Latest Wind and Solar Curtailment Information: statistics and future estimations in various countries/areas

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Abstract

An international research collaboration under IEA (the International Energy Agency) Wind TCP (Technical Collaboration Programme) Task 25 (Design and Operation of Energy Systems with large amount of Variable Generation) has previously performed an international comparison analysis on the curtailment of wind and solar power in various countries/areas in the world in 2022. This paper gives a comparison overview of the curtailment rates, presented as C-E maps (curtailment as a share of VRE and power system demand). As previous statistical data was as until 2020, some data has been updated. The latest information and the future estimations of curtailment in several countries/areas are summarised, including Ireland, California and Texas in U.S., and Japan. We also discuss the possible impacts of battery storage and demand response, which may contribute to reduced wind & solar curtailment, despite very high VRE (variable renewable energy) shares.

0 Abbreviations

AEMO: Australian Energy Market Operator
BnetzA: Bundesnetzagentur
CAISO: California Independent System Operator
C-E map: curtailment - energy share map
ERCOT: Electricity Reliability Council of Texas
FY: fiscal year
IEA: International Energy Agency
IEA Wind Task 25: Design and Operation of Energy Systems with large amount of Variable Generation
METI: Ministry of Economy, Trade and Industry, Japan
mFRR: manual frequency restriction reserve
NEM: National Electricity Market (in Australia)
PV: photovoltaic
PVPS: Photovoltaic Power Systems Programmes
RR: replacement reserve
SONI: System Operator in Northern Ireland
TCP: technical collaboration programme
TDSO: transmission & distribution system operator
TSO: transmission system operator
U.S.: United States of America
VRE: variable renewable energy

1 Introduction

Curtailment is an integration issue facing the rapid increase of VRE towards net zero emissions across the globe. An international research collaboration under IEA Wind TCP Task 25 previously performed an international comparison of wind and solar power curtailment in various countries/areas in the world in 2022 [1]. The main result, as of 2020, in the paper is shown in Fig. 1, where historical trends in the selected countries/areas are drawn as C-E maps, *i.e.* a correlation map

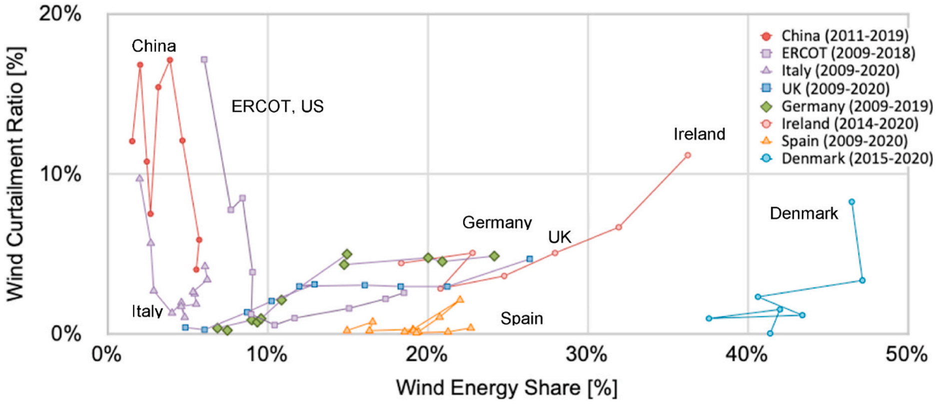

Fig. 1 C-E map of wind energy in selected countries/areas (by IEA Wind Task 25) [1]

between energy share and curtailment ratio. The IEA published a similar map of the latest curtailment trends for wind and solar (VRE), where the latest plots are those as of 2021 (up to June 2023) [2].

This article presents updated C-E maps for several countries/areas, including Ireland, California and Texas in U.S. and Japan. Also, the latest debates regarding grid management and future estimations of curtailment in the selected countries/areas are presented, including discussion of potential impacts of battery storage and demand response that may contribute to reducing wind & solar curtailment, despite very high VRE shares.

2. C-E map methodology

A short description of the C-E map methodology is presented here (detailed further in [1]).

The definition of curtailment can be found in [3], where the following description is seen: "a reduction in the output of a generator from what it could otherwise produce given available resources, typically on an involuntary basis". In Ireland, "curtailment" and "constrained generation" are strictly distinguished, where the former relates to system-wide issues, while the latter relates to dispatch-down due to local network issues [4]. This paper does not distinguish between the two terms and applies a unified term "curtailment" for international comparison. Also, curtailment should be distinguished from a market-based economic reduction (active power management), except in cases where statistical data cannot be distinguished, as in some countries such as U.S. and Denmark.

