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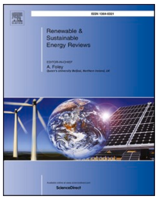

Flexibility chart 2.0: An accessible visual tool to evaluate flexibility resources in power systems

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ABSTRACT

Various aspects of power system flexibility are evaluated within the multi-country study framework of IEA Wind Task 25. Grid components and actions which have been adopted for enhancing flexibility in different areas, countries, regions are addressed, as well as how Transmission System Operators, Independent System Operators, Utilities intend to manage variable generation in their operating strategies. A visual assessment to evaluate the diversity of flexibility sources, called a “flexibility chart”, is further developed to illustrate several flexibility parameters (*e.g.,* hydropower, pumped hydro, gas turbine, combined heat and power, interconnection and battery) in a polygonal radar (fan-shaped) chart. This enhanced version of the Flexibility Chart is an “at-a-glance” and “easy-to-understand” tool to show how to estimate the potential of flexibility resources in a given country or area, and is accessible for non-technical experts. The Flexibility Chart 2.0 is also a useful tool to compare the past and future flexibility of a system. Comparing the historical change of flexibility resources may not only be helpful to discuss energy policy in regions with high installed variable renewable generation, but also to contribute to the discussion in other regions where renewables have not been widely adopted yet.

1. Introduction

Accessing sources of energy system flexibility is one of the most critical steps in achieving high shares of variable generation, including wind and solar. This is relevant for every power system scale; *e.g.,* TSO/ISO/utility operating areas, countries, and synchronous areas. Some countries have developed significant interconnection capacities to manage variability and forecasting errors for wind and solar production, while others have focused on national solutions, such as increasing the share of gas turbines with very fast responses, and/or the share of dispatchable CHP plants, and/or the conversion of old hydro power stations to operate in a flexible PHS mode. There is no ‘silver bullet’, or ‘royal road’, to ensure sufficient flexibility in each system. Instead, flexibility options and

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Abbreviations

AC	alternating current
AU	Australia
AEMO	Australian Electricity Market Operator (market operator in Australia)
ATC	available transfer capacity
BRP	balance responsible party (terminology especially in Europe)
CA	Canada
CAISO	California Independent System Operator (ISO in US)
CAMX	California and Mexico (reliability region in North America)
CCGT	combined cycle gas turbine
CHP	combined heat and power
DC	direct current
DE	Germany
EI	Eastern Interconnection (synchronous area in US)
ENTSO-E:	European Network of Transmission System Operators (union of TSOs in Europe)
ERCOT	Electric Reliability Council of Texas (ISO and Reliability Council in US)
ESS	energy storage system
EV	electric vehicle
FAST	Flexibility ASsessmenT (tool developed by IEA)
FIT	feed-in tariff (promotion policy of renewables especially in Europe and Japan)
GB	Great Britain
GIVAR	Grid Integration of Variable Renewables (IEA project)
GW	giga watt
HVDC	high voltage direct current
IEA	International Energy Agency
IEA Wind TCP	IEA Wind Technology Collaboration Programmes
IGCC	International Grid Control Coordination
IGCC-L:	aggregated area that consists of IGCC countries as of 2020 (tentatively defined in this paper)
IGCC-S:	aggregated area that consists of IGCC countries that joined before 2016 (tentatively defined in this paper)
IRENA	International Renewable Energy Agency
ISO	independent system operator (terminology especially in US)
ISO-NE	Independent System Operator of New England (ISO in US)
JP	Japan
MISO	Midcontinent Independent System Operator (RTO in US)
MRO	Midwest Reliability Organization (reliability organization in North America)
MW	mega watt
NERC	North American Electric Reliability Corporation
NSW	New South Wales
NTC	net transfer capacity
NPCC	Northeast Power Coordinating Council (reliability organization in North America)
NWPP	Northwest Power Pool (reliability organization in US)
NY-ISO	New York Independent System Operator (ISO in US)
OCGT	open cycle gas turbine
PHS	pumped hydro storage
PJM	RTO covered 13 states including Pennsylvania, New Jersey and Maryland
PV	photovoltaic
RE	renewable energy
REE	Red Eléctrica de España (TSO in Europe)
RF	ReliabilityFirst (reliability organization in US)
RMRG	Rocky Mountain Reserve Group (reliability organization US)
RTO	regional transmission operator (interstate system operator in US)
SERC	Southeastern Electric Reliability Council (reliability organization in US)
SEM	Single Electricity Market
SONI	System Operator in Ireland and Northern Ireland (TSO in Europe)
SPP	Southwest Power Pool (RTO in US)
TDSO	transmission and distribution system operator (terminology especially in Japan)
TSO	transmission system operator (terminology especially in Europe)
TYNDP	Ten-Year Network Development Plan (plan published by ENTSO-E)
VRE	variable renewable energy
WI	Western Interconnection (synchronous area in US)
UK:	United Kingdom
US:	United States (of America)

solutions vary greatly, with different strategies being appropriate for different systems. Most systems find that a suite of flexibility options provide a cost optimal way to manage variability and uncertainty.

So far, several tools have been proposed to measure power system flexibility, *e.g.,* IEA's GIVAR Project proposed the FAST Method in their 2011 report [1], where flexible resources are categorized into four types; dispatchable plant, storage, interconnection capacity and demand side response. In Ref. [2], a simplified index, Maximum Share of Wind Power, was evaluated as an indication of how challenging it is to integrate a larger share of wind power in a certain system. Also, a scorecard to measure flexibility was designed [3]. IRENA also released "FlexTool" to evaluate resource flexibility [4]. To address capacity expansion problems for planners, a flexibility solution modulation stack and a flexibility solution contribution distribution were proposed [5–7]. These frequency spectrum analysis-based tools separately quantify the flexibility provision on annual, weekly, and daily timescales. These methods will be useful for quantitative estimation of flexibility in a targeted country/area, but they require quite a lot of data and considerable modelling expertise. ENTSO-E also released a report and a position paper that describe two possible metrics for future flexibility needs; ramping flexibility needs and scarcity period flexibility needs [8,9]. These methods will be useful for quantitative estimation of flexibility in a targeted country/area.

The "*Flexibility Chart*" discussed in this paper was originally proposed in Ref. [10], where the first idea of a Flexibility Chart was shown but only for the Japanese power systems. Soon after, the concept was developed into an international collaboration study under IEA Wind Task 25 on Design and Operation of Energy Systems with Large Amounts of Variable Generation [11]. The chart was designed as an "at-a-glance" graph to visualize the dominant factors of flexibility resources, and compare the variety of solutions adopted in different countries/areas. The aim of the chart is to provide an easy-to-understand tool that clearly shows differences in flexibility strategies, even for non-technical experts, including journalists and policy makers.

In the original Flexibility Chart, five parameters were selected; penetration ratio by capacity (% of peak load) for CCGT, CHP, PHS, hydro and interconnector capacity, according to the FAST method proposed by IEA GIVAR [1]. These five parameters are relatively easy to obtain from published statistical reports in many countries/areas, which makes the chart "easy-to-make" for developing countries and/or countries/areas where RE is not yet established. As there were no reasonable measures to estimate the capacity of demand side management at that time, flexibility from demand side resources, including EVs, was neglected. Also, flexibility from ESS was not evaluated, since there were few statistical data of utility-scale ESSs with batteries in many countries.

In this paper, we propose a new Flexibility Chart, named “Flexibility Chart 2.0” which employs finer tuned data for five parameters, *e.g.* gas turbine including both OCGT and CCGT, CHP, hydropower with reservoir (excluding PHS), PHS and interconnector capacity. Regarding interconnector capacity, ATC values, which better reflect the operational exchange availability with neighbouring areas, are selected if statistical data can be obtained in the selected countries/areas. In Sections 4 and 5, a sixth axis of battery storage is added as a new flexibility resource, even if statistical data is limited to several countries/areas so far. The proposed Flexibility Chart is designed in an expandable approach to incorporate additional axes, such as demand response. The chart could be updated to Flexibility Chart 3.0 in the near future, when many countries publish unified statistical data on the capacity of grid-scale ESSs, as well as demand side flexibility resources, including aggregated capacity of smart charging EV batteries.

2. Construction of flexibility chart

2.1. Methodology

Fig. 1 illustrates the basic concept of Flexibility Chart ver. 1 [11] and Flexibility Chart 2.0 proposed in this paper. In the early development stages of ver. 1, the flexibility options for evaluation incorporate five axes, which were selected as (i) interconnection capacity, (ii) CHP, (iii) CCGT excluding OGCT, (iv) hydro including run-of-river and pumped hydro, and (v) pumped hydro, mainly due to limitations of statistical data. The design of the chart was based on a pentagon-shaped radar chart whose apexes were connected together by straight lines.

Although the main concept has not changed from ver. 1, the new version, Flexibility Chart 2.0, overcomes several weak points that had not been previously solved: (1) hydro capacity might be overestimated in ver. 1, since it was difficult to distinguish between hydro with reservoir and run-of-river; (2) gas turbine capacity might be underestimated since only CCGT was counted, excluding OCGT previously; (3) total map area did not express the total volume, or characteristics, of aggregated flexibility resources and might cause misunderstanding. In Flexibility Chart 2.0, we carefully gather and select a basic data set from statistical information available in many countries and areas. Regarding the appearance of the chart, each axis is based on a square root scale of the capacity ratio per peak, in order to linearly compare the area of the fan to other axes, which can help to avoid possible misunderstanding and confusion between a reader’s intuition and quantitative analysis.

Flexibility Chart 2.0 has two circles corresponding to wind and solar share in capacity. Those shares in the chart are indicative only, and they are not necessarily compared with the flexibility options directly, because flexibility resources do not need to have the same capacity of wind and solar. Also, according to several past research studies [12,13], it is evident that the combined output from wind and solar generation in a certain area has very low correlation, and it is very unlikely that both wind and solar outputs will be high simultaneously. Normally, the maximum output value of VRE, *i.e.* wind + solar, is approx. 60–70% of the aggregated capacity of wind and solar capacity, except in small countries/areas with mainly wind and little solar. So, it is considered sufficient to present wind and solar capacity separately, without presenting the aggregated capacity of wind and solar capacity.

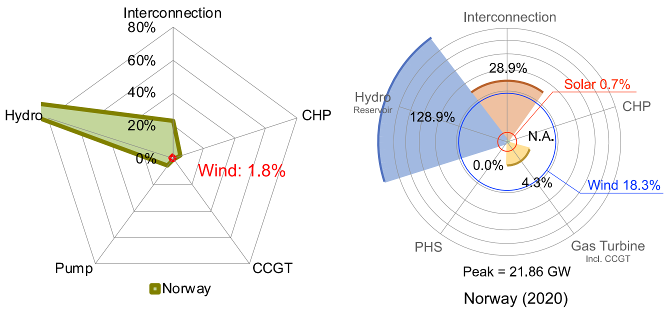


Fig. 1. Samples of Flexibility Chart in Norway: (left) description in ver. 1, data as of 2011 [11] and (b) new description in “Flexibility Chart 2.0” proposed in this paper, data as of 2020.

The statistical data needed to create a flexibility chart in a given country/area are (a) maximum load (peak load), (b) installed wind capacity, (c) installed PV capacity, and various flexibility resources, such as (1) installed gas turbine capacity, including CCGT, (2) installed hydropower capacity with reservoir excluding run-of-river and PHS, (3) installed PHS capacity, (4) installed CHP capacity, (5) capacity of interconnectors to neighbouring countries/areas. Five flexibility parameters are evaluated, indicating the number of axes in Flexibility Chart 2.0.

Regarding interconnector capacities, we chose NTC, or annual maximum transfer capacity, in the year ahead if the data is given in published statistics. Otherwise, nominal capacity was selected, such that the potential flexibility resource may be slightly overestimated.

Note that CHP and gas turbines cannot always operate as dispatchable generation with a quick response. Some types of CCGT, with a high operational temperature are designed as “base-load generation” for very high efficiency operation. Also, CHP plant generally cannot act as flexible resources without flexibility in operation (sometimes including thermal storage), and operation in markets with communication links to aggregators or BRPs, as realized in several countries, such as Denmark and Germany. Even if the flexibility chart is a very useful “at-a-glance” tool to compare options, and to select a strategy to provide suitable flexibility resources in different countries/areas in the world, there is room to improve the data and visualization to better capture flexibility and enable comparisons. For example, the time scale of flexibility could be taken into account, constructing separate plot for short and long term flexibility.

There is one specific aspect of aggregating several flexibility charts into one, which concerns the interconnection capacity, that needs to be considered. When looking at an aggregated area, the flexibility provided by the transmission capacity inside the area is important to be able to aggregate the other flexibility measures. All other numbers (other than interconnection capacity) in the aggregated chart are somehow weighted averages between the individual charts, so the aggregated number lays somewhere between the individual numbers. This property of the aggregated chart appears intuitive, but it is not valid for the interconnection capacity. Interconnection capacity of an aggregated area are not sum of those capacities in sub-areas because the interconnection capacity between two sub-areas is cancelled and only capacities to outside of the aggregated area are counted. This leads to a completely different aggregation-behaviour of the interconnection capacity, which results in generally low numbers (lower than expected otherwise) for interconnection capacity of aggregated flexibility charts.

The remainder of the paper presents a comparison of flexibility trends in different countries using Flexibility Chart 2.0. We evaluate four global regions, *i.e.,* Europe (Subsection 3.1), North America (Subsection 3.2), Japan (Subsection 3.3) and Australia (Subsection 3.4), where published statistical data of the electricity system is has been obtained. These sections provide a somewhat “microscopic” viewpoint, focusing on a control area, or reliability assessment region, as the minimum geographic area to be evaluated, as well as a “macroscopic” investigation of an aggregated synchronous area across multiple control areas or reliability sub-regions.

In Section 5 we discuss historical changes in flexibility resources from past to future in selected areas. Comparison of various levels of geographic area and historical evolution over time provides some strategic insights for countries targeting a higher variable generation share. Also, it is hoped that this tool can provide inspiration and incentives for cooperation and coordination with neighbouring countries/areas targeting a higher share of variable generation.

