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International Comparison of Wind and Solar Curtailment Ratio

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***Abstract*—As the penetration of VRE (variable renewable energy), mainly wind and photovoltaic energy, has developed widely and rapidly, curtailment of VRE has taken on increased interest. This paper introduces a new evaluation tool, named the "*C-P map*", that shows the correlation between VRE curtailment ratios and energy penetration ratios of VRE in selected countries/areas. The C-P map can illustrate historical trends for VRE curtailment ratios in a given country/area at a glance, and help any comparison between historical curves. Using the C-P map, this paper classifies the selected countries/areas into several categories, depending upon the level and trends of VRE curtailment. The classification helps to understand how curtailment occurred in the past and how it may change in the future in the selected grids.**

Keywords- wind power; photovoltaic; VRE (Variable Renewable Energy); curtailment ratio; penetration ratio

I. INTRODUCTION

The incorporation of increasing amounts of renewable energy in electricity systems primarily from variable renewable sources, such as wind energy and solar photovoltaic generation, has become an energy policy priority in a majority of countries. Ever since the possibility of large penetrations of variable renewable generation was first proposed, the ultimate limits on VRE (variable renewable energy) penetration have been the subject of research. One early wind energy study suggested that, if all of the variable renewable output must be utilized, only modest levels of penetration might be possible. Other research showed that, if relatively small amounts of the variable renewable output were foregone or "curtailed", significantly higher penetrations would be feasible. One study that explored the nature of curtailment proposed that it would increase exponentially with increasing wind energy penetration [1]-[3].

Curtailment of VRE is now becoming an increasingly important issue with the increasing penetrations of VRE worldwide. Previous investigations [4]-[5] have explored some trends in the curtailment of VRE: Italy, China and Texas in the U.S. have reduced their curtailment ratios from values in excess of 10%, experienced in the early stages of development, while Spain and Ireland show slight increases with increasing VRE penetration ratios, despite efforts to keep the curtailment ratio less than 1%. After the previous investigations, it is becoming clear that there are some countries that have common features in curtailment trends.

It is important to monitor curtailment, as declining curtailment trends may give evidence for the success of measures to efficiently integrate VRE. Direct comparison of curtailment levels in different systems is not necessarily appropriate, as there are a range of system specific factors that contribute to curtailment. Prior work has provided some high level evaluation tools that may be applied to assess the severity of the challenge for incorporating VRE within particular power systems and allow objective comparison of curtailment levels [6]. Söder *et al.* [7] proposed a "maximal share of wind power" criterion

$$\text{Share of wind power} = \frac{\text{Max. wind power [MW]}}{\text{Min. consumption [MW]} + \text{possible export [MW]}}$$

and applied this to compare wind power penetrations in Gotland, West Denmark, Schleswig Holstein, Ireland and New Mexico. Ackermann [8] applied this criterion to compare wind energy penetration in Denmark, Spain, Ireland and Texas in 2013 and 2020. Yasuda *et al*. [9] proposed the flexibility radar plot as a qualitative indicator of the flexible system resources that might allow curtailment to be minimised in systems with high VRE penetrations.

To investigate such curtailment trends more quantitatively, this paper introduces a new evaluation tool, named the "*C-P map*", that shows the correlation between VRE curtailment ratios (curtailed energy per estimated VRE energy generated) and energy penetration ratios of VRE (VRE energy per annual gross generation) in the selected countries/areas.

The paper also proposes new metrics, namely the "C-P ratio" and "C-P gradient". The former is defined as the quotient of the given curtailment ratio by the given penetration ratio for the selected grid in the selected year, whereas the latter is the gradient of the C-P curve at the given point on the C-P map. Using the C-P map and metrics, this paper classifies the selected countries/areas into several categories depending upon the level and trends of VRE curtailment. The classification helps to understand how curtailment has occurred in the past and how it may change in the future for the selected grids.

II. STATISTICS FOR VRE CURTAILMENT

In general, there are no mandated rules regarding the publishing of unified statistical data on VRE curtailment from TSOs (transmission system operators). The previous papers investigated various documents created by TSOs, regulators and national/international organisations to gather the statistical data on curtailment of VRE in several countries/areas.

