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Measuring inefficiency in international electricity trading

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Abstract

Interconnectors reduce the cost of electricity supply if they are operated efficiently. We show that established metrics used to monitor electricity trading inefficiency become increasingly inaccurate in several trading conditions. We devise the Unweighted and Price-Weighted Inefficient Interconnector Utilisation indices to address these deficiencies. These metrics are substantially more accurate than existing ones and perform equally well whether or not markets are coupled. Our results show a substantial decrease in inefficient trading between Great Britain and both France and the Netherlands after the European Union's market coupling regulations were introduced in 2014.

In view of Great Britain's likely withdrawal from the European Union, the paper also evaluates how market uncoupling would affect cross-border trade. We find that uncoupling would lead to inefficiencies in trade, the electricity price differential between GB and France (Netherlands) rising by 3% (2%), net imports into GB decreasing by 26% (13%), congestion income decreasing by 10% (5%), and infra-marginal surplus decreasing by 2% (2%) of coupled congestion income. We also show that, should the EU decide to implement an equivalent carbon tax to GB's Carbon Price Floor, uncoupling impacts would be slightly magnified due to electricity prices converging (by about 1% of coupled congestion income).

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

JEL Classification : C81; F14 ; F15; Q41

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ABSTRACT

Interconnectors reduce the cost of electricity supply if they are operated efficiently. We show that established metrics used to monitor electricity trading inefficiency become increasingly inaccurate in several trading conditions. We devise the Unweighted and Price-Weighted Inefficient Interconnector Utilisation indices to address these deficiencies. These metrics are substantially more accurate than existing ones and perform equally well whether or not markets are coupled. Our results show a substantial decrease in inefficient trading between Great Britain and both France and the Netherlands after the European Union's market coupling regulations were introduced in 2014.

In view of Great Britain's planned withdrawal from the European Union, the paper also evaluates how market uncoupling would affect cross-border trade. We find that uncoupling would lead to inefficiencies in trade, the electricity price differential between GB and France (Netherlands) rising by 2% (0.6%), net imports into GB decreasing by 22% (6%), congestion income decreasing by 6% (1.5%), and infra-marginal surplus decreasing by 25% (9). We also show that, should the EU decide to implement an equivalent carbon tax to GB's Carbon Price Floor, uncoupling impacts would be magnified due to electricity prices.

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 link national electricity systems and enable countries to trade electricity between markets (e.g. between Great Britain and the island of Ireland), or to create single electricity markets (e.g. on the island of Ireland). Electricity systems have periods of high and low demand, and variable renewable generation creates periods of high and low available supply. Since supply–demand imbalances differ across countries, interconnectors can reduce these imbalances by moving electricity over space (in contrast to storage, which moves energy over time) (Newbery *et al.*, 2018). Europe plans to substantially increase interconnection capacity. For example, GB has 5 GW capacity to four countries, and the UK regulator, Ofgem, has approved projects to increase capacity to 16 GW by 2030 (Castagneto Gissey *et al.*, 2019).

From an economic perspective, 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 and increase consumer welfare in the importing country. However, these benefits of interconnectors will only be realised if electricity flows in the economic direction, and this will not happen unless markets are efficiently integrated. Several metrics have been developed to measure and hence monitor *trading inefficiency* (e.g. in ACER, 2012). In this paper, we critically examine these metrics, and propose a series of improved metrics for future use.

1.1 Electricity trading via interconnectors

Electricity generation for each period (typically an hour) is generally traded in forward, day-ahead, intraday, and balancing markets. Forward market trades can take place months ahead of delivery. 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. Interconnected trading occurs in these electricity markets, but the approach is very different depending on whether the two connected markets are *uncoupled or coupled*.

Historically, national markets were *uncoupled*, which meant interconnector capacity scheduling and purchasing/selling electricity in each market took place separately. The interconnector flow would be planned on the basis of predicted prices, and many of these flows were ultimately in the ‘wrong’ direction for periods where the price differential subsequently reversed. Electricity flows from higher to lower priced regions are termed Flows Against the Price Differential (FAPDs) (ACER, 2012) and are usually[1] caused by the markets for interconnector capacity and delivery of energy closing at diferent times.

The Integrated Electricity Market (IEM) came into force in the EU in 2014 to allow electricity to be traded freely between member states through *coupled* markets, with the aim of reducing trading inefficiency (ACER, 2015). All bids and offers are submitted to the day-ahead market at the same time. A shared algorithm known as EUPHEMIA (ACER, 2017) matches supply and demand and schedules all interconnector flows from low- to high-price regions, until either the price differential is eliminated or the interconnector reaches full capacity with each region then having a different market clearing price. In 2019, 23 European countries had coupled markets.[2] Intra-day coupling became available in 2018 for some European markets, while coupling balancing markets in 2019 was still at an early stage (ACER, 2017).

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[1] Ramping constraints may limit the rate at which the direction and/or volume of flow can respond to price changes.

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

1.2 Previous studies of trading inefficiency

The welfare gains[3] from international electricity trading depend on the price differential between the markets as well as the trading inefficiency (Ochoa and van Ackere, 2015). Several studies estimate trading efficiency. Some have relied upon historic interconnector performance (e.g. ACER, 2012; EU Commission, 2010-Q3). Pariso and Pelagatti (2019) have taken such an approach to evaluate the Italian-Slovenian interconnector. Other studies have used electricity system models (e.g. Pöyry, 2012; Redpoint, 2013; EU Commission, 2015; and Aurora, 2016). Zakeri *et al.* (2018) model the likely efficiency and welfare gains of proposed interconnection between the UK and the Nordic power markets.

Newbery *et al.* (2013) reviewed the literature on the quantitative benefits of market integration, finding substantial monetary advantages (€1 bn/yr from just coupling, twice that if balancing is integrated) from EU market coupling, albeit a modest percentage of total sales value of electricity. Pollitt (2018) concludes that measurable benefits of the Integrated Electricity Market are likely to be small relative to total trade, in part because there has been a large rise in subsidised renewable generation that has not been efficiently allocated across member states.

ACER (2017) compared the success of intraday market coupling for a selection of regions and concluded that markets using implicit allocation (as with market coupling) are 40% inefficient while those using explicit allocation (in which capacity is procured separately from energy) 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. The low inefficiencies reported are a reflection of the still incomplete integration of EU intraday markets.

Following Brexit, it is possible that the UK will no longer have access to the EUPHEMIA platform and will need to return to uncoupled trading with neighbouring markets. Geske *et al.* (2019) develop a model of market frictions based on FAPDs to estimate the impact of higher trading inefficiency and less investment in future interconnection at €700m each year by 2030.

1.3 Contribution and structure of this paper

Previous metrics of trading inefficiency have two important limitations. First, several do not consider the magnitude of flows with and against price differentials, so the relative importance of any FAPDs cannot be measured. Second, they do not consider the magnitude of the price differential for FAPDs, which is important because larger price differentials cause greater economic losses. This paper systematically evaluates existing metrics of day-ahead trading inefficiency for the first time. Based on this analysis, we propose two new measures of trading inefficiency that address these limitations. We evaluate these against existing metrics using a series of trading patterns, and historical trading data for both coupled and uncoupled markets.

We use the insights from our new metrics with an econometric model to explore the potential economic losses caused by the GB electricity market becoming uncoupled from France and the Netherlands. We investigate the impacts on net electricity imports, price differentials, trading inefficiency, and the private and social value of the existing interconnectors. The insights can be used to design policies that minimise welfare losses.

The paper is structured as follows. In Section 2, existing measures of trading inefficiency are described, and our two new measures are defined. We evaluate our novel metrics against existing metrics in Section 3. In Section 4, we analyse the economic impact of market uncoupling. We conclude by considering the policy implications in Section 5. More detailed

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[3] Information about estimating welfare gains is given in Appendix 1 of the Supplementary Information (SI).

information about trading inefficiency metrics and our methods are available in Appendices 1–8, which are available in the online-only Supplementary Information (SI).

2 Measures of trading inefficiency

We focus on trading inefficiency in the day-ahead market. Metrics of cross-zonal capacity utilisation inefficiency determine how inefficiently interconnector transmission capacity is used: the percentage of capacity not allocated in the correct direction (from lower to higher priced zones).

Analyses of day-ahead and intra-day trading inefficiency involve several approaches and varying degrees of complexity. We categorise metrics of trading inefficiency as: (i) price-based; (ii) flow-based; and, (iii) price- and flow-based metrics. Studies using these measures are listed 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 inefficiency. * indicates the present study.

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). A full description of price-based and flow-based metrics is provided in Appendix 2.

2.1 Price-and-flow-based metrics

We focus on price-and-flow-based metrics as the most informative and widely used for policy purposes.

2.1.1 Flows Against the Price Differential (*FAPD*)

FAPD measures the fraction of times electricity flows from higher to lower 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*:

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

Similarly, for Flows With the Price Differential (FWPD) *UFWPD* is calculated as N^+/N.

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 but it ignores the quantity of electricity traded unprofitably and the price differentials at which these trades occurred. For example, 53% of potentially valuable trade was exchanged between Belgium–Netherlands during FAPDs, despite these comprising only 0.01% of all flows (Figure 1). Hence judging the inefficiency of an interconnector utilisation based solely on *UFAPD* could be highly misleading.

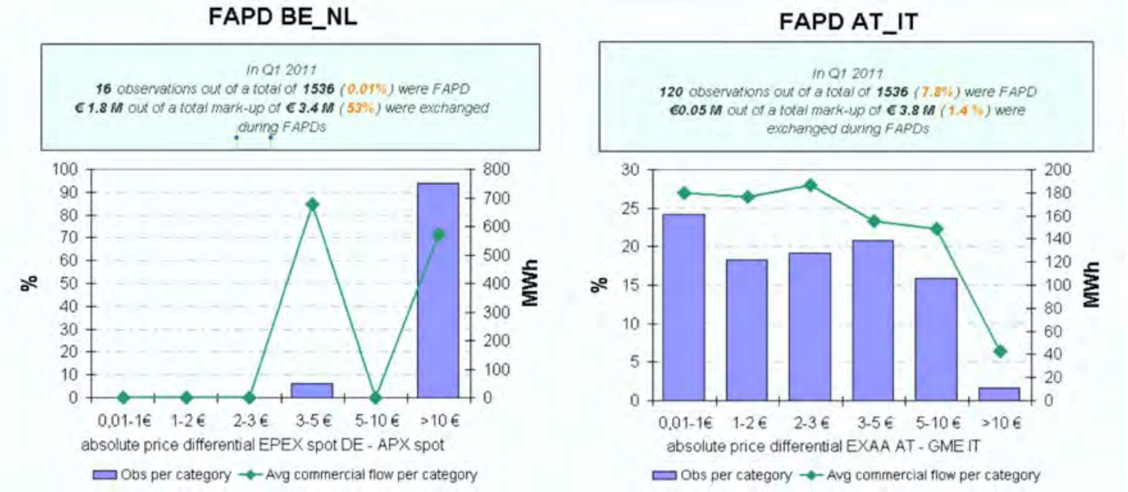

Figure 1. Chart of inefficient flows for the Belgian-Dutch and Austrian-Italian markets. Numbers in brackets indicate Unweighted FAPD (FAPD) and Weighted FAPD (WFAPD). Source: European Commission (2011-Q1).

