly unlikely.

Post market coupling data such as cross-zonal flow, electricity price and NTC are available for several markets for recent years since coupling but are limited for the pre-coupling period. This limitation constrained our study to focus on one interconnector (IFA) and one market coupling model (FBMC). Additional insights into the metrics' relative performance in measuring the success of market coupling can be gained by widening the scope of the analysis to include other market coupling models and/or other interconnectors.

As the new metrics measure the distance from the efficient *S-curve*-shaped trading pattern, they have no knowledge of operational/engineering constraints in the interconnector that might have resulted in inefficient flows, or lack of flows during an existing price differential. Such inefficiencies would be incorrectly captured by *UIIU* and *PWIIU* and would result in an overestimation of the inefficiency. Any model or metric is only as good as the data it is provided with, and with the appropriate data preparation, these metrics can provide a useful indication of trading efficiency.

There are ramping constraints that limit the rate of change of interconnector flows (e.g. 1%/minute maximum change), which can cause apparently inefficient flows if there are large price swings (e.g. caused by the one-hour time difference between GB and France during the early morning rise in demand.

The analysis has assumed that market prices reflect social costs, and this is clearly not the case when GB imposes an additional carbon tax that is not matched by its neighbours. Newbery *et al.* (2019) show how to measure social costs and benefits as distinct from commercial income.

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[21] Due to friction costs such as bilateral credit limits, exchange margining, etc.

[22] The simulated dataset did not include any zero price differential. In the six-year historical dataset, our calculations showed only 5 hours of zero price differential.

Finally, it would be worthwhile to relate the various weighting schemes to the economic cost of the trade errors. Yet this would require more detailed structural modelling of the underlying private and social trading costs.

7.4 Policy implications

Market coupling followed from a series of EU legislative packages that laid the foundations of the EU Internal Electricity Market. Any tool used to monitor changes in trading inefficiency must not be biased by market conditions. We have shown in Figure 8 that current metrics can substantially overstate or understate the benefits of market coupling, which could underpin poor market design decisions in the future.

Interconnector regulatory regimes vary widely, from fully regulated regimes in which interconnector revenues are part of the total remuneration to transmission, with excess congestion revenue passed back to consumers, to full market regimes in which revenues are sought competitively from congestion rents. A ‘cap and floor’ mechanism was introduced to GB interconnectors in 2013 as a hybrid of these two approaches, with the aim of continuing the market-based approach while reducing the risk of investment losses for interconnector owners. Under this regime, any shortfall in revenues below a pre-imposed floor is paid for by consumers through higher network charges. Since interconnector congestion rent is expected to decrease due to the fall in price differentials that follows the coupling of electricity markets, it is important to accurately track trading inefficiency to ensure the cap and floor levels are appropriate.

The current Flow Based Market Coupling (FBMC) adapted into the EUPHEMIA algorithm is one of several available coupling models to have been adopted in the EU (EU Commission, 2010), in addition to others such as Interim Tight Volume Coupling (ITVC) and Price Coupling. The relative success of each model can only be evaluated if accurate metrics are available. ACER (2017) compared the success of intra-day market coupling for a selection of regions and concluded that markets using implicit allocation are 40% inefficient while those using explicit allocation are 53% inefficient. However, they focus exclusively on flows that have ‘a value’ (i.e. those flowing in the correct economic direction) and so ignore inefficient flows. Excluding such information from the headline figures leaves room to the possibility of over- or under-stating the relative benefits of implicit and explicit allocation models. This can be remedied by using metrics such *UIIU* and *PWIIU* as they include as many meaningful factors in their calculations as possible.

7.5 Market uncoupling: inefficiency and economic loss

Trading in an uncoupled market could substantially increase the inefficiency of cross-border trading between GB and both France and the Netherlands unless compensated by trading on local power exchanges and buying physical capacity on interconnectors ahead of time.[23] It discourages market price convergence (not the same as social cost convergence), yielding a 3% larger GB-FR average price differential relative to market coupling. Risk-averse traders may not make full use of capacity on IFA and market uncoupling could result in a some reduction in congestion revenue, result in suboptimal use of the interconnector and an attendant very slight loss in infra-marginal (market, not social) surplus.

GB’s day-ahead price is typically greater than the French day-ahead price, partly due to asymmetric carbon taxes between the two markets. As a result, with the French market closing before the GB market, despite uncoupling bringing uncertainty toward GB prices, a trader

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[23] The simulations used to measure the impact of uncoupling do not model such compensatory actions by traders, and so should be treated with great caution.

would still believe that GB's price would most likely be greater than the French price, and would therefore schedule to import electricity most of the time. When the price differences are predicted to be small, the imported amount could be lower, resulting in inefficient use of the interconnector, although the value of the loss would also be small. The impact of market coupling on BritNed is similar, but smaller due to the lower NTC as well as the greater GB-NL price differential.

We also find that, if the British Carbon Price Support (CPS) asymmetry were removed, ideally by the EU implementing an equivalent CPS across its member states, then GB prices would converge to Continental market prices. In such cases the impact of market coupling on traded volumes would be higher than with the asymmetric carbon tax (but not the absolute value of congestion income, which would be smaller). Again, it needs stressing tha removing the asymmetry would deliver welfare gains that may well outweigh the impact of uncoupling.

8 Conclusions

Monitoring the efficiency of electricity trades between countries is essential to ensure that welfare gains from policies designed to improve market integration – including market coupling and policies to spur investments in new interconnectors – are achieved. We have systematically reviewed the metrics used by policymakers to measure cross-border electricity trading inefficiency and have identified several deficiencies, which cause their accuracy to vary greatly depending on the trading patterns. Using both hypothetical market conditions and historical data, we have shown that some metrics rely too much on inefficient flows (the indices *UFAPD* and *WFAPD*) or efficient flows (*SCURED*). We have developed two new metrics of market coupling that address these issues.

Our *UIIU* and *PWIIU* metrics leverage available information on basic interconnector use such as available *NTC*, flow direction, and price differential magnitude. Importantly, the new metrics are not impaired by the state of market coupling, which facilitates comparisons between countries and over time.

We have demonstrated that the new indices are not affected by extreme price and flow differentials. They consistently define the degree of trading inefficiency under numerous potential market conditions, which both provides confidence and further emphasises the limitations of existing measures. Given the improvements, we believe they should be used instead of existing metrics, where possible, to measure the efficiency of electricity trading between countries and to evaluate the impacts of market coupling.

In addition, we studied the impact of market uncoupling on cross-border trade. We found that market uncoupling would lead to more inefficient trading. It would also lead the price differential between GB and France (the Netherlands) to rise by €0.4/MWh or by 3% (by €0.3/MWh, or 2%), net imports into GB to decline by 3.3 TWh or 34% (1 TWh/yr, or 15%), congestion income to reduce by €23 million, or 11% (€7 m/yr, or 5%), and infra-marginal surplus to decline by €4 million, or 30% (€2 m/yr, or 19%).

The impact of market coupling increases with the capacity of the interconnector, and decreases with the average price differential, implying less uncertainty on the sign of the price differential and therefore on the direction of flow. Uncoupling would therefore result in greater inefficiency and a reduction in congestion income and infra-marginal surplus.

Finally, we should stress that the metrics deal with market prices and revenues, and in the presence of asymmetric carbon prices, these will not reflect social values, nor the social value of trade. Additional measures will be needed to uncover and measure such inefficiencies.

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Appendix A

1 Methodological appendix: metrics

1.1 Derivation of the new metrics

For any hour h of the day, in any two regions A and B, electricity flows of magnitude f_h (MW) move across an interconnector in the direction $A \rightarrow B$ at a price differential (€/MWh) $X_{BA(h)} :=$

$P_{B(h)} - P_{A(h)}$. Ideally,[24] arbitrageurs import electricity into market *A* from market *B* when prices are lower in *B* and conversely, import into *B* from *A* (*A* → *B*) when prices are lower in *A*. Efficient trading behaviour in idealised conditions give rise to the step-curve[25] (S-curve) pattern in Left diagram of Figure A1.