Tables I - IV show available statistical data for VRE curtailment in available European countries, several RTOs (regional transmission operators) in North America, China and Japan, respectively. It is noted that most cases of curtailment, excluding Japan, were associated with wind energy. So far, there is limited information available on curtailed PV energy across the world. In contrast, several

TABLE I. STATISTICAL DATA FOR VRE CURTAILMENT IN EUROPEAN COUNTRIES

Country	Year	Total Generation (GWh)	Wind (GWh)	PV (GWh)	Curtailed Energy (GWh)	Penetration Ratio	Curtailment Ratio
		A	*B*	*C*	*D*	*E = (B+C)/A*	*F = D/(B+C)*
Denmark	2014	31,905	13,079	596	almost zero	42.9%	0.00%
Germany	2011	613,068	48,883	19,599	0.421	11.2%	0.61%
	2012	629,812	50,670	26,380	0.385	12.2%	0.50%
	2013	635,267	53,400	30,000	0.127	13.1%	0.15%
Ireland	2011	27,472	4,380	—	0.106	15.9%	2.42%
	2012	27,592	4,010	—	0.103	14.5%	2.57%
	2013	26,041	4,541	—	0.171	17.4%	3.77%
Italy	2009	292,641	6,543	676	0.700	2.5%	9.70%
	2010	302,064	9,126	1,874	0.527	3.6%	4.79%
	2011	302,584	9,856	10,688	0.264	6.8%	1.29%
	2012	299,277	13,407	18,637	0.166	10.7%	0.52%
	2013	289,807	14,811	21,228	0.152	12.4%	0.42%
	2014	277,897	14,966	23,299	0.121	13.8%	0.32%
Portugal	2014	52,886	12,103	630	0	24.1%	0.00%
Spain	2008	313,758	31,777	2,562	0.108	10.9%	0.31%
	2009	294,620	36,991	5,961	0.070	14.6%	0.16%
	2010	301,527	43,692	6,425	0.315	16.6%	0.63%
	2011	293,848	42,160	14,882	0.073	19.4%	0.13%
	2012	297,559	48,126	16,386	0.121	21.7%	0.19%
	2013	285,260	54,338	17,950	1.166	25.3%	1.61%

(note) Only wind, no PV, is curtailed in European countries.
(data source) Total generation, wind and PV energy: Ref.[10], curtailed Energy: Ref.[5].

TABLE II. STATISTICAL DATA FOR VRE CURTAILMENT IN NORTH AMERICA

RTO	Year	Total Generation (GWh)	Wind (GWh)	PV (GWh)	Curtailed Energy (GWh)	Penetration Ratio	Curtailment Ratio
		A	*B*	*C*	*D*	*E = (B+C)/A*	*F = D/(B+C)*
ERCOT	2009	N/A	N/A	N/A	N/A	6.2%	17.1%
	2010	N/A	N/A	N/A	N/A	7.8%	7.7%
	2011	N/A	N/A	N/A	N/A	8.5%	8.5%
	2012	N/A	N/A	N/A	N/A	9.2%	3.7%
	2013	N/A	N/A	N/A	N/A	9.9%	1.2%
	2014	N/A	N/A	N/A	N/A	10.6%	0.5%
MISO	2010	N/A	N/A	N/A	N/A	3.6%	4.2%
	2011	N/A	N/A	N/A	N/A	5.0%	3.4%
	2012	N/A	N/A	N/A	N/A	7.1%	2.5%
	2013	N/A	N/A	N/A	N/A	9.0%	4.6%
	2014	N/A	N/A	N/A	N/A	6.1%	5.5%
Hydro-Québec	2014	216,703	6,670	—	0	3.1%	0%

(note) Only wind, no PV, is curtailed in the U.S. and Canada.
(data source) Penetration ratio in ERCOT: Ref.[11], Penetration ratio in MISO: Ref.[12], Curtailment ratio in ERCOT and MISO: Ref.[13]. All data in Hydro-Québec: Ref.[14].

TABLE III. STATISTICAL DATA FOR VRE CURTAILMENT IN CHINA

Country	Year	Total Generation (GWh)	Wind (GWh)	PV (GWh)	Curtailed Energy (GWh)	Penetration Ratio	Curtailment Ratio
		A	*B*	*C*	*D*	*E* = (*B*+*C*)/*A*	*F* = *D*/(*B*+*C*)
China	2012	4,994,038	95,978	6,366	20,820	2.0%	17.12%
	2013	5,432,843	134,900	8,700	16,230	2.6%	10.74%

(note) Only wind, no PV, is curtailed in China.
(data source) Total generation, wind and PV energy in 2012: Ref.[15], others: Ref.[5].