Figure 2 shows the combinations of net scheduled imports and transmission loss-adjusted price differentials relating to trades over the GB–France IFA interconnector before and after market coupling in 2014. This ‘S-curve’ presents the raw *scheduled* commercial exchanges, so does not account for the possibility of unplanned outages. In 2017, there are horizontal bands of observations at multiples of 500 MW because of periodic partial de-rating of one or more cables (IFA has four 500-MW cables). Note the absence of costly imports and low-priced exports in the coupled graph, where electricity flowed in the efficient economic direction. In this case, the S-curve suggests *UFAPDs are* 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.*, 2019), and include: (i) uncertainty arising from separate energy and transmission markets; system operators being required to schedule cross-border flows for congestion and system balancing; and, (ii) strategic trading by generators with market power. The S-curve is dispersed, indicating inefficient trading.

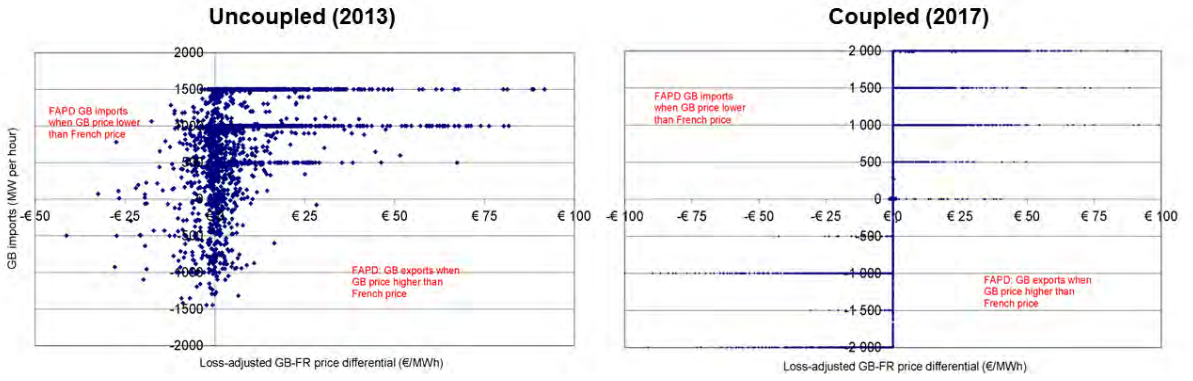

Figure 2. GB scheduled net imports vs price differentials on the IFA interconnector between GB and France before and after the 2014 implementation of the EUPHEMIA market coupling algorithm. For additional related graphs see also Appendix 5 of the Supplementary Information, SI.

2.1.2 Weighted FAPD (*WFAPD*)

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

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

where – and + denote 'wrong' (inefficient) and 'correct' (efficient) direction; $\tilde{f}$ are flows during hour h at a corresponding price differential of x,; 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 1 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.

The 53% value calculated using the *WFAPD* metric improves on the UFAPD. Yet it still does not completely describe interconnector inefficiency because it does not take account of the Net Transfer Capacity (NTC) that is actually available. During periods without inefficient flows, both measures indicate zero inefficiency, even if the interconnector capacity is underused.

2.1.3 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 Net Transfer 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.[4] 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.

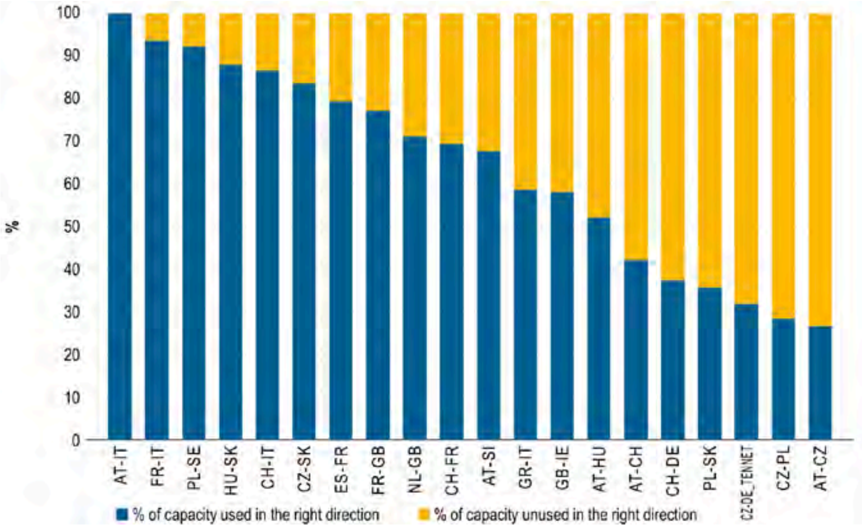

Figure 3. Percentage of NTC used in the correct economic direction for a selection of EU borders in 2011. Note that this was prior to coupling through EUPHEMIA. Source: ACER (2012).

2.1.4 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 €107m/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.

2.1.5 Value destruction

Value destruction is calculated as the physical flow times the price differential for flows against the price differential (FAPDs), indicating the loss that could have been avoided by not flowing.

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

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 based on models of the underlying electricity system. With numerous assumptions varying across models and studies, this makes comparisons with analyses using historic traded data difficult. More information about measures of social welfare is given in Appendix 3 (SI).

2.2 Defining an ideal metric for interconnector trading inefficiency

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.

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.

2.3 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, 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.[5]

Considering a sample size *N* of hourly *price differential* and *flow* combinations, we define the *Unweighted Inefficient Interconnector Utilisation*[6] (UIIU) metric as:

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

where

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

with the superscripts '-', '+', and *'0'*, denoting inefficient-*flow (i.e. a FAPD)*, efficient-*flow* and *no-flow,*[7] respectively. *NTC* stands for Net Transfer Capacity, while $\tilde{f}_h$ is the hourly flow. *UIIU* is an index of trading *inefficiency* ranging from 0 to 1, with a value of 0 indicating no inefficiency

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[5] A case could be made for a metric ranging from -100% to +100%, where -100% implies that all the potential gains are not just foregone but reversed, destroying value. However, it is conventional to state that zero efficiency is full or 100% inefficiency and we follow this convention, hence the halving in equations (4) and (5).

[6] A detailed derivation can be found in Appendix 4 of the Supplementary Information (SI). 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.

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

(or 100% efficiency), and a value of 1 indicating maximum inefficiency (0% efficiency). The level of *efficiency* is 1 – I_4.

Consider two inefficient flows of 900 MW with the first occurring at a price differential of €200/MWh and the second at a €2/MWh price differential. Everything else being equal, the first inefficient flow is more costly and hence more inefficient than the second. As the flows in Equation 4 already adjust for NTC, it remains to adjust for the price differential (analogous to *WFAPD* adjusting *UFAPD*) leading to the *Price-Weighted Inefficient Interconnector Utilisation* (PWIIU) metric.

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

where

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

and x is the price differential. *PWIIU* also ranges between 0 and 1 with values interpreted in the same way as for *UIIU*.

Equation 4 is deliberately specified to blend existing metrics (*UFPAD* and *SCURED*) and can be rewritten as:

$$UIIU = \ (UFAPD)\left(\frac{1}{2N^-}\right)\sum_{h}^{N^-}(1 + |f_h^-|) + \left(\frac{1}{2N}\right)\sum_{h}^{N^+}(1 - SCURED_h) + \left(\frac{N^0}{2N}\right) \tag{6}$$

A Microsoft Excel formula is provided as an attachment to this paper to facilitate estimation. See Appendix 5 (SI).

3 Evaluating the metrics

We benchmark our metrics against *UFAPD*, *WFAPD*, and SCUWED =1 - *SCURED,*[8] 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 and for the BritNed interconnector between Great Britain and The Netherlands for the years 2013 to 2018.

3.1 Stress-testing the metrics using a series of market scenarios

We construct a total of eleven scenarios that represent a range of conditions in coupled and uncoupled markets, with the aim of stress-testing the metrics (assuming a constant NTC of 2,000 MW, full capacity on IFA):

- *Scenarios 1 to 4* span the combination of high price differentials (for both profitable and unprofitable flows) with varying interconnector efficiency utilisations.
- *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.

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

- *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 described in Table 2 and illustrated in Figures 4 to 7. Table 3 contains the metrics for each scenario.

Scenario	Metric outcome	Explanation
1	Medium inefficiency: between 25% and 75%	Efficient flows account for 94% of all flows but are utilised at low levels of available capacity. Inefficient flows occurring at high price differentials flow at high levels of available capacity.
2	Low inefficiency: < 25%	Efficient flows account for 94% of all flows and are utilised at high levels of available capacity. Inefficient flows occurring at high price differentials flow at low levels of available capacity.
3	Medium inefficiency: between 25% and 75%	Efficient flows account for 94% of all flows but are utilised at low levels of available capacity. Inefficient flows occurring at low price differentials flow at high levels of available capacity.
4	Low inefficiency: < 25%	Efficient flows account for 94% of all flows and are utilised at high levels of available capacity. Inefficient flows occurring at low price differentials flow at low levels of available capacity.
5	Low inefficiency: < 25%	Efficient flows account for 100% of all flows and are utilised at high levels of available capacity.
6	High inefficiency: > 75%	Efficient flows account for 0% of all flows (all flows are inefficient) and are utilised at high levels of available capacity.
7	Medium inefficiency: between 25% and 75%	Efficient flows account for 98% of all flows and are utilised at low levels of available capacity.
8	Medium inefficiency: between 25% and 75%	Efficient flows account for only 2% of all flows. However, they occur at very high levels of price differentials and use more of the available capacity than the FAPDs.
9	Very high inefficiency: > 95%	Efficient flows account for 0.01% of all flows (only one such observation): FAPDs are captured at high levels of available capacity.
10	Low inefficiency: < 25%	Efficient flows account for 100% of all flows: larger proportion of flows occurred at 50% of available capacity than at 100% of available capacity
11	Low inefficiency: < 25%	Efficient flows account for 100% of all flows: larger proportion of flows occurred at 50% of available capacity than at 100% of available capacity

Table 2. Scenarios and metric outcome description.

Scenario	N+	N-	UFAPD	WFAPD	SCUWED	UIIU	PWIIU
1	699	45	6%	85%	86%	46%	66%
2	699	45	6%	17%	5%	6%	32%
3	699	45	6%	17%	76%	41%	41%
4	699	45	6%	1%	5%	6%	5%
5	744	0	0%	0%	5%	2%	2%
6	0	744	100%	100%	UND	98%	98%
7	729	15	2%	70%	86%	44%	56%
8	15	729	98%	30%	32%	56%	44%
9	1	743	100%	100%	10%	97%	98%
10	168	0	0%	0%	34%	17%	18%
11	168	0	0%	0%	34%	17%	17%

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 direction, in the wrong direction, and no flows, respectively.

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

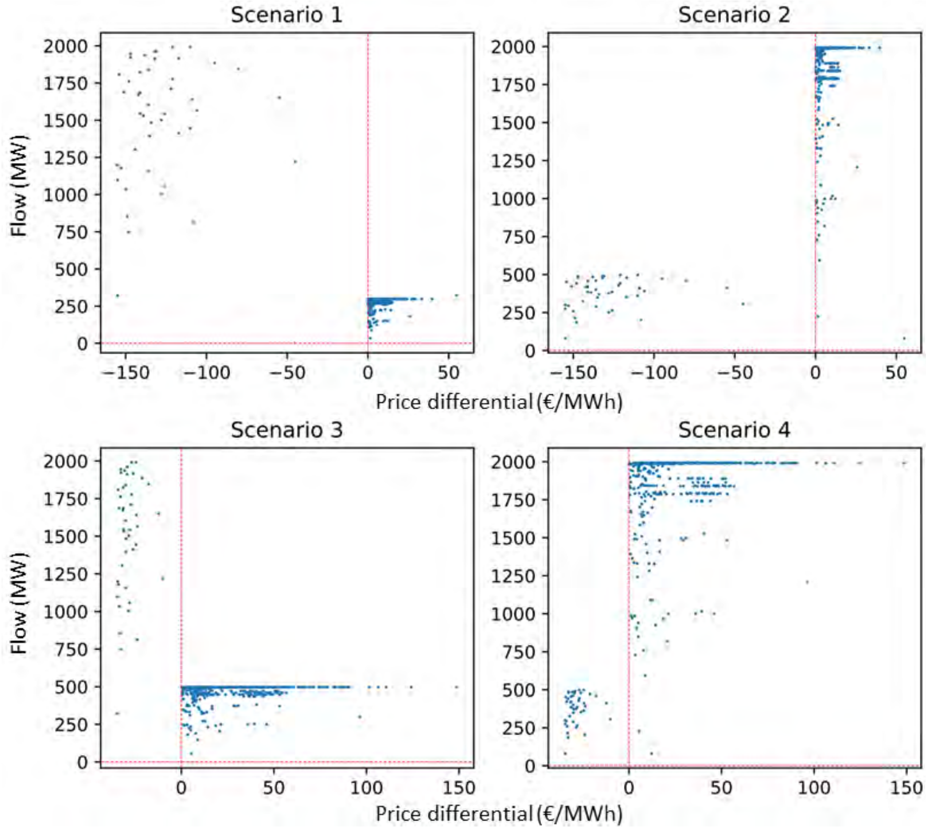

Figure 4. Scenarios 1–4: Low number of inefficient flows.