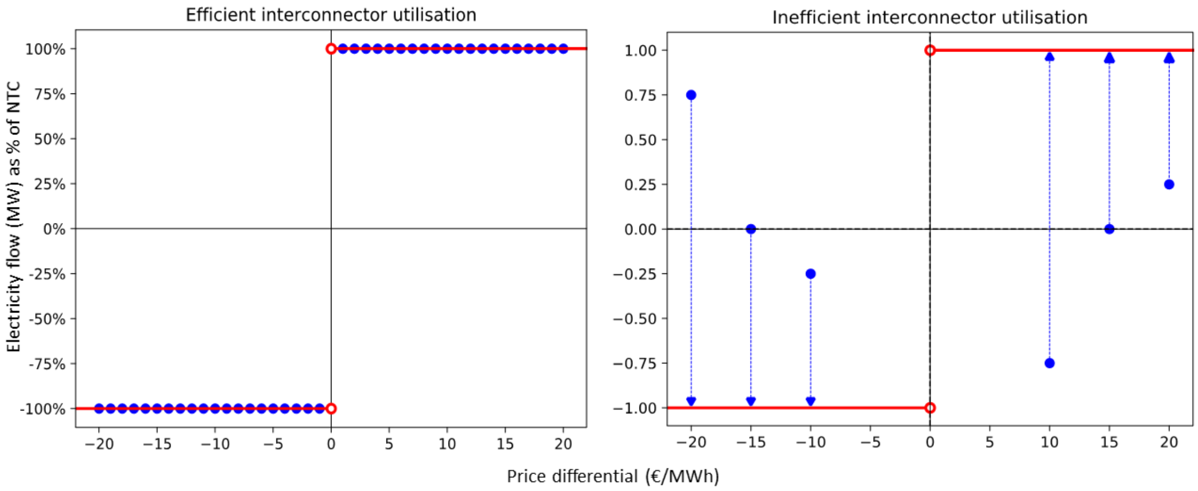

Figure A1. Here, the S-curve is reported as a ratio of available to used capacity, as opposed to Figure 1, for simplicity. LEFT: S-curve (in red) of the efficient utilisation pattern by interconnector arbitrageurs (blue points) across markets A, B. x-axis denotes the price differential $X_{BA(h)}$. The y-axis denotes the electricity flow as a percentage of NTC in direction A→B. RIGHT: Red and blue areas denote adverse and favourable flow quadrants; the blue line is the distance of the inefficient flow from the S-curve.

The distance of non-maximal flows from the S-curve in the right-hand side diagram of Figure A1 is then

distance(adverse-flows) + distance(favourable-flows) + distance(no-flows)

which we define as

$$I_4 = \left(\frac{N^-}{N}\right)\left(\frac{1}{N^-}\right)\sum_h^{N^-}\frac{(1+|f_h^-|)}{2} + \left(\frac{N^+}{N}\right)\left(\frac{1}{N^+}\right)\sum_h^{N^+}\frac{(1-|f_h^+|)}{1} + \left(\frac{N^0}{N}\right)\left(\frac{1}{N^0}\right)\sum_h^{N^0}\frac{(1-|f_h^0|)}{1}$$

where

$$\begin{aligned} N &= N^- + N^+ + N^0 \\ F &= f^- + f^+ + f^0 \\ |y| &= absolute\ value\ of\ y \\ f_h &= \frac{\tilde{f}_h}{NTC_h} \end{aligned}$$

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[24] Synchronicity of market gate closures and capacity allocation, perfect information set, no physical constrains such as ramping, loop-flows, etc.

[25] Under the idealised conditions, arbitrageurs should not import or export when the market prices in region A and B are equilibrated and there are positive losses across the link: Hence the $X_{BA} = 0$ discontinuity.

with the superscripts '-' , '+', *0*[26], denoting adverse-flow,[27] favourable-flow and no-flow,[28] respectively. *NTC* denotes net transfer capacity and $\tilde{f}_h$ the hourly flow.

$$I_4 = (UFAPD)(\zeta) + \left(\frac{N^+}{N}\right)(1 - SCURED^*) + \left(\frac{N^0}{N}\right)$$

1.2 ACER's NTC metric as a lower bound for new metric

Rewriting Equation (4)

$$UIIU = (UFAPD)(\zeta) + \left(\frac{N^+}{N}\right)(1 - SCURED^*) + \left(\frac{N^0}{N}\right)$$

as

$$I_4 = \left(\frac{N^-}{N}\right)X + \left(\frac{N^+}{N}\right)Y$$

where without loss of generality we've assumed $N^0 = 0$. Then,

$$\left(\frac{N^-}{N}\right)X + \left(\frac{N^+}{N}\right)Y < Y \ \Rightarrow X < Y$$

and we establish that whenever the unweighted adverse distance (X) is lower than its counterpart (Y), *SCURED* will fail to provide a lower bound for *UIIU*.[29]

1.3 Additional price-weighting schemes

Equation (5) adjusts to equation (4) by weighing the interconnector underutilisation by price differential weight according to *w_h*.

Other weightings schemes, such as

$$\begin{aligned} w_1 &= \frac{x_h^2}{\sum x_h^2} \\ w_2 &= \frac{e^{\beta x_h}}{\sum e^{\beta x_h}} \\ w_3 &= \frac{e^{\beta |x_h|}}{\sum e^{\beta |x_h|}} \end{aligned}$$

can be applied where the degree of convexity will determine the influence of price differential outliers on the computed metric. Due to its linear nature, our choice of weighting scheme results in minimum bias from outliers. It would be equally appropriate[30] to apply a scheme

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[26] By definition $\mathrm{f}_\mathrm{h}^0 = 0$.

[27] Adverse-flow is synonymous with flow against price differential (FAPD) and analogous with flows in the correct economic direction.

[28] A no-flow is the event of zero IC utilisation given that a non-zero price differential occurred.

[29] Although mathematically possible, analysis performed on weekly intervals yielded only 2 such occurrences in a total of 314 weekly samples. See Table Appendix A10.

[30] When dealing with underdetermined systems and optimisation.

with symmetric emphasis on outliers via w_1 (or w_3 with $\beta = 0.05$), or with adverse flows asymmetrically penalised (w_2 with $\beta = -0.01$).[31]

There is a good argument for the quadratic weighting scheme w_1 as the cost of distortions or the welfare gains from price spread reductions increases as the *square* of the differentials (Newbery, 1990).

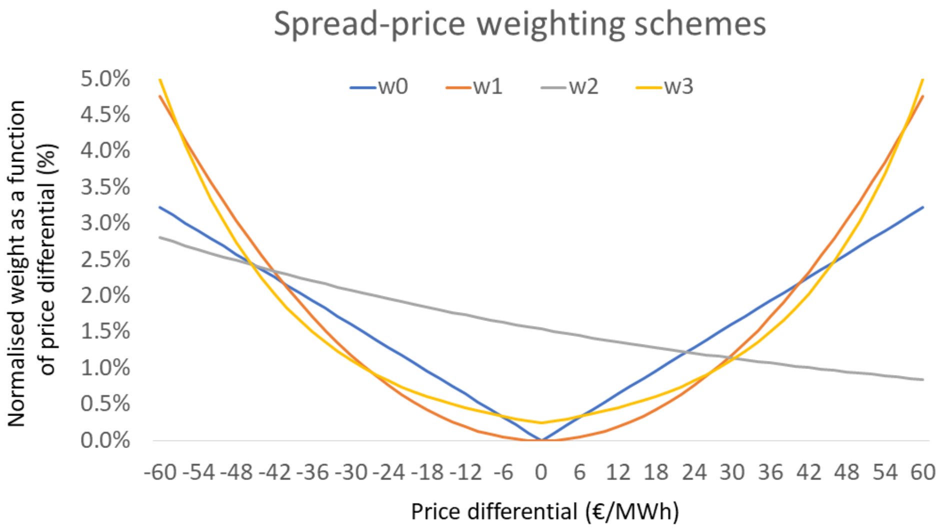

Figure A2. Price differential weighting according to different weighting schemes. w0 is the price differential weighting applied in equation (5), w1-w3 as per Section 1.3. of this document (SI) For w2 and w3, β = -0.01 and 0.05 respectively.

2 Additional results

2.1 Data source (RTE vs ENTSO-E)

The historical data is sourced as reported in Table 3 of the main paper. We address the choice of flow proxy by applying the same metrics to a different dataset where we replace the RTE commercial forecast with ENTSO-E cross-border physical flows. Results are included (annual level only) in this section. We observe that although the absolute levels change, the behaviour of the temporal evolution of the indices does not.

Year	N^+	N^-	N^0	*UFAPD*	*WFAPD*	*SCURED*	*UIIU*	*PWIIU*
2013	7,677	1,077	5	12.3%	1.9%	15.6%	23.4%	12.7%
2014	8,388	370	0	4.2%	0.2%	10.3%	13.2%	9.3%
2015	8,001	757	0	8.7%	0.3%	11.6%	17.5%	9.6%
2016	8,405	349	29	4.0%	0.2%	22.5%	24.4%	18.2%
2017	8,542	208	10	2.4%	0.1%	20.2%	21.2%	14.1%
2018	8,559	199	1	2.3%	0.1%	18.0%	19.0%	14.1%

Table A1. Annual results based on ENTSO-E cross-border physical flows (IFA).

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[31] Appendix figure A2 provides a profile of these alternative weighting methods.

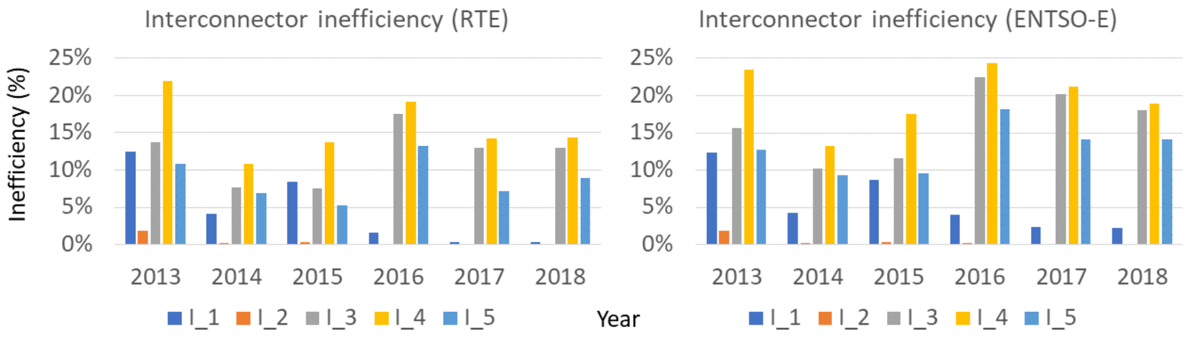

Figure A3. Results of metrics by year according to the RTE and ENTSO-E flow proxy, respectively (IFA).

