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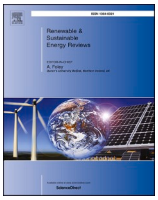

C-E (curtailment – Energy share) map: An objective and quantitative measure to evaluate wind and solar curtailment

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ABSTRACT

As the share of VRE (variable renewable energy) has grown rapidly, curtailment issues have arisen worldwide. This paper evaluates and compares curtailment situations in selected countries using an objective and quantitative evaluation tool named the "*C-E map*" (curtailment-energy share map). The C-E map is a correlation map between curtailment ratios that mean curtailed wind (or solar) energy per available energy and energy shares of wind (or solar). The C-E map can draw a historical trend curve in a given country/area, as an at-a-glance tool to enable historical and/or international comparison. The C-E map also can classify the given countries/areas into several categories, according to the current levels of curtailment ratio and historical trends. The C-E map helps institutional and objective understanding of curtailment for non-experts including policy makers.

1. Introduction

Variable Renewable Energy (VRE), mostly wind and solar, is increasing world-wide, which leads to curtailment becoming a major problem in many countries. In 1990, an early study showed that only modest shares of VRE could be realized without allowing curtailments [1]. Another study later showed that significant VRE shares would be feasible if a part of the VRE were curtailed [2]. Other research claimed that curtailment would rise exponentially with increasing shares of VRE [3].

Curtailment can be understood as "a reduction in the output of a generator from what it could otherwise produce given available resources, typically on an involuntary basis" [4]. Although some reports, such as Ref. [5], distinguish "curtailment" (system-wide) and "constrain" (dispatch-down to local network), this paper does not distinguish between the two terms and applies a unified term "curtailment" for any reason, except a market-based economic reduction (for example, the US and Denmark data include market-based economic reductions). Ref. [4] also noted that "… Definitions of curtailment and

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Abbreviations

BnetzA	Bundesnetzagentur (a German regulator)
CAISO	California Independent System Operator
CHP	combined heat and power
COVID-19	coronavirus disease 2019
CREZ	Competitive Renewable Energy Zone (in Texas)
DC	direct current
DE	Germany
DK	Denmark
DLR	dynamic line rating
EIA	Energy Information Administration (an agency in US)
EPCO	electric power company (a term mainly in Japan)
ERCOT	Electricity Reliability Coordinator of Texas
ES	Spain
GB	Great Britain
GW	giga watt
GWh	giga watt hour
HVDC	high voltage direct current
IE	Ireland
IT	Italy
ISO	independent system operator (a term mainly in US)
ISO-NE	Independent System Operator of New England
MISO	Mid-continent Independent System Operator
NI	Northern Ireland
NO	Norway
NYISO	New York Independent System Operator
PJM	a RTO covering Pennsylvania, New Jersey, Maryland and other states and district
PSCO	Public Service Company of Colorado
PT	Portugal
PV	photovoltaic
RES	renewable energy source
RTO	regional transmission organization (a term mainly in US)
SNSP	system non-synchronous penetration
SONI	System Operator in Northern Ireland
SPP	South Power Pool (a RTO in US)
STATCOM	STATic synchronous COMpensator
TERNA	Transmission System Operator of Italy
TDSO	transmission and distribution system operator (a term mainly in Japan)
TSO	transmission system operator (a term mainly in Europe)
UK	United Kingdom
US	United States (of America)
VRE	variable renewable energy

data availability vary. Understanding curtailment levels can be complicated by relatively new market-based protocols or programs that dispatch wind down or limit wind generation to schedules and the lack of uniformity in data collection".

Curtailment is not always a "bad" thing. Wind operators can provide upward reserves when a part of accessible energy is curtailed, which is for example applied for primary reserves in the ERCOT system in the USA, and Xcel/PSCO gets secondary reserves thanks for curtailment [6]. In the end, loosing energy provides the basis for the provision of these valuable power system services. The relation between VRE curtailment and VRE reserve capacity is a topic that should be discussed more [7]. Optimally dispatching wind gives it a role not only as energy provider, but also as provider for flexibility and system services. *E.g.* ramping wind can reduce the (residual) ramping needs of the system, thus replacing the flexibility previously provided by a thermal power station [8].

Whenever grid support services are not drawn from wind power, curtailment is simply a loss of clean energy (a "bad" thing), not only for generators and investors, but also for TSOs (Transmission System Operators) and regulators because of a lack of system flexibility or appropriate market design. Here, we focus on forced (or involuntary) curtailment rather than voluntary (or market-based) dispatch-down excluding some countries/areas such as Denmark and the US, whose statistical data does not distinguish between "market-based" curtailment and "forced" curtailment by TSOs/ISOs.

Wind curtailment is now becoming a significant concern as wind energy generation increases in many countries. Many reports and papers have been published in several countries *e.g.* Ireland [5], Spain [9–11], UK [12], the U.S. [4], and China [13–16]. Only a few studies investigate international comparisons on curtailment [17–22]. Estimated future curtailments can also be used as one important outcome from integration studies [7,23,24].

Historical curtailment data and trends may contain evidence for the performance of VRE integration measures. The curtailment level can serve and an indicator for integration challenges in power system studies. However, directly comparing curtailment levels in different countries/areas is not always straight forward, as several specific factors in their power system are likely to contribute to the degree of curtailment. Some high-level evaluation tools have been proposed for objective comparison and assessment of the severity of the VRE integration challenge. A "maximal share of wind power" criterion was proposed in Ref. [25] to compare the challenges and wind power shares in Gotland in Sweden, West Denmark, Schleswig Holstein in Germany, Ireland and New Mexico in the USA. It was shown that rather high VRE shares (30–40%) do not necessarily result in high curtailment needs [26]. Several studies, listed in Ref. [27], show that flexibility measures like transmission, flexible generation, and demand side response can reduce curtailments. A qualitative indicator named "Flexibility Chart" has been proposed in Ref. [28], which assesses the flexible resources of a power system that contribute to the reduction of VRE curtailment.

A good understanding of the status and trends for wind curtailment is important for several reasons. From a financial point of view, the economics of a project are directly dependent on the ability of a site to harvest the expected energy. While project investors are increasingly building in a safety factor to account for curtailment, excessive curtailment can drive down project returns and make the project uneconomical. For a given site or region, the investor will want to know the expected trends for curtailment before making a decision. From the system point of view, reducing the output from emission-free generation might impact the low carbon targets set. Also, aggregated flexibility resources within the larger area may affect curtailment levels. However, options for mitigating curtailment are strongly dependent upon regulations in the given countries/areas. Solving flexibility issues (curtailment) within a country is also desirable rather than exporting flexibility problems to neighboring countries.

The reasons for the possibility of curtailment are important. Transmission system congestion may be a signal that transmission expansion is required. Another reason for curtailment may be the mismatch between system load and wind energy availability. Transmission expansion may again be used as a mitigation for that. A local transmission system upgrade may relieve a local congestion problem, while a regional upgrade plan may be required to relieve a load mismatch problem. Timing of construction may be important in the event of either a planned local upgrade or regional upgrade to take advantage of planned load growth, energy storage additions, or demand response. A third possibility is that stability export limits may be imposed as the wind plant expansion increases in a weak area of the system. Understanding market design evolution is also a critical factor. The ability of wind plants to participate in ancillary service markets, which may be a function of curtailment, or the ability to participate in a capacity market, may provide additional sources of revenue.

A C-E map, which will be defined in detail in Section II, is a two-dimensional plane that consists of two axes; the horizontal axis representing an energy share and the vertical axis a curtailment ratio. A combination of curtailment and energy share data in a given country/area in a year can be drawn as a plot on the C-E map. The C-E map can illustrate visually and quantitatively multiple plots of curtailment and energy share data for different countries/areas in a given year. Also, it can reveal a historical trend in a given country/area as a curve tied by multiple plots on the map. The advantage of the C-E map is that it is a simple method that does not require much data, yet provides a useful basis for an intuitive and quantitative comparison of curtailment situations.

Several of the authors of this work have previously introduced an evaluation tool, named the "*C–P map*", in order to quantitatively visualize curtailment trends. This C–P map shows the correlation between VRE curtailment ratios (curtailed VRE energy per generated VRE energy) on the y-axis, and energy shares from VRE per annual consumption on the x-axis, for given countries/areas [18]. This article enhances the preliminary concept of the C–P map, and renames it to "C-E Map" since the neutral terminology "energy share" of VRE is preferred over the term "penetration ratio". The novelty of the current study is a direct result of time passing since Ref. [18] was published. Individual systems now incorporate much higher shares of renewables than even a few years ago, the reasons for, and consequences of, curtailment have grown, and various measures have been introduced to moderate, or even reduce, curtailment levels.

