An Objective Measure of Interconnection Usage for High Levels of Wind Integration

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***Abstract*—This paper analyzes selected interconnectors in Europe using several evaluation factors; capacity factor, congested time, and congestion ratio. In a quantitative and objective evaluation, the authors propose to use publically available data on maximum net transmission capacity (NTC) levels during a single year to study congestion rates, realizing that the capacity factor depends upon the chosen capacity of the selected interconnector. This value will be referred to as "*the annual maximum transmission capacity* (*AMTC*)", which gives a transparent and objective evaluation of interconnector usage based on the published grid data. While the method is general, its initial application is motivated by transfer of renewable energy.**

Keywords- wind power; grid integration; flexibility; interconnector; congestion time; duration curve

ABBREVIATIONS AND SYMBOLS

A. Abbreviations and Acronyms

AMTC *Annual Maximum Transmission Capacity*
ENTSO-E *European Network of Transmission System Operators for Electricity*
EU *European Union*
EWIS *European Wind Integration Study*
IEC *International Energy Agency*
NTC *Net Transmission Capacity*
TBCF *Transmission Bi-lateral Capacity Factor*
TCF *Transmission Capacity Factor*
TEBR *Transferred Energy Balance Ratio*
TRM *Transmission Reliability Margin*
TSO *Transmission System Operator*
TTC *Total Transmission Capacity*

B. Abbreviations (Name of Nations and Areas)

DE Germany
DKE Denmark East
DKW Denmark West
ES Spain
FR France
GB Great Britain
IT Italy
NL The Netherlands
SE Sweden
NO Norway

C. Symbols

CF^{+} [%] TCF (in export direction)
CF^{-} [%] TCF (in import direction)
CF_{BL} [%] TBCF
C^{+}_{AMTC} [MW] AMTC (in export direction)
C^{-}_{AMTC} [MW] AMTC (in import direction)
C^{+}_{NTC} [MW] NTC (in export direction)
C^{-}_{NTC} [MW] NTC (in import direction)
P^{+} [MWh/h] exported physical energy flow per hour
P^{-} [MWh/h] imported physical energy flow per hour
$R_{balance}$ [%] TEBR
R_{C} [%] congestion ratio
T_{C} [h] congested time

I. INTRODUCTION

For high levels of grid integration of variable renewable energy including wind power, the "flexibility" of the grid will become increasingly important. Four important components of grid flexibility are (i) dispatchable generation, (ii) energy storage, (iii) interconnectors and (iv) demand side management [1]. In this paper, the authors will focus on the third component; interconnectors, comparing and analyzing several European interconnectors.

In the European and US grid, some reports have pointed out that there are bottlenecks in selected interconnectors used to transfer variable renewable energy; this is one barrier to increasing wind penetration levels.

This paper analyzes selected interconnectors in Europe, using several evaluation factors; capacity factor, congested time, and congestion ratio. In a quantitative and objective evaluation, the authors propose several new definitions for the capacity factor of interconnectors, which are based on transparent published data of net transmission capacity (NTC). This is because the capacity factor depends upon the capacity of the chosen interconnector.

Although the installed transmission capacity looks like the most impartial indicator, it is not always easy to get the latest data from TSOs. NTC is the most transparent parameter in Europe, because it is published by every TSO and ENTSO-E. However, it is not a constant value but a variable across the year. Also, thermal capacity is not always transparent because not all TSOs release the latest value. Therefore, a new factor, "*the annual maximum transmission capacity* (*AMTC*)", based on the annual net transmission capacity, is defined in this paper. This factor is transparent and objective based on the published grid data.

Definitions of congested time and congestion ratio are also prepared using the AMTC, as further described in Section II.

Using the analysis as described below, the potential usage of the existing interconnectors can be investigated to examine the opportunity for improved flexibility. Synchronous wind plant output time series data will be required for a detailed analysis.

II. Definition of Evaluation Method for Interconnection Usage

To evaluate how to measure the usage of interconnectors quantitatively and objectively, the authors propose the following indicators; (1) annual maximum transmission capacity, (2) capacity factor, (3) congestion time and (4) congestion ratio. In this section, definitions of each indicator will be introduced.

A. Annual Maximum Tranmission Capacity

What is "transmission capacity"? It is not easy to concisely answer the question. There are numerous sources of uncertainty regarding the determination of the transmission capacity [2]. Some TSOs do not publish installed capacity (thermal capacity) of their interconnectors. ENTSO-E had published an annual Statistical Yearbook [3] in the past, but no updated version has been published since 2011.

