

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 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
FVPD	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 usually¹ caused by the markets for interconnector capacity and delivery of energy closing at different 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).

1.2 Previous studies of trading inefficiency

The welfare gains³ 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

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.

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

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 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 <i>et al.</i> (2019)	Unweighted Inefficient Interconnector Utilisation (UIIU) – Eq.4*
		Montoya <i>et al.</i> (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 <i>et al.</i> (2019)	Value Destruction.
		Newbery <i>et al.</i> (2019)	Percentage of potential congestion revenue.
		Meeus (2011)	Test on unused capacity times price differential.
		Simulation-based analysis	ACER (2011)
De Jong <i>et al.</i> (2007)			
Newbery <i>et al.</i> (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 :

$$FAPD = UFAPD = I_1 = \frac{N^-}{N} \quad (1)$$

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.

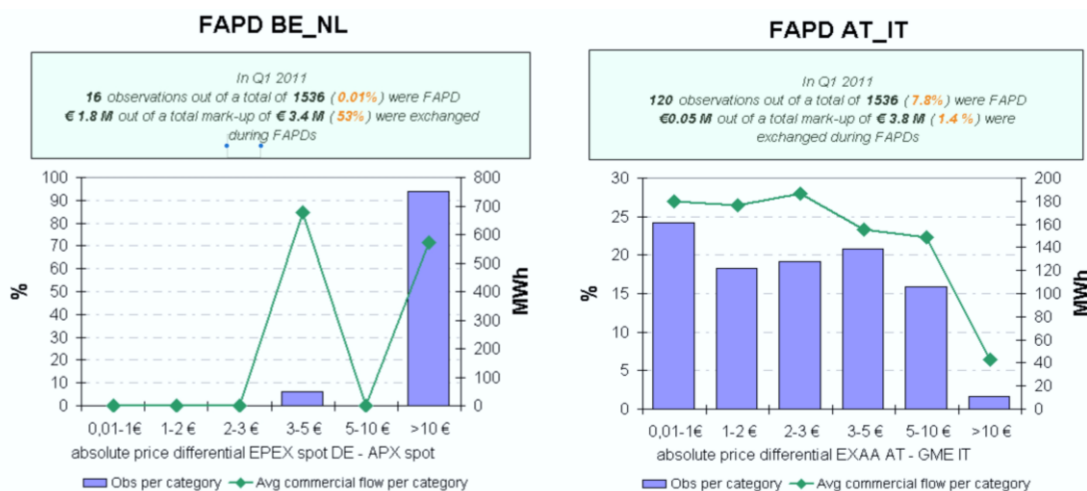


Figure 1. Chart of inefficient flows for the Belgian-Dutch and Austrian-Italian markets. Numbers in brackets indicate Unweighted FAPD (FAPD) and Weighted FAPD (WFAPD). Source: European Commission (2011-Q1).

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.