This paper covers the main VRE-rich countries/areas across three continents; countries that have promoted wind in Europe, several ISOs (Independent Transmission Operators) and RTOs (Regional Transmission Operators) in the US and Canada, wind-rich provinces in China and a PV-rich area in Japan. In Section II, we summarize tables of statistical data that we are able to gather from the countries/areas in our investigation. It is not easy to obtain information on VRE curtailment for many countries/areas because they are scattered across many statistical databases, reports and documents in various formats or were never made public before. One of the values of this study is that we have gathered data from a number of countries/areas at different stages of RES development and discussed the reasons for their different curtailment trends using our knowledge of and familiarity with the various systems. The summarized data themselves are therefore one of the original and novel contributions of this paper. Also, we define terminology on curtailed energy, energy share ratio of VRE and curtailment ratio for unified objective comparisons worldwide.

This paper also proposes metrics, namely the "C-E ratio" and "C-E gradient", originally shown in Ref. [18] as "C–P ratio" and "C–P gradient". The former is defined as the quotient of the given curtailment ratio by the given energy share ratio for the selected grid in the selected year, whereas the latter is the gradient of the C-E curve at the given point on the C-E map. Using the C-E map and metrics, this paper classifies the selected countries/areas into several categories depending upon the level and trends of VRE curtailment. Further explanation of these concepts is shown in Section III. The classification helps to explain how curtailment has occurred in the past and how it may change in the future for the selected grids.

The aim of this paper is to establish an objective and quantitative comparison method to obtain macroscopic trends of curtailment in a given grid. Grid circumstances may differ according to the geographical and/or political environment in each jurisdiction. For a microscopic analysis focusing on technical and political elements, one should refer to previous papers, such as Ref. [21].

2. Methodologies for "C-E map" and relative indicators

Before evaluating curtailment levels in different countries using the C-E Map, we first clarify how a C-E map can be constructed, including detailed definitions of the curtailment ratio and energy share, based on various statistical data from different countries. In addition, since a comprehensive and unified international database on curtailment levels does not exist, we have compiled available data on curtailment ratios and energy shares from various countries/areas.

2.1. Curtailment ratio definitions

Here, we define important parameters, energy share and curtailment ratio, as below:

$$E_w = \frac{G_w}{T_c} \tag{1}$$

$$C_w = \frac{W_w}{G_w + W_w} \tag{2}$$

$$E_s = \frac{G_s}{T_c} \tag{3}$$

$$C_s = \frac{W_s}{G_s + W_s} \tag{4}$$

$$E_v = \frac{G_w + G_s}{T_c} \tag{5}$$

$$C_v = \frac{W_w + W_s}{G_w + G_s + W_w + W_s} \tag{6}$$

where.

C_W: Curtailment ratio of wind energy in a given country/area [%],

C_S: Curtailment ratio of solar energy in a given country/area [%],

C_V: Curtailment ratio of VRE in a given country/area [%],

E_W: Energy share of wind in a given country/area [%],

E_S: Energy share of solar in a given country/area [%],

E_V: Energy share of VRE in a given country/area [%],

T_C: Annual total consumption in a given country/area [GWh],

G_W: Annual wind generation in a given country/area [GWh],

G_S: Annual solar generation in a given country/area [GWh],

W_W: Annual curtailed (lost) wind energy in a given country/area [GWh], and.

W_S: Annual curtailed (lost) solar energy in a given country/area [GWh].

Note that the wind energy share is defined here based not on annual total *generation* but *consumption,* since a difference may exist between the two measures due to imports/exports via interconnections and energy loss during transmission and distribution. Also, the curtailment ratio defined here is based on the sum of generated energy and curtailed (lost) wind energy. Some articles may define these terms differently, including our previous report [18].

2.2. Curtailment statistics for different systems

Tables 1–3 present data for drawing C-E maps. These data are collected from several European countries, markets in the U.S. and Canada, and Chinese provinces with substantial wind installations, respectively.

For this analysis, we used data from IEA's Electricity Information or TSOs for total consumption and wind generation annually for the European countries examined. With respect to curtailment data, there are no uniform requirements by regulators or TSOs to publish data on renewable energy curtailment. Germany [31] and Ireland [5] are the only two European countries that we have identified that publish data on curtailment. For other countries, such as Italy, Spain and Great Britain, past curtailment data can be found in papers prepared by independent researchers [9,11,21], or from unpublished data provided by

Table 1

Statistical data for wind curtailment in European countries.

Country		2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Data source
Denmark *[1]	T_c	32,409	33,018	32,584	32,073	32,152	31,569	33,616	33,987	34,018	34,169	34,211	35,093	[29]
	G_w	6721	7809	9774	10,270	11,123	13,079	14,133	12,782	14,777	13,895	16,150	16,353	[29]
	W_w	–	–	–	–	–	–	215	120	170	325	553	1463	[30]
	E_w	20.7%	23.7%	30.0%	32.0%	34.6%	41.4%	42.0%	37.6%	43.4%	40.7%	47.2%	46.5%	
	C_w	–	–	–	–	–	–	1.5%	0.93%	1.14%	2.29%	3.3%	8.2%	[30]
Germany	T_c	513,665	547,284	540,560	539,516	537,331	525,904	528,133	530,374	531,324	532,756	510,542	510,542	[29]
	G_w	38,647	37,793	48,883	50,670	51,708	57,357	79,206	78,598	106,601	111,590	123,545	129,769	[29]
	W_w	73	125	410	359	480	1221	4125	3530	5287	5247	6273	–	[31]
	E_w	7.5%	6.9%	9.0%	9.4%	9.6%	10.9%	15.0%	14.8%	20.1%	20.9%	24.2%	25.4%	
	C_w	0.2%	0.3%	0.8%	0.7%	0.9%	2.1%	5.0%	4.2%	4.7%	4.5%	4.8%	–	
Northern Ireland (SONI)*[2]	T_c	–	–	–	–	–	8766	8777	8725	8413	8403	8347	7987	[5]
	G_w	–	–	943	1020	1259	1453	1803	1715	2270	2578	2763	2961	[5]
	W_w	–	–	13	7	24	41	95	51	109	250	297	461	[5]
	E_w	–	–	–	–	–	16.6%	20.5%	19.7%	27.0%	30.7%	33.1%	37.1%	
	C_w	–	–	1.3%	0.7%	1.9%	2.7%	5.0%	2.9%	4.6%	8.8%	9.7%	13.5%	
Republic of Ireland (EirGrid)*[2]	T_c	–	–	–	–	–	27,957	28,776	29,509	29,993	30,868	31,340	31,825	[5]
	G_w	–	–	4256	4102	4642	5140	6573	6147	7444	8640	10,019	11,549	[5]
	W_w	–	–	106	103	171	236	348	177	277	457	711	1448	[5]
	E_w	–	–	–	–	–	18.4%	22.8%	20.8%	24.8%	28.0%	32.0%	36.3%	
	C_w	–	–	2.4%	2.4%	3.6%	4.4%	5.0%	2.8%	3.6%	5.0%	6.6%	11.1%	
All Ireland*[2]	T_c	–	–	–	–	–	36,723	37,553	38,235	38,406	39,272	39,688	39,811	[5]
	G_w	–	–	5198	5112	5901	6593	8376	7862	9714	11,217	12,782	14,510	[5]
	W_w	–	–	119	110	196	277	442	228	386	707	1008	1909	[5]
	E_w	–	–	15.0%	14.4%	16.1%	18.0%	22.3%	20.6%	25.3%	28.6%	32.2%	36.4%	
	C_w	–	–	2.2%	2.1%	3.2%	4.0%	5.0%	2.8%	3.8%	5.9%	7.3%	11.6%	
Italy	T_c	320,268	330,455	334,640	328,220	318,475	310,535	316,897	314,261	320,548	321,910	319,600	302,800	[32]
	G_w	6543	9048	9775	13,333	14,812	15,089	14,705	17,523	17,565	17,318	20,034	18,547	[32]
	W_w	700	541	268	173	292	154	252	328	447	462	696	811	[32]
	E_w	2,0%	2,7%	2,9%	4,1%	4,7%	4,9%	4,6%	5,6%	5,5%	5,4%	6.3%	6.1%	
	C_w	9,7%	5,6%	2,7%	1,3%	1,9%	1,0%	1,7%	1,8%	2,5%	2,6%	3.4%	4.2%	
Portugal	T_c	48,773	50,613	49,114	47,110	46,273	46,139	46,849	47,325	47,661	48,838	48,810	46,723	[29]
	G_w	7577	9182	9161	10,259	12,014	12,111	11,607	12,474	12,246	12,650	13,576	12,172	[29]
	W_w	–	–	–	–	–	–	–	–	–	–	–	*almost zero*	[33]
	E_w	15.5%	18.1%	18.7%	21.8%	26.0%	26.2%	24.8%	26.4%	25.7%	25.9%	27.8%	26.1%	
	C_w	–	–	–	–	–	–	–	–	–	–	–	0.0%	
Norway	T_c		132,000	125,100	130,000	129,200	126,700	130,400	133,100	134,100	136,700	134,700	133,700	[35]
	G_w		900	1300	1600	1900	2200	2500	2100	2800	3900	5500	9900	[35]
	W_w		–	–	–	–	–	–	–	–	–	–	–	
	E_w		0.7%	1.0%	1.2%	1.5%	1.7%	1.9%	1.6%	2.1%	2.9%	4.1%	7.4%	
	C_w		–	–	–	–	–	–	–	–	–	–	0.0%	
Spain	T_c	252,660	260,530	254,786	251,700	246,200	243,500	247,200	249,200	252,200	254,000	242,843	228,345	[8,9]
	G_w	37,889	43,208	41,799	48,100	54,300	50,600	48,100	47,700	46,900	49,100	54,289	54,424	[8,9]
	W_w	70	315	73	120	1160	520	50	90	50	20	49	182	[8,9,35]
	E_w	15,0%	16.6%	16.4%	19.1%	22.1%	20.8%	19.5%	19.1%	18.6%	19.3%	22.4%	23.8%	
	C_w	0.18%	0.72%	0.17%	0.2%	2.1%	1.0%	0.1%	0.2%	0.1%	0.0%	0.1%	0.3%	
UK	G_T	330,018	337,509	325,918	325,483	324,321	310,807	310,982	311,139	307,914	311,241	302,662	286,868	[29]
	G_w	9281	10,286	15,963	19,847	28,397	31,959	40,317	37,367	49,605	57,116	64,335	75,775	[29]
	W_w	–	–	59	45	380	659	1276	1134	1542	1724	1940	3696	[36]
	E_w	2.8%	3.0%	4.9%	6.1%	8.8%	10.3%	13.0%	12.0%	15.9%	18.4%	21.3%	26.4%	
	C_w	–	–	0.4%	0.2%	1.3%	2.0%	3.1%	2.9%	3.0%	2.9%	2.9%	4.7%	
GB	G_T	–	–	–	–	–	302,219	302,457	302,825	303,019	303,141	294,767	279,363	*calculated by difference between UK and NI data*
	G_w	–	–	–	–	–	30,616	38,621	35,868	47,571	54,725	61,873	73,145	
	W_w	–	–	–	–	–	621	289	1086	1440	1474	1940	3235	
	E_w	–	–	–	–	–	10.1%	12.8%	11.8%	15.7%	18.1%	21.0%	26.2%	
	C_w	–	–	–	–	–	2.0%	0.7%	2.9%	2.9%	2.6%	3.0%	4.2%	