Fortunately, net transmission capacities (NTCs) for all international interconnectors in Europe are published on the ENTSO-E Transparence Platform [4]. For each border or set of borders, the NTC is determined individually by all adjacent countries through negotiation between the involved TSOs. As the NTC varies dynamically from the grid reliability viewpoint, sets of NTCs are published as hourly (day-ahead), monthly and annual values by every TSO and ENTSO-E. On the ENTSO-E's web site "Transparency Platform", sets of day-ahead hourly NTCs on every international interconnector on the borders between member countries can be found [4].

The calculation method of the NTC is not universal and is not fully clarified by many TSOs. Normally, the total transmission capacity (TTC), which means the maximum capacity to satisfy grid reliability, is determined by a certain method. Then, the NTC is calculated by subtraction of the transmission reliability margin (TRM) from the TTC to provide a margin of safety. However, the TTC and TRM are not generally publicly available.

In this report, the authors define a new indicator "*annual maximum transmission capacity*" (*AMTC*) to evaluate interconnector usage quantitatively and objectively from transparent NTC data.

Using a set of the published NTC data, the AMTC, or maximum available NTC in each direction over the course of the year, is defined as follows;

$$C^{+}_{AMTC} \approx \mathrm{Max}\left(C^{+}_{NTC}(1), C^{+}_{NTC}(2), \cdots, C^{+}_{NTC}(8760)\right) \quad (1)$$

$$C^{-}_{AMTC} \approx \mathrm{Min}\left(C^{-}_{NTC}(1), C^{-}_{NTC}(2), \cdots, C^{-}_{NTC}(8760)\right) \quad (2)$$

The calculated AMTC can be considered nearly the same as the thermal capacity of the selected interconnector. The important point is that an objective indicator can be obtained from transparent published data. In this way, it is possible to determine capacity factor and congested time quantitatively and objectively.

B. Transmission Bi-lateral Capacity Factor

The capacity factor is normally an indicator that evaluates the performance of a generator. In this paper, the authors try to give a similar definition for an interconnector. While the capacity factor of a generator is calculated on the basis of rated (nominal) power, transmission capacity factor (TCF) of an interconnector is determined on the basis of the above discussed AMTC in each direction:

$$CF^{+}\,[\%] = \frac{\sum_{i}^{8760} P^{+}(i)}{C^{+}_{AMTC} \times 8760} \times 100 \quad (3)$$

$$CF^{-}\,[\%] = \frac{\sum_{i}^{8760} P^{-}(i)}{C^{-}_{AMTC} \times 8760} \times 100 \quad (4)$$

The *transmission bi-lateral capacity factor (TBCF)*, is simply defined as the sum of the transmission capacity factors in the export and import directions:

$$CF_{BL}[\%] = CF^{+} + CF^{-} \quad (5)$$

Here, the TBCF of the given interconnector is calculated as the sum of the TCBs in both export/import directions. However, it never exceeds 100% because only one of the capacity factor parameters can have a non-zero value at any given time. The metric calculates the hourly available capacity and normalizes the average.

The newly defined TBCF of an interconnector can be considered as a useful indicator to evaluate how much the selected interconnector is used in a given year and how much room there is to accept more renewables.

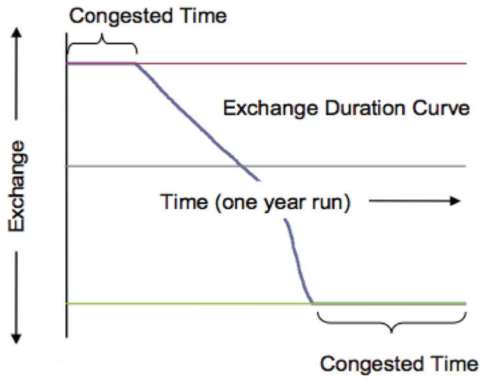


Figure 1. Definition of congested time. [5]

C. Congested Time

There is another indicator that evaluates interconnector usage; "congested time", as can be seen in the European Wind Integration Study (EWIS) report [5]. In the EWIS report, the congested time is calculated as shown in Figure 1. However, there is no description about a base transfer capacity in the report. In our paper, using the proposed AMTC, a congested time can be clearly defined as;

$$C_T[\mathrm{h}] = \sum\left(\mathrm{countif}\left(P^+(i) \geq C^+_{AMTC}\right) + \mathrm{countif}\left(P^-(i) \leq C^-_{AMTC}\right)\right) \quad (6)$$

D. Congestion Ratio

It is not difficult to calculate a congestion ratio if the congested time can be determined objectively. The definitions based on the AMTC are respectively given as following;

$$R_C[\%] = \frac{T_C}{8760} \times 100 \quad (7)$$

Regarding the congestion ratio, an earlier study done in the Western US in 2003 used a different congestion metric. It is based on the percentage of time that a given interface is within 10% of its maximum rated capacity [6], [7].