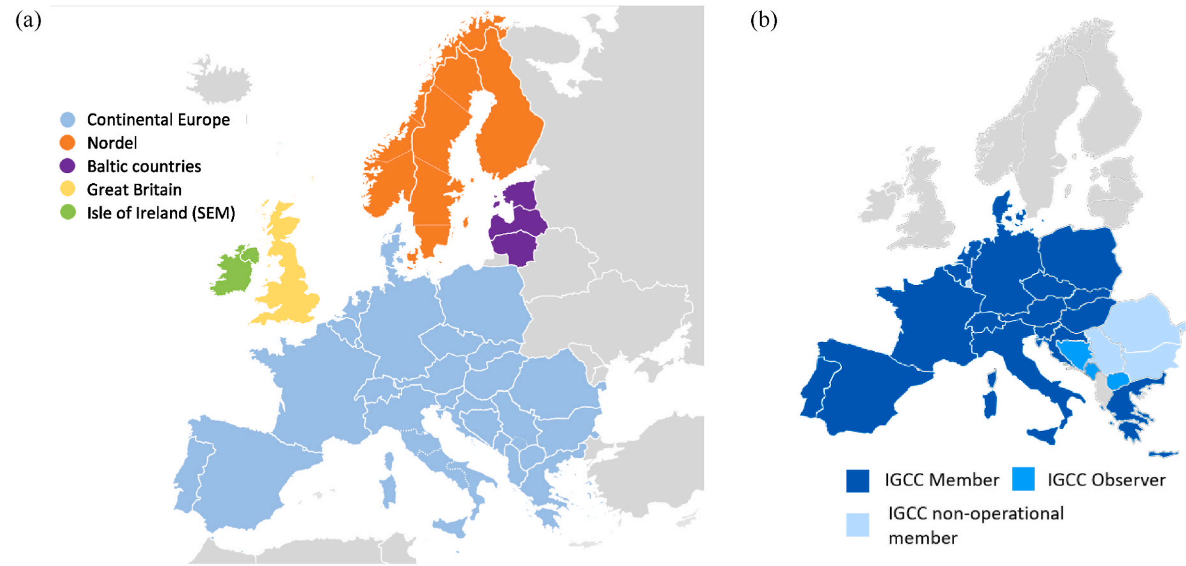


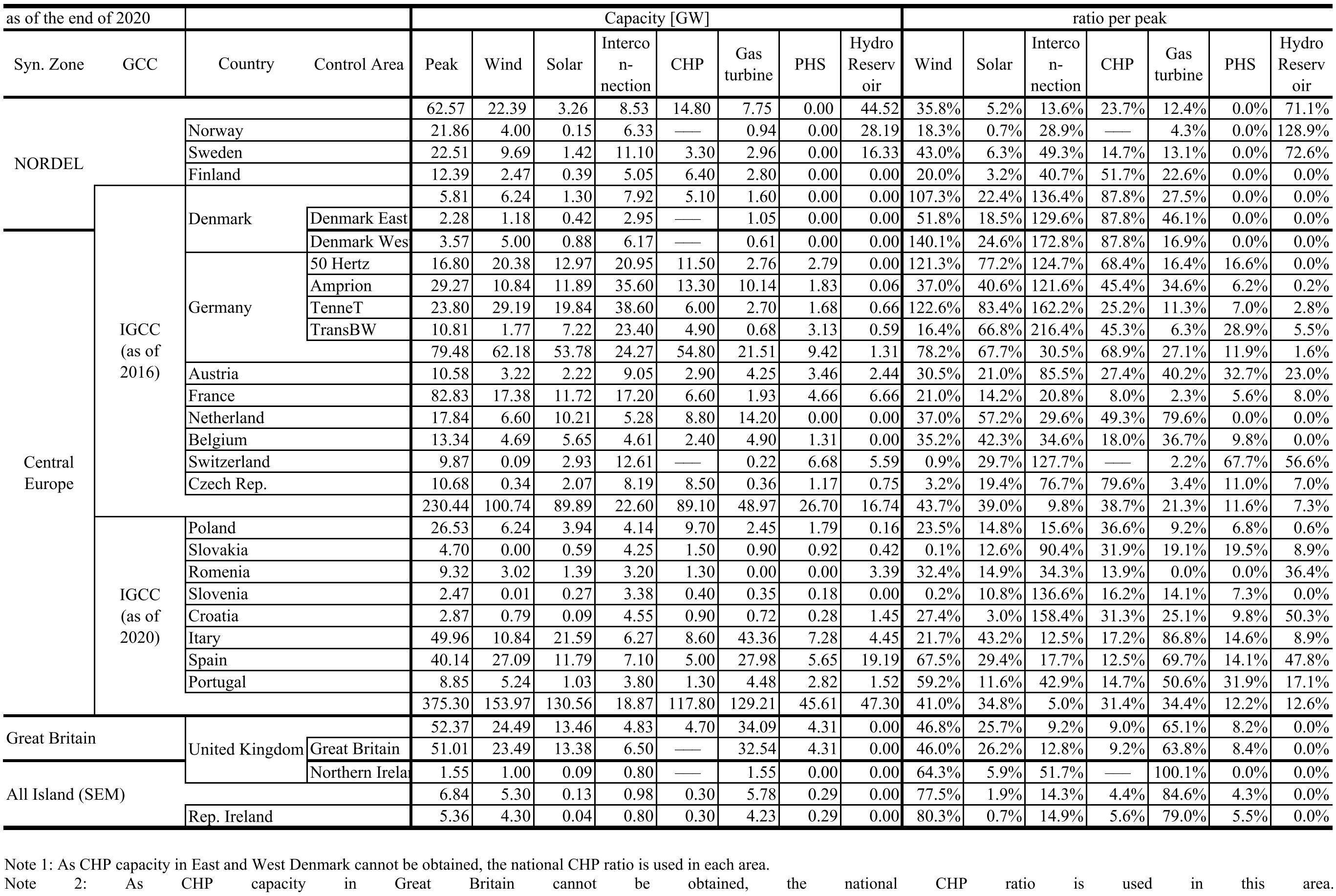
Fig. 2. Map of synchronous zones; (a) European Grid as of 2020 (arranged in legends by the authors after Ref. [14]), (b) IGCC countries [15].

2.2. *Basic statistical data for flexibility chart*

Europe consists of 5 synchronous zones, as shown in Fig. 2(a). In this subsection, we will evaluate (1) Nordic zone excluding Iceland, (2) selected countries in ENTSO-E zone, (3) Great Britain, and (4) all Ireland. The selected countries in the ENTSO-E zone are IGCC members, as shown in Fig. 2(b). We evaluate here the smaller area, named here as IGCC-S, that includes countries which joined before 2016, *i.e.* Germany, Denmark, Netherlands, Switzerland, Czechia, Belgium, Austria and France, and the larger area IGCC-L, including IGCC-S countries, plus

Table 1

Basic Statistical Data for Flexibility Charts in European Countries (year 2020, reference in Appendix).



as of the end of 2020				Capacity [GW]								ratio per peak						
Syn. Zone	GCC	Country	Control Area	Peak	Wind	Solar	Interconnection	CHP	Gas turbine	PHS	Hydro Reservoir	Wind	Solar	Interconnection	CHP	Gas turbine	PHS	Hydro Reservoir
NORDEL				62.57	22.39	3.26	8.53	14.80	7.75	0.00	44.52	35.8%	5.2%	13.6%	23.7%	12.4%	0.0%	71.1%
		Norway		21.86	4.00	0.15	6.33	——	0.94	0.00	28.19	18.3%	0.7%	28.9%	——	4.3%	0.0%	128.9%
		Sweden		22.51	9.69	1.42	11.10	3.30	2.96	0.00	16.33	43.0%	6.3%	49.3%	14.7%	13.1%	0.0%	72.6%
		Finland		12.39	2.47	0.39	5.05	6.40	2.80	0.00	0.00	20.0%	3.2%	40.7%	51.7%	22.6%	0.0%	0.0%
	IGCC (as of 2016)	Denmark		5.81	6.24	1.30	7.92	5.10	1.60	0.00	0.00	107.3%	22.4%	136.4%	87.8%	27.5%	0.0%	0.0%
			Denmark East	2.28	1.18	0.42	2.95	——	1.05	0.00	0.00	51.8%	18.5%	129.6%	87.8%	46.1%	0.0%	0.0%
Central Europe			Denmark Wes	3.57	5.00	0.88	6.17	——	0.61	0.00	0.00	140.1%	24.6%	172.8%	87.8%	16.9%	0.0%	0.0%
		Germany	50 Hertz	16.80	20.38	12.97	20.95	11.50	2.76	2.79	0.00	121.3%	77.2%	124.7%	68.4%	16.4%	16.6%	0.0%
			Amprion	29.27	10.84	11.89	35.60	13.30	10.14	1.83	0.06	37.0%	40.6%	121.6%	45.4%	34.6%	6.2%	0.2%
			TenneT	23.80	29.19	19.84	38.60	6.00	2.70	1.68	0.66	122.6%	83.4%	162.2%	25.2%	11.3%	7.0%	2.8%
			TransBW	10.81	1.77	7.22	23.40	4.90	0.68	3.13	0.59	16.4%	66.8%	216.4%	45.3%	6.3%	28.9%	5.5%
				79.48	62.18	53.78	24.27	54.80	21.51	9.42	1.31	78.2%	67.7%	30.5%	68.9%	27.1%	11.9%	1.6%
		Austria		10.58	3.22	2.22	9.05	2.90	4.25	3.46	2.44	30.5%	21.0%	85.5%	27.4%	40.2%	32.7%	23.0%
		France		82.83	17.38	11.72	17.20	6.60	1.93	4.66	6.66	21.0%	14.2%	20.8%	8.0%	2.3%	5.6%	8.0%
		Netherland		17.84	6.60	10.21	5.28	8.80	14.20	0.00	0.00	37.0%	57.2%	29.6%	49.3%	79.6%	0.0%	0.0%
		Belgium		13.34	4.69	5.65	4.61	2.40	4.90	1.31	0.00	35.2%	42.3%	34.6%	18.0%	36.7%	9.8%	0.0%
		Switzerland		9.87	0.09	2.93	12.61	——	0.22	6.68	5.59	0.9%	29.7%	127.7%	——	2.2%	67.7%	56.6%
		Czech Rep.		10.68	0.34	2.07	8.19	8.50	0.36	1.17	0.75	3.2%	19.4%	76.7%	79.6%	3.4%	11.0%	7.0%
				230.44	100.74	89.89	22.60	89.10	48.97	26.70	16.74	43.7%	39.0%	9.8%	38.7%	21.3%	11.6%	7.3%
	IGCC (as of 2020)	Poland		26.53	6.24	3.94	4.14	9.70	2.45	1.79	0.16	23.5%	14.8%	15.6%	36.6%	9.2%	6.8%	0.6%
		Slovakia		4.70	0.00	0.59	4.25	1.50	0.90	0.92	0.42	0.1%	12.6%	90.4%	31.9%	19.1%	19.5%	8.9%
		Romenia		9.32	3.02	1.39	3.20	1.30	0.00	0.00	3.39	32.4%	14.9%	34.3%	13.9%	0.0%	0.0%	36.4%
		Slovenia		2.47	0.01	0.27	3.38	0.40	0.35	0.18	0.00	0.2%	10.8%	136.6%	16.2%	14.1%	7.3%	0.0%
		Croatia		2.87	0.79	0.09	4.55	0.90	0.72	0.28	1.45	27.4%	3.0%	158.4%	31.3%	25.1%	9.8%	50.3%
		Itary		49.96	10.84	21.59	6.27	8.60	43.36	7.28	4.45	21.7%	43.2%	12.5%	17.2%	86.8%	14.6%	8.9%
		Spain		40.14	27.09	11.79	7.10	5.00	27.98	5.65	19.19	67.5%	29.4%	17.7%	12.5%	69.7%	14.1%	47.8%
		Portugal		8.85	5.24	1.03	3.80	1.30	4.48	2.82	1.52	59.2%	11.6%	42.9%	14.7%	50.6%	31.9%	17.1%
				375.30	153.97	130.56	18.87	117.80	129.21	45.61	47.30	41.0%	34.8%	5.0%	31.4%	34.4%	12.2%	12.6%
Great Britain		United Kingdom		52.37	24.49	13.46	4.83	4.70	34.09	4.31	0.00	46.8%	25.7%	9.2%	9.0%	65.1%	8.2%	0.0%
			Great Britain	51.01	23.49	13.38	6.50	——	32.54	4.31	0.00	46.0%	26.2%	12.8%	9.2%	63.8%	8.4%	0.0%
All Island (SEM)			Northern Irela	1.55	1.00	0.09	0.80	——	1.55	0.00	0.00	64.3%	5.9%	51.7%	——	100.1%	0.0%	0.0%
				6.84	5.30	0.13	0.98	0.30	5.78	0.29	0.00	77.5%	1.9%	14.3%	4.4%	84.6%	4.3%	0.0%
		Rep. Ireland		5.36	4.30	0.04	0.80	0.30	4.23	0.29	0.00	80.3%	0.7%	14.9%	5.6%	79.0%	5.5%	0.0%

Note 1: As CHP capacity in East and West Denmark cannot be obtained, the national CHP ratio is used in each area.
Note 2: As CHP capacity in Great Britain cannot be obtained, the national CHP ratio is used in this area.

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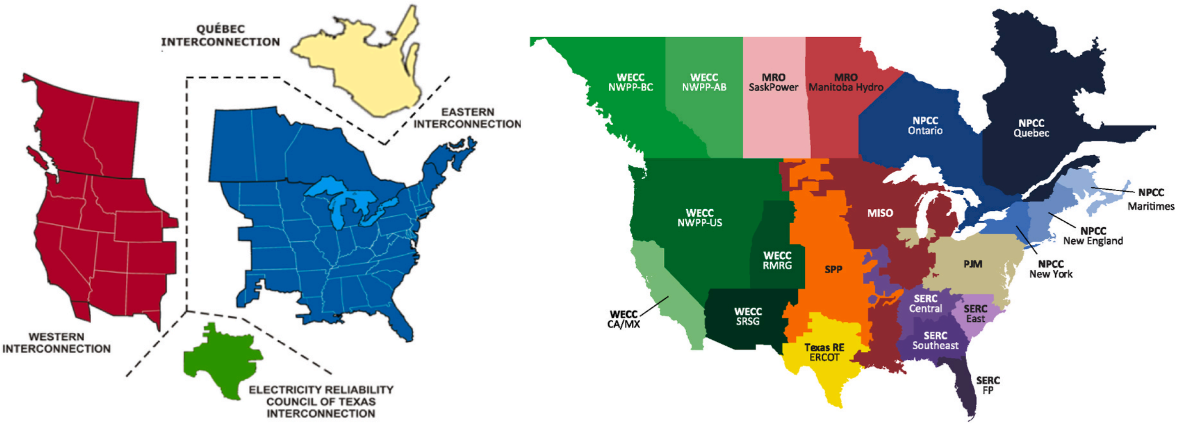

Fig. 3. Grid map in North America; (a) Synchronous zones [16], and (b) NERC reliability assessment areas [17].

newly joined countries as of 2020, *i.e.* Croatia, Slovenia, Italy, Poland, Hungary, Slovakia, Spain, Portugal.

Table 1 summarises the data set obtained for the European countries, with a detailed corresponding table indicating references to the basic data in the Appendix.

In North America, as shown in Fig. 3(a), there are 4 interconnections; Eastern Interconnection (EI), Western Interconnection (WI), Electric Reliability Council of Texas (ERCOT), and Quebec (note that “interconnection” here is a particular terminology in North America meaning a synchronous zone, rather than an interconnecting transmission line). The Eastern and Western Interconnections span portions of the U.S., Canada and Mexico. The ERCOT and Quebec interconnections are totally contained in the U.S. and Canada, respectively. Control areas and reliability assessment regions represent smaller areas within EI and WI, while ERCOT and Hydro Quebec are the only entities which have responsibility for balancing and reliability in their synchronous area. In this subsection, we evaluate flexibility charts on the basis of reliability assessment regions, as shown in Fig. 3(b).

Table 2 shows a basic statistical data set to form the flexibility charts for each region in North America. As it is challenging to gather data on actual installed capacities of various generation types for every region in the U.S. and Canada, we employed estimated values for 2020, following on from a 2019 reliability assessment [15]. Also, as many RTO/ISOs in North America do not publish the total interconnection capacity to neighbouring regions, we substituted for “net firm capacity transfer” from the NERC reliability assessment. Thus, the interconnection ratio in the flexibility charts may be underestimated. As the CHP data set in the U.S is not on the basis of reliability regions, but rather states, and the borders for some reliability regions and RTO/ISO areas are notably different from those of states, we assumed that all CHP capacity in a given state belongs to the reliability region containing the largest part of the state. This creates a small degree of uncertainty in the flexibility charts. For further information on a detailed data reference, see the Appendix.