In creating the C-E map, the following definitions are necessary.

$$E_w = \frac{G_w}{T_c} \quad (1)$$

$$C_w = \frac{W_w}{G_w + W_w} \quad (2)$$

$$E_s = \frac{G_s}{T_c} \quad (3)$$

$$C_s = \frac{W_s}{G_s + W_s} \quad (4)$$

$$E_v = \frac{G_w + G_s}{T_c} \quad (5)$$

$$C_v = \frac{W_w + W_s}{G_w + G_s + W_w + W_s} \quad (6)$$

where,

- C_w: Curtailment ratio of wind energy [%],
- C_s: Curtailment ratio of solar [%],
- C_v: Curtailment ratio of VRE [%],
- E_w: Energy share of wind [%],
- E_s: Energy share of solar [%],
- E_v: Energy share of VRE [%],
- T_c: Annual total consumption [GWh],
- G_w: Annual wind generation [GWh],
- G_s: Annual solar generation [GWh],
- W_w: Annual curtailed (lost) wind energy [GWh], and
- W_s: Annual curtailed (lost) solar energy [GWh].

Annual generation by wind and solar PV differ in most countries. In this situation, evaluating the C-E map by the total volume of VRE, combining wind and solar, could be misleading as it may result in an underestimation/ overestimation of the levels of individual wind/solar curtailment [1], see also Figs. 5, 8 and 9.

3 Latest situations in various countries/areas

3.1 Germany

German curtailment data of wind and solar is available in Monitoring Reports [5] annually published by the German regulator, Bundesnetzagentur (BnetzA). The latest report indicates that the curtailment ratios for both wind and solar have been kept below 4%, while the energy ratios of both have fluctuated due to reduced electricity consumption caused by COVID-19 pandemic, and a low wind and solar year in 2021 (see Fig. 2).

The BnetzA report stated that "Over the past few years, there has been a continual increase in the proportion of curtailment from feed-in management measures with causes in the distribution network". The latest ratios (in 2021) of curtailment seen by TSOs and DSOs are 73% and 27%, respectively [5].

3.2 Ireland

The previous work [1] reported on dispatch down levels in Ireland and Northern Ireland until 2020. This particular year was windier than the average, while the pandemic tended to reduce the system demand, such that wind energy contributed 36.4% (13.8 TWh) of the demand with 12.1% being dispatched down (5.9% curtailed due to system-wide stability issues, and 6.2% constrained due to local network issues). 2021 was much less windy than the year before (11.7 TWh, 30.6% of demand), with dispatch down levels also reducing (7.4%), while 2022 saw a recovery to 13.7 TWh (34.1%) and 8.5% dispatch down [4]. The first half of 2023 has shown strong wind power production in the first 3 months of the year (39.6% of demand with 7.9% dispatch down), but decreasing production in the second quarter (25.5% of demand with 5.3% dispatch down). As yet, the vast majority of solar farms across the island are located in Northern Ireland, approx. 350 MW

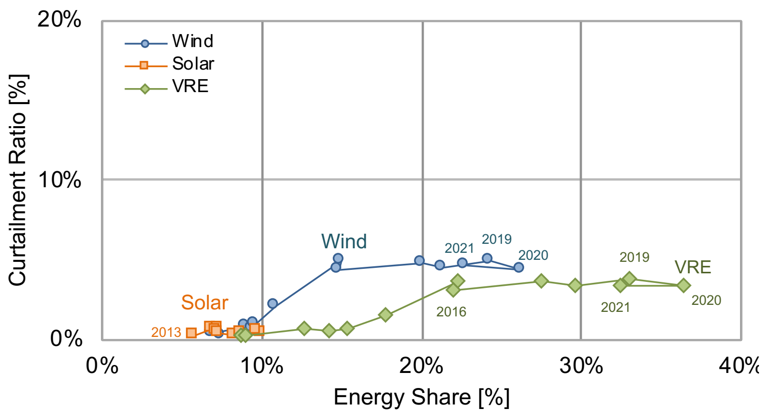

Fig. 2 Historical trends of wind, solar and VRE curtailment ratios and energy shares in Germany (data source: [5],[6]).

and contributing approx. 0.5% of all-island demand. They are subject to the same dispatch down procedures as wind energy, such that 6.3%, 2.9% and 4.2% output reductions occurred between 2020 and 2022, mostly due to constraint reasons, although curtailment levels are noticeably higher during the autumn/winter months. The historical trends of wind curtailment ratio and wind energy share in Ireland, Northern Ireland and All Island on a C-E map are shown in Fig.4. Figure 5 shows those of solar, wind and VRE in Northern Ireland.