E. Transferred Energy Balance Ratio

While some interconnectors are operated with a balance between exported and imported energy, others seems to be dominated by export or import only. This usage of the interconnector may give some indication of future potential to accept more renewables. To evaluate these situations, we proposed a new indicator; *transferred energy balance ratio (TEBR)* $R_{balance}$ as follows:

$$R_{balance}[\%] = \frac{\left|\sum_i^{8760} P^+(i) - \sum_i^{8760} P^-(i)\right|}{\sum_i^{8760} P^+(i) + \sum_i^{8760} P^-(i)} \times 100 \quad (8)$$

If export and import are balanced, $R_{balance}$ become zero according to the above equation, whereas it becomes 100% if either export or import dominates.

III. Comparison Analysis on Major Interconnectors in Europe

In this chapter, comparison analysis on several major interconnectors in Europe are performed using the above defined indicators.

A. Selected Interconnectors

Here, we evaluate the following indicators; (i) AMTC, (ii) capacity factor, (iii) congested time, (iv) congestion ratio, and (v) TEBR, against the following selected international interconnectors in Europe as shown in Figure 2.

1. DKW > NO (DC)
2. DKW > SW (DC)
3. DKW > DE (AC)
4. DKE > SE (AC)
5. DKE > DE (DC)
6. FR > DE (AC)
7. FR > GB (DC)
8. FR > IT (AC)
9. FR > ES (AC)
10. NO > NL (DC)
11. NL > GB (DC)

The direction (>) indicates the export (positive) direction of the energy transfer in each interconnector.

All the data on the selected interconnectors were obtained from the ENTSO-E Transparency Platform [4]. In the current analysis, we downloaded a set of hourly cross-border physical flows $P^+(i)$ [MWh/h] and $P^-(i)$ [MWh/h] and day-ahead hourly NTC C_{NTC} [MW] during 1st January 2013 to 31st December 2013 (8760 hourly data per data set).

B. Qualitative Analysis using Duration Curves

Figure 3 shows various duration curves of physical flows in the selected interconnectors. A quick comparison clearly shows the variety of usage of individual interconnectors. For example, some interconnectors (like DKW > NO, FR > GB and NO > NL) have flat horizontal lines at the left-top and/or right-bottom corners on their duration curves. It denotes that the interconnector is fully used in some degree. Another group (*e.g.* DKW > DE, FR > DE and IE > GB) shows steep peaks at the left-top and/or right-bottom corners, which means the interconnector is not fully used.

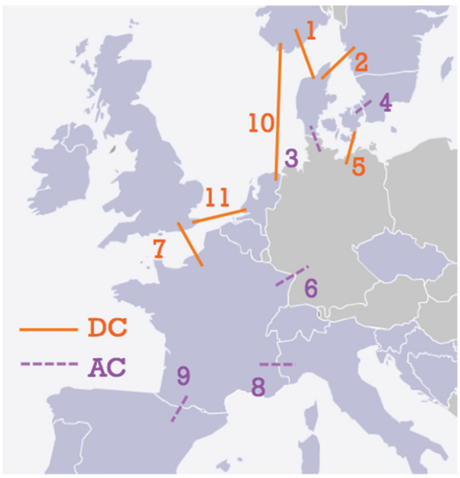
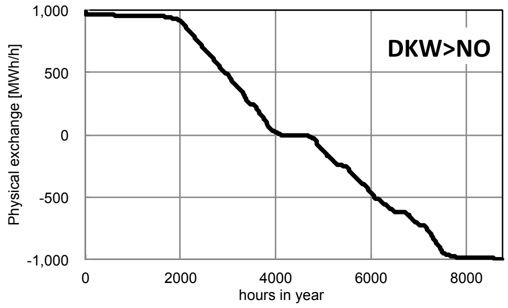
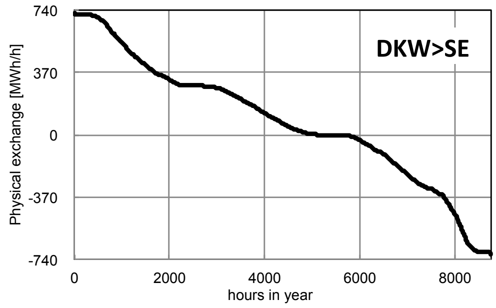