Note: *1 the figure is the sum of wind production closure due to three categories: i) negative spot prices; ii) 'general down regulation' *i.e.* congestion in the Danish grid; iii) 'special down regulation', which is congestion in the German grid. While i) is solved by the market – *i.e.* not "curtailment" in its classical understanding; category ii) reflects a classical understanding while category iii) is a cross-border issue and accounts for different rules on either side of the border between Denmark and Germany. Between 2015 and 2020, category iii) reflected 86% of the total curtailment.

Note: *2 Although EirGrid and SONI define that "Dispatch Down" consists of TSO constraints, curtailment and wind testing [5], we relabel their collective term "dispatch down" as the collective term "curtailment", in order to compare with the other countries/areas. Small-scale and micro-generation wind data are also included.

Table 2
Statistical data for wind curtailment in US and Canada.

Area		2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Data source
SPP	E_w	–	–	–	–	–	12.0%	13.6%	18.1%	23.0%	23.9%	[37]
	C_w	–	–	–	–	–	0.7%	0.9%	1.6%	2.8%	1.3%	
ERCOT	E_w	6.1%	7.7%	8.5%	9.1%	9.0%	10.5%	11.7%	15.1%	17.4%	18.6%	
	C_w	17.1%	7.7%	8.5%	3.8%	1.2%	0.5%	1.0%	1.6%	2.2%	2.5%	
MISO	E_w	2.7%	3.4%	4.6%	6.2%	6.8%	5.7%	6.2%	6.9%	7.7%	7.3%	
	C_w	1.9%	3.9%	3.2%	2.6%	4.7%	5.5%	5.4%	4.3%	4.3%	4.2%	
CAISO	E_w	–	–	–	–	–	–	5.3%	6.0%	6.0%	7.3%	
	C_w	–	–	–	–	–	–	0.4%	0.5%	0.2%	0.2%	
NYISO	E_w	–	–	–	1.9%	2.2%	2.5%	2.4%	2.4%	2.7%	2.5%	
	C_w	–	–	–	0.3%	1.4%	0.7%	0.9%	0.6%	1.0%	1.7%	
ISO-NE	E_w	–	–	–	–	–	1.4%	1.7%	2.0%	2.6%	2.8%	
	C_w	–	–	–	–	–	3.3%	2.4%	4.3%	2.9%	2.8%	
PJM	E_w	–	–	–	1.7%	1.9%	1.9%	2.1%	2.2%	2.7%	2.7%	
	C_w	–	–	–	2.0%	1.9%	0.7%	0.3%	0.2%	0.4%	0.2%	
Hydro-Québec	E_w	–	–	–	–	–	–	–	–	–		[38]
	C_w	–	–	–	–	–	–	–	–	0%		

Table 3
Statistical data for wind curtailment in China.

Province		2011	2012	2013	2014	2015	2016	2017	2018	2019	Data source
All China	T_c	4,700,090	4,976,260	5,420,340	5,638,370	5,802,000	6,129,700	6,482,100	6,347,800	7,268,600	[39]
	G_w	74,067	102,999	134,900	153,386	186,300	241,000	305,700	366,000	405,700	[40]
	W_w	10,113	20,783	16,231	12,376	33,900	49,700	41,900	22,700	16,860	[40–47]
	E_w	1.6%	2.1%	2.5%	2.7%	3.2%	3.9%	5.0%	6.0%	5.6%	
	C_w	12.0%	16.8%	10.7%	7.5%	15.4%	17.1%	12.1%	5.8%	4.0%	
Inner Mongolia 内蒙古	T_c	186,407	201,676	218,190	241,674	254,287	260,500	289,200	335,300	365,300	same as above
	G_w	22,742	28,427	35,600	36,075	40,800	46,400	55,100	63,200	66,600	
	W_w	5672	11,335	6389	3567	9100	12,400	9500	7240	5120	
	E_w	12.2%	14.1%	16.3%	14.9%	16.0%	17.8%	19.1%	21.9%	18.2%	
	C_w	20.0%	28.5%	15.2%	9.0%	18.2%	21.1%	14.7%	10.3%	7.1%	
Xinjiang 新疆	T_c	83,910	109,080	153,975	190,024	216,000	231,600	200,100	213,800	286,800	same as above
	G_w	2844	4967	7800	13,225	14,800	22,000	31,900	35,900	41,300	
	W_w	94	215	431	2334	7000	13,700	13,250	10,690	6610	
	E_w	3.4%	4.6%	5.1%	7.0%	6.9%	9.5%	15.9%	17.9%	14.4%	
	C_w	3.2%	4.1%	5.2%	15.0%	32.1%	38.4%	29.3%	22.9%	13.8%	
Gansu 甘肃	T_c	92,345	99,456	107,325	109,548	109,900	106,500	116,400	129,000	128,800	same as above
	G_w	7103	9378	11,900	11,200	12,700	13,600	18,800	23,000	22,800	
	W_w	1454	3024	3102	1384	8200	10,400	9180	5400	1880	
	E_w	7.7%	9.4%	11.1%	10.2%	11.6%	12.8%	16.2%	19.8%	17.7%	
	C_w	17.0%	24.4%	20.7%	11.0%	39.2%	43.3%	32.8%	19.0%	7.6%	
Jilin 吉林	T_c	63,015	63,700	65,385	66,781	65,200	66,800	70,300	75,100	78,000	same as above
	G_w	5019	6427	7172	6678	6000	6700	8700	10,500	11,500	
	W_w	1028	2032	1572	1002	2700	2900	2260	770	300	
	E_w	8.0%	10.1%	11.0%	10.0%	9.2%	10.0%	12.4%	14.9%	14.7%	
	C_w	17.0%	24.0%	18.0%	13.0%	31.0%	30.2%	20.6%	6.8%	2.5%	
Shanxi 山西	G_T	98,247	106,675	115,222	122,601	122,200	135,700	149,500	167,900	191,400	same as above
	G_w	1307	3598	4200	7362	10,000	13,500	16,500	21,200	22,400	
	W_w	0	16	0	0	300	1400	1100	240	260	
	E_w	1.3%	3.4%	3.6%	6.0%	8.2%	9.9%	11.0%	14.2%	11.7%	
	C_w	0.0%	0.4%	0.0%	0.0%	2.9%	9.4%	6.3%	1.1%	1.1%	
Yunnan 云南	G_T	120,407	131,586	145,981	152,938	143,900	141,100	153,800	167,900	181,200	same as above
	G_w	961	2931	4569	6211	9400	14,800	19,900	22,000	24,200	
	W_w	0	170	169	621	300	600	570	0	60	
	E_w	0.8%	2.2%	3.1%	4.1%	6.5%	10.5%	12.9%	14.3%	13.4%	
	C_w	0.0%	5.5%	3.6%	9.1%	3.1%	3.9%	2.8%	0.0%	0.2%	

TSOs [30,32–34].