As noted above, the collective term dispatch down is adopted in Ireland and Northern Ireland, which elsewhere would be known as curtailment. Instead, curtailment and constraint have specific meanings, relating to system-wide and locally induced reductions in renewable output. In 2022, the combined all-island system achieved the historic situation whereby 100% of the demand was instantaneously met by wind generation (the individual records for Ireland and Northern Ireland are 98% and 162%). In 2022, dispatch down due to excess supply peaked at 29%, with an average value of 0.11%. Consequently, for future years (2023 onwards) it is intended that renewable dispatch down periods will be separately classified as due to local network constraints, system-wide stability constraints, and (newly) excess supply, when renewable production exceeds the indigenous demand.

A number of measures are being trialled and/or studied offline to reduce dispatch down levels, including an increase in the RoCoF (rate of change of frequency) standard from 0.5 Hz/s to 1 Hz/s, and reducing the minimum number of "large" online generating units from 8 to 7 (both of which will reduce the requirement for conventional units to be online contributing to the inertial response), and reducing the requirement for negative reserve (safeguard against tripping of a large load or HVDC interconnector in export mode) to be held in Northern Ireland (such that conventional units can operate at lower outputs). The maximum system non-synchronous penetration (SNSP) level was also increased from 65% to 70% (April 2021) and now 75% (April 2022). Low carbon inertia system services (LCIS) are also being procured, for expected deployment in 2026, to provide synchronous inertia, short circuit contribution and reactive power support services [9]. It is expected that synchronous condenser tenders will win out, which will reduce the need for conventional plant (with a minimum generation output) to be online, and hence curtailment and locational constraint volumes will be reduced.

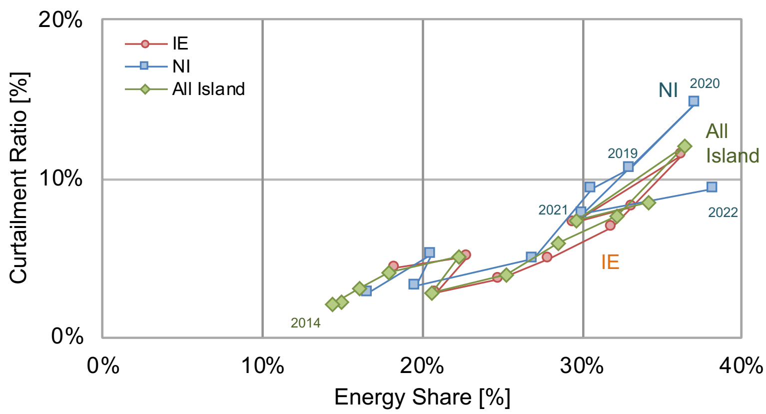

Fig. 3 Historical trends of wind curtailment ratios and wind energy shares in Ireland, Northern Ireland and All Island (data source: [7]).

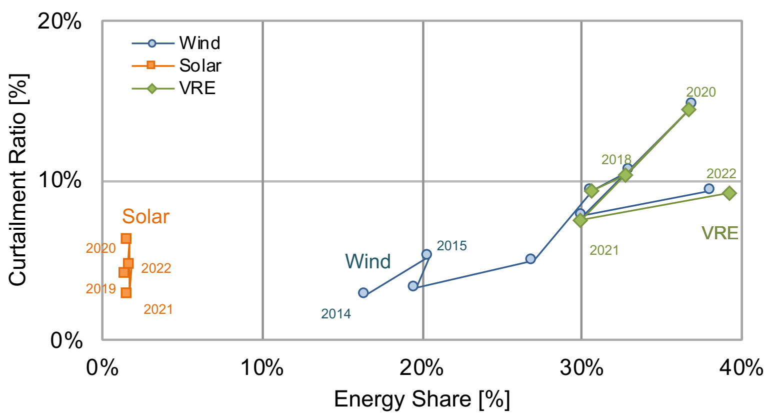

Fig. 4 Historical trends of solar, wind and VRE curtailment ratios and their energy shares in Northern Ireland (data source: [7], [8]).

A number of major transmission system upgrades in NW and SW Ireland in recent years have further helped to control the need to constrain wind production. However, in Northern Ireland, constraint levels have been rising due to increased wind capacity, in conflict with the need to keep a minimum number of conventional units online and concerns for a system split if the 220/275 kV tie line between Ireland and Northern Ireland trips. A second tie line is planned for 2025, which will notably reduce the operational risk, and improve constraint levels in Northern Ireland.