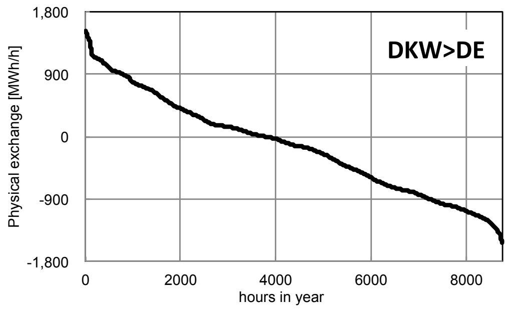
Figure 2. Selected main interconnectors in Europe.



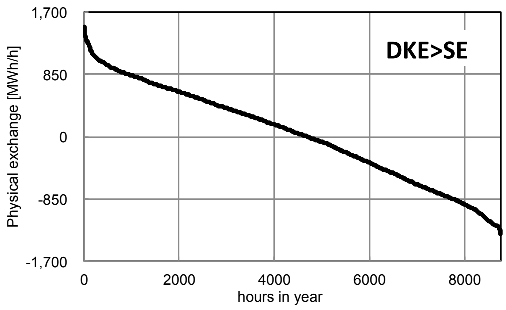
(1) DKW > NO



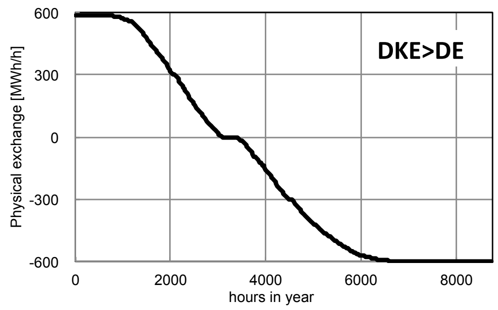
(2) DKW > SE



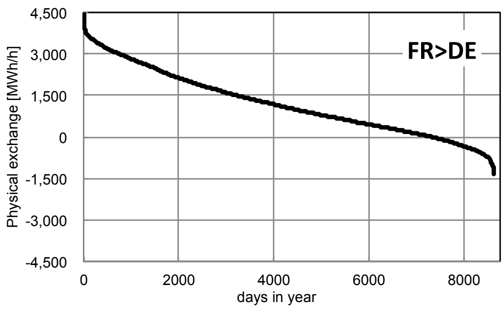
(3) DKW > DE



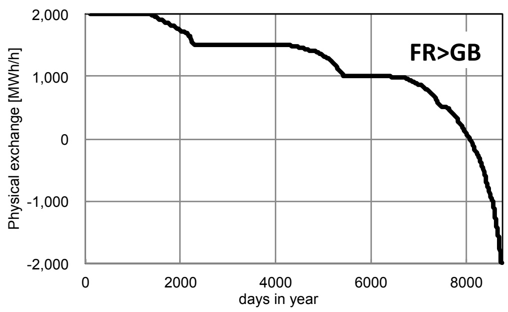
(4) DKE > SE



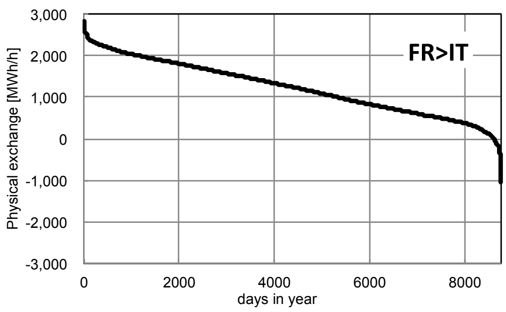
(5) DKE > DE



(6) FR > DE



(7) FR > GB



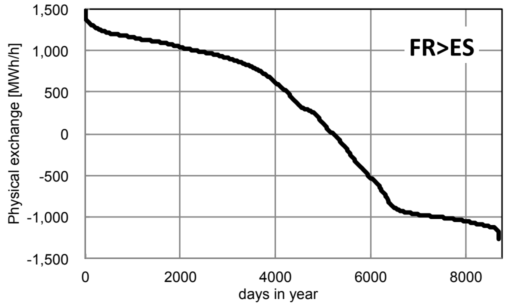
(8) FR > IT

Figure 3. Duration curve of physical flows in the selected interconnectors.