TABLE IV. STATISTICAL DATA FOR VRE CURTAILMENT IN JAPAN (FUTURE ESTIMATES)

Utility	Case	Total Generation (GWh)	Wind (GWh)	PV (GWh)	Curtailed Energy (GWh)	Penetration Ratio	Curtailment Ratio
		A	*B*	*C*	*D*	*E* = (*B*+*C*)/*A*	*F* = *D*/(*B*+*C*)
Hokkaido	Current situation (2014)	33,134	663	217	0	2.7%	0.00%
	Case I: acceptable VRE capacity	32,723	1,704		49	5.2%	2.90%
	Case II: higher penetration	32,723	3,001		394	9.2%	13.14%
Tohoku	Current (2014)	83,829	1,631	312	0	2.3%	0.00%
	Case I	80,366	11,535		692	14.4%	6.00%
	Case II	80,366	15,205		1,728	18.9%	11.37%
Kyushu	Current (2014)	87,783	607	992	0	1.8%	0.00%
	Case I	88,736	11,773		494	13.3%	4.20%
	Case II	88,736	17,473		1,919	19.7%	10.99%

(note) Only PV, no wind, will be curtailed in estimates from Japanese utilities.
(data source) Ref.[16].

Japanese utilities have estimated possible curtailment for PV, due to its anticipated rapid growth in the near future.

III. ANALYSIS USING C-P MAPS

To analyse the statistical VRE curtailment data from various countries/areas quantitatively, the paper proposes a new evaluation tool, named the "C-P map", as a correlation map between VRE curtailment ratios and VRE penetration ratios. Figures 1, 2 and 3 show C-P maps for the selected countries/areas grouped by their historical tendencies.

A. C-P Map of Group I: Well-operated

Figure 1 shows a group of (European) countries, *i.e.* Denmark, Portugal, Spain, Ireland and Germany, where VRE curtailment has been minimised in a "well-operated" system management paradigm. For every country in this group, VRE curtailment (only wind, in fact) has been restrained to less than 4%, despite high VRE penetration ratios. The fact that all of these countries are ranked in the top-five countries with the highest VRE penetration ratios in the world is not a coincidence. It can be understood that the TSOs in these countries have suitably planned and operated their grids to accept large volumes of VRE, with available legislative and regulatory schemes in the last decade.

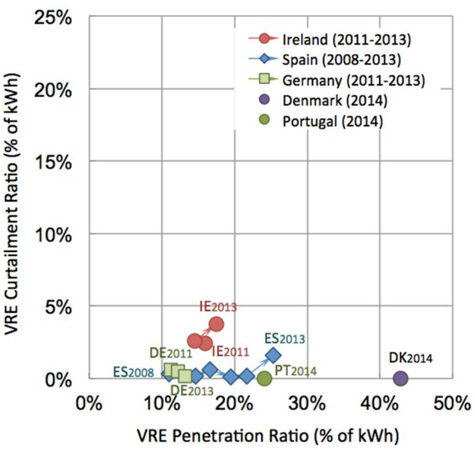


Figure 1. C-P map of selected countries (Group I)

According to Spain's TSO, Red Eléctrica de España (REE), deviations from imposed (wind) setpoints are occurring, during curtailment periods and the recovery of production once the limitations are released. REE has proposed a new mechanism to minimise undesired production losses, by performing dynamic curtailment management, allowing control centres to modify the setpoints according to prevailing weather conditions and maintain production as constant as possible. In this way it can help maintain power system operations, maximising the integration of wind energy. REE expects to curtail 1.6 TWh (2.2% of variable RES) in 2016, and for 2020, it is estimated that 3.6% of wind and solar generation may be curtailed [17].

B. C-P Map of Group II: To be improved and improving

In contrast, Fig.2 shows a second grouping where VRE curtailment ratios are significantly higher than those in group I. Although the selected countries/areas, *i.e.* China, Italy and two RTOs in the U.S. have relatively low penetration ratios, the curtailment ratios are plotted in a wide range, but less than 20%. It is interesting to note, in general, the countries/areas show decreasing trends in their historical C-P map curve.