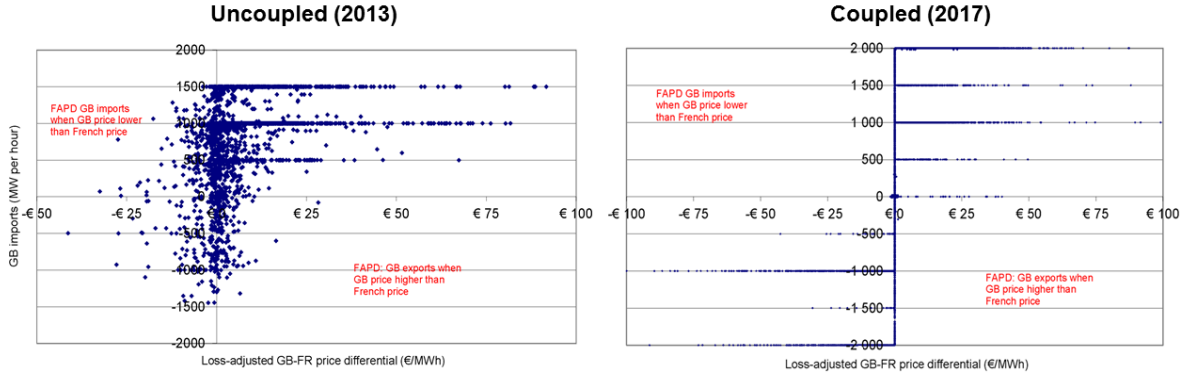


Figure 2. GB scheduled net imports vs price differentials on the IFA interconnector between GB and France before and after the 2014 implementation of the EUPHEMIA market coupling algorithm. For additional related graphs see also Appendix 3 of the Supplementary Information, SI.

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:

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

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:

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

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.

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

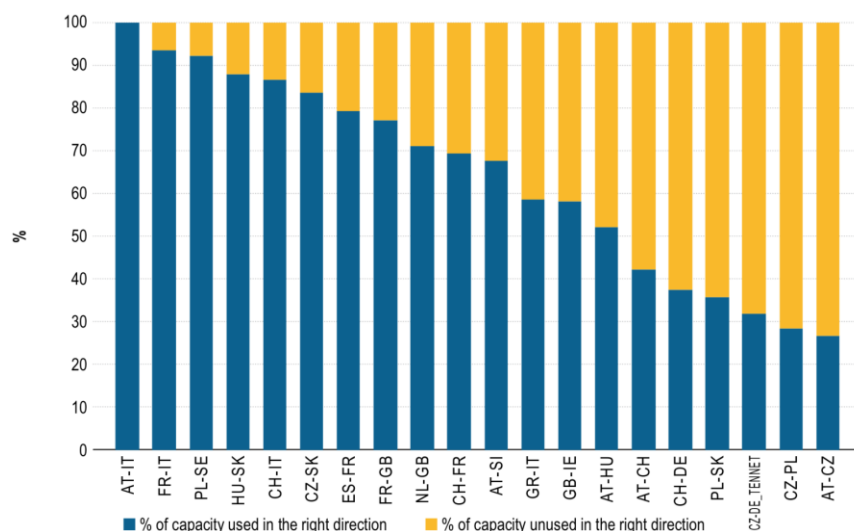


Figure 3. Percentage of NTC used in the correct economic direction for a selection of EU borders in 2011. Note that this was prior to coupling through EUPHEMIA. Source: ACER (2012).

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. 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 1 (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:

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.

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

where

$$\begin{aligned}
 N &= N^- + N^+ + N^0 \\
 F &= f^- + f^+ + f^0 \\
 |f| &= \text{absolute value of } f
 \end{aligned}$$

$$f_h = \frac{\tilde{f}_h}{NTC_h}, f_h^0 = 0,$$

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 (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

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

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

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 ($UFAPD$ and $SCURED$) and can be rewritten as:

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

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.

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

- *Scenarios 7 and 8* represent a very low number of extreme price differentials in instances of profitable and unprofitable flows.
- *Scenario 9* contains only a single profitable flow at a low price differential that is captured at 90% of available NTC.
- *Scenarios 10 and 11* contain 100% profitable flows and differ in the degree to which the large price differentials are captured with interconnector use.

These scenarios are 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 N⁰ 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)