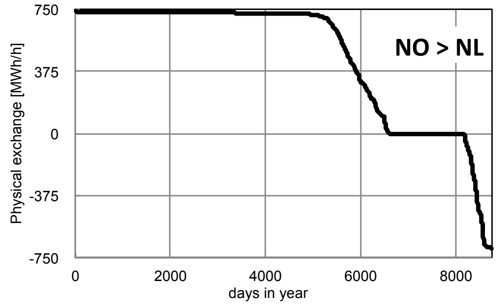
Moreover, some graphs show clearly unbalanced curves between the upper quadrant (export) and lower quadrant (import).

From the qualitative observation of the above characteristics of the duration curves, four groups as shown in Table I can be categorized. The groups by row are classified by whether the shape of the curve is convex (facing upwards) or concave (facing downwards), whereas those in column are classified by whether they are symmetric or not.

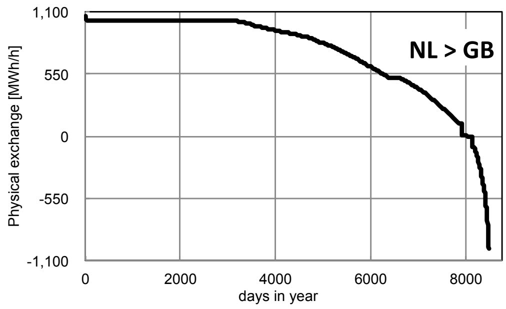
A convex characteristic in the duration curve indicates that the given interconnector is heavily loaded, which means there is little ability to accept more renewables. In contrast, a concave curve denotes a less heavy use of the interconnector, indicating it has significant potential to accept more renewable energy and enhance flexibility.



(9) FR > ES



(10) NL > NO



(11) NL > GB

Figure 3. Duration curve of physical flow in the selected interconnectors. (cont.)

TABLE I. QULALITATIVE CLASSIFICATION OF DURATION CURVES OF SELECTED INTERCONNECTORS

	(I) Concave	**(II) Convex**
(a) Symmetric	(1) DKW>NO (2) DKW>SE (5) DKE>DE	(3) DKW>DE (4) DKE>SE (9) FR>ES
(b) Asymmetric	(7) FR>GB (10) NO>NL (11) NL>GB	(6) FR>DE (8) FR>IT

C. Quantitative Analysis using the proposed Indicators

To confirm these characteristics identified visually from the duration curves, we employ the quantitative indicators defined in Section II. Table II shows the calculated results of ATMC, TBCF, congested time, congestion ratio, and TEBR of the selected interconnectors as determined from Equations (1) - (8).

Figure 4 illustrates bar graphs that summarize the information given by Table II, where TBCF and congestion ratios based on AMTC are compared. Figure 5 plots the congestion ratio against the TBCF for the selected interconnectors. The data can be divided into two groups. These two groups correspond to the classification Groups I and II according to the qualitative characteristics in the duration curve discussed in Table 1 above.

Another comparison can be made by plotting the TBCF against the TEBR. From Figure 6, four groups clearly can be recognized in the graphs. These groups correspond to Groups Ia, Ib, IIa and IIb, as discussed in Table I. There is one exception, the interconnector between France and Germany (FR >DE), which cannot be categorized from the duration curve because the ATMCs in both directions are originally asymmetrical. Although it is difficult to distinguish into which group the given interconnector should be categorized, it is easy to classify using the quantitative indicators proposed in this paper.

TABLE II. EVALUATION ON INTERCONNECTOR USAGE USING PROPOSED INDICATORS (2013)

Inter-connector	**link**	**AMTC**		**CAPACITY FACTOR**			**Congested Time**	**Congestion Ratio**	**TEBR**
		C^{+}_{AMTC} [MW]	C^{-}_{AMTC} [MW]	CF^{+} [%]	CF^{-} [%]	CF_{BL} [%]	T_C [h]	R_C [%]	$R_{balanced}$ [%]
equations		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
DKW > NO	DC	1,000	1,000	32.4	29.2	61.5	162	1.8	5.3
DKW > SE	DC	740	680	25.3	16.0	41.3	359	4.1	26.4
DKW > DE	AC	1,780	1,500	12.4	24.3	36.7	20	0.2	24.5
DKE > SE	AC	1,700	1,300	17.1	20.5	37.6	9	0.1	4.3
DKE > DE	DC	565	600	23.6	47.4	71.0	2,502	28.6	34.5
FR > DE	AC	1,800	3,000	68.8	1.9	70.7	2,605	29.7	91.4
FR > GB	DC	2,000	2,000	62.8	3.0	65.8	1,287	14.7	90.9
FR > IT	AC	2,750	1,160	44.7	0.3	45.1	2	0.0	99.4
FR > ES	AC	1,300	1,000	39.4	29.2	68.6	515	5.9	22.9
NO > NL	DC	700	700	70.5	3.8	74.3	5,233	59.7	89.6
NL > GB	DC	1,016	1,016	72.2	1.6	73.8	3,210	36.6	95.8