Japan is a small country, consisting of isolated islands, but with a relatively large electricity consumption. The annual electricity consumption is approximately one third that of Europe, with more than 30 countries, or one fifth that of North America. The Japanese power system consists of three synchronous areas connected to each other via DC interconnectors, and, in total, ten control areas, as shown in Fig. 4 (note

Table 2
Basic Statistical Data for Flexibility Charts in North America (year 2020; reference in Appendix).

as of the end of 2020				Capacity [GW]								ratio per peak						
Country	Syn. Zone	Reliability Region	ISO/RTO	Peak	Wind	Solar	Interconnection	CHP	Gas turbine	PHS	Hydro Reservoir	Wind	Solar	Interconnection	CHP	Gas turbine	PHS	Hydro Reservoir
Canada	Québec	NPCC	Québec	37.08	3.63	0	11.18	0.84	0.00	0.00	38.69	9.8%	0.0%	30.1%	2.3%	0.0%	0.0%	104.3%
USA	EI		Maritimes	5.30	1.146	0.01	2.63	0.32	0.76	0.00	0.44	21.6%	0.2%	49.6%	6.1%	14.3%	0.0%	8.4%
			New England	23.70	1.39	1.21	4.83	3.25	15.80	1.85	1.28	5.9%	5.1%	20.4%	13.7%	66.7%	7.8%	5.4%
			New York	30.62	1.90	0.03	1.73	5.57	18.07	1.41	3.32	6.2%	0.1%	5.7%	18.2%	59.0%	4.6%	10.8%
			Ontario	23.33	4.43	0.42	4.61	2.38	7.44	0.12	6.11	19.0%	1.8%	19.8%	10.2%	31.9%	0.5%	26.2%
				120.03	12.50	1.67	—	12.36	42.06	3.39	49.84	10.4%	1.4%	—	10.3%	35.0%	2.8%	41.5%
		RF	PJM	144.19	8.01	1.55	1.41	10.20	84.51	5.23	3.13	5.6%	1.1%	1.0%	7.1%	58.6%	3.6%	2.2%
		SERC		177.24	0.49	2.87	—	9.59	111.08	6.50	10.49	0.3%	1.6%	—	5.4%	62.7%	3.7%	5.9%
		MRO	MISO	120.11	19.17	0.28	1.43	18.66	61.53	2.76	1.53	16.0%	0.2%	1.2%	15.5%	51.2%	2.3%	1.3%
			SPP	49.57	20.49	0.28	2.94	1.03	29.58	0.00	3.43	41.3%	0.6%	5.9%	2.1%	59.7%	0.0%	6.9%
			Manitoba	4.76	0.25	0.00	2.39	0.02	0.40	0.00	5.15	5.2%	0.0%	50.3%	0.5%	8.5%	0.0%	108.2%
			SaskPower	3.88	0.24	0.01	0.44	0.54	2.17	0.00	0.86	6.2%	0.2%	11.4%	13.8%	56.0%	0.0%	22.2%
				178.32	40.15	0.57	—	20.25	93.69	2.76	10.97	22.5%	0.3%	—	11.4%	52.5%	1.5%	6.2%
				702.73	70.01	8.33	13.75	63.92	373.40	21.26	85.60	10.0%	1.2%	2.0%	9.1%	53.1%	3.0%	12.2%
	WI	WECC		171.69	23.75	16.46	1.32	19.68	88.29	2.78	45.08	13.8%	9.6%	0.8%	11.5%	51.4%	1.6%	26.3%
			Alberta	12.32	2.14	0.34	1.45	5.10	7.74	0.00	0.89	17.4%	2.7%	11.8%	41.4%	62.8%	0.0%	7.3%
			British Colom	12.43	0.70	0.00	4.35	0.81	0.43	0.00	12.21	5.6%	0.0%	35.0%	6.5%	3.5%	0.0%	98.2%
			CAMX	54.84	6.19	11.78	2.43	8.95	35.14	2.18	5.73	11.3%	21.5%	4.4%	16.3%	64.1%	4.0%	10.4%
			NWPP	52.32	9.76	2.48	0.75	3.97	20.21	0.20	24.04	18.7%	4.7%	1.4%	7.6%	38.6%	0.4%	46.0%
			RMRG	13.41	3.79	0.46	0.00	0.68	6.71	0.28	1.46	28.3%	3.5%	0.0%	5.1%	50.0%	2.1%	10.9%
			SRSG	26.37	1.16	1.40	0.00	0.17	18.07	0.12	0.75	4.4%	5.3%	0.0%	0.6%	68.5%	0.5%	2.8%
	Texas	Texas R	ERCOT	81.89	22.09	1.86	1.25	17.34	48.53	0.00	0.46	27.0%	2.3%	1.5%	21.2%	59.3%	0.0%	0.6%

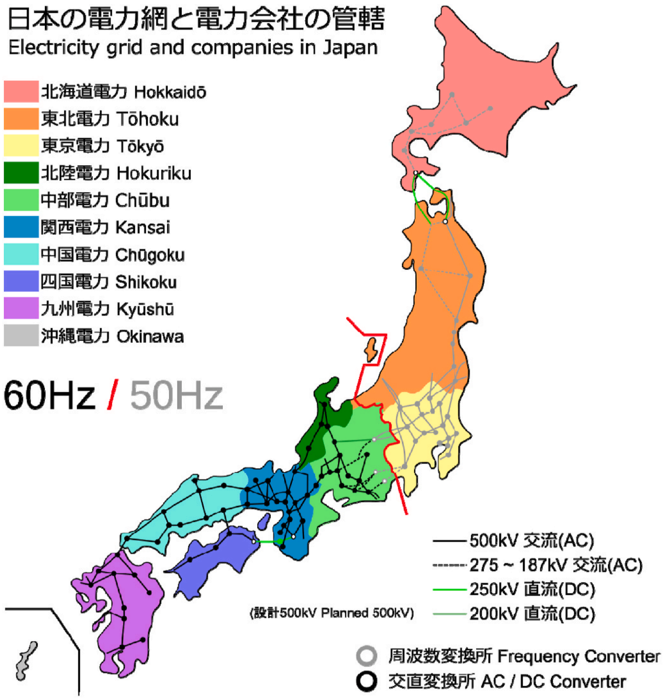

Fig. 4. Illustrative map of Japanese grid [18].

that, here, the area of Okinawa is not evaluated, as it is a small isolated island). In April 2020, all vertically-integrated Japanese utilities were divided into generation-retailer companies and TDSOs (transmission and distribution system operators) in a "legal unbundling", and now ten TDSO owners operate their own control areas.

Table 3 contains a set of basic statistical data, gathered from the TDSOs and other relevant public organizations. Some hydro data may include uncertainty, since it is not straightforward to distinguish reservoir from run-of-river, and hence may be overestimated as a potential flexibility resource. As the latest CHP data in Japan was not available, we employed a 2018 data set, which was assumed to be not that different from 2020 figures due to low development speed of CHP in Japan. Consequently, the low CHP ratio is not of concern. See Appendix for detailed data references.

Fig. 5. Map of Australian main grid [19].

Australia has five control areas, excluding the completely isolated system in the western part of the continent, as illustrated in Fig. 5. The main synchronous area in the mainland consists of four control areas tied by AC links (and partly by a DC link). The fifth control area, Tasmania, is an isolated system with a DC link to the mainland. A set of basic statistical data on Australia for the flexibility chart is listed in Table 4. See Appendix for detailed data references.

Note that gas turbines and hydro may include steam turbines and run-of-river, respectively, since it is difficult to distinguish between them from available statistical information. Thus, their capacity ratio may be overestimated. Interconnection capacity may also be overestimated since the given value may not be the ATC, but rather the nominal interconnector capacity.

Table 3
Basic Statistical Data for Flexibility Charts in Japan (year 2020, reference in Appendix).

as of the end of 2020			Capacity [GW]								ratio per peak						
Country	Synchronous Zone	Control Area	Peak	Wind	Solar	Interco n- nection	CHP	Gas turbine	PHS	Hydro Reserv oir	Wind	Solar	Interco n- nection	CHP	Gas turbine	PHS	Hydro Reserv oir
Japan			169.87	4.48	59.70	0.00	10.70	61.39	27.92	17.78	2.6%	35.1%	0.0%	6.3%	36.1%	16.4%	10.5%
	Hokkaido	Hokkaido	5.41	0.53	1.97	0.90	0.30	0.57	0.90	0.71	9.8%	36.4%	16.6%	5.5%	10.5%	16.6%	13.1%
	East		70.84	2.03	22.76	1.80	5.05	32.36	11.91	5.03	2.9%	32.1%	2.5%	7.1%	45.7%	16.8%	7.1%
		Tohoku	14.80	1.60	6.44	5.45	0.67	7.36	0.71	1.15	10.8%	43.5%	36.8%	4.5%	49.7%	4.8%	7.8%
		Tokyo	56.04	0.43	16.32	7.40	4.38	25.00	11.20	3.88	0.8%	29.1%	13.2%	7.8%	44.6%	20.0%	6.9%
	Central West		93.62	1.92	34.97	1.20	5.35	28.46	15.11	12.03	2.1%	37.4%	1.3%	5.7%	30.4%	16.1%	12.9%
		Chubu	26.24	0.37	9.49	6.20	1.80	13.74	4.49	3.10	1.4%	36.2%	23.6%	6.9%	52.4%	17.1%	11.8%
		Hokuriku	5.34	0.16	1.07	5.00	0.00	0.42	0.12	1.33	3.0%	20.0%	93.6%	0.0%	8.0%	2.2%	24.9%
		Kansai	29.10	0.17	6.05	10.45	1.84	8.32	5.23	3.44	0.6%	20.8%	35.9%	6.3%	28.6%	18.0%	11.8%
		Chugoku	11.24	0.35	5.35	8.35	0.72	2.39	2.01	1.92	3.1%	47.6%	74.3%	6.4%	21.3%	17.9%	17.1%
		Shikoku	5.33	0.28	2.90	2.60	0.25	0.59	0.67	0.64	5.3%	54.4%	48.8%	4.7%	11.0%	12.6%	12.0%
		Kyushu	16.37	0.59	10.11	3.10	0.74	3.00	2.58	1.61	3.6%	61.8%	18.9%	4.5%	18.3%	15.8%	9.8%

Table 4
Basic Statistical Data for Flexibility Charts in Australia (year 2020, reference in Appendix).

as of the end of 2020			Capacity [GW]								ratio per peak						
Country	Synchronous Zone	Control Area	Peak	Wind	Solar	Interco n- nection	CHP	Gas turbine	PHS	Hydro Reserv oir	Wind	Solar	Interco n- nection	CHP	Gas turbine	PHS	Hydro Reserv oir
Australia	Main land		36.53	5.78	12.01	0.59	0.26	9.40	1.34	4.55	15.8%	32.9%	1.6%	0.7%	25.7%	3.7%	12.5%
		Queensland	9.97	0.39	4.54	1.29	0.16	2.64	0.50	0.16	3.9%	45.5%	12.9%	1.6%	26.4%	5.0%	1.6%
		NSW	13.83	1.34	3.48	2.89	0.03	1.77	0.84	2.13	9.7%	25.1%	20.9%	0.2%	12.8%	6.1%	15.4%
		Victoria	9.62	2.13	2.44	3.01	0.05	2.24	0.00	2.26	22.2%	25.3%	31.3%	0.6%	23.3%	0.0%	23.5%
		South Australi	3.11	1.92	1.56	0.82	0.02	2.75	0.00	0.00	61.6%	49.9%	26.3%	0.7%	88.2%	0.0%	0.1%
	Tasmania		1.76	0.31	0.16	0.59	0.00	0.37	0.00	2.17	17.5%	8.9%	33.8%	0.0%	21.1%	0.0%	123.3%

3. Flexibility charts in various area in the world

3.1. European countries

Fig. 6 shows flexibility charts for the Nordel Synchronous Zone, which consists of three countries in Northern Europe, *i.e.,* Norway, Sweden and Finland, and a control area in Denmark East (DK1). It is clearly shown that Norway has a rich hydropower resource with high flexibility potential. It is easy to understand Norway's "green battery" strategy to export flexible RE via new interconnectors to other European countries [20]. Sweden has similar characteristics.

Fig. 6 also shows an aggregated flexibility chart for the Nordel synchronous zone, which corresponds quite well to a combination of Norway and Sweden, the two most dominant countries (by capacity) in this synchronous area. The high hydro capacity in Nordel enables higher potential to accommodate VRE in this area for the future, with headroom to export surplus flexibility resources to neighbouring areas. The Finland chart in Fig. 6 looks quite similar to that of Denmark East. However, when aggregated, the total interconnection capacity is much smaller than the interconnection capacities of the individual areas, indicating that most of the individual countries interconnection capacity is within Nordel. Plans to install additional interconnectors to other areas is stated in TYNDP by ENTSO-E [21], not only to help with future VRE, but also to provide flexibility to central Europe.

Denmark is divided into two control areas, Denmark East (DK1) and Denmark West (DK2), as shown in Fig. 7. The former belongs to the Nordel synchronous zone via AC subsea cables to Sweden and Norway. The latter is connected to Germany via AC transmission lines, and hence forms part of the Continental Europe synchronous zone. The two Danish areas are connected via a single DC interconnector named "Great Belt". Both areas have resources in the form of flexible CHP as well as large interconnection capacity. Fig. 7 also shows an aggregated flexibility chart for all of Denmark. As the flexibility chart characteristics for East and West Denmark are similar to each other, the aggregated chart naturally looks similar to each of them, with interconnectors and CHP as flexibility resources. The large amount of interconnection capacity, which is preserved through the aggregation process, indicates that most interconnection capacity is linking to other areas, while the mentioned Great Belt link plays a limited role. In practice, variability and uncertainty, due to increasing VRE, have been mitigated through expanding interconnectors and making CHP operation more flexible in Denmark [22].

(note: As CHP capacity in the two control areas in Denmark cannot be obtained, the national CHP ratio is used in each area.)

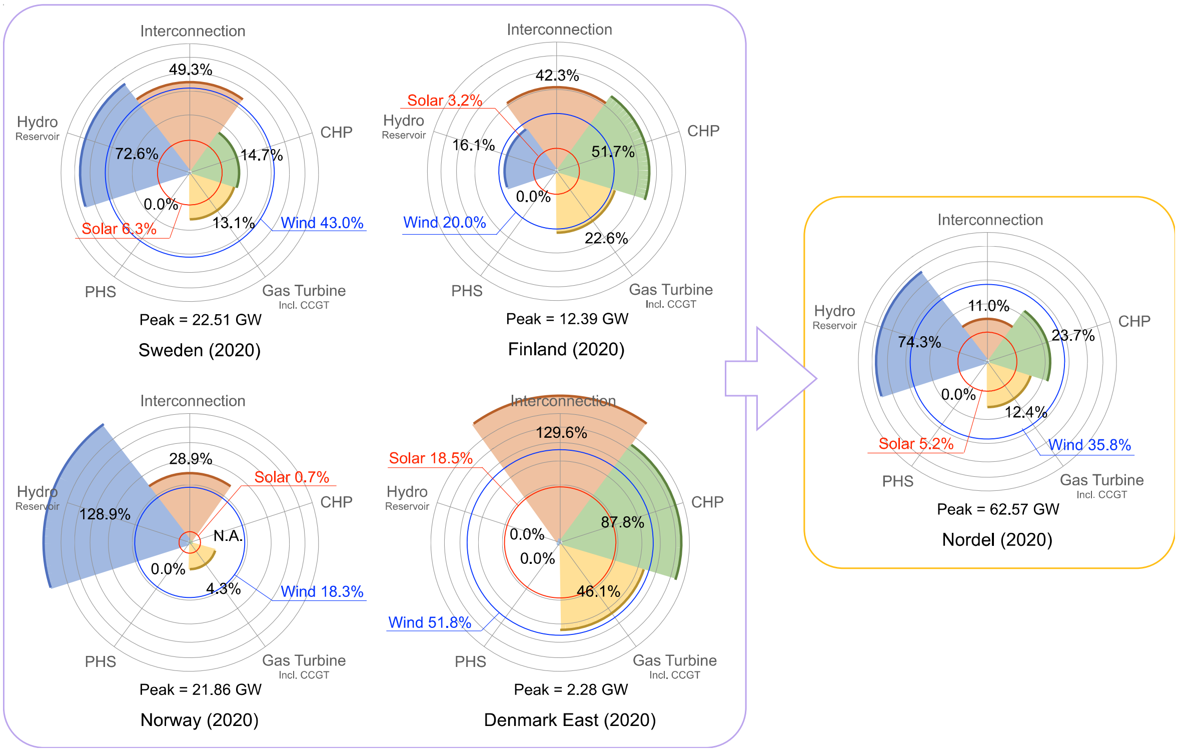

Fig. 6. Flexibility Charts of Nordel Synchronous Zone with individual countries and areas.