Previously, the 2030 renewable target in both jurisdictions was 70% of demand, but in 2021 this was separately raised to 80% in both jurisdictions. However, particularly in Ireland, a greater focus is being placed on a carbon budget for the electrical sector, which requires a 75% reduction in emissions relative to 2018, despite any demand growth. In order to support the renewable targets, there has been one offshore and three onshore renewable auctions, implemented through (offshore) renewable electricity support schemes (ORESS and RESS). For the RESS-1 and RESS-2 auctions curtailment (not constraints) beyond 10% is compensated, but for later onshore/offshore auctions the 10% threshold has been reduced to 0%, leading to the concept of unrealised available energy compensation (UAEC) [10]. The logic behind the UAEC concept is that high dispatch down volumes, seen in recent years, are "costed in" to higher auction bids for new wind/solar farms, so by the government

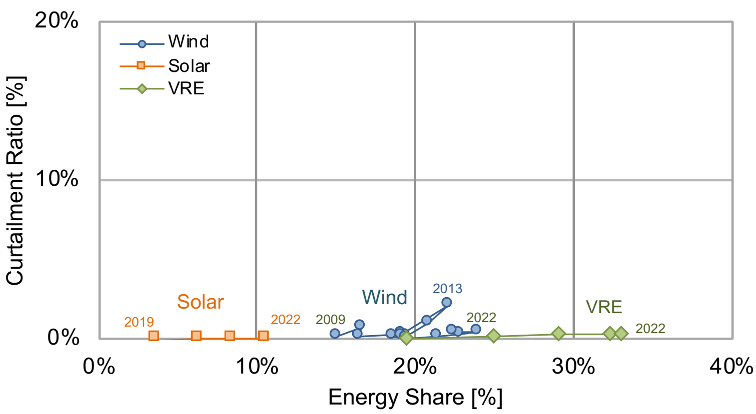

Fig. 5 Historical trends of wind, solar and VRE curtailment ratios and energy shares in Spain (data source: [11]).

guaranteeing UAEC payments it is anticipated that auction bids will be lower, as the investment risk is reduced, which will ultimately reduce the electricity cost to the consumer.

3.3 Spain

To accomplish the goals outlined in the National Energy and Climate Plan (NECP), Spain's installed VRE capacity has significantly increased in recent years. As a result, the installed capacity of photovoltaic solar energy rose, almost tripling from 8,454 MW at the end of 2019 to 21,319 MW by the end of July 2023. In the same time frame, the rise in wind energy was from 25,310 MW to 29,717 MW [11]. Thus, in the months of June and July 2023, PV production exceeded wind power production. Higher VRE generation, particularly in the case of solar PV, as a result of this growth, has increased curtailment to levels akin to those in 2013, when the historically maximum degree of curtailment was attained [1]. This follows a period between 2014 and 2019 in which curtailment ratios have been almost negligible.

Solar curtailment statistics in Spain can be obtained from 2019 while those of wind has been available since 2009. However, according to the statistics, curtailed ratio of solar was only 0.075% in 2022, when solar energy share exceeded 10% for the first time. The total curtailed ratio of VRE has been also keep very low less than 0.4% in resent four years despite the VRE share exceeded 30%.

Figure 5 shows the C-E map for Spain for the period 2009- 2022. It is worth highlighting the increase in the curtailment ratio of solar photovoltaic energy once the 10% energy share of this technology has been exceeded. In wind energy the ratio has no clear dependence on the energy share and the combination of low demand and a combination of high VRE offers periods of high curtailment.

As the Iberian power system has been known as a quasi-isolated system with low interconnection capacity between neighbouring areas, one of the main reasons why the curtailment ratio can be maintained so low in Spain is wind and solar PV downward participation in mFRR and RR markets. These services began in February 2016 and since May 2022 a 15 min scheduling to gate closure is available. This allows less forecast errors and a better congestion management in the system.

3.4 U.S.

The DOE in the U.S. publishes historical statistical data in the main ISOs/RTOs almost every year. The latest publication summarises data up to 2021 [12]. Figure 6 shows historical wind curtailment trends in the main ISOs/RTOs in the U.S. on a C-E map.

The trend curve of SPP on the C-E map shows a rapid increase in curtailment ratio almost reaching 10%, due to the increase in wind energy share in recent years, after the fall in 2018. ERCOT has also experienced increased curtailment ratios, and the recent upward trend on the C-E map is greater than for the last several years. The wind share in MISO exceeded 10% in 2020, but it is interesting to note that the curtailment ratio is reducing.