2.2 Data pre-processing

Pre-processing data can be helpful to focus on a meaningful price differential, or attempt to account for reverse flows, loss-factors, etc. This data reduction can lead to subjective choices of thresholds to filter out information to be (or not) included in analysis. In our analysis, we opted not to apply any filtering to the data. Applying a filter of €1 to the price differential, shows how the temporal evolution of the indices remain unchanged.

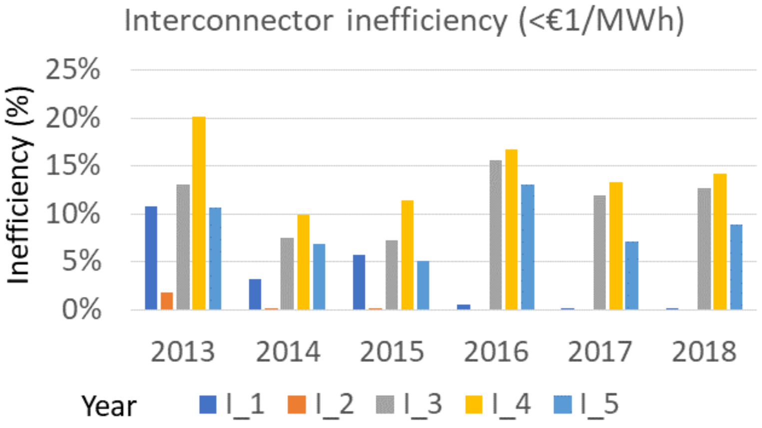

Figure A4. Results of metrics by year (IFA). Filter = X denotes the (absolute) value below which price differentials are ignored for the analysis, as done in many ACER and EU Commission reports.

2.3 *UIIU* and *PWIIU* by hour of the day

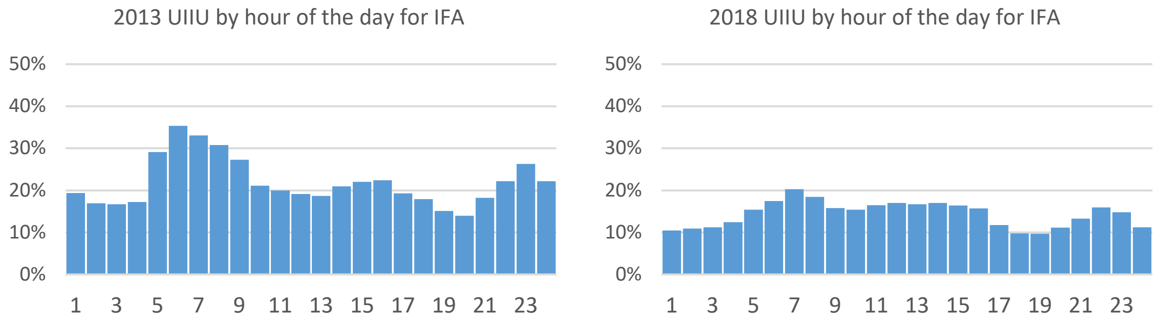

Figure A5(a). Unweighted interconnector inefficient utilisation metric (UIIU) (%, y-axis) averaged by hour of the day (x-axis) for selected years, for the IFA interconnector.

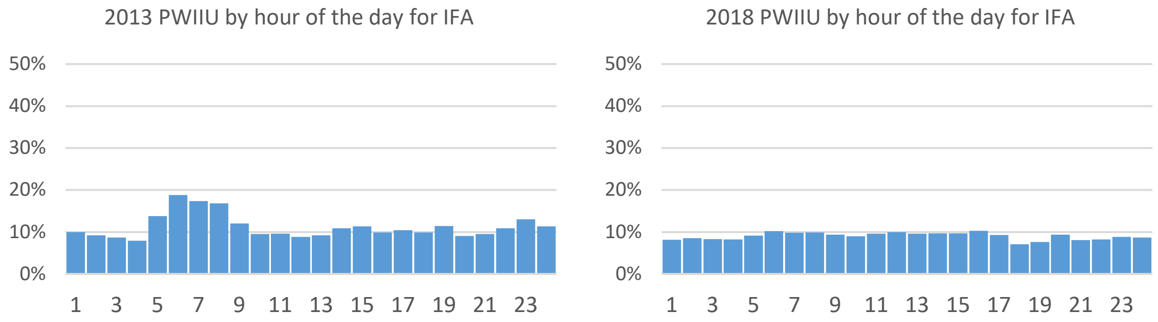

Figure A5(b). Price-Weighted Interconnector Inefficient Utilisation (PWIIU) metric (%, y-axis) averaged by hour of the day (x-axis) for selected years, for the IFA interconnector.

3 Worksheet prototype implementation of metrics

We provide a spreadsheet implementation of both indices here introduced, I_1 and I_5.

Date	hour	flow	NTC	gb -fr
01/01/2013	1	1500	1500	€ 24.30
01/01/2013	2	1500	1500	€ 28.54
01/01/2013	3	1500	1500	€ 23.42

Table A2. Summary table of user input data.

Interconnector utilisation data is first provided in the format of Table A2. Intermediate calculations in Table A3 are performed with corresponding formulae provided in Table A4.

flow_adj	year	month	y&m	flow/NTC	fpd	uD(S)	|gb_fr|	w_h(m)	w_h(y)	wD(S)_y	CR
1500	2013	1	2013-1	100%	1	0.00%	24.30	0.31%	0.02%	0.00%	€ 36,456
1500	2013	1	2013-1	100%	1	0.00%	28.54	0.37%	0.02%	0.00%	€ 42,817
1500	2013	1	2013-1	100%	1	0.00%	23.42	0.30%	0.02%	0.00%	€ 35,123

Table A3. Intermediate calculations required for estimation of metrics i_1 -- I_5. flow_adj is used only in the calculation of *SCURED*.

column	Formula
flow_adj	=ABS(IF(ABS([@flow])<=[@NTC],[@flow],SIGN([@flow])*[@NTC]))
year	=YEAR([@date])
month	=MONTH([@date])
y&m	=[@year]&[@month]
flow/NTC	=[@flow]/[@NTC]
fpd	=SIGN([@[gb-fr]]*[@flow])
uD(S)	=IFS([@fpd]>0,(1-ABS([@[flow/NTC]])), [@fpd]<0, (1+ABS([@[flow/NTC]]))/2,[@fpd]=0,1)
|gb_fr|	=ABS([@[gb-fr]])
w_h(m)	=[@[|gb_fr|]]/VLOOKUP([@[y&m]],**sum_abs_spreads_months**,2,FALSE)
wD(S)_m	=[@[w_h(m)]]*[@[uD(S)]]

w_h(y)	=[@[|gb_fr|]]/VLOOKUP([@year],**sum_abs_spreads_years**,2,FALSE)
wD(S)_y	=[@[w_h(y)]]*[@[uD(S)]]
CR	=[@[gb-fr]]*[@flow]

Table A4. Formulae for intermediate calculations in Table A7. Boldface denotes named ranges described in Tables A5 and A6.

The spreadsheet '*Table B'* object is the union of Tables A2 and A3 and is used in the final calculation of the annual and monthly results of Table A9 and A10 with their respective formulae provided in Tables A7 and A8.

Y&M	M_sum(| x |)	Formula
2013-1	7735	=SUMIFS(Table13[|gb_fr|],Table13[year],"=2013", Table13[month],"=1")
2013-2	5506	=SUMIFS(Table13[|gb_fr|],Table13[year],"=2013", Table13[month],"=2")
2013-3	10922	=SUMIFS(Table13[|gb_fr|],Table13[year],"=2013", Table13[month],"=3")

Table A5. Detail of 'sum_abs_spreads_months' named range. The named range is given by the first two columns. The thirds column is the formula for column two (M_sum|x|).