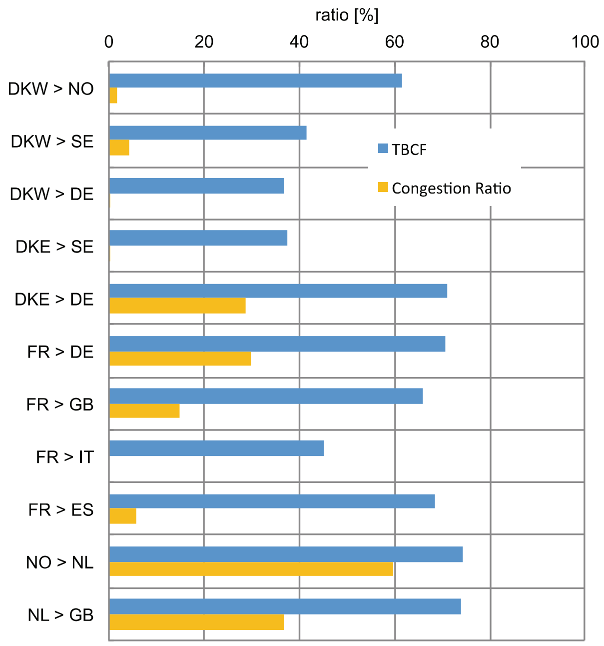


Figure 4. TBCF and congestion ratio in the selected interconnectors.

IV. Concluding Remarks

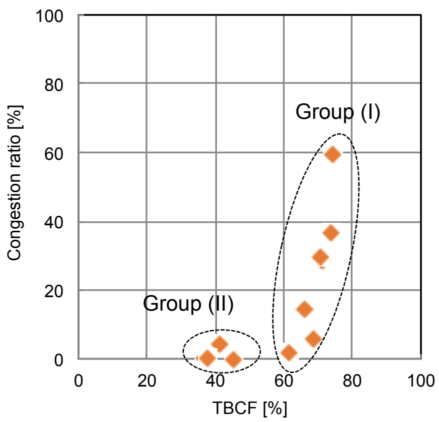


Figure 5. Correlation between TBCF and congestion ratio.

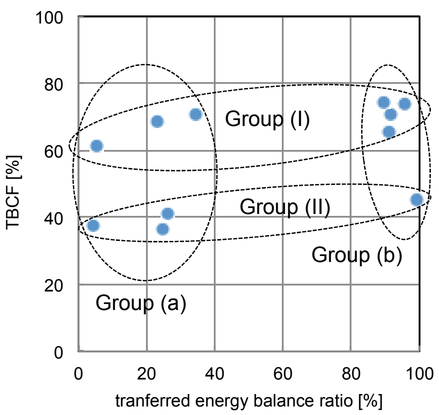


Figure 6. Correlation between TEBR and TBCF.

This paper proposed a novel indicator, *annual maximum transmission capacity* (*AMTC*), for quantitative and objective evaluation of interconnector usage for high penetration of renewables. Using a very transparent parameter, *i.e.* a set of day-ahead hourly NTCs, the AMTC can be calculated in an objective fashion. The authors also propose definitions for transmission bi-lateral capacity factor (TBCF), congested time, congestion ratio and transferred energy balance ratio (TEBR) using the above-mentioned AMTC.

Using these objective and quantitative indicators, the usage of the selected interconnectors in Europe was evaluated. From the correlation of the TBCF, congestion ratio and TEBR, it is clear that the selected interconnectors can be categorized into several groups that correspond to the qualitative characteristics of the duration curves given from the physical energy flow data.

It is hoped that the proposed indicators will help to evaluate any interconnector to determine if additional capacity is available to enhance grid flexibility and enable transfer of additional renewable energy.

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