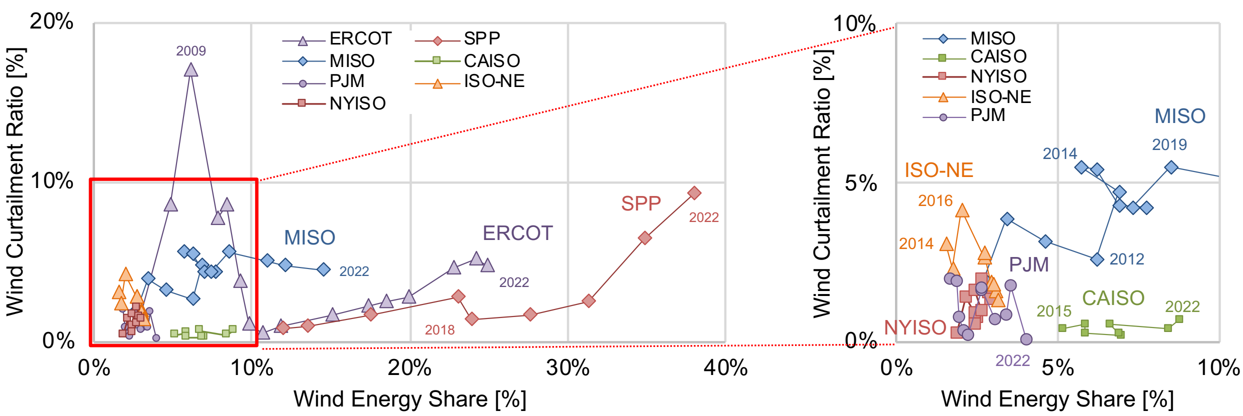

Fig.6 Historical trends of wind curtailment ratios and wind energy shares in the main ISOs/RTOs in the U.S. (data source: [12])

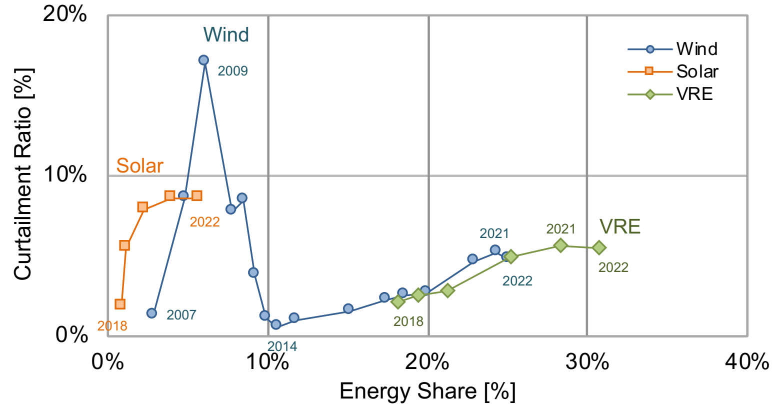

Fig. 8 Historical trends of solar, wind and VRE curtailment ratios and wind energy shares in ERCOT, U.S. (data source: [12],[15],[16],[17])

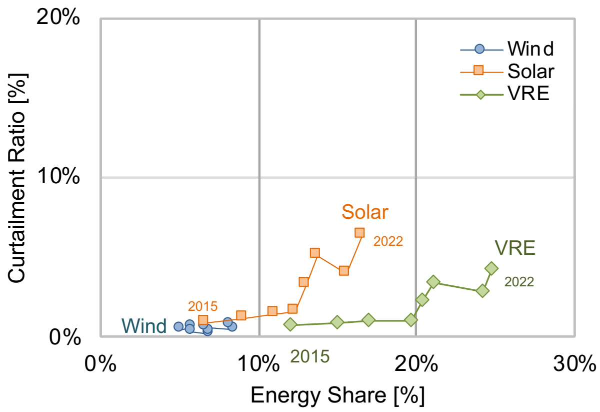

Fig. 7 Historical trends of solar, wind and VRE curtailment ratios and wind energy shares in CAISO, U.S.
(data source: [13])

The ISO in California, CAISO, includes information on solar curtailment [13]. Figure 7 is a C-E map that illustrates the historical trends of solar, wind and VRE curtailment ratios and wind energy shares in the CAISO area. The curtailment ratio for solar, and VRE, fell in 2021, but the ratio has since risen to a record value. CAISO anticipates that curtailment in 2023 will break the record again [13].

According to Energy Storage News, "Battery storage has a big role to play in helping reduce renewable energy curtailment in California but the amount of shedded load will still grow in 2023" [14]. It is also reported that "Interestingly, CAISO's storage sector manager Gabe Murtaugh told *Energy-Storage News* in April 2022 that battery storage was shifting up to 6 GWh of energy a day from low-price to high-price periods, but that the majority of this was just moving mainly gas-generated energy across the day, rather than renewable load shifting" [14].