Year	Y_sum(|x|)	Formula
2013	152536	= SUMIF(Table13[year],"=2013",Table13[|gb_fr|])
2014	155106	= SUMIF(Table13[year],"=2014",Table13[|gb_fr|])
2015	153612	= SUMIF(Table13[year],"=2015",Table13[|gb_fr|])

Table A6. Detail of 'sum_abs_spreads_years' named range. The named range is given by the first two columns. The third column is the formula for column two (Y_sum|x|).

column	Formula
N	=COUNTIF(Table13[year],"=2013")
N+	=COUNTIFS(Table13[year],"=2013",Table13[fpd],"1")
N-	=COUNTIFS(Table13[year],"=2013",Table13[fpd],"-1")
N0	=COUNTIFS(Table13[year],"=2013",Table13[fpd],"0")
I1	=COUNTIFS(Table13[year],"=2013",Table13[fpd],"-1")/COUNTIF(Table13[year],"=2013")
I2	=ABS(SUMIFS(Table13[CR],Table13[year],"=2013", Table13[fpd],"=-1"))/(SUMIFS(Table13[CR],Table13[year],"=2013", Table13[fpd],"=1") + ABS(SUMIFS(Table13[CR],Table13[year],"=2013", Table13[fpd],"=-1")))
I3	1 - (SUMIFS(Table13[flow_adj],Table13[year],CONCATENATE("=",T2),Table13[fpd],"=1")/ SUMIFS(Table13[NTC],Table13[year], CONCATENATE("=",T2),Table13[fpd],"=1"))
I4	=(SUMIFS(Table13[uD(S)],Table13[year],"=2013", Table13[fpd],"=1")+SUMIFS(Table13[uD(S)],Table13[year],"=2013", Table13[fpd],"=-1")+SUMIFS(Table13[uD(S)],Table13[year],"=2013",Table13[fpd],"=0"))/COUNTIF(Table13[year],"=2013")
I5	=(SUMIFS(Table13[wD(S)_y],Table13[year],"=2013",Table13[fpd],"=1")+SUMIFS(Table13[wD(S)_y],Table13[year],"=2013", Table13[fpd],"=-1")+SUMIFS(Table13[wD(S)_y],Table13[year],"=2013", Table13[fpd],"=0"))

Table A7. Formulae corresponding to columns in Table A4. The example provided is for calendar year 2013.

column	Formula
N	=COUNTIFS(Table13[year],"=2013", Table13[month],"=1")
N+	=COUNTIFS(Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"1")
N-	=COUNTIFS(Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"-1")
N0	=COUNTIFS(Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"0")
I1	=COUNTIFS(Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"-1")/COUNTIFS(Table13[year],"=2013", Table13[month],"=1")
I2	=ABS(SUMIFS(Table13[CR],Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"=-1"))/(SUMIFS(Table13[CR],Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"=1") + ABS(SUMIFS(Table13[CR],Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"=-1")))
I3	=1-(SUMIFS(Table13[flow_adj],Table13[year],CONCATENATE("=",AH2), Table13[month],CONCATENATE("=",AI2),Table13[fpd],"=1")/SUMIFS(Table13[NTC],Table13[year],CONCATENATE("=",AH2), Table13[month],CONCATENATE("=",AI2),Table13[fpd],"=1"))
I4	=(SUMIFS(Table13[uD(S)],Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"=1")+SUMIFS(Table13[uD(S)],Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"=-1")+SUMIFS(Table13[uD(S)],Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"=0"))/AI2
I5	=(SUMIFS(Table13[wD(S)_m],Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"=1")+SUMIFS(Table13[wD(S)_m],Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"=-1")+SUMIFS(Table13[wD(S)_m],Table13[year],"=2013", Table13[month],"=1",Table13[fpd],"=0"))

Table A8. Formulae corresponding to the columns in Table A4. The example provided is for the month of January 2013.

Appendix B

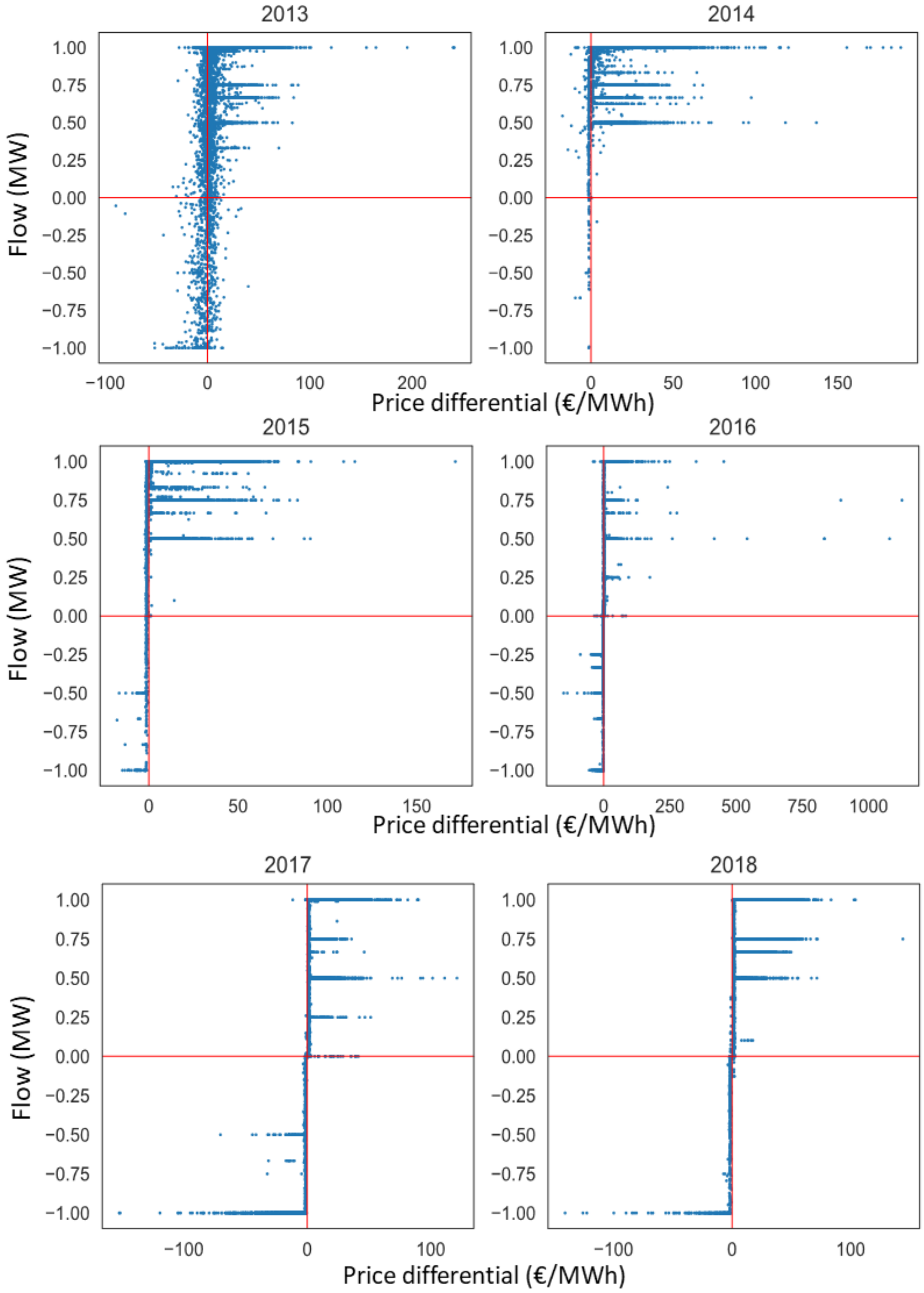

Figure A7. Plot of GB-FR Day-ahead price vs FR->GB RTE flow. Y-axis is flow re-scaled by NTC. Day-ahead NWE coupling went live on 04-02-2014.

Appendix C

3.1 IFA

Year	**Month**	N^+	N^-	N^0	***UFAPD***	***WFAPD***	***SCURED***	***UIIU***	***PWIIU***
2013	1	567	177	0	23.80%	5.20%	21.30%	32.70%	16.30%
2013	2	482	190	0	28.30%	9.00%	28.00%	39.30%	26.20%
2013	3	608	136	0	18.30%	4.00%	32.30%	36.80%	23.60%
2013	4	603	117	0	16.30%	3.60%	9.70%	21.10%	10.80%
2013	5	717	27	0	3.60%	0.30%	0.50%	3.60%	0.50%
2013	6	713	7	0	1.00%	0.10%	15.00%	13.00%	11.40%
2013	7	726	18	0	2.40%	0.20%	2.40%	4.50%	2.30%
2013	8	721	23	0	3.10%	0.30%	14.00%	15.00%	11.20%
2013	9	670	50	0	6.90%	0.80%	7.60%	11.90%	5.50%
2013	10	643	100	0	13.50%	2.30%	31.70%	34.20%	24.90%
2013	11	623	97	0	13.50%	1.90%	17.60%	22.70%	10.30%
2013	12	597	147	0	19.80%	3.90%	16.10%	28.80%	9.80%
2014	1	698	46	0	6.20%	0.70%	2.30%	7.50%	1.50%
2014	2	649	23	0	3.40%	0.60%	1.70%	4.40%	1.10%
2014	3	729	15	0	2.00%	0.10%	31.50%	31.40%	31.20%
2014	4	702	18	0	2.50%	0.10%	2.60%	4.00%	1.30%
2014	5	734	10	0	1.30%	0.00%	0.70%	1.70%	0.40%
2014	6	702	18	0	2.50%	0.10%	19.10%	20.10%	18.60%
2014	7	744	0	0	0%	0%	0.20%	0.20%	0.20%
2014	8	740	4	0	0.50%	0.00%	0.00%	0.50%	0.00%
2014	9	704	16	0	2.20%	0.10%	9.10%	10.70%	9.80%
2014	10	668	74	1	10.00%	0.50%	24.50%	29.00%	24.40%
2014	11	703	17	0	2.40%	0.10%	0.20%	2.30%	0.10%
2014	12	622	119	3	16.00%	0.70%	3.80%	15.60%	2.20%
2015	1	596	148	0	19.90%	1.40%	21.60%	32.70%	21.60%
2015	2	513	156	3	23.20%	1.90%	11.00%	27.40%	8.80%
2015	3	656	86	2	11.60%	0.60%	14.20%	21.90%	15.10%
2015	4	701	19	0	2.60%	0.10%	5.80%	6.80%	3.90%
2015	5	739	5	0	0.70%	0.00%	0.30%	0.90%	0.10%
2015	6	717	3	0	0.40%	<0.01%	2.00%	2.30%	2.20%
2015	7	722	22	0	3.00%	0.10%	0.30%	2.90%	0.30%
2015	8	743	1	0	0.10%	<0.01%	0.00%	0.20%	<0.01%
2015	9	712	8	0	1.10%	0.00%	0.10%	1.10%	0.10%
2015	10	631	112	1	15.10%	0.80%	32.70%	38.20%	31.10%
2015	11	632	88	0	12.20%	0.60%	8.10%	16.40%	5.90%
2015	12	655	89	0	12.00%	0.40%	5.70%	14.40%	4.00%
2016	1	689	55	0	7.40%	0.20%	4.70%	9.70%	1.10%
2016	2	675	21	0	3.00%	0.10%	0.50%	3.00%	0.20%
2016	3	734	10	0	1.30%	0.10%	0.30%	1.50%	0.20%
2016	4	718	2	0	0.30%	<0.01%	19.80%	19.90%	21.10%
2016	5	744	0	0	0%	0%	0.30%	0.20%	<0.01%
2016	6	720	0	0	0%	0%	9.80%	9.60%	8.60%
2016	7	744	0	0	0%	0%	7.30%	6.70%	6.70%
2016	8	737	7	0	0.90%	<0.01%	6.20%	6.20%	0.50%
2016	9	692	28	0	3.90%	<0.01%	42.10%	42.50%	33.90%
2016	10	704	8	32	1.10%	<0.01%	52.40%	44.90%	44.20%
2016	11	698	4	18	0.60%	<0.01%	25.30%	19.50%	13.30%
2016	12	718	6	20	0.80%	<0.01%	57.30%	54.90%	49.70%