These trends indicate that efforts to improve the undesirable (curtailment) situation by the given TSOs/RTOs has gradually borne fruit in the form of negative gradients for their historical curve. While the fact that China and

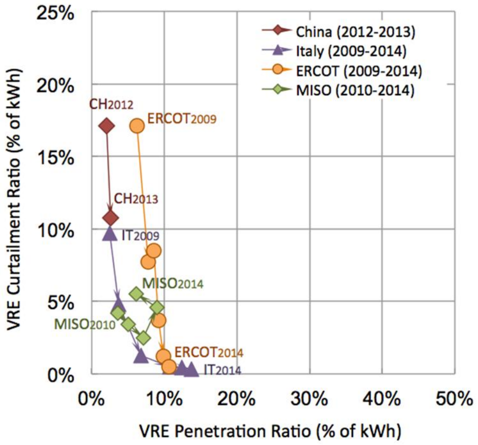


Figure 2. C-P map of selected countries/areas (Group II)

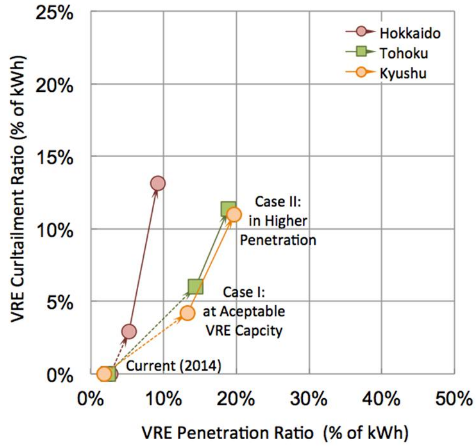


Figure 3. C-P map of selected areas (Group III)

Texas (ERCOT) display similar trends may be coincidental, a common cause can be surely considered. China has a strong national movement to install wind turbines, despite a delay in the construction of long-distance transmission lines between the inner continental area and the high population coastal areas. Also, Texas established a CREZ (Competitive Renewable Energy Zone) scheme, which promotes investment for wind power plants in inner desert areas before the completion of transmission lines to the coastal metropolitan area. In recent times, wind curtailment and associated negative electricity prices in Texas have been dramatically improved, following the gradual completion of transmission lines in the CREZ scheme [18]. Italy also overcame an uncomfortable situation with a high curtailment ratio of nearly 10% in former years, to finally achieve a low ratio less than 1%.

C. *C-P Map of Group III: Possiblly deteriorating*

The final group for the C-P map relates to estimated PV curtailment in the near future, completed by several utilities in Japan. The country is now facing strong PV growth after enforcement of a FIT (Feed-in Tariff) Law in 2012, while other renewables, including wind, biomass, micro hydro and geothermal, have not yet developed in a similar fashion, due to a mismatch of renewable policies, including strict environmental assessment schemes.

Several Japanese utilities announced their “acceptable VRE capacity”, *i.e.* the maximum installed capacity whereby they can curtail PV and wind energy without compensation according to the FIT Law and the relevant Ministerial Order. At a working group of the METI (Ministory of Economy, Trade and Industory, Japan), held in December 2014, the utilities published their estimated results for the case of high PV penetration in the near future. Figure 3 shows selected results, summarised in Ref. [8], from the published data, and indicate the possibility of significantly high curtailment ratios associated with future PV development.

The results may well be overestimates, and remain a matter of debate, given that the selected data in Table IV and Fig. 3 represents the worst case for each utility. However, the anouncement by the utilities and the METI resulted in considerable negative impact on the Japanese renewables market.

IV. C-P Ratio and C-P Gradient

The previous section showed C-P maps for selected countries/areas, divided into several groups according to historical trends. Here, more quantitative analysis is performed using new evaluation indicators, named the “*C-P ratio*” and the “*C-P gradient*”.

A. *Definition of C-P Ratio*

The C-P ratio is a simple metric to show the VRE curtailment level in a given country/area. A C-P ratio, *R,* is simple defined as the quotient of the curtailment ratio *C* and the energy penetration ratio *P*, as following:

$$R \equiv \frac{C}{P}. \quad (1)$$

The C-P ratio, therefore, indicates the location of the individual plot for a given year of the selected countries/areas in the C-P map.