The United States does not have a centralized data clearinghouse for VRE curtailment data. Annual consumption and wind generation data in each state can be obtained from the website of EIA (US Energy Information Agency). Data from each ISO/RTO needs to be obtained individually. In this paper, we referred to Ref. [37], where only the calculated result of the wind energy share and the curtailed wind ratio in several ISOs and RTOs is shown. Also in Canada, there are few published statistical data on wind energy share and curtailment. Note that statistical data in some ISOs, such as NYISO and ISO-NE, may include “market-based” curtailment, that are not currently distinguished from “forced” curtailment by the ISO. According to Hydro-Québec [38], there has been no curtailment of wind generation so far.

China’s statistical data concerning consumption and wind generation can be obtained from published reports by the state [39]. As wind curtailment is considered a big issue in China, annual summary reports have been published in these years [40–45] and other reports [46,47].

2.3. Creating a C-E map

This subsection explains procedures for deriving objective indicators, the “*C-E ratio*” and the “*C-E gradient*”, from the information drawn on the C-E map, as originally proposed in Ref. [16].

The C-E ratio is an indicator to describe the curtailment level. A ratio R is defined as a quotient of a curtailment ratio C divided by an energy share E, as follows:

$$R \equiv \frac{C}{E} \tag{7}$$

The C-E ratio, therefore, means gradient of a vector of an individual point against the origin on the C-E map.

Fig. 1 shows an illustrative example of the C-E Map. The map is divided into three zones based on the C-E ratio, R. Here, each zone is determined experimentally; the "green" zone is where R is less than 0.1, the "yellow" zone is where R is greater than 0.1 and less than 0.5, and the "red" zone is where R *is* greater than 0.5, respectively.

The C-E gradient shows a historical curtailment trend. The definition of the C-E gradient, G, is given by the following equation:

$$G \equiv \frac{\Delta C}{|\Delta E|} \tag{8}$$

where ΔC and ΔE are the backward difference of C and E, respectively.

The C-E gradient, G, is an indicator that shows a historical trend in the C-E map. If G is negative, it represents a declining curtailment ratio at that time. Also, when G is positive and greater than 0.5, it shows an increasing trend, that would need mitigation not to end in rising curtailment in future. Fig. 2 is a conceptual illustration with three cases of the C-E gradient. The curve on the C-E map may sometimes reverse direction due to the relationship between consumption and wind generation in windy or not-so-windy years. Even in these cases, the C-E gradient G can indicate whether the trend is "going down" or "going up".

3. Analysis by C-E maps

To analyze the statistical data on curtailment for the selected countries/areas, the authors use the "C-E map", with updated data from Ref. [18]. Figs. 3–5 show the status of curtailment in Europe, the U.S, and China. In order to facilitate comparison of the data, these three figures are presented with the same scale for the horizontal and vertical axes.

3.1. C-E map of european countries

Fig. 3(a) shows a C-E map of selected European countries with various wind energy shares: Denmark, Republic of Ireland, Portugal, Spain, Germany, United Kingdom, Norway and Italy. Although the time ranges are slightly different for each country/area, since data availability tends to depend on a sufficiently high level of renewables share being reached, the main purpose here is to compare curtailment levels for different VRE shares noting that different countries are at different stages of VRE development. The shape of the C-E map for a particular system reflects the adequacy of flexibility resources for the given share of wind/solar power.

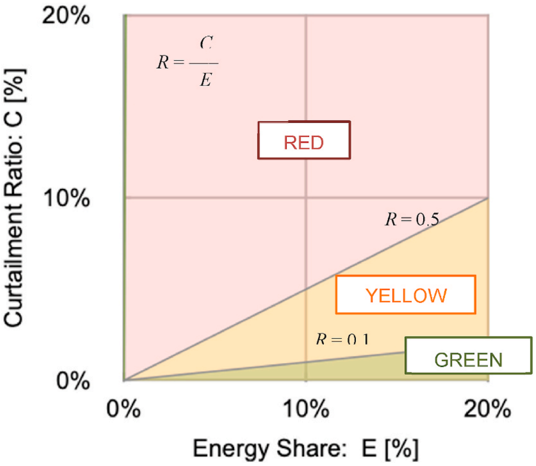


Fig. 1. Illustrative Concept of the C-E ratio R in a C-E map.

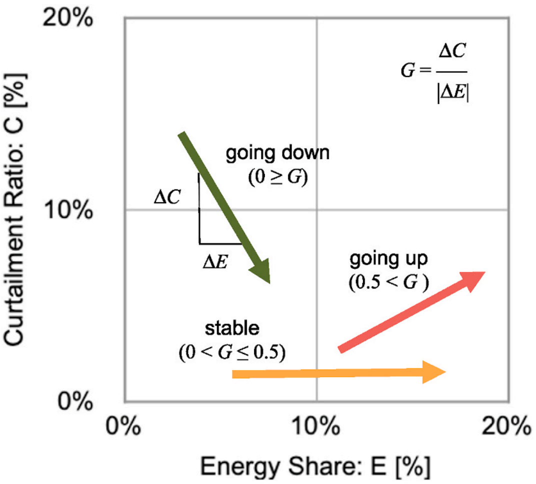


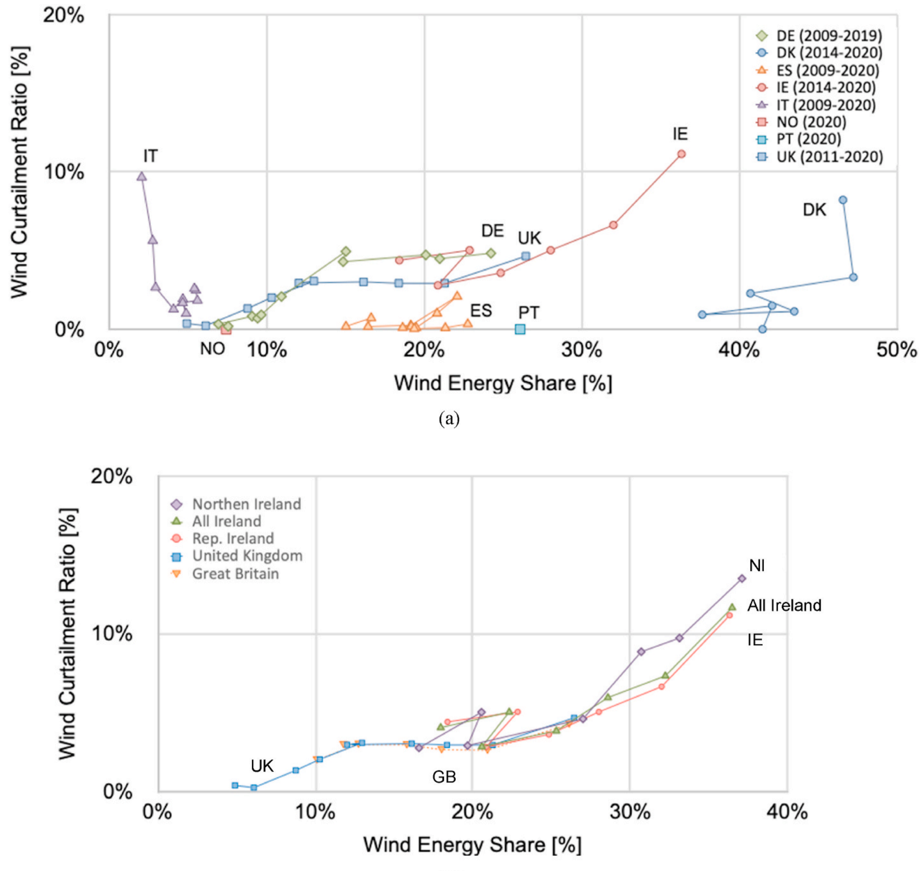
Fig. 2. Illustrative Concept of the C-E gradient E in a C-E map.

It is clear that the relationship between energy share and curtailment ratio, for many countries, is not monotonically increasing, as commonly assumed, but, instead, curtailment levels can reduce or even progress in a "zigzag" manner. These complex patterns are associated with different policy measures (at different points of time) and the utilization of different flexibility resources in different countries and systems. In this section, we examine the reasons for the historical trends in some countries.

So far there is one exceptional country with minimal wind energy curtailment despite their high wind energy share, *i.e.* Portugal. Besides flexibility from hydro units, low curtailment rates in Portugal are a result of reinforcement and expansion of the high-voltage grid ahead of VRE development, in addition to interconnection improvements. Portugal-Spain market splitting decreased from 62% to 7% of the time in the period 2008–2017 [33].

In Denmark, negative prices have sometimes been experienced in spot markets. In 2018 this caused a total of 25 GWh (approx. 0.2%) of wind energy to be voluntarily dispatched down by the wind energy producer – a reaction to a market signal. For the same year, curtailment, as defined in this article, i.e. due to congestion, in the Danish grid was only 10 GWh, forced down-dispatch required by the TSO. An additional 290 GWh was curtailed in Denmark due to congestion in the German grid, following a cross-border agreement [30]. The main reasons for Denmark's low curtailment numbers are 1) a strong domestic transmission grid, 2) a high capacity of interconnectors to neighboring countries, 3) very flexible thermal generation plants, and 4) Denmark being part of well-developed European electricity markets [48].