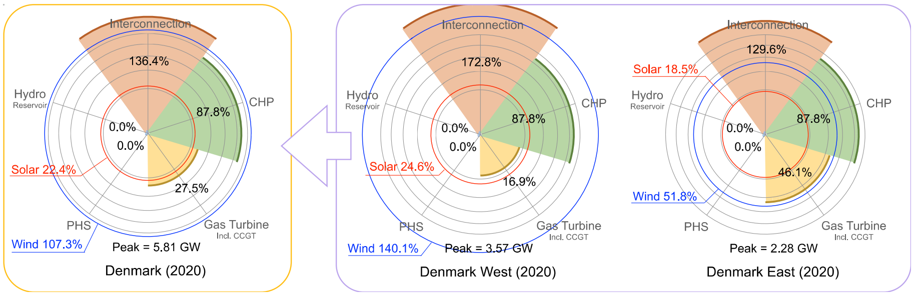

Fig. 7. Flexibility Charts for Denmark and its two control areas in 2020.

Germany consists of four TSOs, being an exceptional case in Europe. Fig. 8 shows the Flexibility Charts for the four TSO control areas, which clearly indicates that the TSOs have a large interconnection capacity. However, some of the TSOs, namely 50 Hz and TenneT, are facing a shortage of flexibility resources to accommodate high wind and solar shares. The characteristics of the flexibility chart for all Germany looks similar to that for Denmark (Fig. 7), from the viewpoint of a rich CHP flexibility resource, and there is a relatively high capacity of gas turbines. The aggregated interconnection ratio is much lower, indicating that most of the individual interconnection capacity is between the German TSO areas and not to other countries.

(note: As ATM values of interconnection in German 4 TSOs are not available, 50% of the sum of thermal capacity of interconnectors is used in each area.)

For other selected countries in the Continental Europe synchronous zone, we evaluate here the IGCC countries. Fig. 9 shows the flexibility charts of IGCC countries excluding Denmark and Germany, which are already shown in Figs. 7 and 8. The "at-a-glance" combination of these charts shows a strong diversity of flexibility resources across countries; Austria has a good balance of all kinds of flexibility resource, and still has the potential to export flexibility to neighbouring countries, while France has few flexibility resources, possibly due to a high nuclear share. The Netherlands and Belgium possess similar characteristics, with almost no hydro capacity due to their flat topography, but with significant flexibility from gas turbines. Switzerland has a high capacity of reservoir hydro and PHS, as well as interconnectors, despite almost no wind and solar share in the country, which offers strong potential to export flexibility. The chart for Czechia looks similar to Germany, but with higher interconnection capacity, and much lower wind and solar shares. Many countries in Eastern Europe show a good combination of various flexibility resources despite a low VRE share. Italy has a large gas turbine capacity, in addition to a good balance of other flexibility resources. However, being a peninsula, the interconnection capacity is limited when compared with its high PV and wind share.

Looking to the Iberian Peninsula as shown in Fig. 10, the Spanish chart shows similar characteristics to Italy, with a relatively high flexibility resource from gas turbines, but not so much interconnection. While hydro and gas, as flexibility resources, look sufficient at present for on the Iberian Peninsula, increasing PHS capacity (mainly in Portugal) and interconnectors (mainly in Spain) are ongoing [23,24]. Portugal has a well-balanced flexibility resource. Although the well-balanced characteristics in Portugal look quite similar to those in Austria, its total flexibility resource should be expanded to manage higher future wind shares. The Portuguese mix includes relevant

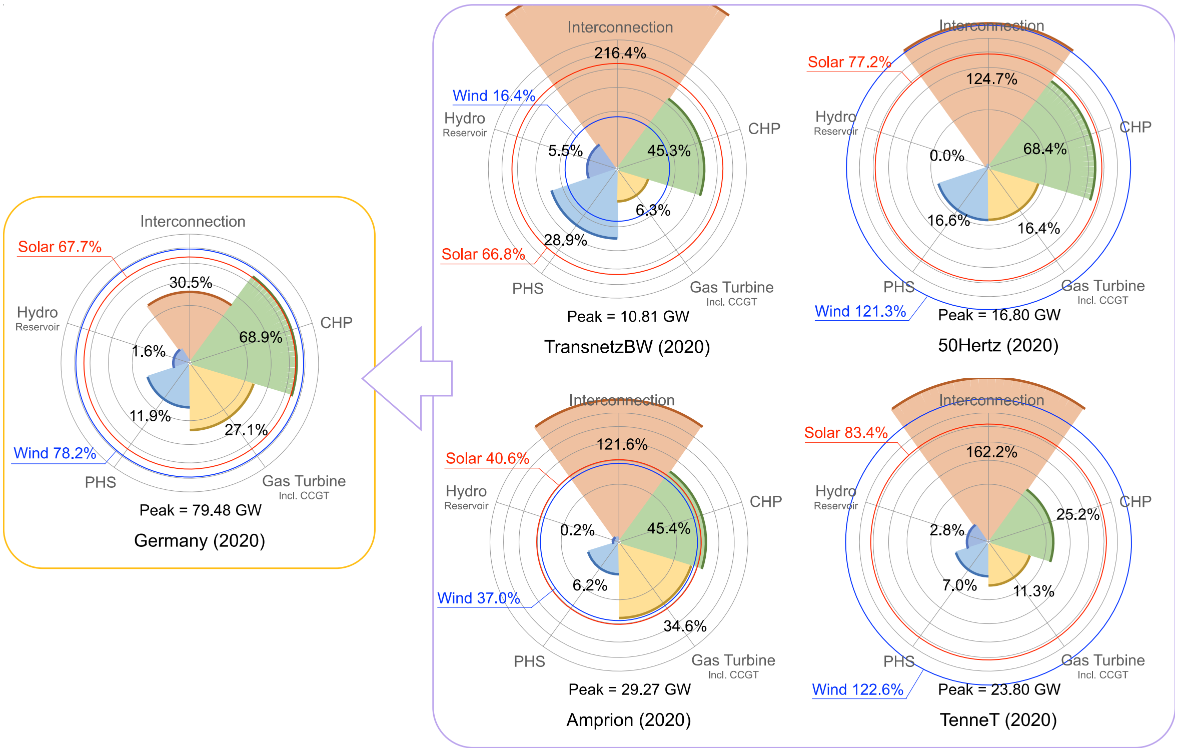

Fig. 8. Flexibility Charts of Germany and its four control areas in 2020.

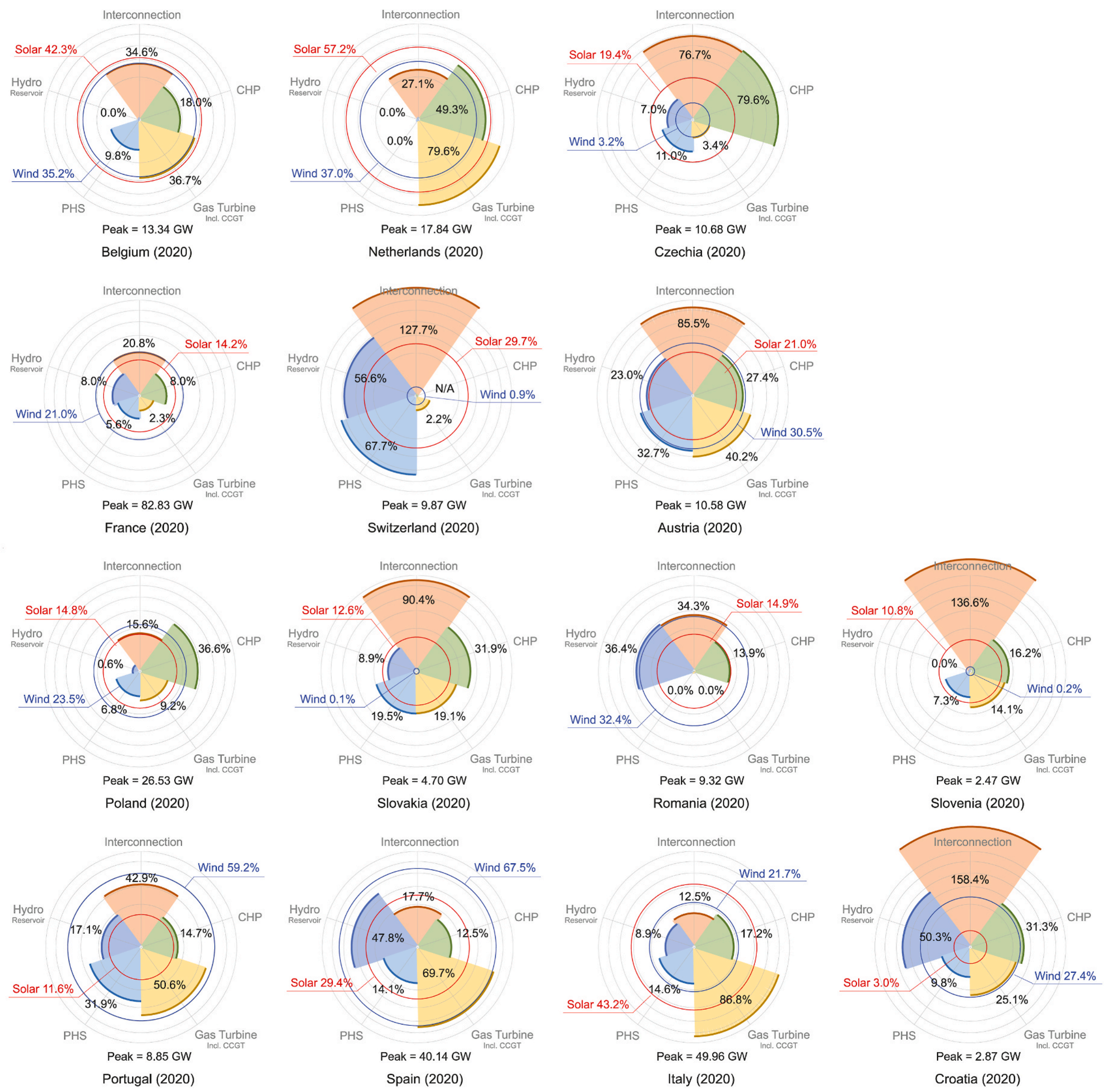

Fig. 9. Flexibility Charts of IGCC countries in 2020, excluding Denmark and Germany.

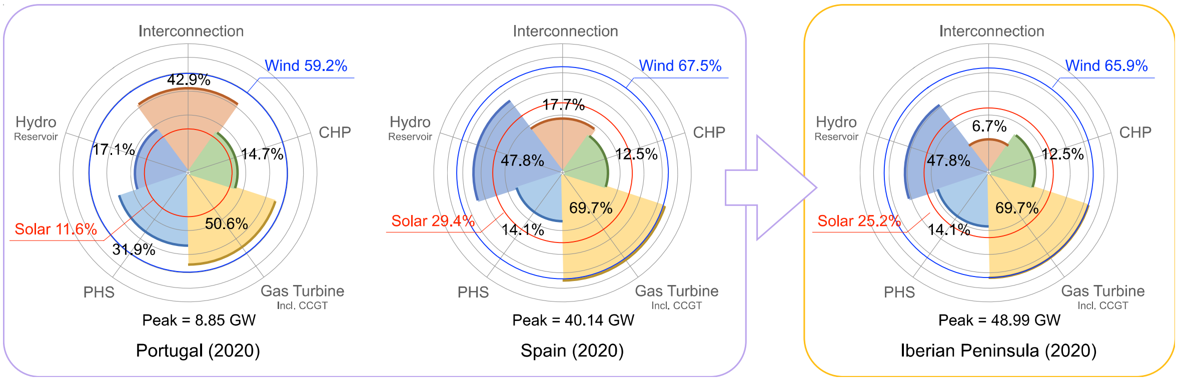

Fig. 10. Flexibility charts of Iberian Peninsula in 2020.

interconnection capacity to Spain. This interconnection capacity between the two countries looks much smaller when seen from the Spanish perspective, as it is related to a much larger peak load. Even though Spain has additional interconnection capacity, which AC and DC ties to France (and almost negligible capacity to Morocco), its interconnection ratio is significantly smaller than the ratio Portugal. For the aggregated chart of the Iberian Peninsula, interconnection ratio is very low, as the links between the two countries do not appear here.

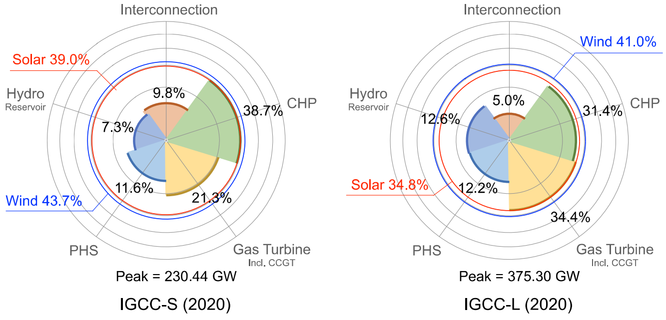

Fig. 11. Flexibility Charts of IGCC-S and IGCC-L areas in 2020.

The aggregated charts for IGCC-S and IGCC-L areas are shown in Fig. 11. Though both charts have well-balanced combinations of various flexibility resources, IGCC-L has a much higher gas turbine capacity and relatively high reservoir hydro and CHP capacities. This comparison can help to understand why IGCC has expanded to larger areas, *i.e.* to aggregate a wider range of flexibility resources to manage future higher VRE shares.

Fig. 12, which shows the flexibility charts for UK & Ireland, looks quite different compared to other areas, although the charts for UK and Republic of Ireland (EirGrid control area) look similar to each other; gas turbine capacity is quite high, but other flexibility resources are limited. Northern Ireland (SONI control area) also depicts unique characteristics, completely different to any other area, noting the dependence on neighbouring areas, *i.e.* Republic of Ireland, via interconnectors, as a major flexibility source. Although interconnection capacity in Northern Ireland is relatively high compared to other areas, it is not sufficient to handle high wind shares, due to N-1 security concerns. In fact, Northern Ireland has faced a high curtailment ratio exceeding 13%, an increasing trend as evaluated in Ref. [25].