These scenarios represent a range of low inefficient flow proportions combined with varying degrees of price differentials and NTC utilisation**.** As an absolute measure of inefficiency, Table 3 demonstrates the inability of the *UFAPD* index to address an interconnector's underutilisation of efficient flows in Scenario1. Likewise in Scenario 3, *WFAPD* underestimates the inefficiency as it fails to capture the underutilisation of NTC by beneficial 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.

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

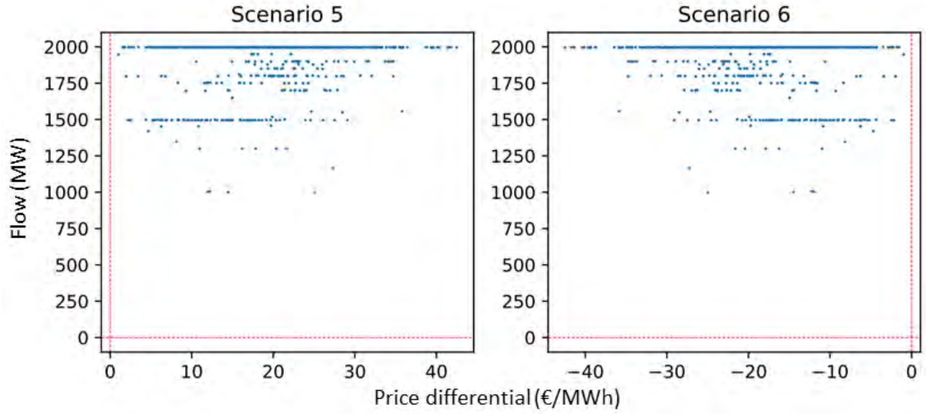

Figure 5. Scenarios 5–6: 0% and 100% inefficient flows.

UFAPD and *WFAPD* results are binary: they indicate either 0% or 100% inefficiency. *SCUWED*, *UIIU* and *PWIIU* provide greater accuracy as they are relative to NTC. *SCUWED* is undefined for Scenario 6 as that metric solely focuses on FWPDs. *WFAPD* understates inefficiency in Scenario 5 as by design it is not rescaled by NTC. Scenarios 5 and 6 are mirror images of one another and UFAPD, *UIIU* and *PWIIU* reflect this as their results add up to 1 over both those scenarios.

3.1.3 Scenarios 7–8 (Low NTC utilisation)

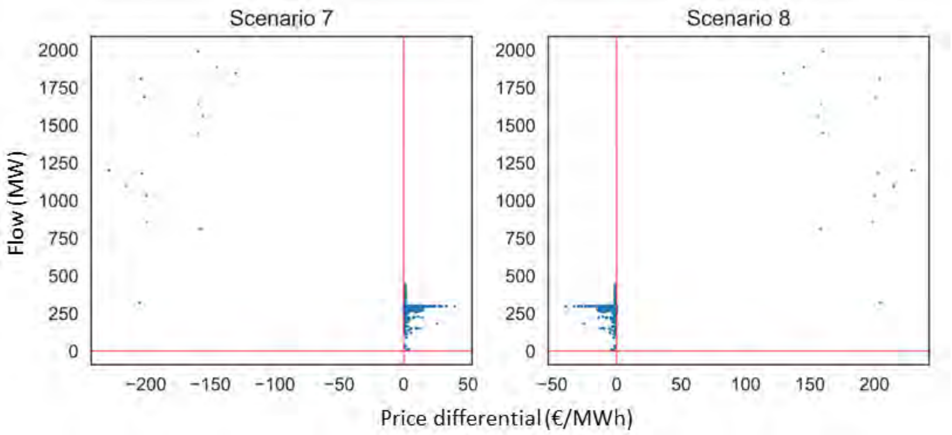

Figure 6. Scenarios 7–8: Low NTC utilisation.

Scenario 7 is inspired by Figure 1 but at varying levels of NTC utilisation by the FAPDs. The very high number of efficient flows in that scenario underutilise NTC and as such their efficiency is negated by the low number of FAPDs. Scenario 8 is a mirror image of Scenario 7. *UFAPD* provides an unrealistically low inefficiency in Scenario 7 since it only focuses on the low number of inefficient flows. The change in *WFAPD*'s 'welfare loss' over the two scenarios is what drives the large decrease in its value. *PWIIU* reacts in a similar fashion to *WFAPD* due to its weighting scheme.

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

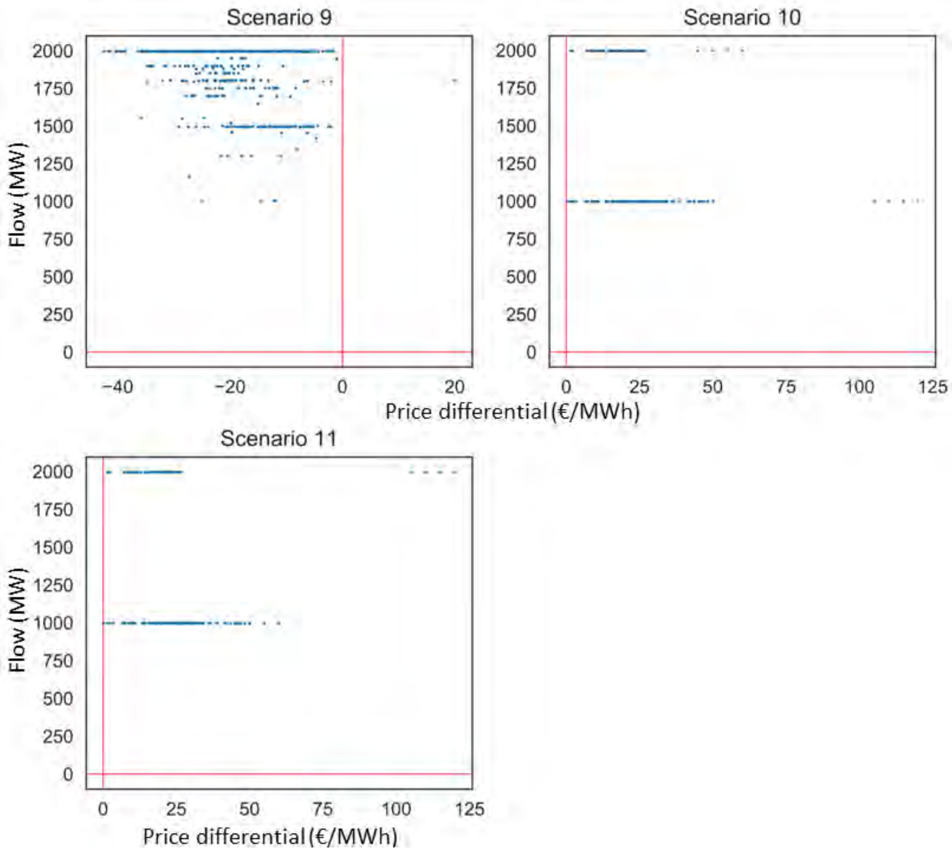

Figure 7. Scenarios 9–11: 1 inefficient flow and 0% inefficient flows.

Scenario 9 has just one efficient flow at 90%, yet *SCUWED* 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. As *PWIIU* is weighted by price, it is the only metric between Scenarios 10 and 11 that detects a change (from 18.5% to 17.0%) whereas the other metrics retain their respective values. As NTC is constant and all flows are FWPDs, we see that for scenarios 10 and 11 $UIIU = 2(SCUWED)$.[9]

3.2 Evaluation against historical data

Historical data for the IFA and BritNed interconnectors from 1 Jan 2013 to 31 Dec 2018 includes 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[10] in the second (2015-2018). In the calculations, we ignore samples where the

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[9] See Appendix 5 of the SI.

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

price differential is equal to zero and cap[11] the flow series by the corresponding NTC and ignore any records when NTC was zero. Table 4 reports the data sources by time period.

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 4. Data sources by time series and historical period.

Table 5 reports the results for the metrics based by year for IFA and BritNed.

A. IFA									
Year	N	N^+	N^-	N^0	UFAPD	WFAPD	SCUWED	UIIU	PWIIU
2013	8739	7649	1090	0	12%	2%	8%	14%	4%
2014	8736	8371	361	4	4%	0%	1%	4%	0%
2015	8760	8019	736	3	8%	0%	1%	8%	0%
2016	8765	8573	141	51	2%	0%	7%	5%	0%
2017	8733	8624	20	89	0%	0%	8%	5%	0%
2018	8756	8600	27	128	0%	0%	7%	4%	0%

B. BritNed									
Year	N	N^+	N^-	N^0	UFAPD	WFAPD	SCUWED	UIIU	PWIIU
2013	8630	7222	1394	14	16%	3%	14%	18%	7%
2014	7542	7093	449	0	6%	0%	2%	6%	1%
2015	8630	8122	505	3	6%	0%	5%	7%	1%
2016	8678	8493	185	0	2%	0%	5%	4%	0%
2017	8652	8418	234	0	3%	0%	8%	6%	1%
2018	8631	8282	347	2	4%	0%	12%	9%	1%

Table 5. 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 direction, in the wrong direction, and no flows, respectively.

3.2.1 Years 2013–2016

All metrics show a general decrease in inefficiency between the year before market coupling (2013) 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 2015, *SCURED*, *UIIU* and *PWIIU* see an increase in inefficiency. This is due to the large utilisation of NTC by an increasing number of inefficient flows compared to the previous year. 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.

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

The aforementioned deterioration might be explained by the fact that coupling does not always result in a decrease in FAPDs, 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).

3.2.2 Market coupling during years 2016–2018

Most indices for IFA measure more efficient interconnector trading in 2018 compared to 2017 and 2016.[12] *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 analysis, potentially using our metrics as explanatory variables in regression analysis. The markets are perfectly coupled after adjusting the loss factor for IFA of 1.17% and for BritNed of 3%. The reasons for non-zero FAPDs and *WFAPDs* are: (i) using the unadjusted price differential; and, (ii) 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.

3.2.3 Market coupling analysis using monthly intervals

At monthly intervals, the historical data produced periods similar to our stress data in which the existing metrics do not 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.

Examples of these occurrences and discrepancies between metrics for selected years are shown in Appendix 6 (SI), in Table A8 for IFA and in Table A9 for BritNed. In October 2016 *UFAPD* and *WFAPD* understate the degree of interconnector inefficiency due to the low number of FAPDs.[13] In February 2015, a high number of FAPDs (156) leads to *UIIU* reporting a larger inefficiency than *SCUWED*. Once price-weighting is considered, *PWIIU* reports a lower inefficiency than most other metrics.[14]

3.3 Discussion

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 enables them to outperform metrics that are currently used to measure inefficient trading, with the proviso that they are based on commercial incomes that may not properly measure social value.