Table A9. Monthly historical dataset results for years 2013 to 2016 for all indices UFAPD–PWIIU (IFA).

3.2 BritNed

Year	Month	N	N+	N-	N0	*UFAPD*	*WFAPD*	*SCURED*	*UIIU*	*PWIIU*
2013	1	744	592	150	2	20.2%	3.5%	21.4%	31.3%	14.0%
2013	2	672	584	86	2	12.8%	1.4%	16.1%	23.3%	7.9%
2013	3	744	630	113	1	15.2%	3.1%	7.6%	18.6%	6.3%
2013	4	720	528	191	1	26.5%	6.7%	24.3%	36.8%	21.2%
2013	5	744	563	181	0	24.3%	4.5%	18.1%	30.8%	14.6%
2013	6	720	585	123	12	17.1%	2.6%	16.8%	25.7%	14.8%
2013	7	744	666	78	0	10.5%	1.8%	7.5%	15.2%	5.0%
2013	8	744	662	82	0	11.0%	2.0%	8.9%	16.8%	6.3%
2013	9	720	525	74	121	10.3%	1.6%	14.4%	17.6%	23.1%
2013	10	744	616	123	5	16.5%	2.2%	14.3%	24.0%	8.2%
2013	11	720	635	85	0	11.8%	1.6%	10.9%	18.5%	6.5%
2013	12	744	635	108	1	14.5%	2.2%	13.5%	22.4%	8.9%
2014	1	744	635	60	49	8.1%	1.0%	4.3%	16.6%	10.0%
2014	2	672	0	0	672	0.0%	0.0%	0.0%	7.3%	100.0%
2014	3	744	417	16	311	2.2%	0.2%	2.2%	9.5%	46.5%
2014	4	720	696	24	0	3.3%	0.2%	3.0%	12.3%	0.7%
2014	5	744	704	39	1	5.2%	0.4%	2.1%	12.7%	1.2%
2014	6	720	678	42	0	5.8%	0.5%	2.1%	13.5%	1.0%
2014	7	744	725	19	0	2.6%	0.2%	0.9%	9.5%	0.4%
2014	8	744	713	31	0	4.2%	0.3%	1.7%	11.5%	0.7%
2014	9	720	527	32	161	4.4%	0.5%	2.2%	12.2%	28.1%
2014	10	744	703	41	0	5.5%	0.4%	1.4%	12.7%	0.7%
2014	11	720	687	33	0	4.6%	0.2%	1.4%	12.0%	0.5%
2014	12	744	608	112	24	15.1%	1.2%	2.8%	21.3%	4.9%
2015	1	744	664	80	0	10.75%	0.57%	7.43%	14.85%	1.73%
2015	2	672	617	55	0	8.18%	0.39%	8.62%	13.93%	1.64%
2015	3	744	708	36	0	4.84%	0.18%	5.75%	9.04%	0.94%
2015	4	720	710	10	0	1.39%	0.05%	2.36%	3.34%	0.33%
2015	5	744	642	36	66	4.84%	0.19%	3.10%	6.27%	7.10%
2015	6	720	693	27	0	3.75%	0.18%	3.79%	6.61%	0.55%
2015	7	744	714	30	0	4.03%	0.17%	3.19%	6.01%	0.54%
2015	8	744	726	18	0	2.42%	0.11%	2.27%	4.06%	0.38%
2015	9	720	643	12	65	1.67%	0.10%	4.04%	5.02%	13.76%
2015	10	744	691	51	2	6.85%	0.26%	5.48%	10.30%	1.03%
2015	11	720	654	66	0	9.17%	0.37%	4.64%	11.06%	0.94%
2015	12	744	660	84	0	11.29%	0.30%	5.27%	13.16%	0.84%
2016	1	744	704	40	0	5.38%	0.19%	1.78%	5.66%	0.42%
2016	2	696	693	3	0	0.43%	0.01%	1.19%	1.47%	0.07%
2016	3	744	740	4	0	0.54%	0.01%	0.98%	1.46%	0.09%
2016	4	720	718	2	0	0.28%	0.00%	1.63%	1.80%	0.09%
2016	5	744	678	2	64	0.27%	0.01%	3.71%	3.59%	11.86%
2016	6	720	716	4	0	0.56%	0.01%	7.24%	7.57%	0.73%
2016	7	744	740	4	0	0.54%	0.02%	9.61%	10.02%	1.20%
2016	8	744	742	2	0	0.27%	0.01%	4.06%	4.24%	0.34%
2016	9	720	650	28	42	3.89%	0.16%	11.88%	13.76%	33.73%
2016	10	744	729	15	0	2.02%	0.06%	9.78%	11.00%	0.79%
2016	11	720	699	21	0	2.92%	0.11%	4.49%	6.65%	0.43%
2016	12	744	684	60	0	8.06%	0.41%	8.18%	13.46%	1.51%

Table A10. Monthly historical dataset results for years 2013 to 2016 for all indices UFAPD–PWIIU (BritNed).

Appendix D: Methodological appendix: simulation

We use a simulation-based methodology to derive the expected cross-border price differentials and flows between GB and both France and the Netherlands with an assumption of uncoupled markets. Our simulation assumes a cross-border market where, after the foreign price has been set, risk-averse traders are required to anticipate the GB price, and any anticipation errors would result in either an inefficient use of interconnectors or Flows Against Price Differences (FAPDs). We then compare the simulated price differentials and flows with actual data under market coupling to assess the impact of coupling on the cross-border electricity markets. The simulation model is based on Geske *et al.* (2018).

Our analysis in this section only focuses on the day-ahead market, where the GB electricity market is fully coupled with France and the Netherlands. We use a simulation-based methodology to derive the expected cross-border price differentials and flows between GB and both France and the Netherlands in the case of uncoupled markets. Our simulation assumes a cross-border market where, after the French electricity price has been set, risk-averse traders need to anticipate the GB electricity price, and any anticipation errors would result in either an inefficient use of interconnectors or Flows Against Price Differences (FAPDs). We then compare the simulated price differentials and flows with actual data under market coupling to assess the impact of coupling on the cross-border electricity markets.

Before the 2014 day-ahead market coupling EU regulations came into force, the day-ahead (DA) market closed in France before it did in GB. This meant that traders had to predict GB prices, thereby facing uncertainty. Based on Geske *et al.* (2019), we assume that traders have a mean-variance utility function and, for simplicity, we assume the data is always collected from the import side (i.e. after accounting for transmission losses). We assume a single trader[32] who maximises their utility function, U_h, at each hour, *h*

$$\text{Max}\,\mathrm{E}(U_h) = T\left(\mathrm{E}\left(P_h^{GB}\right) - P_h^{FR}\right) - \frac{\lambda}{2}\left(T * C''_{GB,h} * \sigma_{GB,D}\right)^2,$$

where $\mathrm{E}(U_h)$ is the expected utility of the trader, which is given by the difference between congestion revenue and a penalty term to evaluate the trader's level of uncertainty; T is GB's net import from France in GW; P_h^{GB} and P_h^{FR} are the GB and French DA electricity prices, respectively, in €/MWh; λ is the trader's discount factor towards price volatility; $C'_{GB,h}$ is GB's aggregated marginal cost function and $C''_{GB,h}$ is the marginal value of electricity sales; and $\sigma_{GB,D}$ is the standard error of traders' forecast of GB electricity demand.