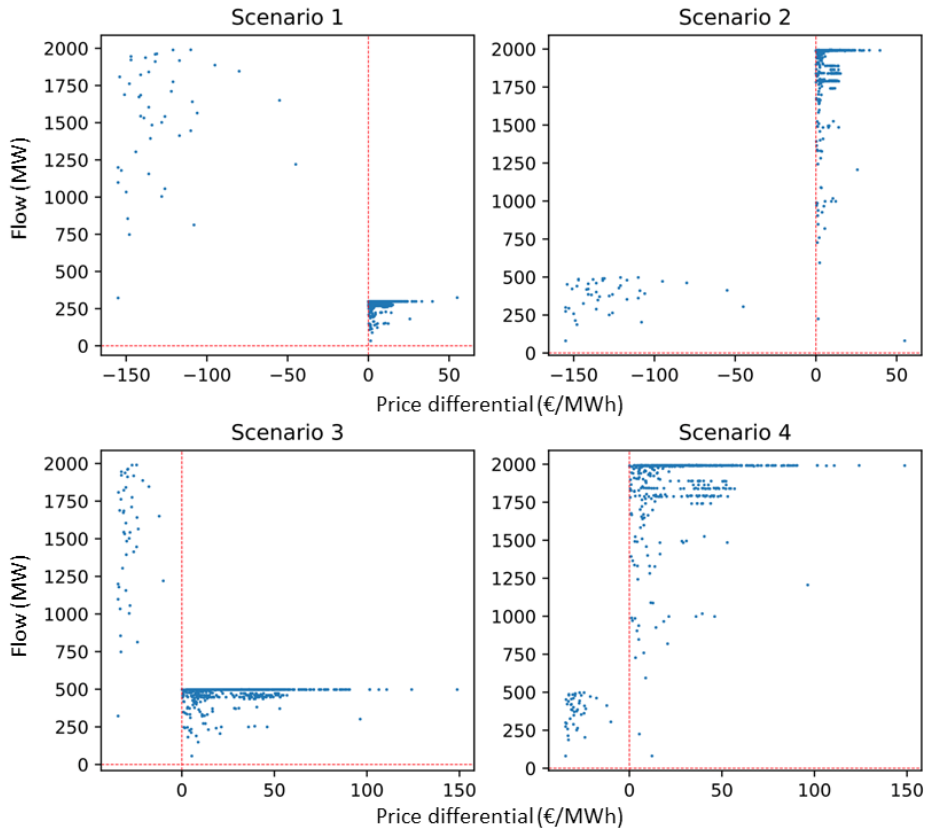


Figure 4. Scenarios 1–4: Low number of inefficient flows.

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 Scenario 1. 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)

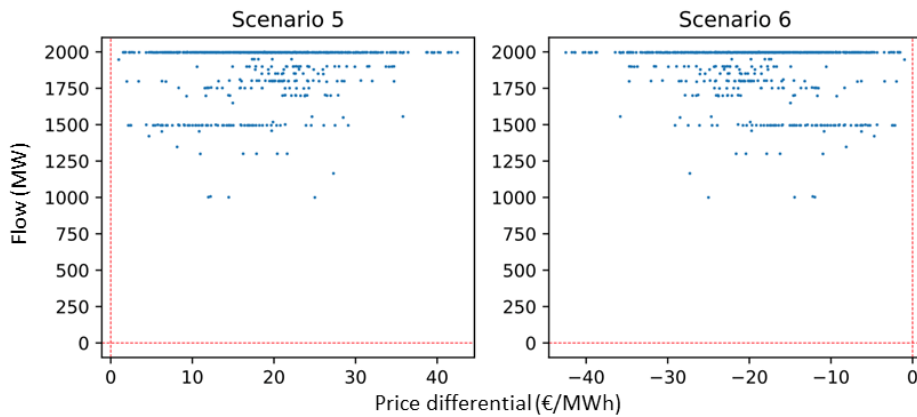


Figure 5. Scenarios 5–6: 0% and 100% inefficient flows.

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)