The synchronous zones of UK and Ireland correspond to a geographical division, *i.e.* Great Britain and Island of Ireland (Republic of Ireland and Northern Ireland). Fig. 12 also shows aggregated flexibility charts for the synchronous zone of the Island of Ireland and for the entire UK (Great Britain and Northern Ireland). It is interesting to note that the chart characteristics for each control area (excluding Northern Ireland), and aggregated areas, look similar, despite differences in peak demand level. This is due to a common geographical region, with few resources from hydro due to flat lands, with relatively low interconnection capacity due to island systems. Ireland now permits a very high instantaneous wind (non-synchronous) share of 75%, and increasing, while investigating solutions for low inertia conditions [26]. GB is facing a similar situation in the near future.

3.2. *North America*

Fig. 13 shows flexibility charts for the NPCC reliability region. Hydro Québec, part of NPCC, but an independent synchronous zone, is well known as a hydro-rich area and historically has exported hydro energy to other areas via HVDC links. It is interesting to note that the characteristics here are very similar to those of Norway, as shown in Fig. 6, which suggests that future strategies could be similar, regarding more export flexibility from hydro resources and greater installation of interconnectors.

The two regions belonging to the U.S. in NPCC, *i.e.* control areas of ISO-NE and NY-ISO, show quite similar portfolios in their flexibility charts in Fig. 13, with gas turbines as the dominant flexibility resource in both cases. The characteristics in the flexibility charts of the two regions are quite similar to those of Italy (Fig. 9), and Great Britain and Ireland (Fig. 12).

The aggregated flexibility chart for the NPCC region has quite specific characteristics, where hydro resources come from Canada, and flexibility from gas turbines is contributed by two large US regions. Development of wind and solar has not yet matured in the NPCC region, and there remains a large opportunity to accept future VRE generation from a flexibility viewpoint.

Fig. 14 illustrates flexibility charts for the PJM and SERC reliability regions. PJM is a single reliability region. Although SERC is divided into

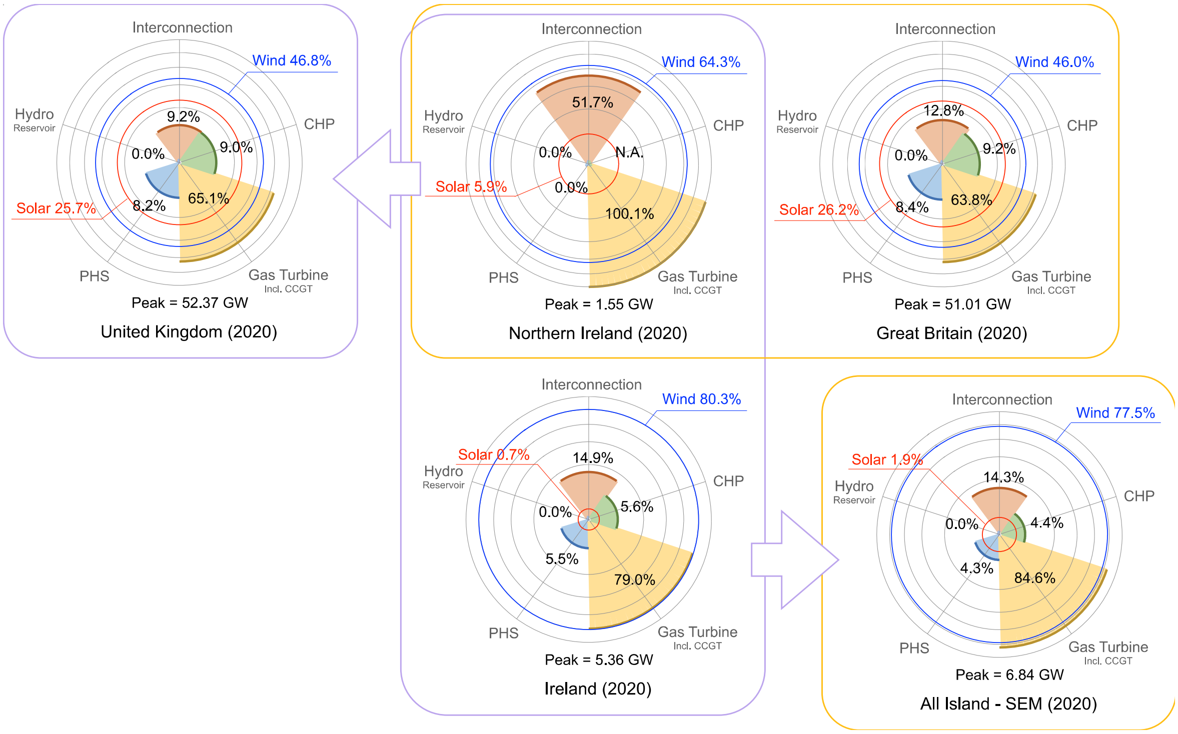

Fig. 12. Flexibility Charts of UK & Ireland and individual control areas in 2020. (Note: As CHP capacity in Great Britain cannot be obtained, the national CHP ratio is used in this area.)

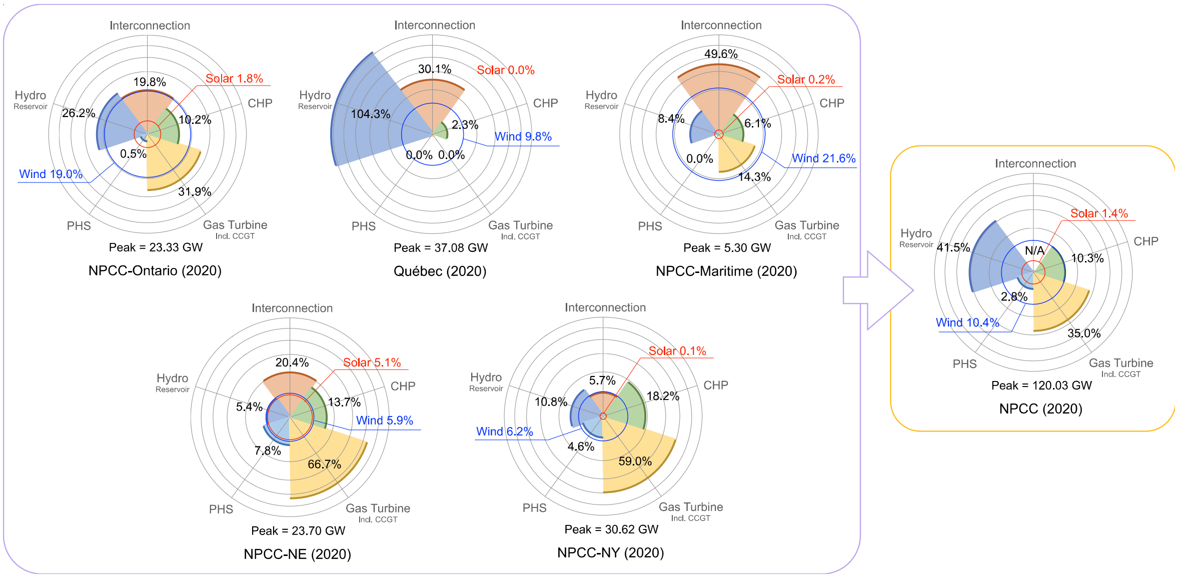

Fig. 13. Flexibility Charts in NPCC reliability region.

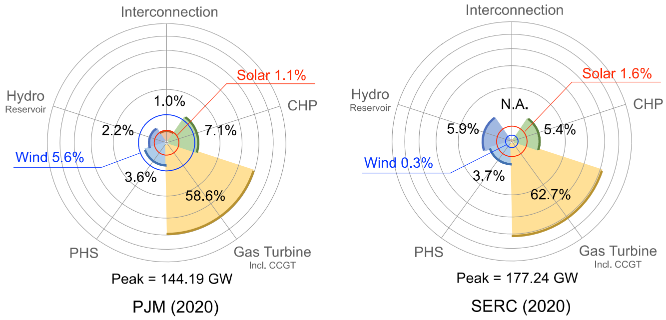

Fig. 14. Flexibility Charts of PJM and SERC reliability regions.

several sub-regions, as shown in the left figure of Fig. 3, we only evaluate the entire SERC region, due to low existing and planned VRE shares. The flexibility chart characteristics for both regions look quite similar to those for New England and New York, as shown in Fig. 13.

MRO has four sub-regions for reliability assessment, two of which are located in Canada (SaskPower and Manitoba) and two in the US (MISO and SPP). Although the Manitoba flexibility chart, shown in Fig. 15, looks similar to Québec, the aggregated chart for the entire MRO is strongly affected by those of MISO and SPP, which are similar to Italy, Great Britain and Ireland in Europe and ISO-NE and NY-ISO in the U.S. The reason is simply that the grids for the two US regions are much larger than those of Manitoba and SaskPower. As SPP now shows the highest installed wind capacity of the seven ISOs in the U.S., due to rich wind conditions in the Great Plain, the time is coming to consider adding more flexibility resources in SPP, or else enhancing interconnection capacity to neighbouring regions.

The set of 6 figures shown in Fig. 16 denote the flexibility resource characteristics in the 6 sub-regions of the WECC reliability region. The British Columbia flexibility chart looks similar to that for Québec, with large hydro capacity and strong interconnections, providing the potential to export flexibility to other WECC regions. On the other hand, although NWPP has a relatively high hydro share, it is not straightforward to export flexibility due to poor interconnection capacity (note that the ratio shown in the chart may be underestimated, due to "net firm capacity transfers" in NERC's reliability assessment being substituted for the total aggregated ATC of interties, as described before).

The CAMX region, which includes CAISO and a small part of Mexico, has the highest installed solar capacity in the U.S. CAMX is different from other control areas, given the higher share of PV than wind, which is unusual compared to other areas in the world (some exceptions are Italy, already shown in Fig. 9, and the Kyushu area in Japan, as later shown in Fig. 21. In fact, California is now facing a serious balancing problem due to a shortage of upward ramping capacity after sunset, the so-called "Duck Curve Problem", which doesn't occur in wind-rich areas. The portfolio of flexibility resources in CAMX looks strong, with the dominant source being gas turbines. There is a need to enhance flexibility, including intertie capacity to other regions to accommodate more solar and wind in the near future. Plans for battery ESS options will be discussed in Section 4.

Fig. 17 shows aggregated flexibility charts for the two main synchronous zones in North America, *i.e.* EI (Eastern Interconnection) and WI (Western Interconnection). Both charts look similar to each other, due to many US regions having similar characteristics in terms of flexibility resources, with gas turbines being the dominant flexibility resource. The hydro flexibility resource tends to come from Canada.

The final region in North America is ERCOT as shown in Fig. 18, a completely independent region that is isolated from other regions via HVDC interties. Given its isolation, the ERCOT flexibility chart looks different to other regions in North America and Europe. Although there is a slight similarity with gas turbines being the dominant flexibility capacity, hydro reservoirs and PHS are quite poor due to the flat terrain, interconnection capacity is much lower than that of other independent synchronous zones, such as Ireland and Great Britain (see Fig. 12). Given the anticipated growth in wind and solar, the future ERCOT strategy may naturally have common measures, *e.g.* inertia response [27], with those for GB and all Ireland, which represent examples of isolated systems in Europe facing a similar future.

3.3. Japan

Figs. 19–21 illustrate flexibility charts for three synchronous zones in Japan, with the last two zones consisting of two and six control areas respectively. The first is Hokkaido, as shown in Fig. 19, which is a northern island in Japan connected to the only neighbouring area, Tohoku, via three DC links. The second synchronous zone named West Japan, shown in Fig. 20, consists of two control areas; Tohoku and Tokyo. The last synchronous zone is Central-West, which spreads from

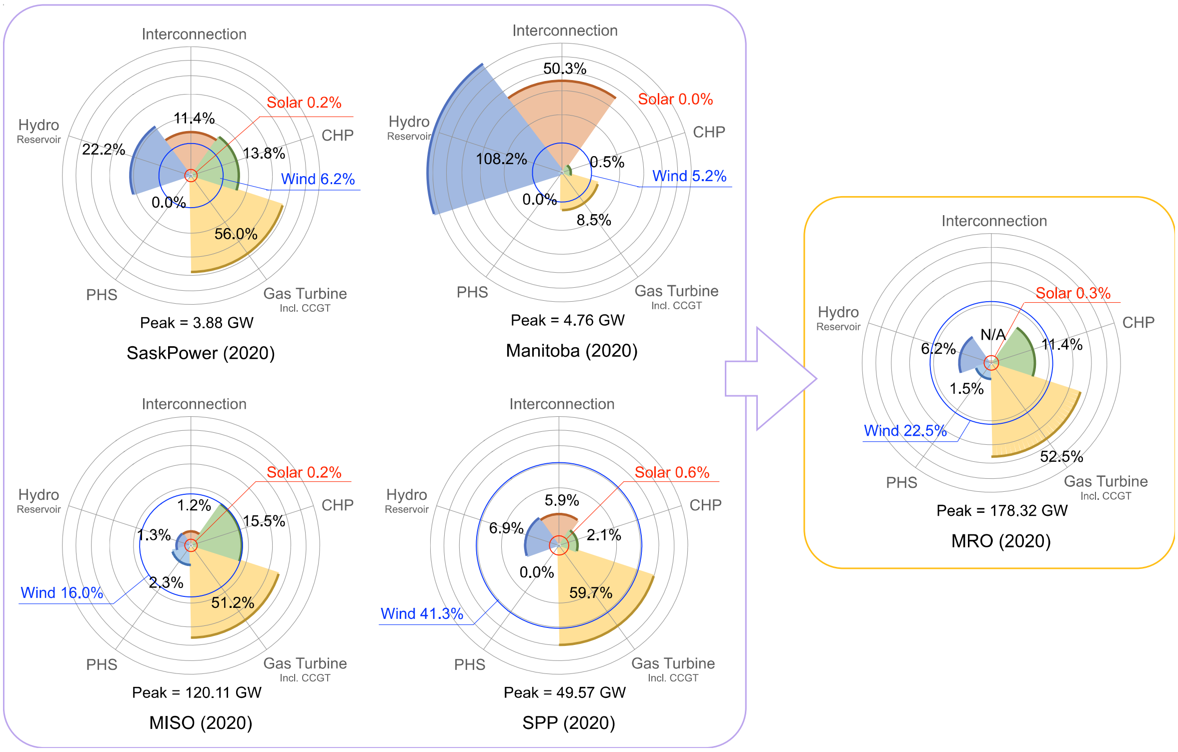

Fig. 15. Flexibility Charts in MRO reliability region.

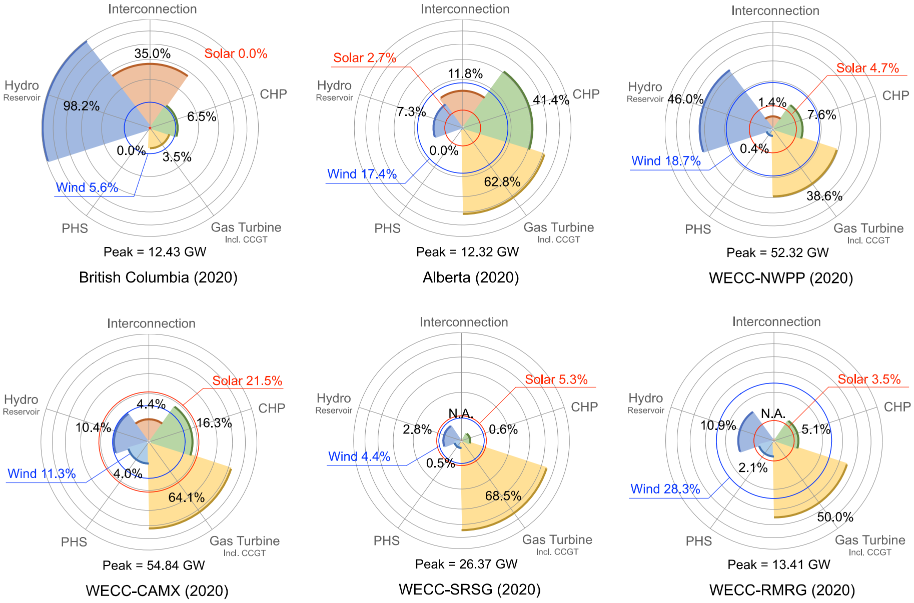

Fig. 16. Flexibility Charts of 6 sub-regions in WECC reliability region.

the western half of the main island in Japan, to Shikoku Island and Kyushu Island in the south. This zone consists of six control areas, namely Chubu, Hokuriku, Kansai, Chugoku, Shikoku and Kyushu, whose flexibility charts can be seen in Fig. 21.