Figure 4 illustrates a conceptual map where the C-P plane was divided into three zones, “green”, “yellow” and “red” according to the critical C-P ratio, *R*. In this paper, each zone is experimentally defined as the area where *R* is less than 0.1, greater than 0.1 and less than 0.5, and greater than 0.5, respectively. The green zone reflects the “well-operated” countries, such as Denmark, Germany, Ireland, Portugal, and Spain with high penetration ratios but low curtailment ratios. The red zone indicates the “to be improved” situation, with a high curtailment ratio despite a

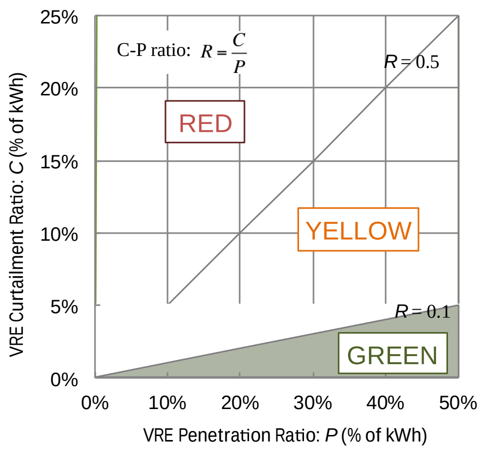


Figure 4. Conceptual illustration of the C-P ratio in a C-P map

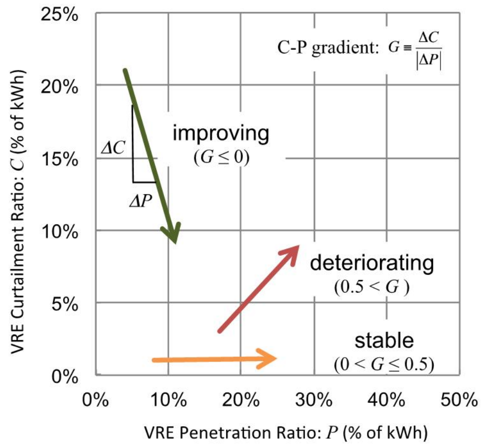


Figure 5. Conceptual illustration of the C-P gradient in a C-P map

low penetration ratio, which includes part of the historical plots of Group II.

B. *Definition of C-P gradient*

In contrast, the C-P gradient shows the historical curtailment trends. The definition of the C-P gradient, *G*, is given by the following equation:

$$G \equiv \frac{\Delta C}{|\Delta P|}, \tag{2}$$

where ΔC and ΔP are the backward difference of *C* and *P*, respectively.

The C-P gradient *G* indicates the trend of the historical curve for the selected countries/areas: a negative G implies an improving effort to reduce the curtailment ratio, a positive G greater than 0.5 expresses a warning of a possible deterioration in the curtailment ratio for the future. Figure 5 illustrates a sample concept with various cases of the C- P gradient.

C. *Quantitative analysis using C-P ratio and C-P gradient*

Given that the groupings employed in the previous section were qualitatively and tentatively proposed, a quantitative analysis is now performed using the above-proposed indicators, the C-P ratio and the C-P gradient.

Figure 6 presents the resulting analysis, as the correlation map between the C-P ratios and C-P gradients for the selected countries/areas. Figure 7 also illustrates an evaluation of the correlation map linking the two indicators. The previous sections introduce three status levels, with "green", "yellow" and "red" identified by the C-P ratios, and three trends including "deteriorating", "stable", and "improving", according to the C-P gradients. Therefore, classifications with nine categories can be defined in the correlation map of the two indicators as follows:

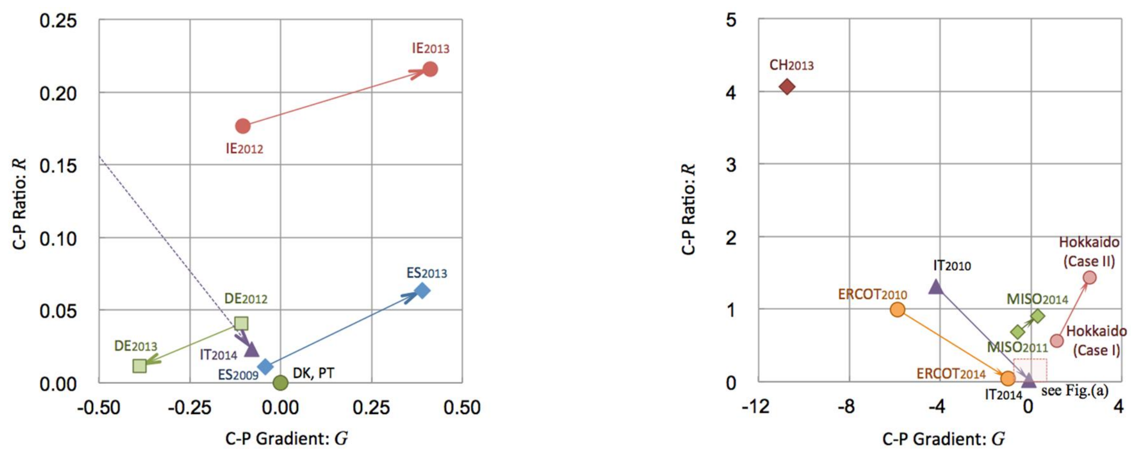
(1a) red but improving,
(1b) red and stable,
(1c) red and even deteriorating,
(2a) yellow and improving,
(2b) yellow and stable,
(2c) yellow and deteriorating,
(3a) green and still improving,
(3b) green and stable,
(3c) green but deteriorating.

By matching the plots and history of the corresponding map in Fig. 6 to the conceptual map in Fig. 7, trends for selected countries become clear; *e.g.* Italy and ERCOT have both significantly improved and finally achieved a "good" condition, while China requires more effort for the future. Ireland is gradually heading towards the yellow zone, as system stability limits become increasingly active, while Spain, similar to several utilities in Japan, will reach the red zone in the near future without reform to their grid planning and operations. Until now, Hydro-Québec has not conducted any curtailment, but this could become a real possibility in the future.

The reasons for curtailment vary among countries/areas and have changed over time. In Ireland, curtailment is for reliability/stability reasons. ERCOT and China were in the process of building transmission that was not yet ready when the wind plants were installed. MISO has network congestion in windy regions.

Summarising the results from Fig. 6, a classification into nine categories is given in Table V, which provides an overview on worldwide curtailment trends by objective and quantitative indicators, with information expressed visually and qualitatively by the C-P maps of Figs. 1, 2 and 3.

For example, Italy and ERCOT have moved from position (1a) to (3a) in the last five years, which indicates that an undesirable situation has been successfully



(a) closing-up correlation map

(b) correlation map in wider area

Figure 6. Correlation maps between the C-P ratios and C-P gradients of selected countries/areas

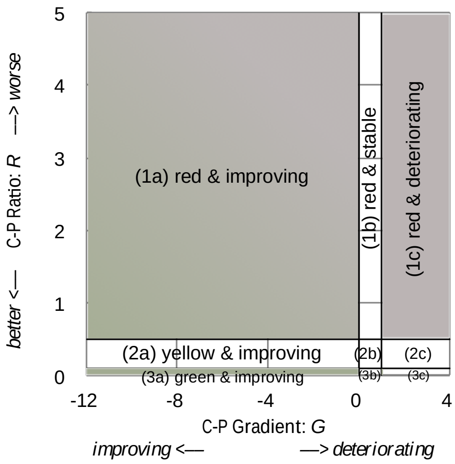


Figure 7. Classification of Curtailment Trend by the C-P ratio and the C-P gradient

improved, while China remains in position (1a), and requires further improvement. Spain has gradually fallen into (3b) from (3a), and may reach (3c) or (2c) in the near future. Also, Ireland is at risk of sliding into (2c) without appropriate countermeasures (which are indeed in hand), which follows from its synchronously isolated grid. The latest trend for MISO was slightly surprising and needs further investigation of what happened and how to resolve the situation. The Japanese utilities also require effort to reduce curtailment towards (1b) or (2b) in the near future.

V. Conclusions

This paper proposed a novel tool, *C-P map*, and new indicators, *C-P ratio* and *C-P gradient*, for a quantitative and objective evaluation of curtailment trends from VRE (variable renewable energy; *i.e.* wind and solar) in an international comparison. Using these objective and quantitative indicators, the historical trends for VRE curtailment were classified and compared across several countries/areas.