3.3.1 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

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

[13] Delving into the data reveals the average absolute utilisation of NTC at 80.1% for IFA over that period.

[14] The data reveals that for that period, FAPDs occurred at an average of €1.16 and FWPDs at €10.49.

in CWE (See EU Commission, 2012-Q3; 2012-Q4). Existing metrics are biased by inefficient flows and this 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.

The development 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 of efficient flows and the poor performance of this measure in scenarios with inefficient flows. The left panel in Figure 1 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 is an underestimate of the monetary inefficiency as 53% of total mark-up (€1.8m/€3.4m) was exchanged during inefficient flows. This shortcoming is caused by it focusing on the volumetric dimension and ignoring inefficient flows and price differentials.

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.

3.3.2 Added value of new metrics

Our 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 so are more accurate. Conversely, if inefficient flows are more likely, *SCURED* will underestimate the true inefficiency. Again, as *UIIU* and *PWIIU* consider inefficient flows, 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, documented in Appendix 5 (SI).

3.4 Limitations of the new metrics

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 A3 in the SI) when the price differential is exactly zero. From an arbitrageur's perspective it would be uneconomic[15] 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[16] across all of our analyses by filtering out all occurrences. With full price convergence across the IEM, the tendency is for prices across different regions to

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

[16] 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.

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 have become available for several markets for recent years, since market coupling commenced, but data are limited for the pre-coupling period. For this reason, we focused on one interconnector (IFA) and one market coupling model (FBMC). Widening the scope of the analysis to include other market coupling models and/or other interconnectors would provide additional evidence to measure the benefits of the new metrics.

As the new metrics measure the distance from the efficient *S-curve*-shaped trading pattern, they do not account for operational/engineering constraints in the interconnector that might have resulted in apparently 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 will be limited by the quality of the data being analysed.

Interconnector transmission losses may affect estimations unless accounted for. Losses imply a discontinuity in the S-curve, so an interconnection flow at a zero-price differential (not loss-adjusted) is an inefficient flow, incurring avoidable losses. Also, 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). Neither of these system characteristics are considered by any of the metrics although they may indicate the need to study the hourly evolution of flows.

Finally, 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 would be needed to uncover and measure such inefficiencies.

4 Trading inefficiency and market coupling

We use an econometric model to define the annual average degree of utilisation inefficiency of the interconnectors between Great Britain and France (through IFA) between 2014 and 2019,[17] as well as between Great Britain and the Netherlands (through BritNed) between 2015 and 2018,[18] 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, hence on the 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),[19] we also simulate the cases with the GB Carbon Price Support (CPS) removed. This examines the impacts of market uncoupling if the CPS is

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

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

[19] 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.

abolished or extended to other EU countries. Further details about the methods used in this part of the paper are provided in Appendix 7 (SI).

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 8 (SI). Here, we provide a summary for each interconnector.

4.1 IFA interconnector

Market coupling led the price differential between GB and France to fall by €0.26/MWh (2%), net imports into GB to increase by 2.3 TWh (or by 22%), congestion income to increase by €14m (or by 6%), and infra-marginal surplus to increase by €3m (or 25%).

We compare the inefficiency of the coupled and uncoupled markets using the examined trading inefficiency metrics, with results shown in Table A12. Market coupling reduced the inefficiency of cross-border trading. On average, during 2014–2019, the share of FAPDs fell from 12% to 3%, and the Weighted FAPDs (*WFAPDs*) from 1.6% 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 more difficult to accurately forecast the sign of the price differential between two markets, and hence to choose the trade direction, resulting in greater trading inefficiency by some measures (although with small price differentials the welfare cost is low).

Without the CPS, average differences in prices (€/MWh), net imports (TWh), congestion income (€m), and infra-marginal surplus (€m) for coupled and uncoupled trading over IFA between 2016-2018 are reported in the last three rows of Table A11. 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 €19m/yr without the CPS, compared to €14m/yr with the CPS, a difference of 2% of the coupled congestion income, and the difference in the loss of infra-marginal surplus is less than 1% of coupled congestion income.

4.2 BritNed interconnector

The impact of market coupling on BritNed is shown in Table A15. 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 €0.09/MWh (by 0.6%), increased net imports into GB by 0.42 TWh/yr (by 5.6%), raised congestion income by €1.9m/yr (by 1.5%), and boosted infra-marginal surplus by €0.9m/yr (by 8.6% 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 relative impact on congestion income and infra-marginal surplus.

Table A15 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 7.9% (0.7%). *SCURED*, *UIUU*, and *PWIIU* also substantially increased.

It is also worth mentioning that the metrics ($I_{1\text{-}5}$) shown in Table A15 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 €7.1/MWh, much lower compared to 2015-2018, as shown in Table A15 (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 relative 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 the volume of 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.

4.3 Discussion

Interconnectors have provided welfare benefits to electricity systems, and these have been increased where market coupling has been introduced and the coupled markets are workably competitive and undistorted (Newbery *et al.*, 2019). Our analysis suggests that trading in an uncoupled market could 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.[20] 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 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 about subsequent GB prices, a trader 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.

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[20] The simulations used to measure the impact of uncoupling do not model such compensatory actions by traders, and so exaggerate the inefficiency, perhaps considerably.

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 that removing the asymmetry would deliver welfare gains that would likely outweigh the impact of uncoupling.

5 Conclusions and policy implications

Monitoring the efficiency of electricity trades between countries guides policies designed to improve market integration such as market coupling, integrating balancing and investing in new interconnectors. Regulators are familiar with the *UFAPD*, *WFAPD*, and *SCURED* metrics, which have been widely used in measuring the success of market coupling. Using both hypothetical market conditions and historical data, we have shown that these metrics rely too much on either inefficient flows (the indices *UFAPD* and *WFAPD*) or efficient flows (*SCURED*). The new *UIIU* and *PWIIU* metrics that we have proposed address these shortcomings and perform better for both uncoupled and coupled market trading, facilitating comparisons between countries and over time. They are not affected by extreme price and flow differentials, and consistently define the degree of trading inefficiency under numerous potential market conditions.

Market coupling in the EU Internal Electricity Market was designed to reduce trading inefficiency. 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. We have shown that current metrics can substantially overstate or understate the benefits of market coupling, which could underpin poor market design decisions in the future. Adopting our new metrics would give a more accurate picture of trading inefficiency and aid policy development to improve market operation. If the UK markets are uncoupled from neighbouring markets once it has left the EU, then the new metrics could be used to more accurately identify and minimise trading inefficiencies.

We found that uncoupling the UK markets would increase inefficient trading. It could lead the price differential between GB and France (the Netherlands) rising by €0.26/MWh or by 2% (by €0.09/MWh, or 0.6%), net imports into GB decreasing by 2.3 TWh or 22% (0.4TWh/yr, or 6%), congestion income decreasing by €14m, or 6% (€2m/yr, or 1.5%), and infra-marginal surplus decreasing by €3m, or 25% (€0.9m/yr, or 9%).

The benefits of market coupling increase with interconnector capacity, and decreases with the average price differential, here a larger price differential implies less uncertainty about the sign of the price differential and therefore on the direction of flow. Determining the efficient flow direction will become harder under uncoupling as price differentials fall as a result of planned new interconnectors and if European price differentials narrow due to the removal of the Carbon Price Floor in the future, although the value of this loss of predictability will be smaller with smaller price differentials.

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Supplementary Information

Appendix 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.

Appendix 2: Price-based metrics and flow-based metrics

2.1 Price-based metrics

Interconnectors promote price convergence as traders buy and sell electricity until expected prices equalise. 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 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 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 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 Β-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.

2.2 Flow-based metrics

Flow-based metrics are imperfect as they do not consider price differentials and hence the value of inefficient flows.

Indexed annual aggregation of hourly NTC values*.* 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 efficiency of interconnector use.[1]

Capacity utilisation ratio*.*[2] The ratio of the number of hours when capacity was used to the number of hours when it was available. ACER (2012) compared the intra-day capacity utilisation to that in the day-ahead timeframe, concluding that intra-day capacity utilisation was relatively low.[3] In addition, the authors concluded that implicit allocation (as under market coupling) was less inefficient than explicit (or other) allocation methods.[4]

Absolute sum of net nominations per year*.* This measure indicates the level of available cross-zonal market capacity and is considered for *intra-day* markets 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.

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

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

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

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

Appendix 3: Charts of Flow vs Price differential

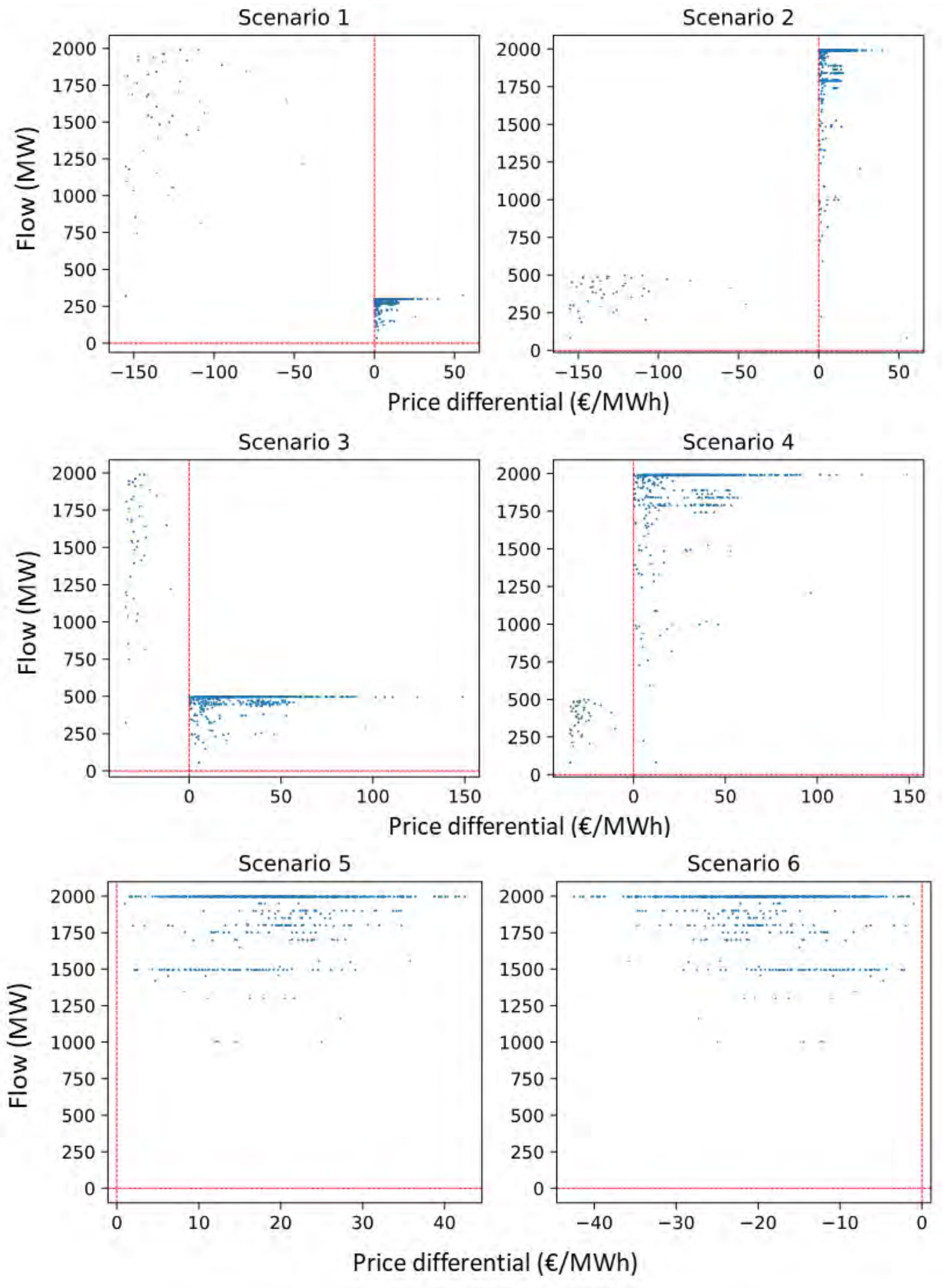

Figure A1(a). Scatterplots of the stress data for Scenarios 1–6.