The overall characteristics of the Japanese flexibility charts can be summarized as follows: 1) rich diversity can be seen in every neighbouring area, which can support greater imports/exports of flexibility, and coordination between multiple areas, 2) some TDSOs have sufficient interconnection capacity to other areas, which is a quite similar characteristic to the German TSOs, as described in Fig. 8, and some countries in Eastern Europe, as shown in Fig. 9, and also may contribute to trading of flexibility resources between TDSOs, and 3) some TDSOs, such as Hokkaido and Kyushu, have well-balanced flexibility resources, which may provide strong advantages in managing multiple options to manage future large VRE shares.

Fig. 20 also shows the aggregated chart for the East Japan synchronous zone, with combined Tohoku and Tokyo control areas. The characteristics of the aggregated chart are quite similar to that for Tokyo, due to the large difference in peak demand between Tohoku (14.80 GW) and Tokyo (56.04 GW). In addition, the Tohoku area, which has a high potential wind resource, and the highest installed wind capacity in Japan, has more potential to accommodate wind power using flexibility

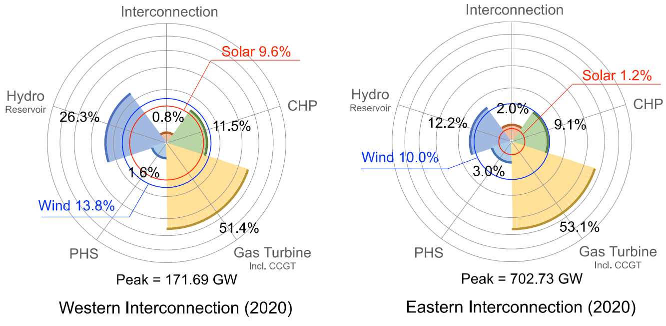

Fig. 17. Aggregated flexibility charts for EI and WI.

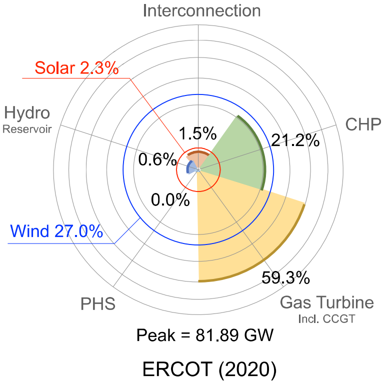

Fig. 18. Flexibility chart for ERCOT.

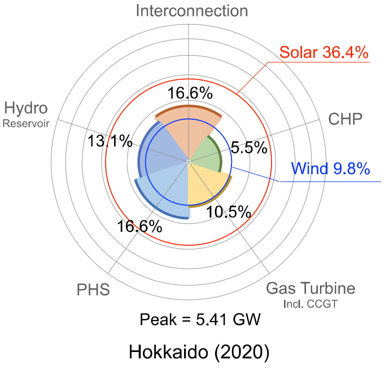

Fig. 19. Flexibility chart of Hokkaido, Japan.

resources from the Tokyo area via interconnectors. As the PV and wind share per peak load in the synchronous zone has not reached a high level, there is headroom to accept further VRE capacity. The existing interconnection capacity for Tohoku, and relatively high PHS capacity in Tokyo offer a good combination to coordinate flexibility resources between both areas.

Except for interconnection capacity, the aggregated shape of the flexibility chart in Fig. 21 is somewhat similar to that for Kansai and Chubu, which have the highest and second highest demand peak in this area. Interconnection to the Tokyo area is via back-to-back DC converters with small capacities through three routes.

Kyushu is the area with the highest PV share in Japan, and is facing a shortage of flexibility resources. Kyushu is now the only area in Japan where PV and wind curtailment has occurred since Autumn 2018, as evaluated in Ref. [25]. Although Kyushu is facing a lack of flexibility resources, a key potential source would be to use the interconnectors via Chugoku to Kansai.

The aggregated interconnection capacities in East Japan (in Fig. 20) and Central-West Japan (in Fig. 21) look to small despite of relatively rich interconnection capacities in those sub-areas. This means the interconnectors in each sub-area contributes to transfer inside the synchronous zone but are not always designed to exchange bulk energy and flexibility over outside at the present.

As both of the above synchronous areas extend over a long distance from north to central (for East Japan) and from central to west (for Central-West Japan), with a so-called “fish-bone” shape topology, system stability issues must be studied to accommodate further rapid growth of PV and wind in the near future.

3.4. *Australia*

As shown in Fig. 22, the composition of the four mainland areas is somewhat similar to that for Japan; the variety of flexibility resource is different in each case, and the total capacity (potential) of each flexibility resource is modest.

South Australia has a high wind share, comparable to Denmark, but the flexibility chart characteristics are quite similar to that for Northern Ireland, as shown in Fig. 12. To overcome the current situation with poor flexibility resources, the Government of South Australia and AEMO are seeking a new flexibility resource in the form of battery ESS [28]. Flexibility chart evaluation considering battery ESS will be discussed in the next section. Tasmania has a large hydro capacity, and hence large potential to export flexibility to the mainland. The resulting flexibility chart looks clearly similar to that for Norway in Fig. 6, and Manitoba in Fig. 15.

Four control areas in the Australian mainland are connected to each other by AC lines and form a synchronous area. Although the South Australia control area is short of flexibility resources against a very high instantaneous wind share, the aggregated flexibility chart for the

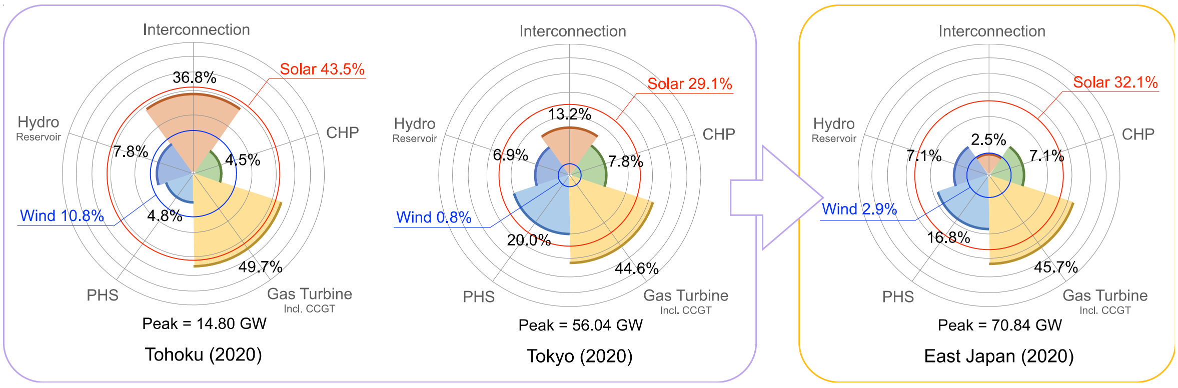

Fig. 20. Flexibility Chart of East Japan with two control areas.

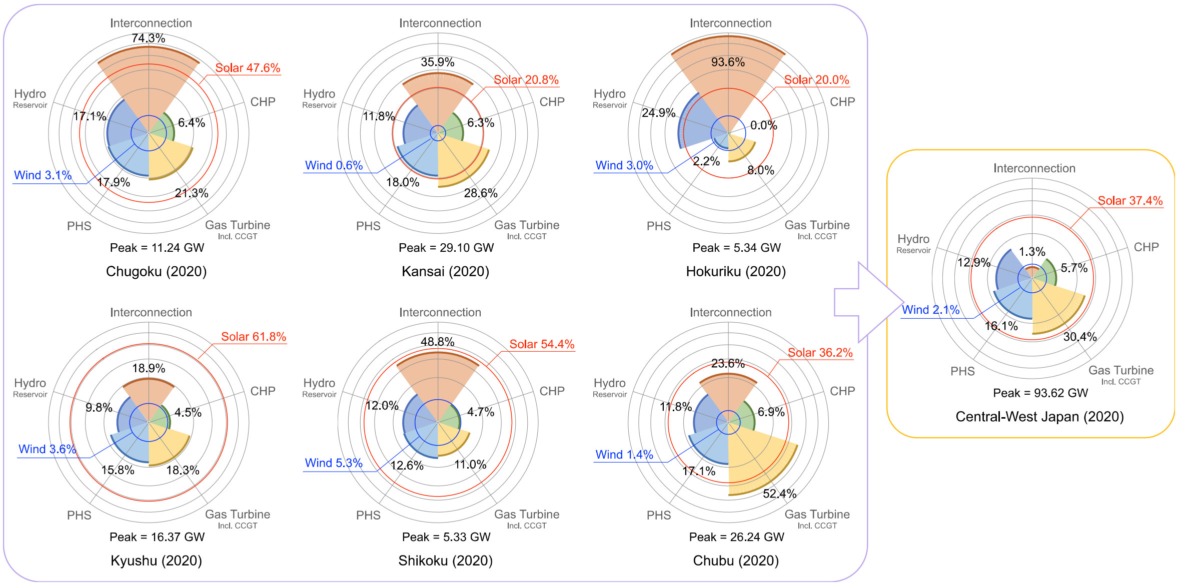

Fig. 21. Flexibility Chart of Central-West Japan with six control areas.

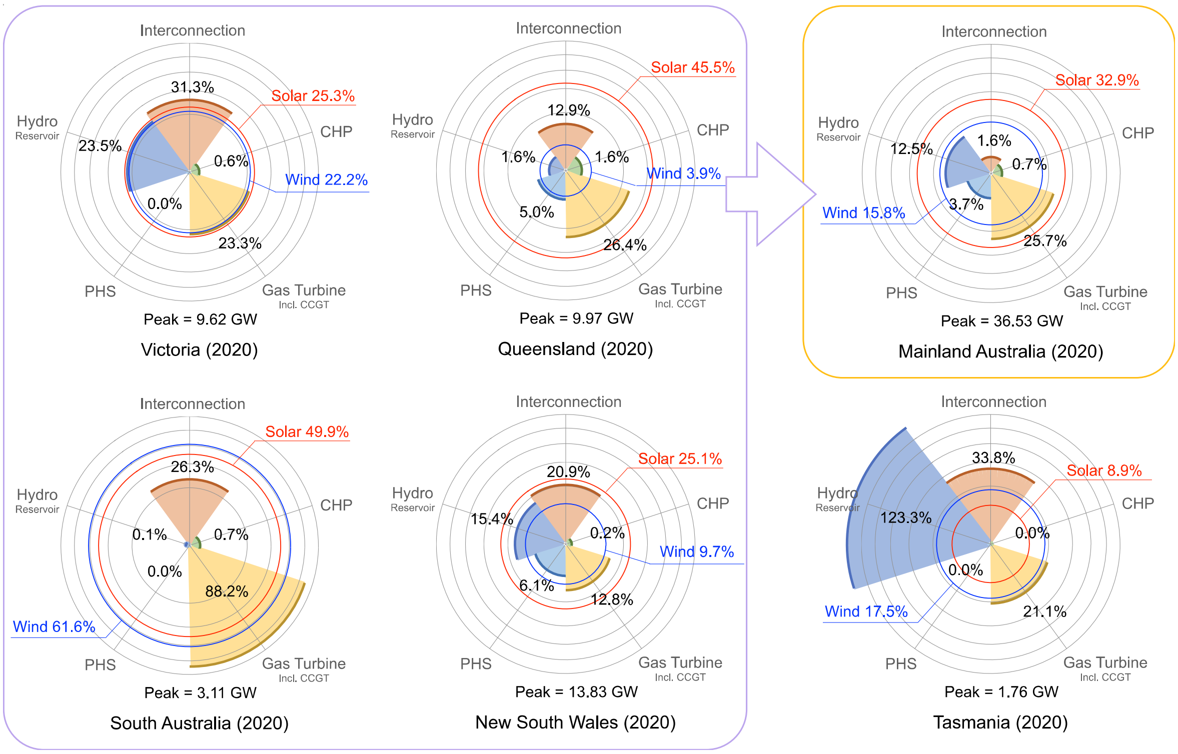

Fig. 22. Flexibility Charts for the five control areas in Australia and aggregated chart for the Mainland.

mainland shows that there is still significant headroom to accommodate wind and PV using existing flexibility resources. This means that flexibility resources from other areas, such as abundant hydro in Victoria, could help to manage high wind shares in South Australia via interconnectors with available capacity. Though the aggregated interconnection capacity, *i.e.* the total capacity to outside areas, in Mainland Australia looks too small, it this natural because the entire Australian power system is isolated from other continents and islands except an interconnector to Tasmanian grid.

4. Adding 6th battery axis

So far, the proposed flexibility chart has five axes, *i.e.* gas turbine, CHP, hydro reservoir, PHS, and interconnection, given that it is convenient to gather the required data from publicly available statistical reports. However, flexibility resource options are not limited to the above five. Although it is difficult to obtain national statistical data for demand side management (DSM) and new ESS, some countries/areas are starting to quantify their DSM capacity, and/or to install utility-scale batteries, such as Ireland, California and South Australia.

The proposed flexibility chart, of course, can integrate additional

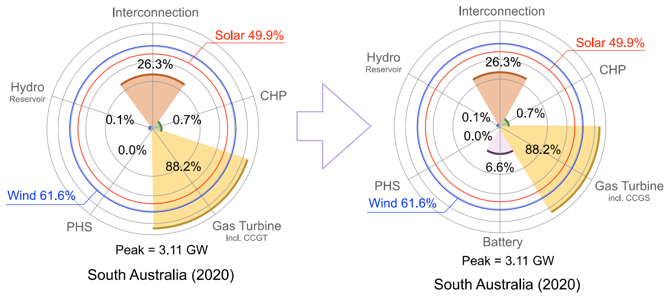

Fig. 23. Flexibility Charts for South Australia in 2000; (left) conventional description with five axes, (right) expanded version with additional battery axis.

flexibility options by adding additional axes. Fig. 23 shows an expanded flexibility chart with a 6th battery axis for South Australia. In the future, if sufficient statistics on demand side flexibility become available, a 7th axis, or more, could be added to the flexibility chart.

Historical changes to evaluate future flexibility resources with a 6th battery axis, in selected areas, will be discussed in the next section.

5. Evaluation of historical trend of flexibility charts

The Flexibility chart is intended as an “at-a-glance” and “easy-to-understand” tool in its original form. So, also, it is useful to trend historical change in the selected countries/areas using a set of flexibility charts. This section presents examples of the evaluation of historical change, focusing on several areas in the world as shown in Table 5. See Appendix for detailed data references.