ERCOT is also an area where solar energy has grown rapidly in recent years. Information on solar curtailment in Texas is limited so far, but one of a few exceptions is released by EIA [15], which reported that the curtailment ratio for solar in 2022 was 9% while that for wind was less than 5%. Figure 8 is a C-E map of ERCOT achieved by combining a number of statistical sources, leading to a number of (small and non-visible) statistical errors on the C-E map. The EIA report also projected that future wind curtailment in ERCOT could increase to 13% of total available wind generation, and solar curtailment could reach 19% by 2035.

3.5 Japan

As of 2020, which was the latest data in [1], the only control area which performed curtailment was Kyushu, across the 9 areas on the Japanese mainland. In 2023, solar and wind curtailment can be seen in 4 areas, namely Tohoku, Chugoku, Shikoku and Kyushu. The other 3 areas, Chubu, Hokuriku and Kansai have also seen curtailment, but the total volumes and ratios are sufficiently small to be neglected. The remaining 2 areas, Hokkaido and Tokyo, have not curtailed any solar and wind, as far as their published statistical data.

Figure 9 shows the historical curtailment trend in the Kyushu area since 2018 illustrated on a C-E map. Note that the data in 2023 is estimated, where the annual curtailment ratios are calculated as 60% from the observed data in the first half of the year, according to the past trends in Kyushu. This follows because curtailment in Japan mainly occurs in the spring, when daytime demand is low but solar output is high.

Kyushu Power Transmission and Distribution, the TDSO in Kyushu area, started so-called "agent control" in 2022, where VRE plants that accept online control are mainly curtailed flexibly, and the lost profits are pro-rated and later claimed to other VRE plants that do not incorporate online control systems. The significant reduction, despite the increased VRE share from 2021 to 2022, can be understood by the introduction of agent control.

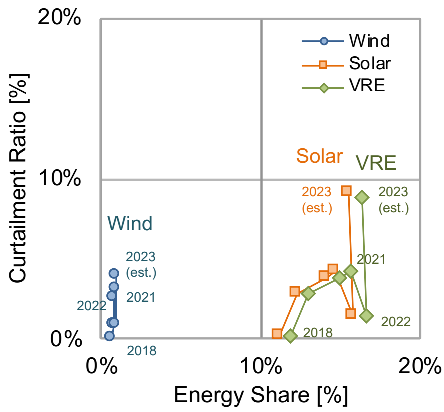

Fig. 9 Historical trend of curtailment in Kyushu, Japan on C-E map (data source: [18])

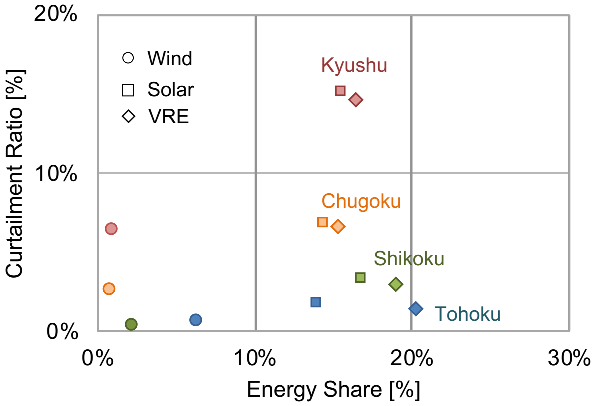

Fig. 10 Comparison of curtailments in the first half in 2023 in 4 areas in Japan on C-E map (data source: [18], [20]-[22])

However, in 2023, it is evident that there is a significant increase in curtailment from the previous year. The reason is explained that "due to an increase in solar output because of an increase in the number of sunny days and a decrease of utilisation ratio in interconnection lines" by the TDSO in Kyushu at a METI council [19]. The estimated VRE annual curtailment ratio by the TDSO is 6.7% in FY2023 at the council (note that a fiscal year in Japan starts from April and ends in March in the next calendar year). The reason for the significant increase requires further detailed study.

Figure 10 illustrates a comparison across 4 areas that curtailed solar and wind more than 1% in the first half of 2023, Tohoku, Chugoku, Shikoku and Kyushu. As the first three areas have merely curtailed VRE before 2022, this is the first year for them to experience curtailment in the statistical data. It is clear that curtailment in Kyushu is notably higher than in other areas, while the next most notable area is Chugoku.

According to analysis of flexibility using a Flexibility Chart [23], the Kyushu area has relatively poor flexibility from interconnection, while Chugoku is categorised as an interconnection-rich area. The reason why curtailment in Chugoku suddenly increased from 2022 to 2023 requires further investigation. It is interesting that curtailment in Hokkaido is almost zero despite a lack of flexibility resources, especially interconnection capacity.