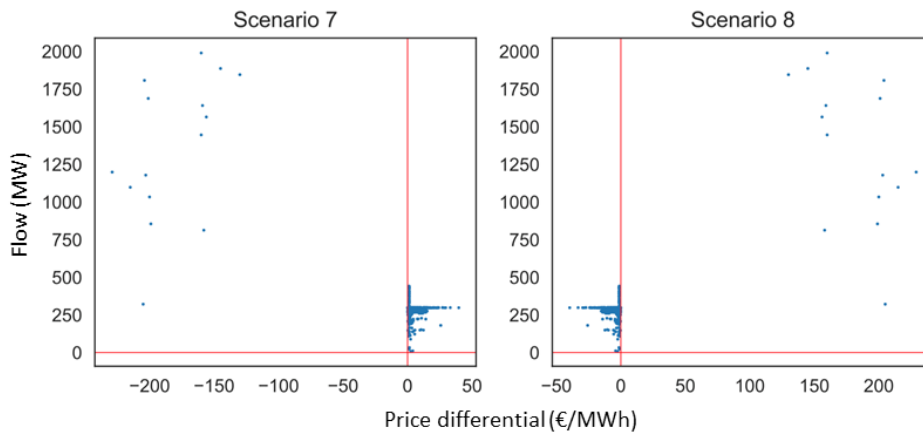


Figure 6. Scenarios 7–8: Low NTC utilisation.

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)

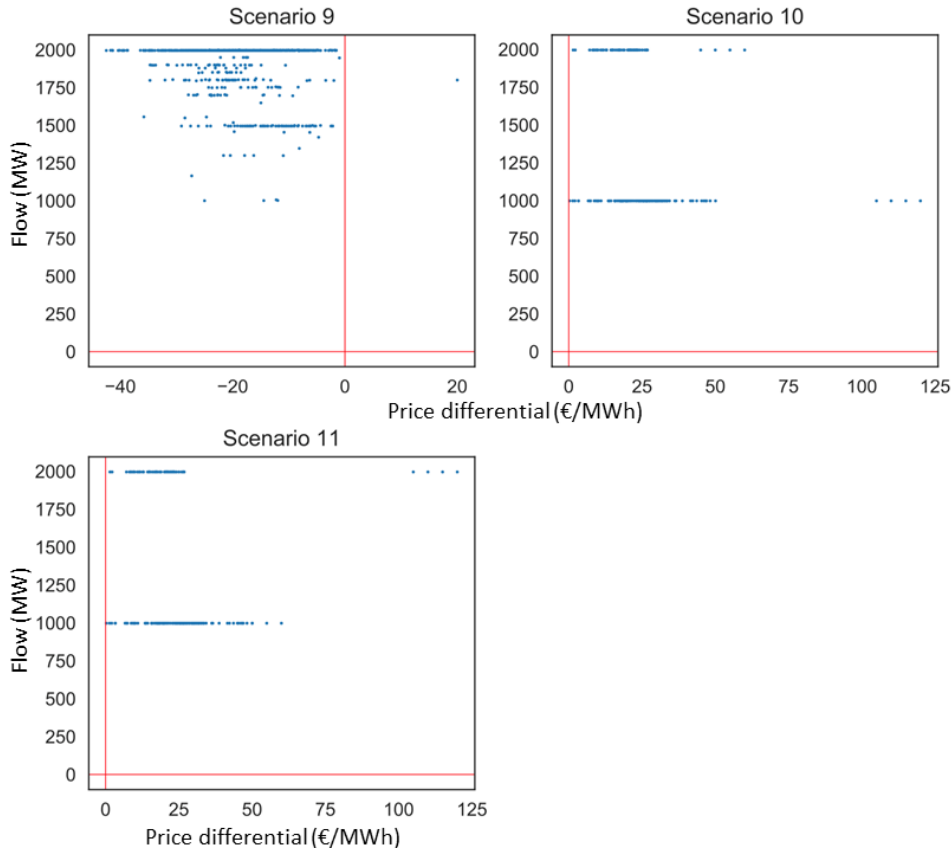


Figure 7. Scenarios 9–11: 1 inefficient flow and 0% inefficient flows.

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 simulated¹⁰ in the second (2015-2018). In the calculations, we ignore samples where the price differential is equal to zero and cap¹¹ 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.

⁹ See Appendix 5 of the SI.

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

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

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 N⁰ 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.

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

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.

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 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

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

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 *PWIIU*, 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 FVPDs, *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 uneconomic¹⁵ 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 differentials¹⁶ 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 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

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.

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 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).

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.

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_{1-5}) 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.

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.

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.

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 proposed *UIIU* and *PWIIU* metrics 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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