Italy is another exceptional country in Europe, where a relatively high curtailment ratio occurred in the earlier years of wind development, due to rapid growth in solar PV and wind projects largely installed in southern regions while main load centers remain in mid-northern cities. This led to dominant energy flow patterns and energy congestion. Since then, significant grid investments have been made which have increased transmission capacity within and between internal market zones according to Terna [32,49]. In addition, dynamic line rating made utilization of the existing network more efficient, and jointly with battery storage has allowed more VRE generation into the grid without necessarily incurring further expansion. All of this gradually decreased curtailment levels from almost 10% in 2009 to 1% in 2014. However, the ratio has increased again recently from 2015 onward, partly explained by the steady increase in RES installations (growing from 27 GW in 2014 to 32 GW in 2020) and delayed network expansion due to unforeseeable circumstances (authorization process, public opposition, etc.). Depressed power demand during the COVID-19



(a)

(b)

Fig. 3. (a). C-E map of selected European countries (note: Danish data includes market-based curtailment, i.e. normal reaction to negative spot prices). Fig. 3(b). C-E map in detail for UK and Ireland.

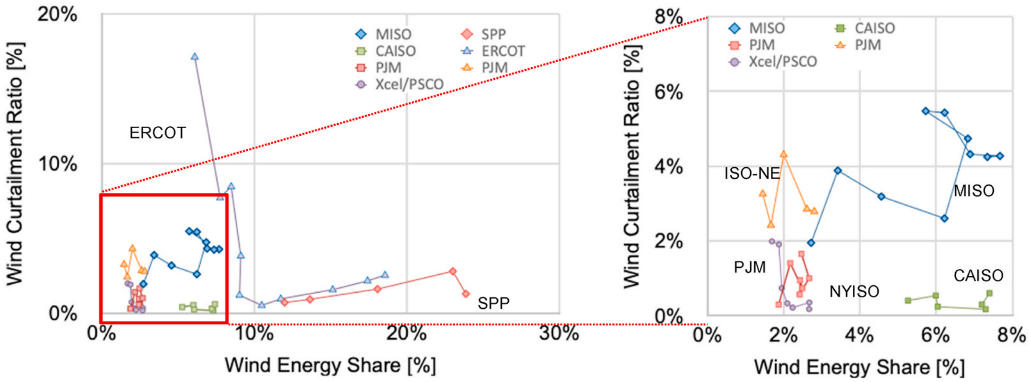


Fig. 4. C-E map of ISOs and RTOs in the U.S. (Left: general graph; Right: enlarged graph, note: data include market-based curtailment).

lockdown was responsible for an increase of wind power curtailment in 2020.

Nevertheless, additional measures to accommodate VRE include the placement of synchronous compensators at strategic parts of the grid which reduce the number of must-run thermal plants necessary for voltage support, consequently leaving more room for wind generation. Ongoing actions to anticipate the effects of 'capital intensive' network strengthening and enable higher utilization of the network *e.g.*, higher line loadings, consist of: installation of DTR on 380-220 kV corridors suffering from congestion from South Italy caused by the limited capacity, punctual removal of bottlenecks, evolution of defense system (special protection schemes, tele tripping of generation), deployment of STATCOM and shunt reactors (for voltage support and power flow control), stabilizing resistor (for power oscillation damping). Beyond that, the Italian TSO, Terna, will test the supply of new dispatching services from wind power through the establishment of pilot projects. Of note, starting from January 2022 the Italian Regulatory Authority will put in place economic incentives for Terna to promote cost-effective measures to reduce the overall costs for dispatching services, wind curtailed energy and "must run" units.

Norway on the contrary, with a similar share of wind energy as Italy, has not seen relevant curtailments yet. This can be explained by significant differences in other influencing factors: In Norway the solar share is still neglectable, while the hydro-power based system is very flexible and can easily adjust to wind power fluctuations. This flexibility exceeds the needs to integrate the Norwegian wind power without

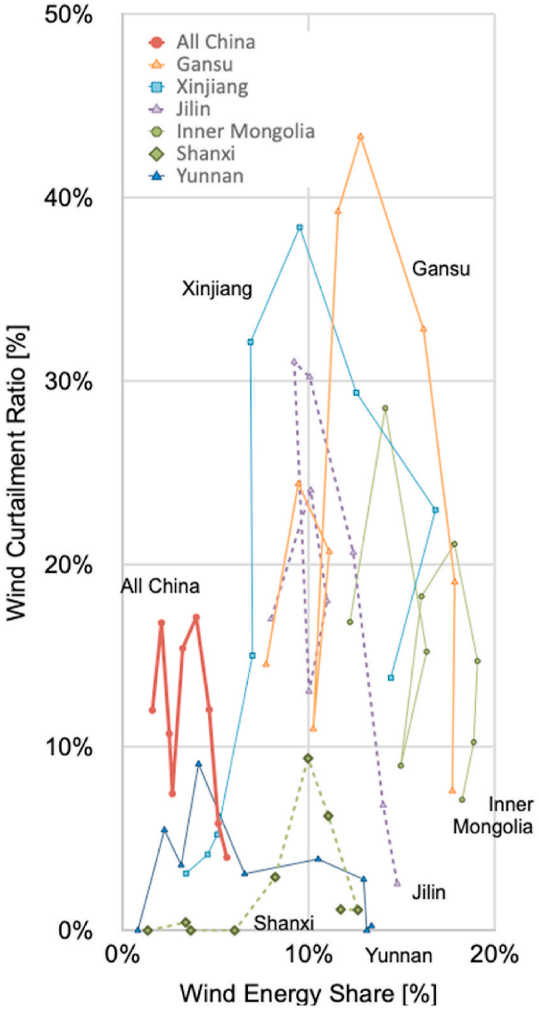


Fig. 5. C-E map of several provinces in China from 2011 to 2019.

curtailment, giving Norway the possibility to export excess flexibility to neighboring countries. With increasing shares of wind and solar power, curtailment might also become a necessity at some point, but this is not foreseen for the near future. A study on future curtailment in the Nordic power system has found that curtailment will gain significance in Sweden and Denmark before eventually reaching Norway [50]. There is, however, a significant potential for increasing flexibility even more (to cope with eventual future curtailment) by upgrading some of the existing hydro-power plants with pumping capabilities. The fourth country in the Nordic electricity market, Finland, has reached 10% share of wind without curtailments – there has so far been only a case of negative market prices for some hours in 2020 when one wind power producer voluntarily curtailed the output.

Fig. 3(a) shows that Denmark has increasing curtailment ratios in recent years. According to unpublished information by the Danish TSO Energinet [30], normal market behavior of wind operators during negative electricity prices was responsible for 88 GWh of down regulation in 2020. Curtailment due to congestions in the Danish grid and special down regulation due to surplus in the German grid and cross-border agreements in 2020 was 22 GWh and 1353 GWh, respectively. The last factor has increased significantly over the last few years.

It should be noted that Spain has successfully maintained a low curtailment ratio despite the fact that the Spanish grid is a relatively isolated grid, where the ratio of interconnection capacity to neighboring countries is only 10% of annual peak demand [9,10]. Expansion of interconnection with France should also further decrease curtailment needs. For instance, market splitting occurred between France and Spain for 72.5% of the time in 2018, which meant congestion hindered the flow of energy between the Iberian Peninsula and the rest of Europe. Recently, the participation of wind power in balancing markets in the downward direction has reduced 'non-integrable generation excess' source curtailment to very low levels [51]. Consequently, in 2018, curtailment arose only due to congestion in the transmission and/or distribution networks [52].

Fig. 3(a) also shows curtailment figures for UK and Ireland, but a more detailed version of this region is available in Fig. 3(b). UK can be divided into two synchronous zones; Great Britain (GB) and Northern Ireland (NI), the latter being part of the synchronous grid of the Island of Ireland. This synchronous zone consists of two control areas, Northern Ireland, controlled by SONI, and the southern network of the Republic of Ireland (IE), which is controlled by EirGrid.

The Island of Ireland grid is relatively small with limited HVDC interconnection to Great Britain, which nearly makes the Island an isolated grid. Of note, the country set an upper threshold for system non-synchronous penetration (SNSP) at 50% in 2010, comprised of non-synchronous generation plus the power coming from non-synchronous interconnectors (HVDC lines), with plans at that time for SNSP to be gradually increased to 75% provided the *right* measures were in place. It should be noted that DC interconnectors do help the Island to export power and thus to reduce curtailment levels. However, power imports through them are similar to generation from wind farms, in the sense that they do not inherently contribute to system stability. The so-called "inertia problem" results in wind curtailment when the SNSP share is higher than the defined limit (65% at end of 2020). The Irish TSOs, EirGrid and SONI, later raised the SNSP limit to 75% (on trial) in 2021 and are currently working to raise it to 95% by 2030, which will be achieved by introducing several countermeasures, such as performance monitoring, new system services, and expanded control room capabilities and tools, encapsulated within the DS3 program [5]. There has been an increasing trend for curtailment in recent years in Ireland and Northern Ireland, strongly linked with the increasing wind (and solar) share, although, due to the Covid-19 pandemic, 2020 was a particular extreme. 2020 was a windier year than normal, and the pandemic led to reduced demand, so that the instantaneous wind energy share was noticeably higher than in previous years. The pandemic also meant that conventional plant maintenance cycles were interrupted or delayed, so that some units with reduced run hours available were made "must not run" until the winter period – a knock-on consequence was that the substitute units had higher minimum generation levels leading to periods of curtailment during low demand hours. Network constraints due to planned transmission line upgrades and upratings were also noticeably higher than in previous years.