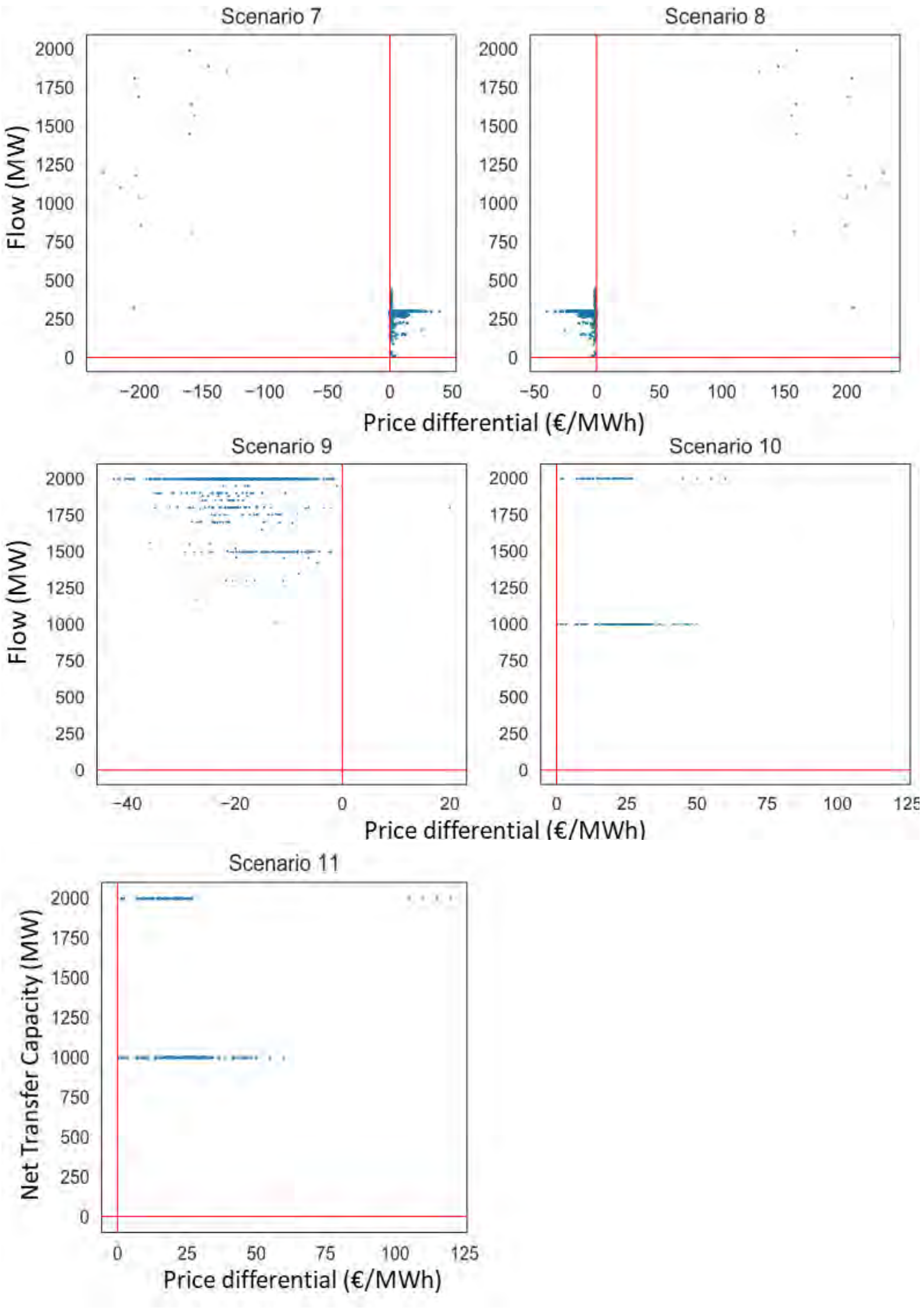

Figure A1(b). Scatterplots of the stress data for scenarios 7–11.

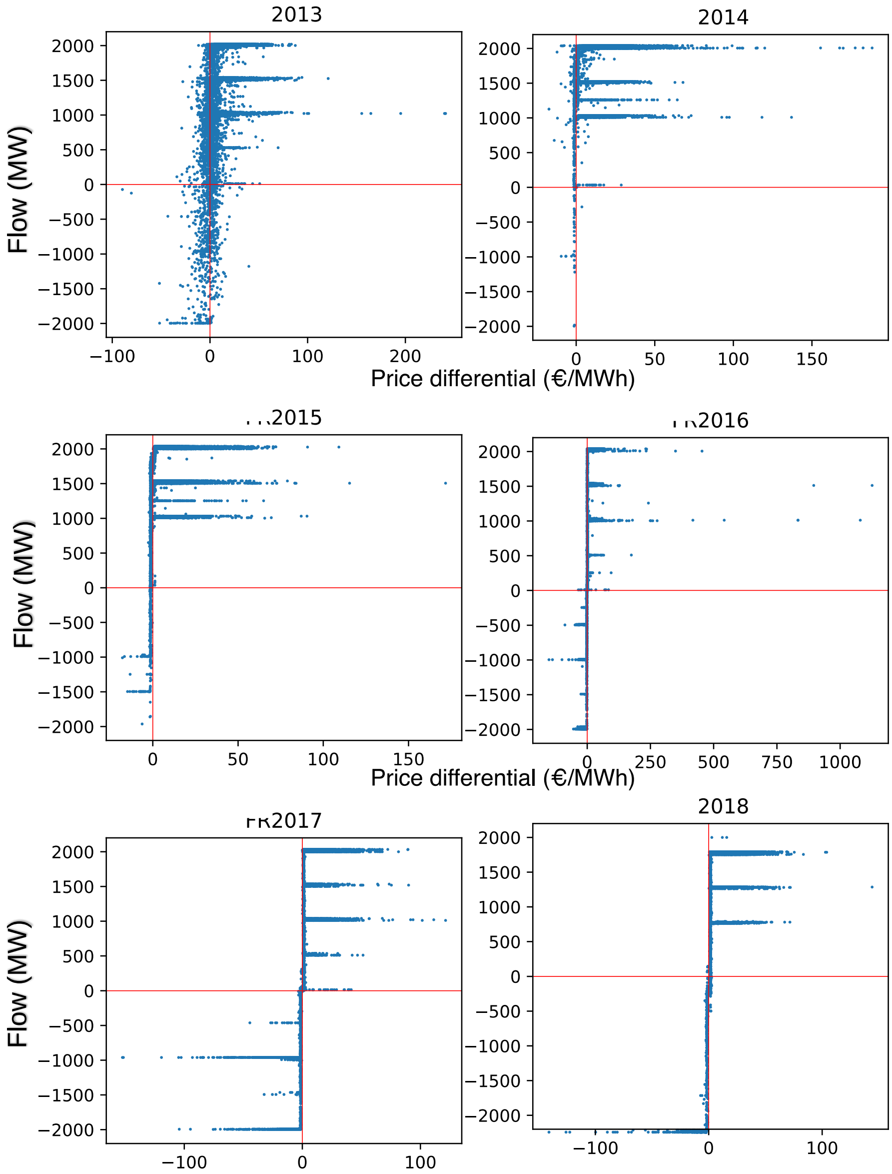

Figure A2. Plot of GB-FR Day-ahead price vs FR->GB RTE flow. Day-ahead NWE coupling went live on 04-02-2014.

Appendix 4: Measures of social welfare

Interconnectors increase welfare by reducing the overall cost of the interconnected electricity systems, creating consumer surplus for importers and producer surplus for exporters. Since social welfare is challenging to calculate, the metrics presented in the paper are used instead to estimate commercial interconnector efficiency, which is a good proxy for social welfare if markets are competitive and externalities properly priced. Some studies have calculated social welfare metrics directly, particularly for examining the potential impacts of deploying new interconnectors which may change prices (usually assuming efficient markets).

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[5] changes for the proposed

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[5] 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.

ElecLink interconnector between Great Britain and France.[6] 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 should include all external costs of CO_2 emissions and other pollutants, as well as correcting for market power (or basing calculations on costs rather than prices). 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 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).

Appendix 5: Methodological appendix: Metrics

5.1 Derivation of the new metrics

For any hour *h* of the day, in any two regions *A* and *B*, electricity flows of magnitude $\tilde{f}_h(MW)$ move across an interconnector in the direction *A*→*B* at a price differential (€/MWh) $D_{BA(h)} \coloneqq P_{B(h)} - P_{A(h)}$. Ideally,[7] arbitrageurs import electricity into market *B* from market *A* when prices are lower in *A* and conversely, import into *A* from *B* (*B*→*A*) when prices are lower in *B*. Efficient trading behaviour in idealised conditions give rise to the step-curve[8] (S-curve) pattern in Left diagram of Figure A1.

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

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

[8] 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 $D_{BA} = 0$ discontinuity.

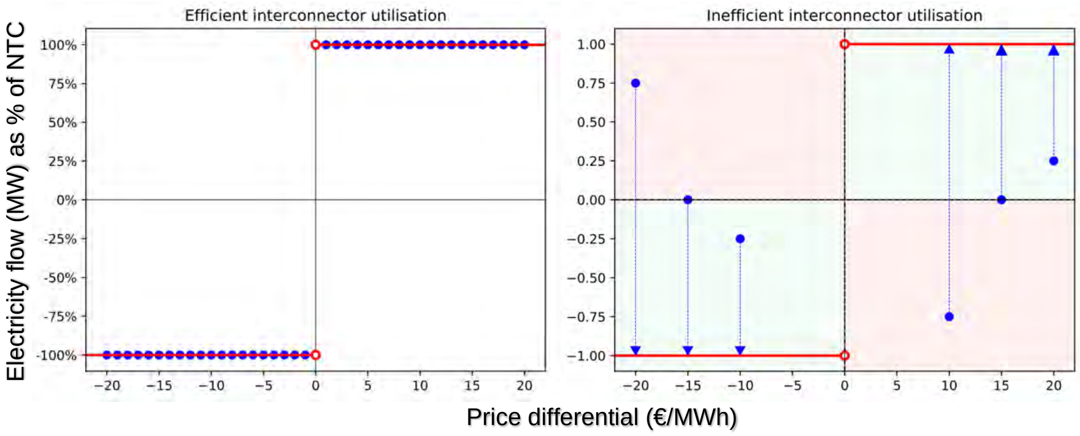

Figure A3. Here, the S-curve is reported as a ratio of available to used capacity, as opposed to Figure 1, for simplicity. LEFT: S-curve (in red) of the efficient utilisation pattern by interconnector arbitrageurs (blue points) across markets A, B. x-axis denotes the price differential $D_{BA(h)}$. The 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

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

where

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

with the superscripts '-' , '+', *0*[9], denoting adverse-flow,[10] favourable-flow and no-flow,[11] respectively. *NTC* denotes net transfer capacity and $\tilde{f}_h$ the hourly flow.