METI also performed future estimation of VRE curtailment in all areas in Japan, where possible curtailment ratios in Hokkaido, Tohoku and Kyushu would be 53.6%, 54.2% and 26% in 2030s, if appropriate measures are not implemented [23]. However, appropriate countermeasures such as demand, supply and grid-side, can significantly reduce expected curtailment, *e.g.,* 0% in Hokkaido, 11.2% in Tohoku and 9% in Kyushu.

METI also proposed a number of countermeasures to reduce future curtailment, as below; in the short term, (1) increase controllability of online plants, (2) decrease minimum stable load of combustion plants, and maximise utilisation of pumped hydro power, (3) implement batteries and electrolysers, as well as demand response from heat pumps, (4) increase power transfers across interconnection lines, and in the long term, (i) increase interconnection capacity, (ii) utilise VRE as a flexibility resource, (iii) control demand and supply via price mechanisms [25].

Regarding solar curtailment in Japan, see the latest report by IEA TCP PVPS Task14 (Solar PV in the 100% RES Power System) [26].

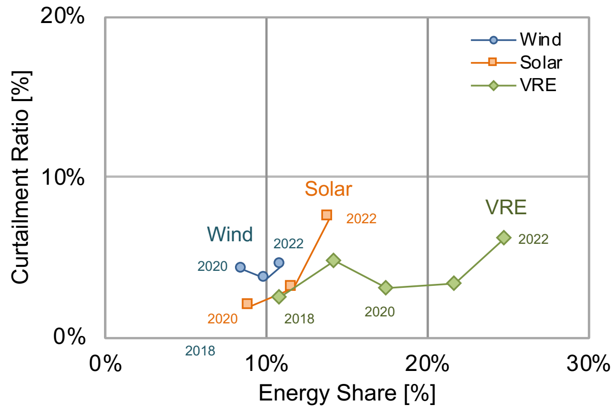

Fig. 11 C-E map of wind, solar and VRE in NEM, Australia (data source: [27],[28])

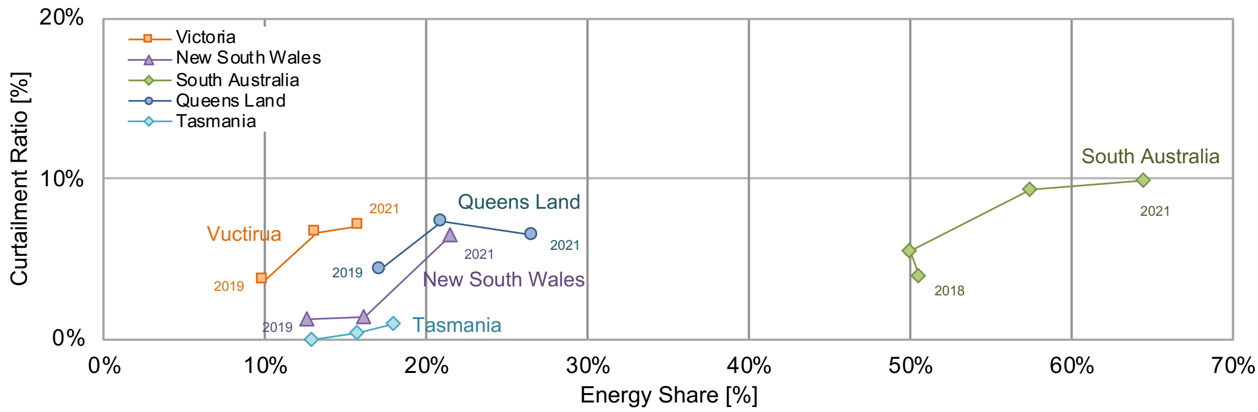

Fig. 12 C-E map of VRE by state in Australia (data source: [27],[28])

3.7 South Australia

Although it is difficult to identify consistent statistics on wind and solar curtailment by state in Australia, AEMO published a series of reports named "Quarterly Energy Dynamics" [27], in which scattered information on curtailment can be seen. Curtailment data that can be split into wind and solar categories is limited, but can be obtained for only three years for the aggregated NEM area. Figure 11 is a C-E map based on the available data. Note that the generated solar energy includes small scale PV, such as roof-top PV, and curtailment data includes economic curtailment, i.e. voluntary dispatch by VRE operators due to negative prices. The recent rapid growth of solar energy across Australia has inevitably resulted in an increased curtailment ratio.