Fig. 24 shows the historical change in flexibility charts for Ireland. The installed wind capacity in Ireland in 2011 was approximately 1.4 GW, before reaching 3.3 GW in 2017. The government of Ireland implemented “Climate Action and Low Carbon Development (Amendment) Act 2021” [29] and stated in the “Climate Action Plan 2021” that “Up to ~8” GW onshore wind and “At least ~5” GW offshore wind and “~1.5–2.5” GW solar PV will be installed by 2030 [30]. Thus, the calculated wind share is expected to be approximately 175% in 2030, as shown in the right chart. At the same time, the total interconnector capacity to other areas is expected to more than double after completing Greenlink Interconnector to Great Britain in 2024 and the Celtic Interconnector to France in 2026 [31]. Moreover, EirGrid, the TSO in Ireland expects that approximately 0.7 GW (hence 10.5% per peak) of utility-scale batteries will be installed by 2030 [32]. A trend of increasing flexibility resources in Ireland can be easily shown in the series of flexibility charts from past to future in Fig. 24.

As CAISO is now facing a challenging situation with a high solar share, and periodic constraining of transmission line power flows, due to risk of wildfires, PV and wind in California are expected to be increasingly developed. Currently, the total installed PV and wind capacity in 2030 is expected to be approximately 26 GW and 10 GW (approximately 50% and 20% of peak, almost double existing capacities). The Government of California plans to install 12 GW of utility-scale batteries, as well as additional hydro power plants and interconnectors [33]. The future flexibility chart drawn in Fig. 25 clearly indicates the role of batteries as an important flexibility option.

So far, Hokkaido, Japan, has not installed much VRE, and has not adopted an ambitious target. Nevertheless, according to current permissions under the FIT scheme, significant PV and wind power plants will be installed in the near future in Hokkaido [34]. The total installed PV and wind capacity by the mid-2020s is expected to be approximately 2.3 GW and 1.8 GW respectively (approx. 45% and 35% of peak demand). Fortunately, in Hokkaido, there have been ongoing plans to increase flexibility resources, including a newly installed gas turbine (first gas turbine in Hokkaido), PHS, and additional interconnector routes in

Table 5
Basic statistical data for historical trend of flexibility charts in selected areas.

Area	Year	Capacity [GW]									ratio per peak							
		Peak	Wind	Solar	Intercon-nection	CHP	Gas turbine	Battery	PHS	Hydro Reservoir	Wind	Solar	Intercon-nection	CHP	Gas turbine	Battery	PHS	Hydro Reservoir
Ireland	2011	4.64	1.39	0.00	0.30	0.30	4.03	0.00	0.29	0.00	29.9%	0.0%	6.5%	6.5%	86.8%	0.0%	6.2%	0.0%
	2020	5.36	4.30	0.04	0.80	0.30	4.23	0.00	0.29	0.00	80.3%	0.7%	14.9%	5.6%	79.0%	0.0%	5.5%	0.0%
	2030	6.67	11.70	1.50	3.00	0.30	4.70	0.70	0.65	0.00	175.4%	22.5%	45.0%	4.5%	70.5%	10.5%	9.8%	0.0%
CAISO, US	2020	54.84	6.19	11.78	2.43	8.95	35.14	0.00	2.18	5.73	11.3%	21.5%	4.4%	16.3%	64.1%	0.0%	4.0%	10.4%
	2030	54.84	10.29	25.91	5.00	8.95	35.14	12.14	2.18	5.73	18.8%	47.2%	9.1%	16.3%	64.1%	22.1%	4.0%	10.4%
Hokkaido, Japan	2017	5.25	0.39	1.33	0.60	0.30	0.00	0.00	0.80	0.71	7.4%	25.3%	11.4%	5.7%	0.0%	0.0%	15.2%	13.5%
	2020	5.41	0.53	1.97	0.90	0.30	0.57	0.00	0.90	0.71	9.8%	36.4%	16.6%	5.5%	10.5%	0.0%	16.6%	13.1%
	mid 2020s	5.41	1.89	2.46	1.20	0.30	1.14	0.15	1.00	0.71	34.9%	45.5%	22.2%	5.5%	21.0%	2.8%	18.5%	13.1%
South Australia	2017	3.10	1.81	0.12	0.82	0.02	1.86	0.10	0.00	0.00	58.4%	3.9%	26.5%	0.7%	60.0%	3.2%	0.0%	0.1%
	2020	3.11	1.92	1.56	0.82	0.02	2.75	0.21	0.00	0.00	61.6%	49.9%	26.3%	0.7%	88.2%	6.6%	0.0%	0.1%
	late 2020s	3.25	5.86	4.83	1.77	0.02	2.53	1.14	0.09	0.91	180.2%	148.5%	54.5%	0.6%	77.8%	35.0%	2.8%	27.8%

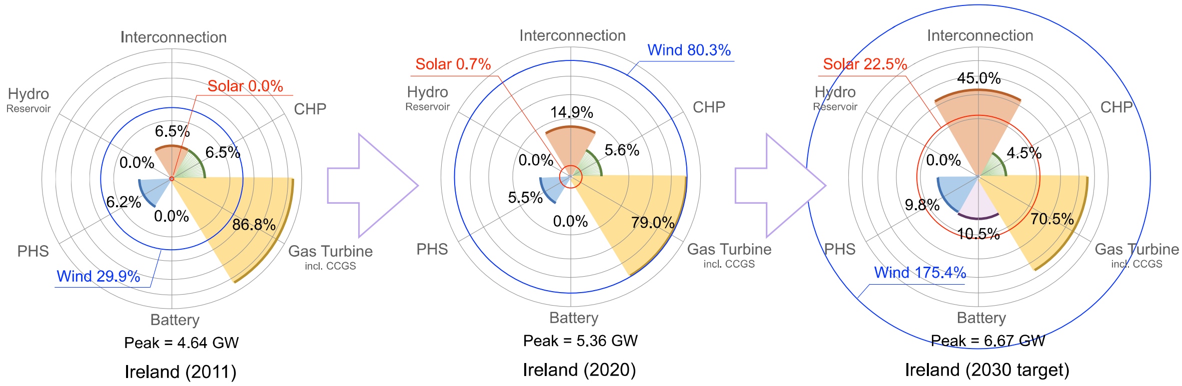

Fig. 24. Historical change of flexibility charts from past to future in Ireland.

the past ten to twenty years. The interconnectors have not been installed due to renewable growth, but rather, for other reasons, such as nuclear power (plans before Nuclear Disaster in 2011), and system resilience (plans after Blackout in September 2018). The estimated future flexibility chart in Fig. 26 shows that flexibility resources in Hokkaido will provide an almost ideal combination to accommodate more VRE. In fact, Hokkaido is expected to become the most promising area for wind development in Japan.

The last example considered here is that of South Australia. The South Australian Government has set an ambitious target for 2030, and AEMO estimates that approximately 6 GW of wind and 3.7 GW of PV will be deployed in the South Australian grid, whose peak is only 3.3 GW [35]. In South Australia, it is well-known that the world's largest battery power plant “Hornsdale Power Reserve” (100 MW) was installed by Tesla Inc. after the Blackout in September 2016. According to AEMO, plans to install several flexibility resource options are quickly

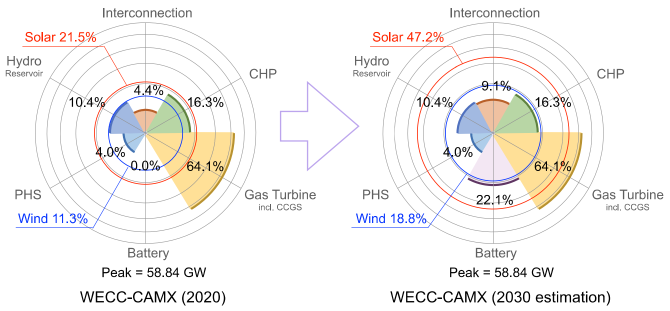

Fig. 25. Historical change of flexibility charts from past to future in California, U.S.

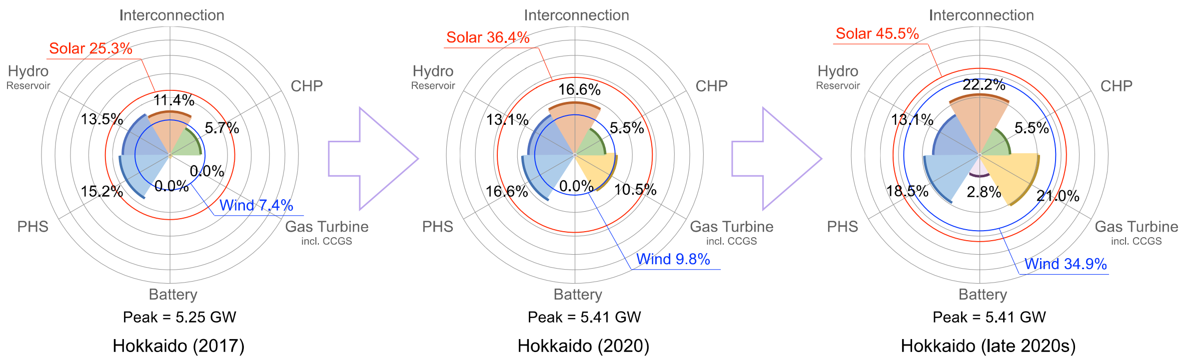

Fig. 26. Historical change of flexibility charts from past to future in Hokkaido, Japan.

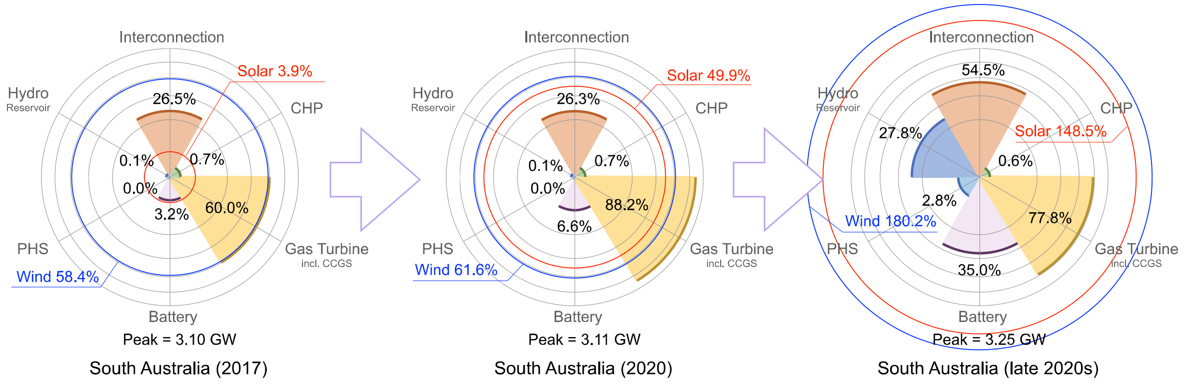

Fig. 27. Historical change of flexibility charts from past to future in South Australia.

Table 6
Summary of Flexibility Portfolios for different countries/areas.

	control area	**aggregated area**	**synchronous zone**
inter-connection-rich	Denmark-West, Denmark-East, German TSOs, Austria, Czechia, Switzerland, Slovakia, Slovenia, Croatia, Manitoba (CA), Hokuriku (JP), Chugoku (JP), Shikoku (JP)	Denmark	
CHP-rich	Finland, Denmark-West, Denmark-East, 50Hetz (DE), TransnetBW (DE), Czechia	Denmark, Germany	
hydro-rich	Norway, Sweden, Switzerland, Croatia, Manitoba (CA), British Columbia (CA)		Nordel, Québec (CA), Tasmania (AU)
gas-rich	Netherlands, Italy, Portugal, Spain, Ireland, Northern Ireland (UK), NPCC-NE (US), NPCC-NY (US), PJM (US), SERC(US), SaskPower (CA), MISO (US), SPP (US), Alberta (CA), CAMX (US), SRSG (US), RMRG (US), Chubu (JP), South Australia (AU)	UK, MRO	Great Britain (UK), All Island (SEM), WI (US), EI (US), ERCOT (US)
gas-dependent	PJM (US), SERC (US), SPP (US), SRSG (US)	UK	Great Britain (UK)
well-balanced	Sweden, 50Herz (DE), Austria, Italy, Spain, Portugal, Slovakia, Croatia, SaskPower (CA), Chubu (JP), Kansai (JP), Chugoku (JP), Ireland (2030 target), CAMX (US, 2030 estimation), South Australia (AU, late 2020s)	Germany, Iberia	Nordel, Hokkaido (JP, mid2020s)

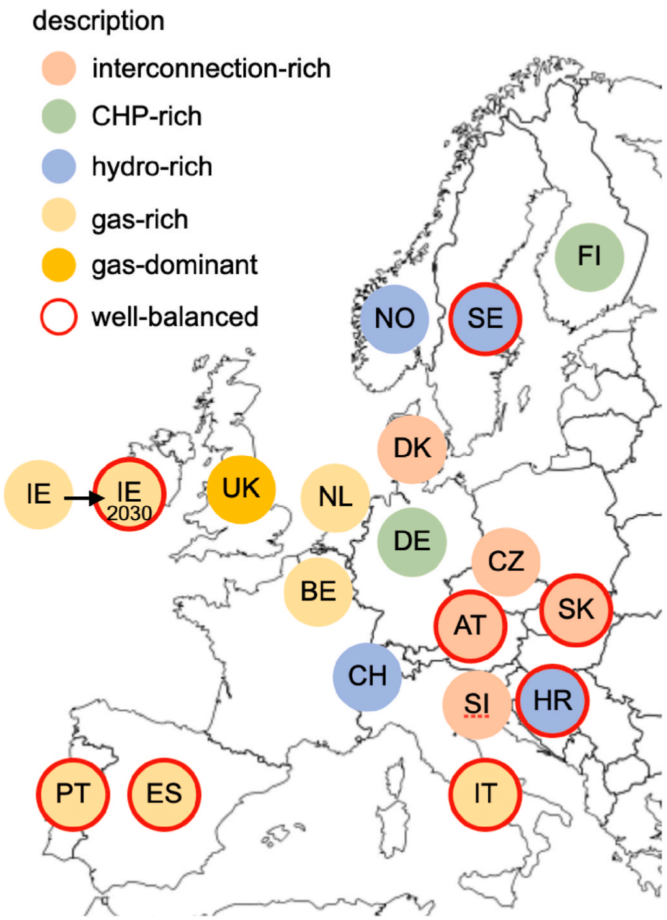

Fig. 28. Flexibility portfolio map for European countries (note: the dominant flexibility is shown for 2+ major flexibility options.).

progressing. The total installed capacity of hydro, interconnectors and utility-scale battery plants in the late 2020s is expected to reach approximately 0.7 GW, 1.7 GW and 1.1 GW (21%, 55% and 35%), respectively. This trend from past to future in South Australia can be visually observed in the set of flexibility charts shown in Fig. 27.

6. Discussions

6.1. Summary of evaluations of flexibility charts

The proposed flexibility chart is useful in illustrating the characteristics of a combination of flexibility resources in a given area to be evaluated for both geographic aggregation and historical trends. Table 6 presents a summary of the results from the previous sections. Figs. 28–31 are coloured mappings of the flexibility portfolios in countries/areas according to the classification defined in Table 6.

As a quantitative and objective criterion in this table, "X-rich" was defined as having the most dominant flexibility (X) ratio per peak of 50% or more, while "X-dependent" means an area which has no flexibility options of 10% or more, except for the dominant flexibility (X). In addition, an area with four or more flexible options with a ratio of 10% or more, and with the sum of the ratios of all flexible options being more 100% or more was defined as "well-balanced".