5.2 SCUWED as a limit for UIIU

When all flows are favourable and NTC is constant Equation(4) becomes

$$UIIU = \frac{1}{2}\left(\frac{1}{N}\sum_h^N\left(1-\left|\frac{\tilde{f}_h}{K}\right|\right)\right) = \frac{1}{2}\left(1-\frac{1}{N}\sum_h^N\left|\frac{\tilde{f}_h}{K}\right|\right) = \frac{1}{2}\left(1-\frac{\sum_h^N|\tilde{f}_h|}{\sum_h^N|K|}\right) = \frac{1}{2}(1-SCURED)$$

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[9] By definition $f_h^0 = 0$.

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

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

5.3 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. Note that surpluses and deadweight loss increase as the square of the price differential so w_1 may be a better welfare weight. Due to its linear nature, our choice of weighting scheme results in minimum bias from outliers. One could also[12] apply a scheme with symmetric emphasis on outliers via w_1 (or w_3 with $\beta = 0.05$), or with adverse flows asymmetrically penalised (w_2 with $\beta = -0.01$) as in figure A4 below.

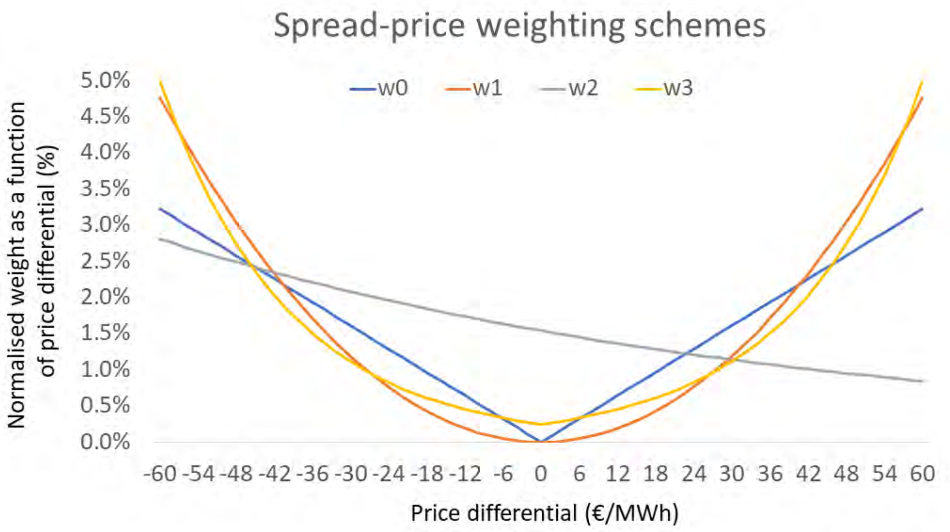

Figure A4. Price differential weighting according to different weighting schemes. w0 is the price differential weighting applied in equation (5), w^1-w^3 as per Section 1.3. of this document (SI) For w^2 and w^3, β = -0.01 and 0.05 respectively.

5.4 Data pre-processing

Pre-processing data can be helpful in deriving 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.

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[12] When dealing with underdetermined systems and optimisation.

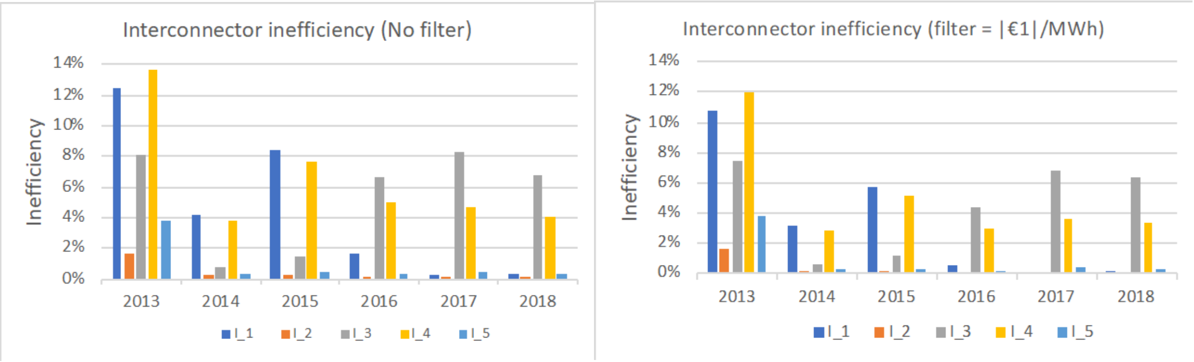

Figure A5. Results of metrics by year (IFA). LEFT: Original series without a filter. RIGHT: Series with a filter of (absolute) €1/MWh below which price differentials are ignored for the analysis, as done in many ACER and EU Commission reports.

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

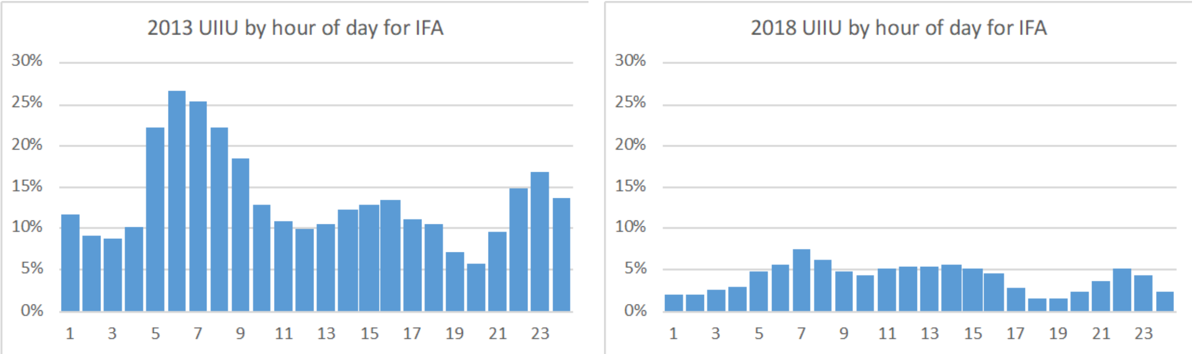

Figure A6(a). Unweighted interconnector inefficient utilisation metric (UIIU) (%, y-axis) averaged by hour of the day (x-axis) for selected years, for the IFA interconnector.

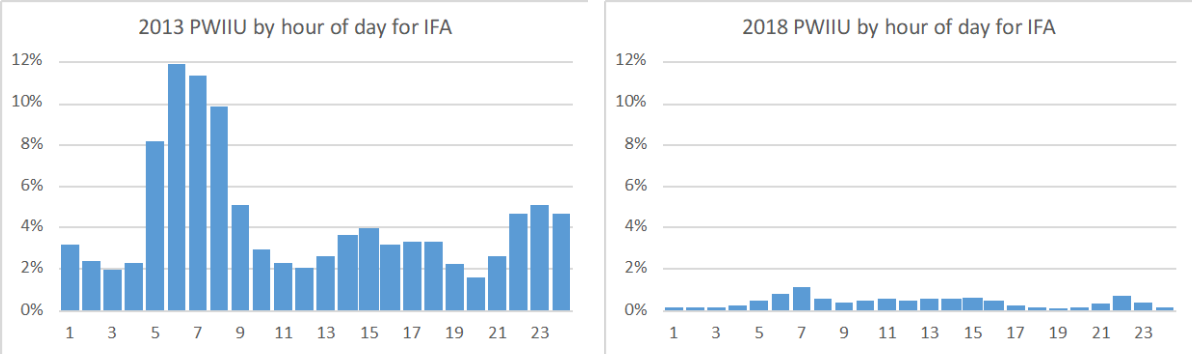

Figure A6(b). Price-Weighted Interconnector Inefficient Utilisation (PWIIU) metric (%, y-axis) averaged by hour of the day (x-axis) for selected years, for the IFA interconnector.

5.6 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 A1. 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 A2. Intermediate calculations required for estimation of metrics i1 -- I5. flow_adj is used only in the calculation of SCUWED.

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)	=IF([@fpd]=-1,1,0) * (1+ABS([@[flow/NTC]]))/2 + IF([@fpd]=1,1,0) * (1-ABS([@[flow/NTC]]))/2 + IF([@fpd]=0,1,0) * (1/2)
|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 A3. Formulae for intermediate calculations in Table A7. Boldface denotes named ranges described in Tables A5 and A6.

The spreadsheet '*TableB'* 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(TableB[|gb_fr|],TableB[year],"=2013", TableB[month],"=1")
2013-2	5506	=SUMIFS(TableB[|gb_fr|],TableB[year],"=2013", TableB[month],"=2")
2013-3	10922	=SUMIFS(TableB[|gb_fr|],TableB[year],"=2013", TableB[month],"=3")

Table A4. 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(TableB[year],"=2013",TableB[|gb_fr|])
2014	155106	= SUMIF(TableB[year],"=2014",TableB[|gb_fr|])
2015	153612	= SUMIF(TableB[year],"=2015",TableB[|gb_fr|])

Table A5. 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(TableB[year],"=2013")
N+	=COUNTIFS(TableB[year],"=2013",TableB[fpd],"1")
N-	=COUNTIFS(TableB[year],"=2013",TableB[fpd],"-1")
N0	=COUNTIFS(TableB[year],"=2013",TableB[fpd],"0")
I1	=[@[N-]]/[@N]
I2	=ABS(SUMIFS(TableB[CR],TableB[year],"=2013", TableB[fpd],"=-1"))/(SUMIFS(TableB[CR],TableB[year],"=2013", TableB[fpd],"=1") + ABS(SUMIFS(TableB[CR],TableB[year],"=2013", TableB[fpd],"=-1")))
I3	=1 - (SUMIFS(TableB[flow_adj],TableB[year],”=2013”,TableB[fpd],"=1")/ SUMIFS(TableB[NTC],TableB[year], “=2013”,TableB[fpd],"=1"))
I4	=SUMIFS(TableB[uD(S)],TableB[year],”=2013”)/[@N]
I5	=(SUMIFS(TableB[wD(S)_y],TableB[year],"=2013",TableB[fpd],"=1")+SUMIFS(TableB[wD(S)_y],TableB[year],"=2013", TableB[fpd],"=-1")+SUMIFS(TableB[wD(S)_y],TableB[year],"=2013", TableB[fpd],"=0"))

Table A6. Formulae corresponding to columns in Table A4. The example provided is for calendar year 2013.

column	Formula
N	=COUNTIFS(TableB[year],"=2013", TableB[month],"=1")
N+	=COUNTIFS(TableB[year],"=2013", TableB[month],"=1",TableB[fpd],"1")
N-	=COUNTIFS(TableB[year],"=2013", TableB[month],"=1",TableB[fpd],"-1")
N0	=COUNTIFS(TableB[year],"=2013", TableB[month],"=1",TableB[fpd],"0")
I1	=COUNTIFS(TableB[year],"=2013", TableB[month],"=1",TableB[fpd],"-1")/COUNTIFS(TableB[year],"=2013", TableB[month],"=1")
I2	=ABS(SUMIFS(TableB[CR],TableB[year],"=2013", TableB[month],"=1",TableB[fpd],"=-1"))/(SUMIFS(TableB[CR],TableB[year],"=2013", TableB[month],"=1",TableB[fpd],"=1") + ABS(SUMIFS(TableB[CR],TableB[year],"=2013", TableB[month],"=1",TableB[fpd],"=-1")))
I3	=1-(SUMIFS(TableB[flow_adj],TableB[year],"=2013", TableB[month],"=1",TableB[fpd],"=1")/SUMIFS(TableB[NTC],TableB[year],"=2013", TableB[month],"=1",TableB[fpd],"=1"))
I4	=(SUMIFS(TableB[uD(S)],TableB[year],"=2013", TableB[month],"=1")/AK2)
I5	=(SUMIFS(TableB[wD(S)_m],TableB[year],"=2013", TableB[month],"=1",TableB[fpd],"=1")+SUMIFS(TableB[wD(S)_m],TableB[year],"=2013", TableB[month],"=1",TableB[fpd],"=-1")+SUMIFS(TableB[wD(S)_m],TableB[year],"=2013", TableB[month],"=1",TableB[fpd],"=0"))

Table A7. Formulae corresponding to the columns in Table A4. The example provided is for the month of January 2013.