Given the above, the utility maximisation problem finds the optimal trading (net import for GB in GW) $\hat{T}$ as:

$$\hat{T}\left(\mathrm{E}\left(P_h^{GB}\right), P_h^{FR}\right) = \begin{cases} Cap_h & Cap_h \leq \theta \\ \theta & 0 \leq \theta < Cap_h \\ 0 & \mathrm{E}\left(P_h^{GB}\right) = P_h^{FR} \\ \theta & -Cap_h \leq \theta \leq 0 \\ -Cap_h & \theta \leq -Cap_h \end{cases}$$

$$\theta = \frac{\mathrm{E}\left(P_h^{GB}\right) - P_h^{FR}}{\lambda\left(C''_{GB,h}\sigma\right)^2}$$

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[32] For simplicity, we assume there is only one trader who participates in day-ahead cross-border electricity trading. We assume that the trader can bid on a maximum volume equivalent to the net transfer capacity, then it is equivalent to assuming that there are n equivalent traders in the market.

where θ denotes net import if there were no capacity constraint; and Cap_h denotes the net transfer capacity (NTC). The numerator of θ denotes the (expected) DA price differential between GB and France, while the denominator, despite the unknown function and parameters, can be regarded as a single parameter. Intuitively, a high expected price differential indicates greater potential for imports, therefore θ is positively correlated with the expected DA price differential.

With forecast errors, θ can be expressed as

$$\theta = \frac{P_h^{GB} + \varepsilon_h^{GB} - P_h^{FR}}{\lambda(C''_{GB,h}\sigma)^2}$$

where $\varepsilon_h^{GB} \sim \mathrm{N}(0, \sigma_{GB,P}^2)$.

We aim to estimate parameters $\lambda(C''_{GB,h}\sigma)^2$ and $\sigma_{GB,P}^2$ such that the simulated[33] DA scheduled commercial exchange for IFA (and BritNed) in 2013 (when the markets are uncoupled) is reasonably close to the actual IFA (BritNed) day-ahead scheduled commercial exchange in 2013, by comparing several commonly used metrics of trading inefficiency considered in this paper.

Once the parameter values for IFA and BritNed have been identified, we can use these and the DA prices for both markets to simulate the uncoupled IFA and BritNed flows and price differentials during the examined electricity years (2014-2019), and then compare the resulting flow with the actual coupled flow and price differentials from the same period.

We measure the degree of interconnector inefficiency before and after market coupling using the metrics *PWIIU*, *UIUU*, *FAPD*, *WFAPD*, and *SCURED*.

Appendix E Results: value of market coupling

3.1 Simulation results for IFA

The measures of the inefficiency of the simulated flows (denoted as “Simulated flow I, II, III” with different values of parameters $\sigma_{GB,P}$ and $\lambda(C''_{GB,h}\sigma)^2$) are reported in Table A11 and are compared with those of the actual uncoupled IFA flow in 2013, denoted as the “Actual DA flow”.

Our results show that an increase in $\sigma_{GB,P}$ would have positive impacts on all metrics I_1 to I_5, while an increase in $\lambda(C''_{GB,h}\sigma)^2$ would further raise I_3, I_4, and I_5, but have a lower impact on I_1 and I_2.

The metrics in Table A11 for “Simulated flow II” are all reasonably close to the metrics for the “Actual DA flow”, therefore we set $\sigma_{GB,P} = 8$ and $\lambda(C''_{GB,h}\sigma)^2 = 8$ as the parameters of uncertainty for IFA without market coupling.

Metric	**Actual day-ahead flow**	**Simulated flow I**	**Simulated flow II**	**Simulated flow III**
		$\sigma_{GB,P} = 5$, $\lambda(C''_{GB,h}\sigma)^2 = 4$	$\sigma_{GB,P} = 8$, $\lambda(C''_{GB,h}\sigma)^2 = 8$	$\sigma_{GB,P} = 8$, $\lambda(C''_{GB,h}\sigma)^2 = 4$
I_1	12.5%	9.7%	13.5%	14.3%
I_2	1.7%	0.8%	1.4%	2.3%
I_3	14.9%	8.2%	15.6%	7.0%

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[33] Note that the day-ahead scheduled commercial exchange in 2013 and 2014 are from ENTSO-E, but the data for 2015-2018 are from simulation as ENSTSO-E no longer provide this data since 2015.

I_4	21.9%	14.6%	22.8%	17.9%
I_5	10.8%	3%	7.4%	4.9%

Table A11. Day-ahead actual and simulated flows.

We then simulate scenarios where trading over IFA occurs without market coupling during 2014-2019 and compare them with the actual data based on market coupling, in terms of net imports into GB, congestion revenue, infra-marginal surplus, social surplus, and trading inefficiency.

We first focus on the short-run effects and ignore the auto-regressive impact of electricity prices, as this will be considered and discussed as a long-run effect thereafter. The results are reported in Table A12.

Among our main findings, based on annual averages, coupling caused the price differential between GB and France to fall by €0.40/MWh, net imports into GB to increase by 3.27 TWh (or by 34.4%), congestion Income increased by €23.4 million (or by 10.6%), and infra-marginal surplus increased by €3.8 million (or 1.7% of uncoupled congestion revenue).

	Price Difference (€/MWh)			**Net GB Imports (TWh)**		
Electricity year	**Coupled**	**Uncoupled**	Δ	**Coupled**	**Uncoupled**	Δ
2014-2015	15.83	16.34	-0.51	15.20	11.24	3.97
2015-2016	18.76	19.11	-0.36	15.52	12.58	2.94
2016-2017	8.54	8.80	-0.26	8.17	6.00	2.17
2017-2018	10.49	10.88	-0.39	11.32	7.85	3.47
2018-2019	13.76	14.22	-0.46	13.66	9.84	3.81
Average	13.48	13.87	-0.40	12.77	9.50	3.27
2016-2017 w/o CPS	-0.45	-0.51	0.06	-0.13	0.00	0.13
2017-2018 w/o CPS	2.59	2.43	0.16	0.54	1.73	1.19
Average w/o CPS	1.07	0.96	0.11	0.20	0.87	0.66
	Congestion Income (million €)			**Infra-marginal Surplus (million €)**		
2014-2015	256.84	233.73	23.11	17.17	13.34	3.83
2015-2016	318.28	296.96	21.32	18.35	15.57	2.78
2016-2017	197.33	176.79	20.54	12.48	9.30	3.19
2017-2018	210.82	184.22	26.60	16.78	12.06	4.72
2018-2019	234.06	208.62	25.44	16.81	12.35	4.46
Average	243.47	220.06	23.40	16.32	12.52	3.80
2016-2017 w/o CPS	154.34	130.25	24.09	12.11	7.48	4.63
2017-2018 w/o CPS	150.91	121.60	29.30	15.88	9.45	6.43
Average w/o CPS	152.62	125.93	26.69	13.99	8.46	5.53

Table A12. Price differential (€/MWh), net GB Imports (TWh), congestion income (million €), and infra-marginal surplus (million €) for coupled and uncoupled trading over IFA, by year.

We compare the inefficiency of the coupled and uncoupled markets using a range of trading inefficiency metrics, with results shown in Table A13. It is straightforward to see that market coupling reduced the inefficiency of cross-border trading. On average, during 2014-2019, the share of FAPDs fell from 13.3% to a negligible 2.8%, and the Weighted FAPDs (*WFAPDs*) from 1.5% to only 0.1%. *PWIIU*, *UIIU*, and *SCURED* also considerably decreased.

Electricity year	Market condition	Metrics				
		UFAPD	*WFAPD*	*SCURED*	*UIIU*	*PWIIU*
2014-2015	**Coupled**	7.6%	0.3%	1.2%	7.5%	0.5%
	Uncoupled	12.2%	1.2%	17.0%	23.3%	10.1%
2015-2016	**Coupled**	5.0%	0.1%	1.0%	5.1%	0.3%
	Uncoupled	8.8%	0.6%	13.4%	18.6%	7.6%
2016-2017	**Coupled**	0.7%	0.0%	8.7%	10.9%	1.2%
	Uncoupled	15.2%	1.8%	20.1%	27.4%	10.5%
2017-2018	**Coupled**	0.2%	0.0%	7.4%	8.2%	1.2%
	Uncoupled	14.9%	2.0%	22.9%	29.4%	13.9%
2018-2019	**Coupled**	0.4%	0.0%	7.4%	8.8%	0.8%
	Uncoupled	13.2%	1.6%	22.1%	27.5%	11.7%
Average 2014-2019	**Coupled**	2.8%	0.1%	5.1%	8.1%	0.8%
	Uncoupled	12.9%	1.5%	19.1%	25.2%	10.8%
2016-2017 w/o CPS	**Coupled**	3.1%	0.1%	4.7%	10.9%	1.3%
	Uncoupled	17.9%	3.1%	26.8%	32.0%	13.9%
2017-2018 w/o CPS	**Coupled**	5.3%	0.2%	4.5%	14.8%	2.3%
	Uncoupled	21.8%	4.1%	30.3%	38.7%	20.9%

Table A13. IFA trading inefficiency with and without market coupling, by year. Key: I_1, I_2, I_3, I_4, I_5 are *UFAPD* (or *FAPD*), *WFAPD*, *SCURED*, *UIIU*, and *PWIIU*, respectively.