Despite the fact that the GB grid is a relatively large system compared with that in Ireland, the GB curve in the C-E map rises above that of Ireland, for equivalent wind energy shares. (The energy share and curtailment ratio in GB look quite similar to those in UK because the total consumption and wind capacity in NI are much smaller than those in GB.) The same occurs with Germany, which is located to the left of Ireland in the C-E map. As a result, Germany, having an even stronger interconnection capacity to neighboring countries, clearly looks much worse than the isolated Irish grid. Curtailment occurrences in both the German and British cases are the result of VRE-load geographical mismatch, not seen to such an extent in the Irish case, in addition to bottlenecks at key points of the transmission network. Grid reinforcement, while still insufficient, has slightly improved both situations, highlighted by lower redispatch costs in early 2018 compared to the previous year for the former and reduced curtailment for the latter.

A detailed description of curtailment policy in each country can be seen in Refs. [17,21].

3.2. C-E map of ISOs and RTOs in the U.S.

There are various reasons for wind curtailment in the US. Transmission congestion may occur, similar to congestion that would be experienced by any other generator at that location. More specific to wind is a type of congestion related to the fact that wind plants can be built faster than transmission, so sometimes wind is curtailed as transmission is built to export that output to load centers (*e.g.* ERCOT, SPP). System-wide over-supply may occur and leads to regular wind curtailment at night when loads are low in places such as ERCOT, Xcel/PSCO, and Maui (see Section IV for regular solar curtailment during the day in CAISO). Wind may also be curtailed to respect transient stability limits in places such as ISO-NE, where wind plants are interconnected to weak grid areas of the system.

Fig. 4 shows a C-E map for some ISOs and RTOs in the U.S. It is interesting to note that part of the historical curves of ERCOT (the ISO and the reliability coordinator in Texas) and SPP (Southwest Power Pool, the RTO covering the mid-south states) look very similar to each other. As can happen in practice, the circumstances of wind development and policy for grid enhancement can follow similar patterns. The early part of the ERCOT curve also looks similar to the Italian curve in Fig. 1, where both show trends of a dramatic reduction in the curtailment ratio to almost zero over several years. In fact, the CREZ (Competitive Renewable Energy Zone) program was approved in 2008 in ERCOT, which facilitated transmission development in wind rich regions of Texas. The CREZ program allowed new transmission lines to be built to serve wind projects, which not only substantially reduced wind curtailment (see Fig. 2) but also mitigated negative electricity prices [53]. Additionally, a number of measures related to system operation have been applied, such as real-time monitoring of inertia and the setting of a so-called *critical inertia* below which available system resources may not be able to effectively respond to a system failure. More recently, stability issues related to weak grid issues have led to increased curtailment in ERCOT. Similar to ERCOT's experience with wind preceding transmission completion, SPP commissioned two new 345 kV lines and a phase shifter at the end of 2017 that reduced curtailment by half for 2018 [20].

MISO obviously "wanders" in the C-E map, showing reducing shares of wind with time. This is due to recent expansion of its footprint, although the recent trend is showing an improvement in reducing wind curtailment. Lack of new transmission in MISO is currently inhibiting further progress. The ISO-NE curve (the ISO in New England) shows the wind curtailment ratio going up and down, with the latest trend promising a better direction. However, although the curtailment ratio for ISO-NE in recent years is low, caution should be exercised here because curtailment occurred even with a very low wind energy share, due to wind projects being built in areas with insufficient transmission. As both the wind energy share and curtailed wind in PJM are small, around 2%, the trend of the historical curve, as shown in the C-E map, looks quite similar to that for ERCOT. On the other hand, the curve for NYISO travels in an unpromising direction despite the low contribution from wind energy. Both minimum load and transmission limitations are issues in New York.

Although the market-based curtailment ratio for NYISO in recent years is low, it is driven by insufficient transmission between the load centers and those regions where the wind plants are located. Additional transmission reinforcement will be required in order to deliver higher levels of wind energy if additional wind plants are located in these constrained regions. Nearly all wind plants in NYISO are dispatched through the markets, thus all of the curtailment reported by NYISO is market-based.

In the ISOs, wind is curtailed via different mechanisms. Some regions, such as MISO, require real-time economic dispatch of wind through their Distpachable Intermittent Resource program. This means that all wind generation responds to price signals and cannot be self-scheduled (must-take). In the US, the production tax credit is an incentive available to wind *only* if it generates. This leads to negatively priced bids by wind in the markets. Wind curtailment (dispatching wind down) is economic based on price signals. CAISO economically dispatches wind but also accepts self-schedules for wind. The economically bid-in wind will be curtailed first and then self-scheduled (must take) wind will be curtailed. Most of CAISO's curtailment is economically dispatched down, rather than curtailment of self-schedules.

3.3. C-E map in some provinces in China

China has strongly supported wind power development nationally since the mid-2000s. However, the country has struggled with a significant lack of transmission capacity between wind-rich inner continental areas and high population areas along the coast. Local trends in Inner Mongolia (内蒙古), Gansu (甘肃), Xinjiang (新疆) and Jilin (吉林), as shown in the C-E map in Fig. 5, show interesting curves with significant recent improvements, after dramatic jumps of 30–40% in the curtailment ratio in 2015. Note that the right-most plot in each curve is an estimated plot. These provinces are located in the northern, northeastern, and northwestern parts of China ("Three North" region), where the country's best wind resources are concentrated and more than 60% of its wind generation capacity is installed [15].

The Three North region is also one of the most coal-rich parts of the country. As there are few gas power or hydropower plants in the region, coal power plants are ramped up and down to keep the grid stable [16]. Many coal power plants have long-term contracts for producing an annual prespecified amount of electricity corresponding to a fixed number of full-load hours, which leaves less room for wind and solar. In addition, the coal power fleet is mostly inflexible, resulting in additional challenges to the integration of wind power. However, China is undertaking a large retrofit program for improving the flexibility of existing coal power plants [54]. Declining curtailment levels in the northern provinces are mostly the result of retrofitting combined heat and power (CHP) units, responsible for providing heat during winter, when the wind resource is also stronger. When driven by heat demand, CHP units bring inflexibility to power system operation. Whenever power and heat generation are not decoupled to some extent, wind curtailment tends to occur during the winter due to significant must-run electricity generation. The latest data shows further significant reductions in curtailment, suggesting that China is making progress towards achieving a lower curtailment ratio, similar to what happened at the beginning of wind deployment growth in Italy and Texas.

There are also provinces with moderate curtailment, such as Shanxi (山西) and Yunnan (云南), whose curves also have a trend similar to those of Italy and ERCOT. This suggests that available grid management approaches, including political and technical schemes, such as those in Italy and ERCOT, have been taken. Experiences from those areas could offer appropriate strategies for how to mitigate excessive VRE curtailment. At the national level in China, yearly publication of a dynamic risk alert system to highlight grid-constrained locations redirects investments to where the grid can readily accommodate additional variable generation.

The first phase of wind curtailment in China, from around 2009 to 2012, was mainly caused by an unprecedented growth of wind generation capacity and the inadequate pace of grid infrastructure development [15]. The curtailment problem was temporarily alleviated in 2013 and 2014 due to the commissioning of additional transmission capacity. However, curtailment rates surged again in 2015 as competition between different power sources intensified due to China's economic deceleration and sluggish electricity demand growth [15].

Addressing wind curtailment has been the focus of several policies introduced since 2015 in China. Most promising are new regulations requiring grid operators to give renewable power sources priority access to the grid [54,55]. Efforts are also being made to shift wind power deployment to demand centers by restricting new wind power projects in several provinces with high curtailment levels in the Three North region. China is also commissioning additional transmission capacity, improving the flexibility of coal-fired power plants, and implementing power sector reforms to provide stronger price signals to generators [56].

3.4. *Summary of comparison on C-E map*

Fig. 6 illustrates the above discussion with a summary C-E graph. Despite the fact that each country/area has unique geographical and grid circumstances, the trend curves can be categorized into several groups. Italy, China and ERCOT (Texas) had relatively high curtailment ratios in their earlier stages (low wind energy share) but have dramatically improved the ratio recently. GB, Germany, All Ireland (NI and IE) and Spain are categorized into another group where the curtailment ratios are gradually going up with higher wind shares, with the ratio remaining less than 5% despite relatively high wind shares of 15–30%.