Appendix 6: Monthly Historical Dataset Results

6.1 IFA

Year	Month	N	N+	N-	N0	*UFAPD*	*WFAPD*	*SCUWED*	*UIIU*	*PWIIU*
2013	1	744	567	177	0	23.8%	5.2%	15.5%	24.7%	10.2%
2013	2	672	482	190	0	28.3%	8.9%	23.8%	29.9%	16.6%
2013	3	744	608	136	0	18.3%	4.0%	14.8%	21.2%	9.0%
2013	4	721	604	117	0	16.2%	3.6%	8.6%	16.2%	6.7%
2013	5	744	717	27	0	3.6%	0.3%	0.4%	3.3%	0.4%
2013	6	720	713	7	0	1.0%	0.1%	0.5%	1.2%	0.2%
2013	7	744	726	18	0	2.4%	0.2%	0.8%	2.6%	0.4%
2013	8	744	721	23	0	3.1%	0.3%	1.7%	3.4%	0.8%
2013	9	698	648	50	0	7.2%	0.8%	5.0%	8.1%	1.7%
2013	10	744	644	100	0	13.4%	2.2%	9.1%	15.0%	4.6%
2013	11	720	623	97	0	13.5%	1.9%	13.4%	16.2%	4.7%
2013	12	744	596	148	0	19.9%	3.9%	17.8%	22.6%	7.6%
2014	1	744	698	46	0	6.2%	0.7%	2.3%	6.5%	1.1%
2014	2	672	649	23	0	3.4%	0.6%	1.7%	3.6%	0.9%
2014	3	720	705	15	0	2.1%	0.1%	0.8%	2.1%	0.2%
2014	4	720	702	18	0	2.5%	0.1%	0.8%	2.4%	0.2%
2014	5	744	734	10	0	1.3%	0.0%	0.4%	1.2%	0.1%
2014	6	720	702	18	0	2.5%	0.1%	0.5%	2.2%	0.1%
2014	7	744	744	0	0	0.0%	0.0%	0.0%	0.0%	0.0%
2014	8	744	740	4	0	0.5%	0.0%	0.0%	0.5%	0.0%
2014	9	720	704	16	0	2.2%	0.1%	0.2%	2.1%	0.1%
2014	10	744	669	74	1	9.9%	0.5%	0.6%	8.8%	0.6%
2014	11	720	703	17	0	2.4%	0.1%	0.3%	2.2%	0.1%
2014	12	744	621	120	3	16.1%	0.7%	2.1%	13.7%	1.1%
2015	1	744	597	147	0	19.8%	1.4%	2.2%	17.6%	1.7%
2015	2	672	513	156	3	23.2%	1.9%	7.1%	21.3%	2.9%
2015	3	744	657	86	0	11.6%	0.6%	2.0%	10.7%	0.9%
2015	4	720	701	19	0	2.6%	0.1%	0.5%	2.5%	0.1%
2015	5	744	739	5	0	0.7%	0.0%	0.2%	0.6%	0.0%
2015	6	720	717	3	0	0.4%	0.0%	0.0%	0.4%	0.0%
2015	7	744	722	22	0	3.0%	0.1%	0.1%	2.6%	0.1%
2015	8	744	743	1	0	0.1%	0.0%	0.0%	0.1%	0.0%
2015	9	720	712	8	0	1.1%	0.0%	0.1%	1.1%	0.1%
2015	10	744	631	112	0	15.1%	0.8%	3.1%	13.2%	1.3%
2015	11	720	632	88	0	12.2%	0.6%	3.0%	11.8%	0.9%
2015	12	744	655	89	0	12.0%	0.4%	2.6%	10.6%	0.7%
2016	1	744	689	55	0	7.4%	0.2%	3.9%	7.5%	0.4%
2016	2	696	675	21	0	3.0%	0.1%	0.3%	2.7%	0.1%
2016	3	744	734	10	0	1.3%	0.1%	0.1%	1.2%	0.1%
2016	4	720	718	2	0	0.3%	0.0%	0.4%	0.4%	0.0%
2016	5	744	744	0	0	0.0%	0.0%	0.3%	0.1%	0.0%
2016	6	720	720	0	0	0.0%	0.0%	0.0%	0.0%	0.0%
2016	7	744	744	0	0	0.0%	0.0%	0.8%	0.4%	0.0%
2016	8	744	737	7	0	0.9%	0.0%	5.9%	3.4%	0.3%
2016	9	720	692	28	0	3.9%	0.0%	24.7%	13.4%	0.7%
2016	10	725	704	8	13	1.1%	0.0%	20.9%	10.3%	0.9%
2016	11	720	698	4	18	0.6%	0.0%	23.1%	11.3%	1.3%
2016	12	744	718	6	20	0.8%	0.0%	18.2%	10.5%	1.3%

Table A8. Monthly historical dataset results for years 2013 to 2016 for all indices UFAPD–PWIIU (IFA).

6.2 BritNed

Year	Month	N	N+	N-	N0	*UFAPD*	*WFAPD*	*SCUWED*	*UIIU*	*PWIIU*
2013	1	745	593	150	2	20.1%	3.5%	21.4%	22.7%	9.8%
2013	2	670	584	86	0	12.8%	1.4%	16.1%	16.2%	5.2%
2013	3	744	630	113	1	15.2%	3.1%	7.6%	15.2%	5.1%
2013	4	720	528	191	1	26.5%	6.8%	24.4%	27.7%	15.7%
2013	5	744	563	181	0	24.3%	4.4%	18.0%	23.7%	11.1%
2013	6	708	585	123	0	17.4%	2.6%	16.8%	19.0%	8.2%
2013	7	744	666	78	0	10.5%	1.8%	7.5%	11.6%	3.7%
2013	8	744	662	82	0	11.0%	2.0%	8.9%	12.6%	4.5%
2013	9	603	525	74	4	12.3%	1.6%	14.4%	15.1%	5.1%
2013	10	744	616	123	5	16.5%	2.2%	14.2%	18.2%	5.8%
2013	11	720	635	85	0	11.8%	1.6%	10.9%	13.4%	4.6%
2013	12	744	635	108	1	14.5%	2.2%	13.5%	16.4%	6.1%
2014	1	694	634	60	0	8.6%	1.0%	4.3%	8.8%	2.2%
2014	2	0	0	0	0	N/A	N/A	N/A	N/A	N/A
2014	3	434	418	16	0	3.7%	0.2%	2.2%	4.0%	0.5%
2014	4	720	696	24	0	3.3%	0.2%	2.9%	4.1%	0.5%
2014	5	743	704	39	0	5.2%	0.4%	2.1%	5.1%	0.7%
2014	6	720	678	42	0	5.8%	0.5%	2.1%	5.7%	0.8%
2014	7	744	725	19	0	2.6%	0.2%	0.9%	2.5%	0.3%
2014	8	744	713	31	0	4.2%	0.3%	1.7%	4.1%	0.6%
2014	9	559	527	32	0	5.7%	0.5%	2.1%	5.8%	0.7%
2014	10	744	703	41	0	5.5%	0.4%	1.4%	5.4%	0.5%
2014	11	720	687	33	0	4.6%	0.2%	1.4%	4.6%	0.4%
2014	12	720	608	112	0	15.6%	1.2%	2.8%	14.0%	1.7%
2015	1	744	664	80	0	10.8%	0.6%	7.4%	11.5%	1.3%
2015	2	672	617	55	0	8.2%	0.4%	8.6%	10.0%	1.1%
2015	3	744	708	36	0	4.8%	0.2%	5.7%	6.3%	0.6%
2015	4	720	710	10	0	1.4%	0.1%	2.4%	2.2%	0.2%
2015	5	679	642	36	1	5.3%	0.2%	3.1%	5.6%	0.3%
2015	6	720	693	27	0	3.8%	0.2%	3.8%	4.8%	0.4%
2015	7	744	714	30	0	4.0%	0.2%	3.2%	4.5%	0.4%
2015	8	744	726	18	0	2.4%	0.1%	2.3%	3.0%	0.3%
2015	9	655	643	12	0	1.8%	0.1%	4.0%	3.5%	0.3%
2015	10	744	691	51	2	6.9%	0.3%	5.5%	7.9%	0.7%
2015	11	720	654	66	0	9.2%	0.4%	4.6%	8.9%	0.7%
2015	12	744	660	84	0	11.3%	0.3%	5.3%	10.8%	0.6%
2016	1	744	704	40	0	5.4%	0.2%	1.8%	4.8%	0.4%
2016	2	696	693	3	0	0.4%	0.0%	1.2%	0.9%	0.0%
2016	3	744	740	4	0	0.5%	0.0%	1.0%	1.0%	0.1%
2016	4	720	718	2	0	0.3%	0.0%	1.6%	1.0%	0.0%
2016	5	680	678	2	0	0.3%	0.0%	3.7%	2.1%	0.1%
2016	6	720	716	4	0	0.6%	0.0%	7.2%	4.0%	0.4%
2016	7	744	740	4	0	0.5%	0.0%	9.6%	5.2%	0.6%
2016	8	744	742	2	0	0.3%	0.0%	4.1%	2.2%	0.2%
2016	9	678	650	28	0	4.1%	0.2%	11.9%	8.9%	0.6%
2016	10	744	729	15	0	2.0%	0.1%	9.8%	6.2%	0.4%
2016	11	720	699	21	0	2.9%	0.1%	4.5%	4.5%	0.3%
2016	12	744	684	60	0	8.1%	0.4%	8.2%	9.7%	1.1%

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

Appendix 7: Methodological appendix: simulation

We use a simulation-based method to derive the expected cross-border price differentials between GB and France and the Netherlands, and flows for IFA and BritNed, had the interconnectors not been coupled. Our simulation assumes a cross-border market where, after the foreign price has been set, risk-averse traders have to forecast the GB price to make trading decisions, and any forecast 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 the cross-border electricity markets. The simulation model is simplified from Geske *et al.* (2018). Our analysis in this section only focuses on the day-ahead market, where the GB electricity market is (up to end 2019) fully coupled with France and the Netherlands.

Before the 2014 market coupling 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). Taking IFA as an example, we assume a single trader[13] who maximises her utility function, U_h, in each hour, *h*

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

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 (by equalising the first-order condition of $\mathrm{E}(U_h)$ to zero) finds the optimal trading (net import for GB in GW) $\hat{T}$ as:

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

$$\theta = \frac{\mathrm{E}\big(P_h^{GB}\big) - P_h^{FR}}{\lambda \cdot \big(C_{GB,h}^{''}\sigma\big)^2} = \frac{\mathrm{E}\big(P_h^{GB}\big) - P_h^{FR}}{\mu}$$

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, $\mu = \lambda \cdot \big(C_{GB,h}^{''}\sigma\big)^2$, is a function of unknown parameters. It is worth noticing that instead of separately identifying λ, σ, and $C_{GB,h}^{''}$, we only need to identify μ to conduct our simulation. Intuitively, a greater expected price differential

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[13] 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.

indicates greater potential for imports, therefore θ is positively correlated with the expected DA price differential.