Similarly, available data that can be distinguished by state is limited, and a figure using only VRE data (*i.e.* data that cannot be split into wind and solar) for three years is shown in Fig.12. The curtailment ratios in Australian states except Tasmania exceed 5%, due to the rapid increase of solar capacity in each state. South Australia has a VRE share exceeding 60%, and it is noteworthy that the curtailment ratio is less than 10%, despite the highest VRE share in the world.

A commissioned report by AEMO states that "At high installations of solar PV, export (feed-in) prices for excess solar generation will be lower and owners may also face greater incidences of curtailment (either due to high local voltages or for system security purposes). These changing conditions, together with lower battery costs, also support greater uptake of batteries in the 2030 to 2050 period." [29]

4 Conclusions

This article provided the latest update on the curtailment of wind and solar in several countries/areas worldwide, including the latest policies and future estimations. Summary C-E maps for wind, solar and VRE in selected countries/areas are shown in Figs. 13-15, which provide both an intuitional and quantitative understanding of historical trends and international comparisons.

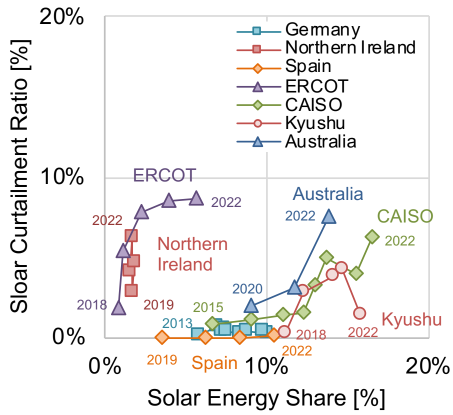

Fig. 13 C-E map of solar in selected countries/areas in the world

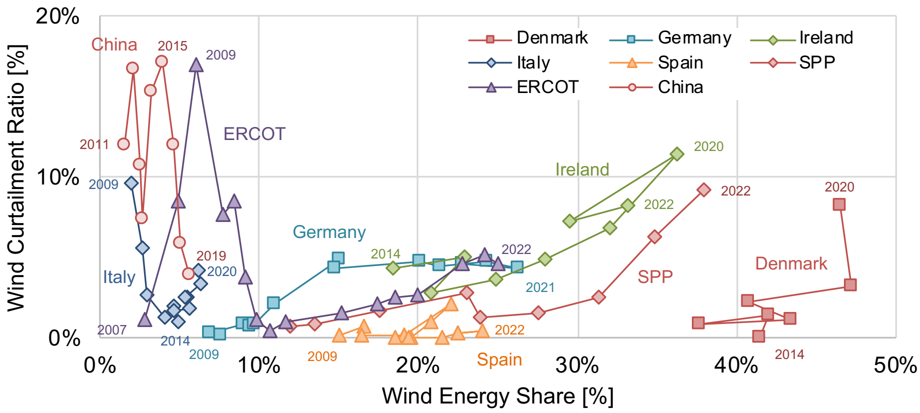

Fig. 14 C-E map of wind in selected countries/areas in the world

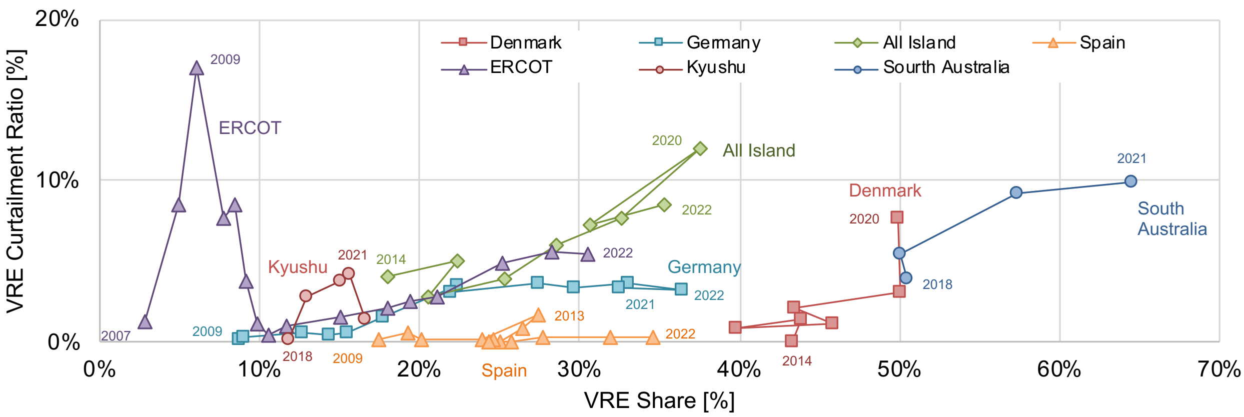

Fig. 15 C-E map of VRE in selected countries/areas in the world

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