Also, it would be useful to move the discussion from curtailment being a "bad" thing, to how advantage can be taken of curtailment to obtain more services from curtailed VRE. For example, ERCOT achieves upward primary frequency reserves from curtailed wind. These ancillary services are valuable and show that curtailment does not need to be seen as a waste of energy. Further discussions are needed to create appropriate market structures with the optimal VRE curtailment and to provide ancillary services from VRE plants.

As grid conditions, energy mix and management of power systems vary, these comparisons should take into account the operating practices and available flexibility of each region. Still, experience and knowledge in one country/area can be informative to others. An international comparison with objective measures can help gather best practices. It is hoped that the newly proposed concepts in this paper, C-P map, C-P ratio and C-P gradient, will enable improved evaluation of VRE curtailment, and provide help in planning and operating power systems in order to further optimise curtailment of wind and solar generation in the future.

Acknowledement

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References

[1] E. O'Dwyer *et al.* "The Case for Wind Energy", CIGRE CE/SC37 (1990)

[2] P. Gardner *et al.*: "The Impacts of Increased Levels of Wind Penetration on the Electricity Systems of the Republic of Ireland and Northern Ireland", Commission for Energy Regulation (2003)

[3] J. Holt *et al.*: "Assessment of the impact of wind energy on the CEGB system", CEC Brussels (1990).

[4] D. Lew *et al.*: "Wind and Solar Curtailment", *12th Wind Integration Workshop*, WIW13-1146 (2013)

[5] L. Bird *et al.:* "Wind and Solar Energy Curtailment: A Review of International Experience", Renewable and Sustainable Energy Review [in review]

[6] H. Holttinen *et al.*: "Design and operation of power systems with large amounts of wind power", Final report of IEA Wind Task 25 Phase one 2006-08 (2009)

[7] L. Soder *et al.* "Experience from wind integration in some high penetration areas", *IEEE Trans. on Energy Conversion*, **Vol.22**, No.1, pp.4-12 (2007)

[8] T. Ackermann *ed.*: "Wind Power in Power Systems, 2nd edition", Wiley (2013)

[9] Y. Yasuda *et al.*: "Flexibility Chart – Evaluation on Diversity of Flexibility in Various Areas", *12th Wind Integration Workshop*, WIW13-1029 (2013)

[10] International Energy Agency (IEA): "Electricity Information" (2015 web version)

[11] U.S. Energy Information Agency (EIA): "Wind generates more than 10% of Texas electricity in 2014", today in energy (Feb. 19, 2015)

[12] Mid-West Independent System Operator (MISO): "2014 State of the Market Report for the MISO Electricity Markets" (2015)

[13] Energy Efficiency & Renewable Energy (EERE), U.S. Department of Energy (DOE): "2014 Wind Technologies Market Report" (2015)

[14] Hydro-Québec: unpublished data

[15] EIA: International Energy Statistics: China (web version)

[16] Y. Yasuda: "International Comparison on Curtailment Ratio of Wind and Solar Energy", *Joint Meeting of High Voltage and Environmental & New Energy, IEEJ*, HV-15-064 (2015) [in Japanese]

[17] S. Martín-Martínez *et al.*: "Wind power curtailment analysis under generation flexibility requirements: the Spanish case study", *IEEE PES General Meeting*, 15PESGM1031 (2015)

[18] EIA: "Fewer wind curtailments and negative power prices seen in Texas after major grid expansion", today in energy (June 24, 2014)

TABLE V. Classification of Curltailment Trends in selected Countries/Areas

class		trend	(a)	(b)	(c)
		C-P Gradient	$G < 0$	$0 \leq G < 0.5$	$0.5 \leq G$
status	C-P Ratio		improving	stable	deteriorating
(1)	$0.5 \leq R$	red	China, Italy(2010), ERCOT(2010)	MISO	Japan (in future)
(2)	$0.1 \leq R < 0.5$	yellow	——	Ireland	——
(3)	$R < 0.1$	green	Germany, Spain(2009), Italy(2014), ERCOT(2004)	Hydro-Québec, Denmark, Portugal, Spain(2013)	——