With forecast errors, θ can be expressed as

$$\theta = \frac{P_h^{GB} + \varepsilon_h^{GB} - P_h^{FR}}{\lambda(C_{GB,h}^{\prime\;\prime}\sigma)^2}$$

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

We aim to identify parameters μ and $\sigma_{GB,P}^2$ such that the simulated[14] 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 proposed metrics of trading inefficiency in this paper.

Once the parameter values for IFA and BritNed have been identified, we can use the parameters and the observed DA prices for both markets to simulate the uncoupled IFA and BritNed flows and price differentials during the examined electricity years (2014-2019). We then compare the simulated uncoupled counterfactuals 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 *SCUWED*.

Appendix 8: Value of market coupling

8.1 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: 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 exposure to volatile prices in the balancing mechanism.[15] 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. After Brexit, it is expected that GB will be uncoupled in the day-ahead market but coupled in the intra-day market.

8.2 Trading in coupled markets

Day-ahead coupling obviates the need to predict day-ahead price differentials. Instead, the EUPHEMIA algorithm will ensure that the DA flow is optimised, based on bids and offers in

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[14] 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.

[15] 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.

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 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.

8.3 Simulation results for IFA

The measures of the inefficiency of the simulated flows (denoted as “Simulated flow 2013, BritNed” with different values of parameters $\sigma_{GB,P}$ and µ are reported in Table A10 and are compared with those of the actual uncoupled IFA flow in 2013, denoted as the “Actual flow 2013, IFA”.

We gradually increase the values of $\sigma_{GB,P}$ and µ until the measures of inefficiency (I_1 to I_5) are reasonably close to the actual measures of inefficiency in 2013. As it is shown in Table A10, when $\sigma_{GB,P}$ =7 and µ= 5, by comparing I_1 to I_5, the simulated flow and the actual flow are similarly inefficient. Therefore, when simulating the uncoupled flow for IFA for 2014-2019, we set $\sigma_{GB,P}$ =7 and µ= 5.

			I_1	I_2	I_3	I_4	I_5
Actual flow 2013, IFA			12.4%	1.7%	8.1%	13.6%	3.8%
Simulated flow 2013, BritNed	**Parameter Values**						
	$\sigma_{GB,P}$	$\lambda(C_{GB,h}^{'\,'}\sigma)^2$					
	4	4	8.7%	0.6%	8.5%	10.4%	1.7%
	5	4	9.7%	0.8%	8.3%	11.2%	2.1%
	5	5	9.6%	0.7%	10.6%	11.5%	2.4%
	6	5	11.3%	1.1%	9.8%	12.9%	2.9%
	7	***5***	***12.8%***	***1.6%***	***9.6%***	***14.1%***	***3.6%***

Table A10. Day-ahead actual and simulated flows for IFA in 2013

We then simulate scenarios where trading over IFA occurs without market coupling during 2014-2019 and compare them with the actual data under market coupling, in terms of net imports into GB, congestion revenue, infra-marginal surplus, and trading inefficiency.The results are reported in Table A11.

Among our main findings, based on annual averages, coupling caused the price differential between GB and France to fall by €0.26/MWh, net imports into GB to increase by 2.26 TWh (or by 21.5%), congestion Income increased by €13.71 million (or by 6%), and infra-marginal surplus increased by €3.3 million (or by 25%, or about 1.4% of uncoupled congestion revenue).

	Price Difference (€/MWh)			**Net GB Imports (TWh)**		
Electricity year	**Coupled**	**Uncoupled**	**Δ**	**Coupled**	**Uncoupled**	**Δ**
2014-2015	15.83	16.20	-0.37	15.20	12.34	2.86
2015-2016	18.76	19.00	-0.24	15.52	13.53	1.99
2016-2017	8.54	8.72	-0.18	8.17	6.65	1.52
2017-2018	10.49	10.75	-0.26	11.32	8.96	2.36
2018-2019	13.76	14.05	-0.29	13.66	11.06	2.60
Average	13.48	13.74	-0.26	12.77	10.51	2.26
2016-2017 w/o CPS	-0.45	-0.54	0.09	-0.13	0.55	-0.68
2017-2018 w/o CPS	2.59	2.42	0.17	0.54	1.81	-1.27
Average w/o CPS	1.07	0.94	0.13	0.20	1.18	-0.98
	Congestion Income (million €)			**Infra-marginal Surplus (million €)**		
2014-2015	256.84	244.53	12.31	17.17	13.84	3.33
2015-2016	318.28	307.42	10.86	18.35	16.03	2.32
2016-2017	197.33	184.13	13.20	12.48	9.56	2.92
2017-2018	210.82	194.16	16.66	16.78	12.77	4.01
2018-2019	234.06	218.54	15.52	16.81	13.10	3.71
Average	243.47	229.76	13.71	16.32	13.06	3.26
2016-2017 w/o CPS	154.34	136.85	17.49	12.11	7.72	4.39
2017-2018 w/o CPS	150.91	130.59	20.32	15.88	10.20	5.68
Average w/o CPS	152.62	133.72	18.91	13.99	8.96	5.03

Table A11. 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 A12. 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 12.1% to a negligible 2.8%, and the Weighted FAPDs (*WFAPDs*) from 1.6% to only 0.1%. *PWIIU*, *UIIU*, and *SCUWED* also considerably decreased.

Electricity year	Market condition	Metrics				
		UFAPD	*WFAPD*	*SCUWED*	*UIIU*	*PWIIU*
2014-2015	**Coupled**	7.6%	0.3%	1.2%	6.8%	0.5%
	Uncoupled	11.7%	1.3%	9.0%	12.9%	3.7%
2015-2016	**Coupled**	4.9%	0.1%	1.0%	4.6%	0.2%
	Uncoupled	8.3%	0.8%	7.0%	9.8%	2.6%
2016-2017	**Coupled**	0.7%	0.0%	8.6%	5.6%	0.6%
	Uncoupled	15.0%	2.0%	12.4%	17.0%	4.9%
2017-2018	**Coupled**	0.2%	0.0%	7.4%	4.2%	0.6%
	Uncoupled	13.4%	2.1%	14.4%	16.2%	5.9%
2018-2019	**Coupled**	0.4%	0.0%	7.4%	4.5%	0.4%
	Uncoupled	12.3%	1.8%	13.4%	14.7%	4.8%
Average 2014-2019	**Coupled**	2.8%	0.1%	5.1%	5.1%	0.5%
	Uncoupled	12.1%	1.6%	11.2%	14.1%	4.4%
2016-2017 w/o CPS	**Coupled**	3.1%	0.1%	4.8%	6.7%	0.7%
	Uncoupled	17.2%	3.5%	17.4%	19.3%	7.0%
2017-2018 w/o CPS	**Coupled**	5.3%	0.2%	4.5%	9.5%	1.3%
	Uncoupled	20.6%	4.3%	19.7%	23.2%	10.3%

Table A12. 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*, *SCUWED*, *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 price differentials between two markets and 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 A11. By removing the CPS, GB prices in 2016-2018 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 €5.2 million/yr and €1.3m./yr respectively) than in cases with the CPS.

8.4 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 (relative to 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[16]), with results shown in Table A13.

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

			I_1	I_2	I_3	I_4	I_5
Actual flow 2013, BritNed			15.9%	2.7%	14.2%	18.2%	7.5%
Simulated flow 2013, BritNed	**Parameter Values**						
	$\sigma_{GB,P}$	$\lambda(C^{'}_{GB,h}{}^{'}\sigma)^2$					
	3	4	14.7%	2.2%	9.2%	16.4%	4.8%
	3	5	14.6%	1.9%	11.4%	16.9%	4.9%
	4	5	17.2%	3.2%	11.5%	19.1%	6.7%
	4	***6***	***16.7%***	***2.8%***	***13.7%***	***19.1%***	***6.8%***
	4	7	15.7%	2.2%	16.6%	19.2%	6.9%

Table A13. Day-ahead actual and simulated flows for BritNed.

When $\sigma_{GB,P} = 4$ and $\mu = 6$, the "simulated flow 2013, BriNed" is reasonably close to the "actual flow 2013, BritNed". We therefore assume the values for parameters to simulate the uncoupled BritNed flow during 2015-2018[17] is $\sigma_{GB,P} = 4$ and $\mu = 6$.

We then assess the impact of market coupling on BritNed, with results shown in Table A14. 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 €0.09/MWh (by 0.6%), increased net imports into GB by 0.42 TWh/yr (by 5.6%), raised congestion income by €1.9 m/yr (by 1.5%), and boosted infra-marginal surplus by €0.9 m/yr (by 0.7% 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.

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[17] 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).

	Price Difference (€/MWh)			**Net Import (TWh)**		
Electricity year	**Coupled**	**Uncoupled**	Δ	**Coupled**	**Uncoupled**	Δ
2015-2016	17.00	17.09	-0.09	8.27	7.89	0.38
2016-2017	15.78	15.88	-0.10	7.85	7.41	0.43
2017-2018	12.82	12.91	-0.09	7.71	7.28	0.43
Average	15.20	15.29	-0.09	7.94	7.53	0.42
2016-2017 w/o CPS	9.60	9.38	0.22	4.26	4.70	-0.45
2017-2018 w/o CPS	7.36	7.08	0.28	3.68	4.32	-0.64
	Congestion Income (million €)			**Infra-marginal Surplus (million €)**		
Electricity year	**Coupled**	**Uncoupled**	Δ	**Coupled**	**Uncoupled**	Δ
2015-2016	148.02	146.77	1.24	11.65	11.01	0.63
2016-2017	137.10	135.03	2.07	11.17	10.25	0.92
2017-2018	112.62	110.12	2.51	10.73	9.62	1.11
Average	132.58	130.64	1.94	11.18	10.30	0.89
2016-2017 w/o CPS	87.76	84.08	3.69	9.23	7.25	1.98
2017-2018 w/o CPS	68.89	65.52	3.37	8.53	6.39	2.13

Table A14. 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 A15 compares trading inefficiency for BritNed, with and without market coupling, for electricity years 2015-2018. Again, uncoupling increases trading inefficiency. *UFAPD* (*WFAPD*) increased from 3.1% (0.1%) to 7.9% (0.7%), while *SCUWED*, *UIUU*, and *PWIIU* also show substantial increases.

It is also worth mentioning that the metrics (I_1-I_5) shown in Table A15 based on uncoupled markets during 2015-2018 are smaller than the metrics in 2013 (Table A10), 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 A15 (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***	***SCUWED***	***UIIU***	***PWIIU***
2015-2016	**Coupled**	4.4%	0.2%	3.1%	5.4%	1.1%
	Uncoupled	6.1%	0.4%	3.6%	7.0%	1.7%
2016-2017	**Coupled**	2.5%	0.1%	6.6%	5.6%	2.7%
	Uncoupled	8.1%	0.6%	5.9%	9.5%	3.7%
2017-2018	**Coupled**	2.3%	0.1%	9.0%	6.7%	1.6%
	Uncoupled	9.6%	1.0%	7.1%	11.4%	3.1%
Average 2015-2018	**Coupled**	3.1%	0.1%	6.2%	5.9%	1.8%
	Uncoupled	7.9%	0.7%	5.5%	9.3%	2.8%
2016-2017 w/o CPS	**Coupled**	0.9%	0.0%	8.9%	11.5%	5.2%
	Uncoupled	13.4%	2.0%	13.0%	16.5%	7.4%
2017-2018 w/o CPS	**Coupled**	1.3%	0.0%	10.9%	13.5%	4.4%
	Uncoupled	16.0%	2.6%	14.2%	18.7%	7.0%

Table A15. 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*, *SCUWED*, *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.