We also simulated the cases where the GB Carbon Price Support (CPS) is removed, finding that when GB and French day-ahead prices are reasonably close (in 2016-2018), and when markets are uncoupled, all metrics of inefficiency would be significantly higher than the cases where the CPS has been implemented and the GB price is much greater than the French price. This is because when prices are closer, it is much more difficult to accurately forecast the sign of a price differential between two markets, hence the direction of flows, resulting in greater trading inefficiency.

The impact of market coupling was also tested by relaxing the assumption of a British CPS and comparing differences between the coupled and uncoupled market. Average differences in price differential (€/MWh), net imports (TWh), congestion income (million €), and infra-marginal surplus (million €) for coupled and uncoupled trading over IFA between 2016-2018, are reported in the last three rows of Table A12. By removing the CPS, GB prices in 2015-2017 would have been reasonably close to the French price, and so the net imports are close to zero (although this is made up of considerable imports and exports, hence the substantial congestion income). Without the CPS, the impact of uncoupling on congestion income and infra-marginal surplus are slightly higher (by €3.3 million/yr and €1.7m./yr respectively) than in cases with the CPS.

3.2 Simulation results for BritNed

BritNed has an interconnector capacity of 1 GW, or half the 2 GW of IFA. Therefore, the change in flows due to market coupling (or uncoupling) may have lower impacts on the BritNed price differential, net imports, and private and social benefit, compared to IFA. As performed for the case of IFA, we begin by comparing the simulated 2013 BritNed DA scheduled commercial exchange with the actual value (from ENTSO-E[34]), with results shown in Table A14.

Metric	Actual day-ahead flow	Simulated flow I	Simulated flow II	Simulated flow III
		$\sigma_{GB,P} = 6$, $\lambda(C''_{GB,h}\sigma)^2 = 4$	$\sigma_{GB,P} = 7$, $\lambda(C''_{GB,h}\sigma)^2 = 8$	$\sigma_{GB,P} = 8$, $\lambda(C''_{GB,h}\sigma)^2 = 8$
I_1	19.3%	22.0%	22.4%	24.8%
I_2	6.2%	7.5%	6.5%	8.4%
I_3	16.8%	8.3%	16.8%	16.6%
I_4	30.6%	27.1%	31.8%	33.8%
I_5	20.1%	12.8%	16.4%	18.6%

Table A14. Day-ahead actual and simulated flows for BritNed.

"Simulated flow II" is reasonably close to the "actual day-ahead flow". We therefore assume the values for parameters to simulate the uncoupled BritNed flow during 2015-2018[35] is $\sigma_{GB,P} = 7$ and $\lambda(C''_{GB,h}\sigma)^2 = 8$.

We then assess the impact of market coupling on BritNed, with results shown in Table A15. Similarly to IFA, market coupling facilitates price convergence, raises congestion revenue and infra-marginal surplus. GB also imports more thanks to market coupling because the GB price is almost always higher than the Dutch price during the period 2015-2018.

On average, market coupling reduced the price differential between GB and the Netherlands by €0.28/MWh (by 1.8%), increased net imports into GB by 1.03 TWh/yr (by 14.9%), raised congestion income by €6.7 m/yr (by 5.4%), and boosted infra-marginal surplus by €1.8 m/yr (by 1.4% of uncoupled congestion revenue). The impact of market coupling on BritNed is smaller than that on IFA. This is not only because of BritNed's lower capacity, but also because the price differential between GB and the Netherlands is much larger than that between GB and France, meaning there is less uncertainty on the sign of the GB-NL price differential. Uncoupling would therefore result in a lower share of FAPDs and an increase in congestion income and infra-marginal surplus.

Similarly to IFA, the removal of asymmetric carbon taxes would result in spot price convergence between GB and the Netherlands. As a result, uncoupling the interconnector would have higher impact on both congestion income and infra-marginal surplus.

	Price Difference (€/MWh)			Net Import (TWh)		
Electricity year	**Coupled**	**Uncoupled**	**Δ**	**Coupled**	**Uncoupled**	**Δ**
2015-2016	17.00	17.23	-0.23	8.27	7.42	0.85
2016-2017	15.78	16.08	-0.29	7.85	6.73	1.12
2017-2018	12.82	13.13	-0.31	7.71	6.58	1.13
Average	15.20	15.48	-0.28	7.94	6.91	1.03
2016-2017 w/o CPS	9.60	9.52	0.08	4.26	4.12	0.13
2017-2018 w/o CPS	7.36	7.21	0.16	3.68	3.88	-0.20

	Congestion Income (million €)			Infra-marginal Surplus (million €)		
Electricity year	**Coupled**	**Uncoupled**	**Δ**	**Coupled**	**Uncoupled**	**Δ**

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[34] For BritNed, ENTSO-E only provides the day-ahead scheduled commercial exchange before 2015, or after 2018.

[35] As there is no freely available public data for the BritNed day-ahead scheduled commercial exchange, we use the simulated data from Guo *et al.* (2019).

2015-2016	148.02	142.91	5.10	11.65	10.30	1.34
2016-2017	137.10	129.44	7.65	11.17	9.25	1.92
2017-2018	112.62	105.06	7.56	10.73	8.67	2.06
Average	132.58	125.81	6.77	11.18	9.41	1.77
2016-2017 w/o CPS	87.76	77.52	10.25	9.23	5.72	3.51
2017-2018 w/o CPS	68.89	59.44	9.45	8.53	4.92	3.61

Table A15. Price differential (€/MWh), net GB Imports (TWh), congestion income (million €), and infra-marginal surplus (million €) for coupled and uncoupled trading over BritNed, by year.

Table A16 compares trading inefficiency for BritNed, with and without market coupling, for electricity years 2015-2018. Again, uncoupling increases trading inefficiency. *UFAPD* (*WFAPD*) increased from 3% (0.1%) to 10.8% (1.7%), while *SCURED*, *UIUU*, and *PWIIU* also show substantial increases.

It is also worth mentioning that the metrics (I_{1-5}) shown in Table A16 based on uncoupled markets during 2015-2018 are smaller than the metrics in 2013 (Table A11), where BritNed was also uncoupled. This is because in 2013, the average GB-NL price differential is €7.11/MWh, which was much lower than in 2015-2018, shown in Table A16 (on average €15.2/MWh under market coupling). This confirms our earlier finding where if prices are closer, uncoupling would have a more negative impact on trading inefficiency.

Electricity Years	**Market Condition**	**Metrics**				
		UFAPD	***WFAPD***	***SCURED***	***UIIU***	***PWIIU***
2015-2016	**Coupled**	4.4%	0.2%	3.1%	7.6%	1.9%
	Uncoupled	8.4%	1.1%	5.7%	13.0%	5.2%
2016-2017	**Coupled**	2.5%	0.1%	6.6%	9.4%	5.2%
	Uncoupled	11.2%	1.8%	8.9%	17.8%	10.0%
2017-2018	**Coupled**	2.2%	0.1%	9.0%	11.6%	3.0%
	Uncoupled	12.7%	2.3%	10.1%	20.0%	8.9%
Average 2015-2018	**Coupled**	3.0%	0.1%	6.2%	9.5%	3.4%
	Uncoupled	10.8%	1.7%	8.2%	16.9%	8.0%
2016-2017 w/o CPS	**Coupled**	0.9%	0.0%	8.9%	22.3%	10.3%
	Uncoupled	20.4%	5.1%	16.1%	29.9%	17.9%
2017-2018 w/o CPS	**Coupled**	1.3%	0.0%	10.8%	26.0%	8.7%
	Uncoupled	21.9%	6.8%	16.8%	31.6%	17.2%

Table A16. BritNed trading inefficiency with and without market coupling, by year. Key: I_1, I_2, I_3, I_4, I_5 are *UFAPD* (or *FAPD*), *WFAPD*, *SCURED*, *UIIU*, and *PWIIU*, respectively.

Without carbon tax asymmetries, the electricity prices between GB and the Netherlands would further converge. As a result, the impact of market uncoupling would be severe, resulting in much higher inefficiency.

Appendix F: additional information

3.1 Estimating welfare gains

Two approaches have been used to estimate welfare gains. For historic interconnector performance, a series of metrics examining different aspects of welfare and trading efficiency have been developed, which are functions of market prices and interconnector flows (e.g. ACER, 2012; EU Commission, 2010-Q3). Since this approach cannot be used to estimate future welfare gains from interconnectors, the second approach is to use complex electricity system models to generate scenarios of flows and prices (e.g. Pöyry, 2012; Redpoint, 2013; ENTSO-E, 2014; EU Commission, 2015; and Aurora, 2016). Assumptions about the underlying electricity system vary widely between studies. Moreover, most models assume coupled markets, perfect foresight, and day-ahead plant dispatch, so account for neither demand uncertainty, trader behaviour, nor intra-day and balancing markets.