4. Solar (and VRE) curtailment

We have identified five countries that officially announced curtailment of solar (PV) energy: Germany, Northern Ireland, Italy, CAISO in the US, and Japan.

Germany has curtailed solar energy since 2009. According to BnetzA [31], curtailed solar energy in Germany in 2009 was 0.4 GWh, which is only 0.006% of annual generation by solar, while the solar energy share in that year was 1.1%. In 2019, the solar energy share was 9.1%, but the curtailed energy rose to 178 GWh, which is still modest, around 0.4%.

In Northern Ireland, solar PV curtailment has only been officially reported since 2019 [5]. Due to a lack of incentives, the installed PV capacity in the Republic of Ireland has been negligible, and hence associated curtailment levels are not, as yet, reported. For curtailment purposes, grid-scale PV is treated in the same way as wind generation, and hence it can be curtailed for stability (SNSP), network constraint, minimum conventional generation, etc. Reasons, but small-scale and micro-scale PV generation is not considered. In 2019, 4.2% of grid-scale solar PV was curtailed, mainly due to network constraints and requirements to keep a minimum number of conventional units online. The wind and solar capacity in Northern Ireland is high relative to the size of the system (maximum instantaneous renewable share of 147% in 2021), and interconnection power flows with Ireland are limited, in case of a system split due to tie line failure, which results in the conventional generation requirement. Additional tie line capacity is planned between Northern Ireland and Ireland, which, when in place, should significantly impact curtailment due to constraints. In 2020, grid-scale PV curtailment levels rose to 6.3%, with two thirds of the time being associated with network constraints, and the remainder being roughly split between high SNSP and low net demand (minimum number of conventional units) situations.

In coordination with main distributors, Italy has developed special protocols to curtail solar energy in case of critical grid situations materialize, such as overgeneration of non-dispatchable resources and lack of reserve margins, and when no other actions on grid topology and conventional generation are possible. In the past six years, solar curtailments have only been made to handle a near to total solar eclipse taking place on a sunny week morning in 2015 and during the very low-consumption days of Easter 2020.

In the U.S., CAISO has one of the highest solar share in the country. It is common for CAISO to have over-supply midday due to the combination of high levels of solar generation, low load levels, and inability to reduce output from other resources (*e.g.* minimum generation levels of thermal plants that are needed to meet the evening peak, hydro runoff in the spring, imports from other regions, etc). Curtailment initially occurred during the day on weekends in the spring, but now occurs throughout the year. Data from CAISO shows that in 2019, utility-scale solar served 13% of the annual load; 3.1% of the available utility-scale solar that year was curtailed [57]. In addition to the 12.7 GW of installed utility-scale solar, California has 8 GW of distributed PV that cannot be controlled, and which contributes to the oversupply situation midday.

In October 2018, Kyushu Electric Power Company (EPCO) in Japan decided to curtail solar and wind power for the first time amongst Japanese utilities, due to a lack of flexible generation and exporting capacity in the interconnection to the adjacent area during a low demand period. While the annual solar and wind energy shares in the area in 2020 were 14.3% and 0.8%, respectively (calculated by the authors according to data from Kyushu EPCO [58]), the annual curtailment ratio of PV, wind and VRE in Kyushu in 2019 was 3.9%, 2.6% and 3.8%, respectively. So far, only Kyushu EPCO have performed curtailment in Japan. However, several other TDSOs (Transmission and Distribution System Operators) in Japan announced they are considering to do so within a couple of years.

Fig. 7(a), (b) (c) and (d) show C-E maps of wind, solar and VRE in Germany, Northern Ireland, CAISO in the U.S., and Kyushu in Japan. While solar curtailment in Germany is almost negligible, it is clear that curtailment in Kyushu and CAISO becomes relatively high once their energy share exceeds 10%. Compared to other systems, PV curtailment in Northern Ireland is quite high given its energy share, but this largely follows from wind and PV generation being treated in a similar manner. Wind curtailment in CAISO is quite low, but in Kyushu it rises steeply despite a very low wind energy share, which suggests that wind generators in Kyushu may suffer from unequal market access or operating conditions compared to PV.

It is clear, therefore, that solar curtailment has occurred in several countries/areas across the world, but so far, it has been much smaller compared to the levels of wind curtailment seen in the rest of the world. In some cases, solar PV may be partly causing the bottlenecks that are resolved by wind curtailment, where wind power plants are larger and easier to control.

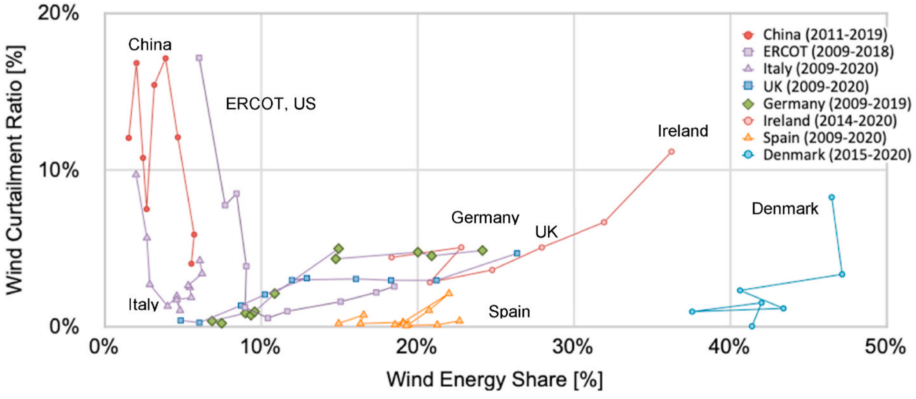
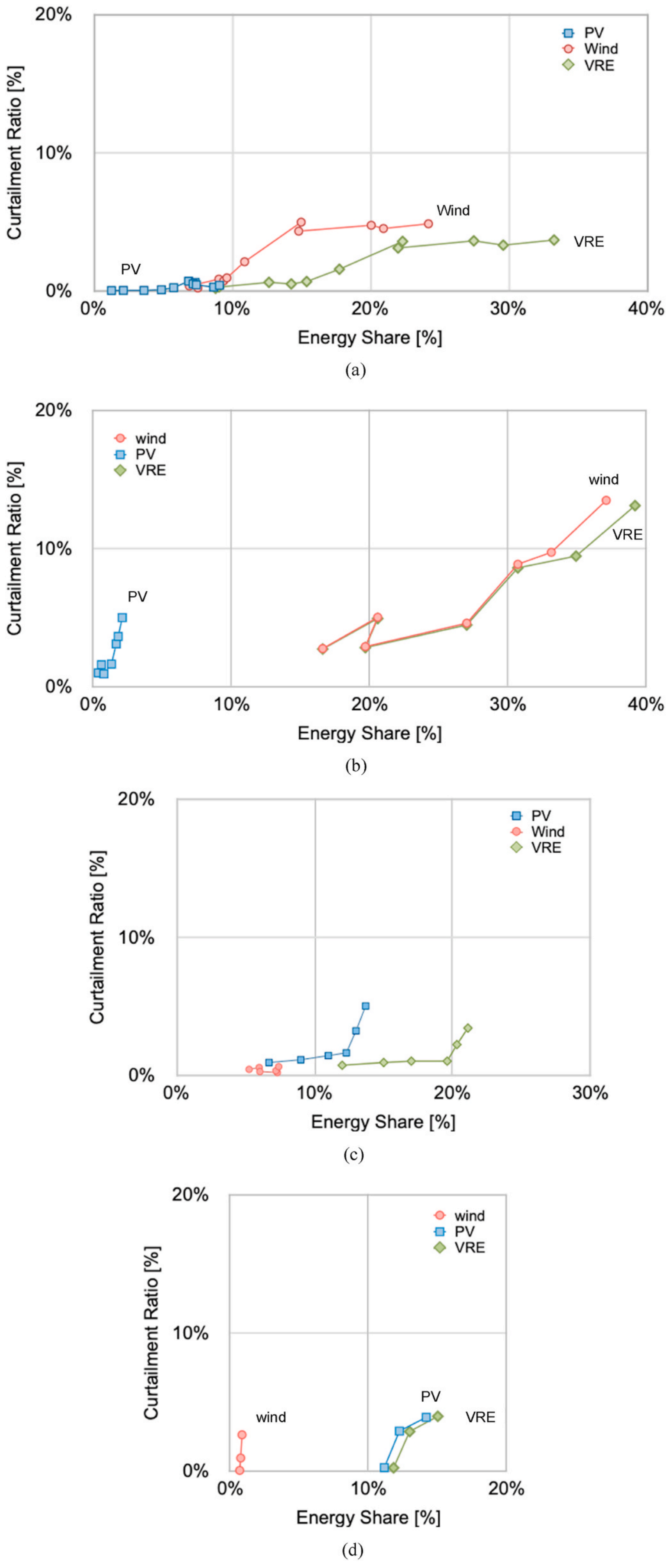


Fig. 6. C-E map of selected countries/areas (summary).