6.2. Future estimations and suggestions

While many countries/areas in the world depend upon gas turbines for their main flexibility option, others have multiple options such as interconnection, CHP and hydro reservoir. Some areas notably in the UK and US have one dominant option, *i.e.* gas turbines, for their flexibility resource, which means these areas may struggle to create additional flexibility due to the energy crisis after the Russian invasion of Ukraine in February 2022. As there is no direct dependence on Russian gas suppliers for the UK and US so far, an interruption of Russian supplies to Europe may indirectly affect these countries. The impacts have been seen in terms of gas prices, recognising interactions between regions. In general terms, when moving towards a low carbon future, the gas power

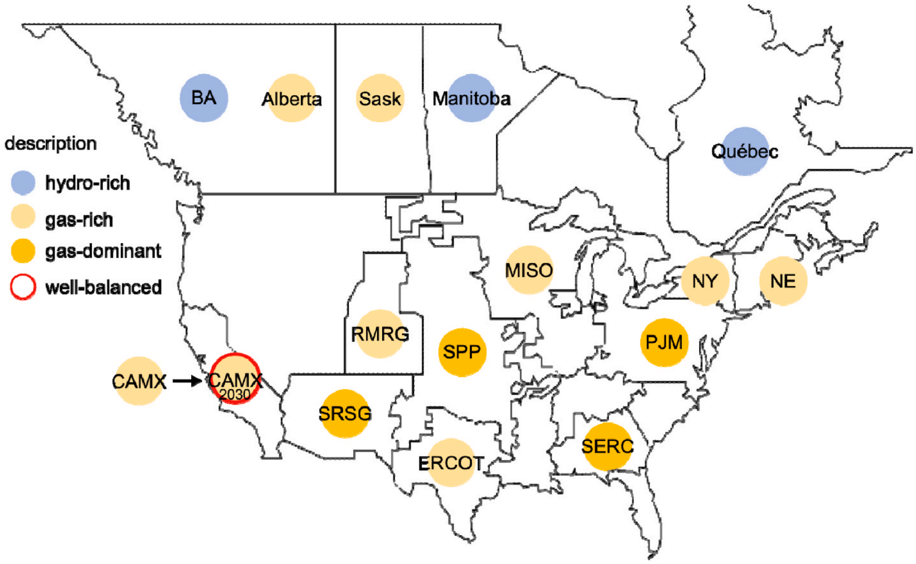

Fig. 29. Flexibility portfolio map for North American systems/states (note: the dominant flexibility is shown in colour when the country has two rich options.).

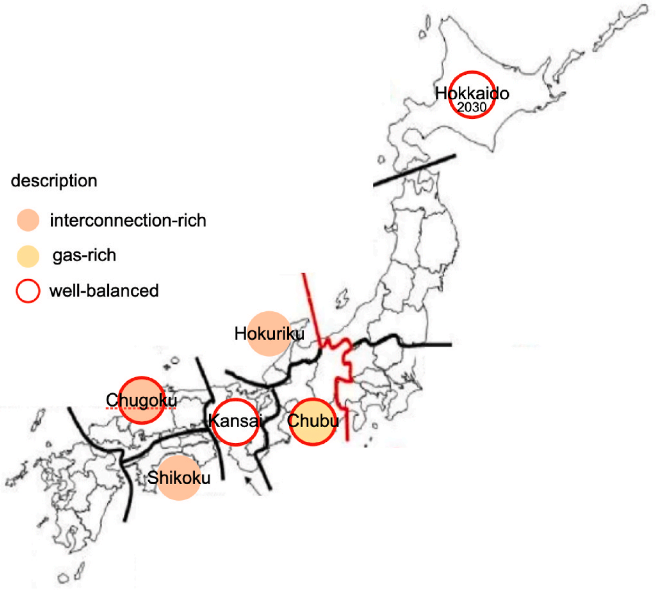

Fig. 30. Flexibility portfolio map for Japan.

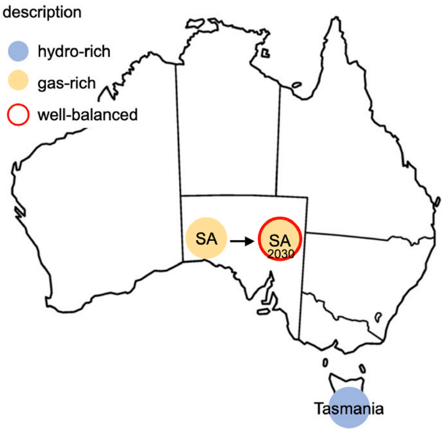

Fig. 31. Flexibility portfolio map for Australia (selected regions).

plants will be more and more operated as peakers, providing longer term flexibility and not so much used for short term flexibility, where other solutions such as interconnections, batteries, demand response, and renewables including wind and solar will dominate.

Countries/areas which possess well-balanced flexibility options at the present time can be considered to have significant potential to accept more VRE. Four areas, Ireland, CAMX, Hokkaido and South Australia, are noteworthy: these were once not rich in flexibility options, but in the near future are expected to succeed in ensuring well-balanced suite of flexibility resources, including battery options.

6.3. Implication for policy making and limitation of flexibility chart 2.0

The original aim of the Flexibility Chart was to create an “at-a-glance” tool to highlight the potentials of various flexibility resources in a given country/area for non-expert persons. The “flexibility” values given on the chart do not necessarily indicate the maximum potential to provide flexibility from a given option, but, rather, the flexibility chart is useful in providing the overall characteristics of existing flexibility resources in those countries/areas being evaluated.

Although the term “flexibility” is widely used and understood by power system experts, it can be a somewhat abstract idea, and may not necessarily be understood by experts from other fields, and by non-technical people, including journalists and policymakers. Even for technical experts, such as energy modelers and grid operators, they might underestimate or overlook the potential of flexibility resources within their own countries/areas. The proposed Flexibility Chart 2.0 clearly shows the potential contribution of individual flexibility resources, such as hydro power or gas turbines, and quantitatively indicates their potentials, as means of supporting non-expert understanding on how flexibility options can help to accommodate more renewables. Furthermore, the Flexibility Chart can enable comparison between countries/areas, as well as considering past and future capability for a given system as a means to support discussions on how to effectively realize ambitions for future power systems with (very) high shares of renewable.

While the Flexibility Chart presented here improves upon the previous iteration, the current version still has limitations. Flexibility Chart 2.0 neither incorporates temporal information for each flexibility resource, nor aims to do so. For deeper understanding, flexibility timescales could be considered, for example, with a separate plot for short-term (seconds to minutes), mid-term (hours to days) and long-term (weeks to seasons or longer) flexibility. Succinctly presenting information, including flexibility timescales for grid operations, to non-expert persons within a single chart is challenging, but important for scientific communication with citizens and the wide range of stakeholders. Other temporal aspect, such as seasonal variations in (hydro) energy supply, are perhaps better scrutinised in specialised tools, such as “FlexTool”, or a further evolution of the Flexibility Chart.

7. Conclusions

This paper introduced the “Flexibility Chart 2.0”, which was originally proposed in Ref. [11], and is considerably improved as a new version here. The features and usefulness of the new version are an “at-a-glance” and “easy-to-understand” tool to show how to estimate the potential of flexibility resources in a given country/area, even for non-technical experts.

Flexibility charts have been presented here for selected countries/areas, along with aggregated charts by synchronous area or country, including charts which show how flexibility resources have evolved over multiple years for several areas. The aggregated flexibility charts for Nordel (Fig. 6) and IGCC (Fig. 11) in Europe, Eastern Interconnection and Western Interconnection in North America (Fig. 17), North-East and Central Japan (Figs. 20 and 21) and mainland Australia (Fig. 22) are better-balanced, in terms of the range and volume of flexibility resources available, than the individual countries/areas that comprise the aggregated area, excluding interconnection. It can be understood that the dominant flexibility resource in some countries/areas contributes to the aggregated area via interconnection. The aggregated interconnection capacity is an exception to other flexibility resources since it is not formed as the sum of the individual capacities, but instead internal connections within an aggregated area are cancelled out. Consequently, although many of the aggregated flexibility charts appear to have low interconnection capacity, it does not necessarily follow that the total flexibility for the aggregated area is low. Additionally, some aggregated areas, such as UK and MRO in U.S. still depend largely on a single resource, *e.g.* gas turbines, for flexibility provision, with related future problems for such areas discussed.

The Flexibility Chart 2.0 is also a useful tool to compare the past and future. In this paper, several noteworthy areas like Ireland, California, Hokkaido in Japan and South Australia were evaluated drawing their Flexibiliy Charts for the past, current and future. Comparing the historical change of flexibility resources may not only be helpful to discuss energy policy with people in the country/area, but also to contribute to the discussion in other countries/areas where renewables have not been promoted yet.

As more data becomes available, emerging flexibility resources, such as battery storage and demand response, can be conveniently added to the chart. Expandability is also one of the remarkable features that the Flexibility Chart fundamentally has. The authors hope that the visual tool will help to contribute to consensus building in countries/areas where renewables have already been strongly promoted, as well as those where ambitious futures are now under discussion.

Credit author statement

Flexibility Chart 2.0: A simple tool to evaluate flexibility resources in various areas, **Yoh Yasuda:** Conceptualization, Formal analysis, Methodology, Investigation, Project administration, Resources, Writing - Original Draft, Visualization, **Enrico Maria Carlini:** Resources, Writing - Review & Editing, **Ana Estanqueiro:** Resources, Writing - Review & Editing, **Peter Børre Eriksen:** Resources, **Damian Flynn:** Resources, Writing - Review & Editing, **Lars Finn Herre:** Resources, Validation, Writing - Review & Editing, **Bri-Mathias Hodge:** Writing - Review & Editing, **Hannele Holttinen:** Data Curation, Project administration, Supervision, Writing - Review & Editing, **Matti Juhani Koivisto:** Resources, Validation, Writing - Review & Editing, **Emilio Gómez-Lózaro:** Resources, **Sergio Martín Martínez:** Resources, Writing - Review & Editing, **Nickie Menemenlis:** Resources, **Germán Morales-España:** Resources, Writing - Review & Editing, Validation, **Christoph Pellinger:** Data Curation, Resources, Validation, **Andrés Ramos:** Resources, Validation, Writing - Review & Editing, **Charlie Smith:** Writing - Review & Editing, **Til Kristian Vrana:** Methodology, Resources, Writing - Review & Editing, Validation.

Declaration of competing interest

Data availability

All the data used in this article are explicitly shown in Tables.

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Appendix. Corresponding Tables of References to Tables 1 – 5

As the statistical data to create flexibility charts in selected countries/areas in this paper vary so widely and is so complex, it is difficult to incorporate every reference to the corresponding data in Tables 1–5 This appendix shows the corresponding tables in Tables A1 to A5, where the reference number in each row and column corresponds to those in Tables 1–5, respectively.

Table A1
*Set of References corresponding to Table 1*3336373839404142

Syn. Zone		Country	Cont. Area	Peak	Wind	Solar	Interconnectio	CHP	Gas turbine	PHS	Hydro Reservoi
NORDEL		Norway		[36]	[37]		[33]	——	[39]	[36]	
		Sweden						[38] *1			
		Finland									[40]
	IGCC (as of 2016)	Denmark									
			Denmark East		[36]			---	[36] *2		
Central Europe			Denmark Wes								
		Germany	50 Hertz				[41] *3	[41], [42] *4			
			TenneT								
			Amprion								
			TransBW								
					[37]		[36]	[38] *1	[39]		
		France							[36] *2		
		Austria							[39]		
		Netherland									
		Belgium									
		Switzerland						——			
		Czech Rep.						[38] *1			
	IGCC (as of 2020)	Poland									
		Slovakia									
		Romenia									
		Slovenia									
		Croatia									
		Italy									
		Portugal									
		Spain									
Great Britain		United Kingdom							[36] *2		
			Great Britain		[36]			---			
All-Island (SEM)			Northern Irela								
		Ireland			[37]			[36] *1	[39]		

*3 As an ATC value cannot be obtained in German TSO's area, a half value of thermal capacity was substituted. *1 as of 2019 *2 may include steam turbine

*4 the sum of 4 German TSO's CHP dose not coincide with German CHP data because of different statistical sources.

Table A2

A Set of References corresponding to Table 2[4344454647484950515253545556]

Country		Syn. Zone	RR	Cont. Area	Peak	Wind	Solar	Interconnectio	CHP*3	Gas turbine *1	PHS	Hydro Reservoi
Canada		Québec		Québec	[43] *1			[44]	[45]	[43] *1		
	USA	EI	NPCC	Maritime				[46] *2	[47]			
				New England				[48] *3	[49] *4			
				New York								
				Ontario				[46] *2	[47]			
			RF	PJM					[49] *4			
			SERC					——				
			MIRO	MISO								
				SPP				[50]			[51] *5	
				Manitoba				[46] *2	[47]			
				SaksPower								
		WI	WECC	Alberta		[50]		[53]	[54]		[52]	
				British Colom				[46] *2	[47]			
				CAMX				[55]	[49] *4			
				NWPP								
				RMRG								
				SRSG								
		Texas		ERCOT				[56] *2				

*1 not actual value but estimation *2 as of 2017 *4 given by state and are not always equivalent with that in ISO/RTO's area

*3 as of 2019 *5 may include run-or-river

Table A3

A Set of References corresponding to Table 3[5758596061626364656667686970]

Country	Syn. Zone	Cont. Area	Peak	Wind	Solar	Interconnectior	CHP	Gas turbine	PHS	Hydro Reservoi
Japan	Hokkaido		[57]	[58]		[57]	[59] *1	[60] *2	[61] *3	
	East	Tohoku		[62]						
		Tokyo		[63]					[64] *4	
	Central-West	Chubu		[65]						
		Hokuriku		[66]					[61] *3	
		Kansai		[67]					[64] *4	
		Chugoku		[68]					[61] *3	
		Shikoku		[69]						
		Kyushu		[70]						

*1 as of FY2017 *2 may include steam turbine *3 as of 2019
*4 may include run-or-river

Table A4

A Set of References corresponding to Table 4[7172]

Country	Syn. Zone	Cont. Area	Peak	Wind	Solar	Interconnectior	CHP	Gas turbine	PHS	Hydro Reservoi
Austraria	Main land	Queensland		[71]		[72] *1	[72] *1	[71] *2	[72]	[71] *3
		NSW								
		Victoria								
		South Australi								
	Tasmania									

*1 nominal capacity as of 2017 *2 may include steam turbine *3 may include run-or-river

Table A5

A Set of References corresponding to Table 5[28303132[3233363839575859606173747576777879808182 83]

Area	Year	Peak	Wind	Solar	Interconnectior	CHP	Gas turbine	Battery	PHS	Hydro Reservoir
Ireland	2011	[39]			[36]	[38]	[39]	——	[75]	—— *1
	2030	[32]	[30]		[31]	—— *1	[76]	[32]	[76]	—— *1
CAMX, U.S	mid 2020s	—— *1	[33] *2			—— *1		[33] *2	—— *1	
Hokkaido, Japan	2017	[57]	[58]		[57]	[59]	[60]	——	[61]	
	late 2020s	—— *1			[77]	—— *1	[78]	[79]	[80]	—— *1
South Australia	2017	[81]	[82]		[72]		[83]		[73]	[81]
	late 2020s	—— *1	[28]		[83]	—— *1	[28]			[28]

*1 As data cannot be obtained, the same value as 2020 is assumed. ıd are not always equivalent with that in CAMX area.

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