3.2 Trading in uncoupled and coupled markets

3.2.1 Trading in uncoupled markets

In uncoupled markets, traders must separately buy electricity in one market, sell in another market, and buy and nominate interconnector capacity from the first market to the second market. Efficient day-ahead nominations require traders to accurately predict the magnitude and direction of the day-ahead auction price differentials. In practice, this can be quite challenging, and prior to market coupling, day-ahead scheduled flow was frequently suboptimal, or even in the wrong direction (ACER, 2012).

Where day-ahead scheduled flow proves economically suboptimal, it is possible for traders to correct it in the intra-day markets. This requires them to buy and nominate intra-day capacity, and either to buy and sell in the different markets, or to accept exposure to the balancing mechanism. In practice, there are generally limited liquidity and significant transaction costs in intra-day markets, and a general reluctance to expose to volatile prices in the balancing mechanism.[36] As a result, interconnector flow will often only be adjusted in the intra-day market where there is a large enough movement in the price differential, or for operational reasons such as an unexpected change in generation or demand.

3.2.2 Trading in coupled markets

Day-ahead coupling obviates the need to predict day-ahead price differentials. Instead, they can release it to the interconnector operator for optimised settlement based on the day-ahead auction process. The EUPHEMIA algorithm will ensure that flow is optimised, based on bids and offers in the two markets and interconnector constraints. The interconnector may be constrained, in which case there is a price differential between the two markets, and capacity holders receive a financial settlement based on the price differential (adjusted for any losses applied by the interconnector operator). Alternatively, the interconnector may be unconstrained, in which case no settlement is made.

As a result of this ability to release interconnector capacity for optimised settlement based on the day-ahead auction, traders are less likely to manually nominate their interconnector capacity. Even if the interconnector capacity is being held as a hedge for offsetting physical

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[36] The SEM Committee (2019) found 92% of trades took place in or prior to the day-ahead market. The remaining 8% of trades took place in declining quantities in the three intraday and continuous markets, falling from 4% in the first intraday market to less than 0.5% in the continuous market.

positions in the two markets, it may still make sense for the capacity and the two physical positions to be closed out financially in the day-ahead market.

3.3 Price-based metrics and flow-based metrics

3.3.1 Price-based metrics

Interconnectors promote price convergence as traders buy and sell electricity until prices equalise. This concept is known as arbitrage and while it can provide useful indications about the potential gains from trade, it does not indicate whether the underlying transmission capacity has been used inefficiently. Coupling markets and increasing interconnection capacity can increase price convergence (Zachmann, 2008). Price convergence can be measured by simply inspecting the mean (or median) price differential between zones.

Price differentials. In 2017, price convergence varied greatly across Europe. The average absolute day-ahead price differential ranged from less than 0.5 €/MWh on the borders between Estonia and Finland, Portugal and Spain, and between Latvia and Lithuania, to more than 10 €/MWh on several other borders, such as those between the Germany/Austria/Luxembourg bidding zone and five of its neighbouring countries, and on all British borders (likely due to GB's Carbon Price Floor). Large price differentials indicate that increasing cross-zonal interconnection capacity, especially on borders with the highest price differentials, would reduce overall electricity system costs (ACER, 2015; 2017). In the absence of interconnection transmission limits, one would expect prices in all zones to converge in a competitive single market (Castagneto Gissey *et al.*, 2014).

Various econometric methods have been used to analyse price differentials, in the form of electricity spot price convergence (De Vany and Walls, 1999; Robinson, 2007; Zachmann, 2008). Using principal component analysis, Zachmann (2008) rejects the overall market integration hypothesis except for certain pairs of European markets. Robinson (2007) employs B-convergence and co-integration tests, suggesting that convergence occurred for most European markets. Bunn and Gianfreda (2010) showed increased market integration for France, UK, Netherlands, Germany, and Spain. Integration was found not to increase with geographical proximity but with capacity of the interconnector. Kalantzis and Milonas (2010) found both interconnection and geographical distance playing a critical role in price dispersion.

Based on correlation and co-integration analyses, Boisseleau (2004) did not detect convergence among wholesale prices. Armstrong and Galli (2005) found convergence among wholesale price differentials in France, Germany, Netherlands and Spain, from 2002 to 2004. Using fractional co-integration analysis, Houllier and de Menezes (2013) showed long memory for price shocks and co-integration to be present only for a few markets, including Germany, France and Netherlands. These studies considered integration between pairs of prices, whilst Castagneto Gissey *et al.* (2014) accounted for a whole system of prices, finding integration to be low but increasing over time and reflecting regulatory integration.

3.3.2 Flow-based metrics

Some flow-based metrics indirectly measure trading inefficiency. As they do not consider prices, they are unable to indicate whether trades occurred inefficiently, since inefficient trades involve electricity flows that increase overall generation cost.

Indexed annual aggregation of hourly NTC values. These are changes in cross-zonal Net Transfer Capacity (NTC) offered to the market for trade are analysed by ACER (2012) for the period 2008–2012, representing a very simple measure of interconnector use. They estimate it for 23 EU borders, finding a 9% increase to be a 'modest [but] positive trend'. Despite this, the recorded values are meaningful only if extra capacities are not utilised inefficiently, so the measure fails to directly consider the inefficiency of interconnector use.[37]

Capacity utilisation ratio*.*[38] This is measured as the ratio of the number of hours when *intra-day* capacity was used to the number of hours when intra-day capacity was available. ACER (2012) compared this measure to that in the day-ahead timeframe, concluding that intra-day capacity utilisation was relatively low.[39] In addition, the authors concluded that implicit allocation was less inefficient than explicit (or other) allocation methods.[40]

Absolute sum of net nominations per year*.* This measure indicates the level of available cross-zonal *intra-day* market capacity and is considered by ACER (2018). They show that, in absolute terms, aggregated cross-zonal allocations nominated across the European network tripled between 2010 and 2017. While this metric is useful to understand the level of capacity nominated on the interconnector, it does not indicate whether this capacity is used inefficiently since it does not involve prices.

3.4 Measures of social welfare

Interconnectors are expected to increase welfare by reducing overall costs across the two electricity systems, through creating consumer surplus to importers and producer surplus to exporters. Since social welfare is challenging to calculate, the metrics presented in the paper are used instead to estimate interconnector use efficiency as a proxy for maximising social welfare. However, some studies have calculated social welfare metrics directly, particularly for examining the potential impacts of deploying new interconnectors.

Models are used to estimate the change in social welfare due to adding an interconnector to connect two systems. For example, the UK electricity regulator, Ofgem, analysed welfare changes by estimating the consumer and producer surplus[41] changes for the proposed ElecLink interconnector between Great Britain and France.[42] This requires an electricity system model to examine the counterfactual situation in which the interconnector has/has not been deployed (depending on whether the study is taking place before or after deployment). Since models include numerous assumptions and simplifications compared with real markets (see Appendix 6.4, SI), it is difficult to compare studies.

Social welfare may include all external costs of CO_2 emissions and other pollutants, as well as, ideally, correcting for market power. Mansur and White (2012) consider the impacts of moving from bilateral trading to simultaneous market dispatch and clearing. By comparing monthly prices before and after a bilaterally cleared zone joined the Pennsylvania-Jersey-Maryland (PJM) nodally-priced market area, they estimated reductions in price differentials and welfare gains, finding potential incremental gains of $3.6m/GW. Ott (2010) used a similar approach and found that the total benefit of efficiently pricing PJM was $2.2bn/yr. De Jong *et al.* (2007) simulated four EU countries, finding welfare effects of flow-based market coupling at about €200m/yr. Meeus (2011) studied historical data relating to the 600 MW Kontek cable linking Denmark to Germany over various coupling initiatives and found imperfect coupling with 5% UFAPDs even after coupling took place, with welfare gains of €10m/yr. The SEM

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[37] See ACER (2012), Section 3.2.2.

[38] These are considered for price differentials greater than €1/MWh, which are viewed as significant by ACER (2016, 2017).

[39] For 2017, 50% utilisation rate in intra-day vs 86% utilisation rate in day-ahead.

[40] See ACER (2012), Section 5.2.

[41] Consumer surplus is the difference between the highest price a retailer is willing to pay and the actual market price of electricity. Producer surplus is the difference between the electricity market price and the lowest price a generator would be willing to accept.

[42]https://www.ofgem.gov.uk/ofgem-publications/84685/appendix2-londoneconomicseleclinkreviewsummary.pdf

Committee (2011) estimated the social costs of not coupling the two interconnectors between Great Britain and the Single Electricity Market (SEM) of the island of Ireland for 2010. The estimated social welfare gains from coupling were €30m/yr based on an average import capacity of 930 MW, or €32m/GWyr.

The relatively modest welfare and efficiency benefits in these studies may be underestimated because the models are too simplistic to account for all of the transmission failures that coupling may relieve, and because they are calibrated based on previous generation portfolios with lower renewable generation (and so less congestion) than seen at present (Newbery *et al.*, 2016). National Grid (2015) estimated that sharing reserves over interconnectors could reduce capacity needs by nearly 3 GW, which could be worth €15m/GWyr. These findings led to regulators requiring coupling of electricity markets in Europe, until 85% of the European power consumption was coupled in 2015 (Geske *et al.*, 2018).