(a)

(b)

(c)

(d)

Fig. 7. (a). C-E map on wind, solar and VRE in Germany (2009–2019). Fig. 7 (b). C-E map on wind, solar and VRE in Northern Ireland (2014–2020). Fig. 7 (c). C-E map on wind, solar and VRE in CAISO, U.S. (2015–2020). Fig. 7(d). C-E map on wind, solar and VRE in Kyushu, Japan (2018–2020).

As mentioned above, solar curtailment is much smaller than wind curtailment despite rapid growth in the solar contribution in many countries/areas. The major reason is that most solar panels are installed on rooftops, which do not typically have a monitoring and control device connected to the grid operator. Controllable grid-scale solar power plants (so-called mega-solar plants) are still not major players in many countries/areas. In this situation, considering the total volume of VRE, combining wind and solar may result in an underestimation of the levels of wind curtailment.

Fig. 8 shows a C-E map of European countries, where the vertical axis is taken as the VRE curtailment ratio rather than wind curtailment ratio (the original data table is omitted here). As shown in the figure, it is easy to understand that the historical curves of VRE curtailment on the C-E map are always lower than those for wind curtailment, as shown in Fig. 3(a). Although some articles, including the authors' previous report [18], calculated the VRE curtailment ratio, it is advisable not to underestimate the curtailment ratio of wind itself. Analyzing wind curtailment rates in relation to total VRE gives a better picture of the integration challenge – both wind and solar may give rise to curtailment needs through congestion of transmission, for example. Wind power plants are usually larger and thus easier to control by the system operator if a period of curtailment is required.

5. Analysis by C-E ratio and C-E gradient indicators

As the two indicators, C-E ratio and C-E gradient introduced in Section 2-3, are quantitative and objective, classification depending upon the past and current situations and historical trends can be performed using the indicators. The authors assumed three status levels, with (1) green, (2) yellow and (3) red, by the C-E ratios, and three trends identified including (a) going down, (b) stable, and (c) going up, according to the C-E gradients. Therefore, classifications with nine categories can be defined in the correlation map of the two indicators as follows:

(1a) green and still going down,
(1b) green and stable,
(1c) green but going up,
(2a) yellow and going down,
(2b) yellow and stable,
(2c) yellow and going up,
(3a) red but going down,
(3b) red and stable, and
(3c) red and going up further.

Table 4 classifies curtailment trends across countries based on the trends of the C-E maps. The table provides an overview on worldwide trends of curtailment. In Table 4, black fonts denote the current situations and trends in the given countries/areas, where the historical trends are calculated compared to data from three years before. The gray fonts describe the past situations and trends in arbitrary years in the given countries/areas.

Table 4 also expresses both the past and current situation concerning curtailment. For example, Italy has moved from position (3a) in early 2010s to (2c) now, which means that an undesirable past situation has been improved, due to successful grid expansion, and other improvements in those areas, while the trend has tuned slightly worse. Similarly, ERCOT has improved from position (3a) to (2b). Also, Shanxi in China recently moved to the most preferable position (1a) from the most unfavorable condition (3c), while other provinces in China are still in position (3a) or (2a), and require more effort for the future.

While Germany and UK belong in position (2b), the high wind-share countries of Denmark and Ireland are increasing wind curtailment in position (2c). However, as the wind share increases further, the TSOs may require further effort on system stability limits and/or available market design. Some of the U.S. ISOs/RTOs are still categorized in position (3a), which means that there may be more room to improve their situation on wind curtailment despite their low wind energy share.

Measures to integrate wind and solar power are sensitive to the particular national context. Successful countries have provided one or

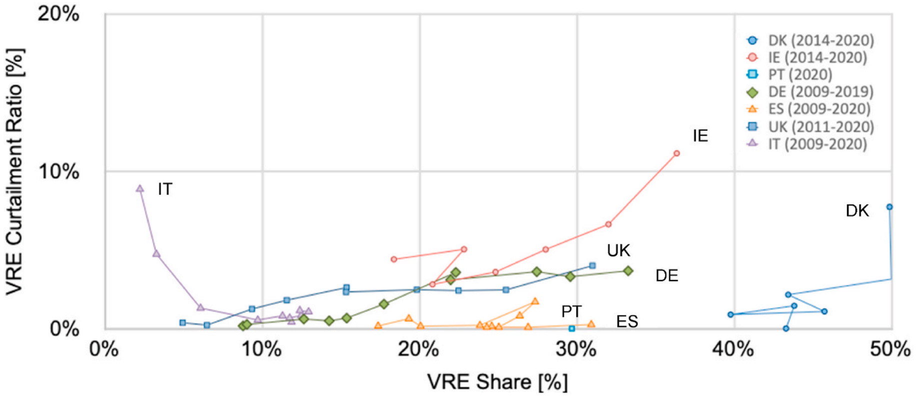


Fig. 8. C-E map of selected European countries using VRE share and VRE curtailment ratio.

Table 4
Classification of Curtailment Trends in selected Countries/Areas.

class		trend	(a)	(b)	(c)
		C-E Gradient	$G < 0$	$0 \le G < 0.5$	$0.5 \le G$
status	C-E Ratio		going down	stable	going up
(1)	$R < 0.1$	green	Spain SPP CAISO PJM Shanxi Yunnan	Portugal Germany (PV) Spain (past) Hydro-Quebec Shanxi (past) Kyushu (PV)	Yunnan (past)
(2)	$0.1 \le R < 0.5$	yellow	Inner Mongolia Gansu Jilin	Germany UK, GB ERCOT	Denmark Rep. Ireland Northern Ireland All Ireland Italy
(3)	$0.5 \le R$	red	Italy (past) ERCOT (past) MISO ISO-NE All China Inner Mongolia (past) Xinjiang	Jilin (past)	NYISO MISO (past) All China (past) Xinjiang (past) Gansu (past) Kyushu (wind)

more of the following conditions:

- **a strong domestic transmission grid** that leads VRE development. Wind and solar plants can be built more quickly than transmission assets, which may also face long authorization processes, public opposition and other impediments.
  - TSOs may publish **Grid Capacity Maps** that highlight grid-constrained locations to guide investment to regions where the grid can more readily accommodate additional VRE.
  - **dynamic line rating, which** is an efficient way to make the best use of existing transmission resources
- a **high capacity of interconnectors to neighboring countries** is beneficial to leveraging flexible regional resources and support grid stability.
- **high flexibility from conventional generators**, such as hydropower units or the decoupling of the generation of power and heat in CHP units.
  - Retrofit programs for improving the flexibility of existing conventional generators can be undertaken, including power sector reforms and market frameworks that provide strong price signals and give incentives for assets to operate in a flexible manner.
- **implement operation-related adjustments** which include real-time monitoring of inertia and the setting of *critical inertia* limits. Setting a threshold for system non-synchronous penetration (SNSP) makes sure that integration is reliably achieved for a specific energy system context. In addition, the placement of synchronous compensators for voltage regulation, and the deployment of STATCOMs and shunt reactors for voltage support and power flow control can be beneficial.

6. Conclusions

This study investigated the relationship between curtailment ratio and energy share of wind (and solar) from many countries/areas across the world. Global curtailment trends were investigated using an objective and quantitative tool, the *C-E map* proposed by the authors. The C-E map helps to easily and visually understand the historical trend of curtailment in the given countries/areas, as well as a comparison of the current status and trend between several countries.

Using the C-E map, the below facts become clear;

- Several countries with high wind-share ratios of over 30% such as Denmark, Ireland and Northern Ireland have increased their curtailment ratio in recent years in spite of having kept low curtailment ratios previously.
- Several countries/areas with wind-share ratios around 20% such as Germany, Spain, UK, and SPP in the U.S. are maintaining moderate curtailment ratios despite their increasing wind share.
- Several countries/areas, *e.g.* Italy, ERCOT in the U.S. and provinces in China, have similar C-E map trend curves, which indicate significant improvement following an unfavorable situation in the start of the deployment.

The *C-E ratio* and *C-E gradient* indicators applied here can be used to conduct comparisons of curtailment levels internationally. This study classified and compared the past and current curtailment levels and historical trends across a variety of power systems in Europe, North America and Asia.

Comparisons of curtailment levels should consider the specific context of the country or region, including operating practices and available flexibility mechanisms. Curtailment levels can be influenced by a variety of factors, including the energy mix, grid conditions, policies and regulations, and operational practices. However, the experience of one country or area can be informative for others. A comparison of global curtailment trends can help identify best practices that could be applied in different regions. The C-E map, C-E ratio and C-E gradient, that are proposed in this paper, will enable improved operational and planning practices, and assist in optimizing curtailment of VRE in future power systems. Finally, as a number of power systems push towards 100% renewables, and, in particular, systems based around wind and solar energy, it will likely become much more common that the available (renewable) energy greatly exceeds the instantaneous demand, including (economic) opportunities for export, storage, or conversion into other energy vectors, such that the term curtailment may need to be more carefully defined.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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