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Flexibility Chart

Evaluation on diversity of flexibility in various areas

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***Abstract*— This paper evaluates various aspects of flexibility in power systems worldwide within the multi-country study framework of IEA Wind Task 25, including grid components and actions which have been favoured for enhancing flexibility in different areas/countries/regions, and how TSOs/ISOs/ utilities intend to manage variable generation in their operating strategies. One methodology to evaluate the diversity of flexibility sources is a "flexibility chart", which can illustrate several flexibility parameters (*e.g.* hydro, CCGT, CHP, interconnection) in a polygonal radar (spider) chart.**

Keywords- wind; variable generation, wind energy, solar energy, system flexibility; interconnection; Combined Cycle Gas Turbine (CCGT); Combined Heat and Power (CHP)

I. Introduction

Accessing sources of system flexibility is one of the most critical steps in achieving high penetration of variable generation, including wind and solar, at every power system scale; *e.g.* Transmission System Operator (TSO) / Independent System Operator (ISO) / utility operating areas, countries, and synchronous areas. Some countries have developed significant interconnection capacities to manage the variability and forecasting errors for wind and solar production, while others focus on national solutions such as increasing the share of combined cycle gas turbines (CCGTs) with very fast responses, or the share of dispatchable combined heat and power (CHP) plants, or the conversion of old hydro power stations to operate in the flexible pumped hydro storage mode (PHS). There is no 'silver bullet' or 'royal road' to ensure the flexibility in each system. Instead, flexibility options and solutions vary greatly, with different strategies being appropriate for different systems.

So far, several trials have been proposed to measure the flexibility of power systems; *e.g.* the International Energy Agency's (IEA's) GIVAR (Grid Integration of Variable Renewables) Project proposed the *Flexibility Assessment (FAST) Method* in their report in 2011 [1]. In [2], the 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]. These methods will be useful for quantitative estimation of flexibility in a targeted country/area.

A proposed "*Flexibility Chart*" [4] is employed to visualize the dominant factors and compare the variety of solutions in different countries/areas. The chart was designed as an "at-a-glance" graph that clearly shows the difference of flexibility strategies and provides an easy-to-understand tool, even for non-technical experts including journalists and policy makers.

According to the FAST method proposed by the IEA GIVAR [1], flexible resources are categorised into four types; dispatchable plant, storage, interconnection capacity and demand side response. In the present Flexibility Chart, five parameters are selected; penetration ratio in capacity (% of peak load) for CCGT, CHP, pumped hydro, hydro and interconnector capacity. As there are no reasonable measures to estimate the capacity of demand side management at the present time, the demand side flexibility is neglected in this analysis.

Note that CHP and CCGT plants cannot always operate as dispatchable generation with quick response. Some types of CCGT with a high operation temperature, especially many plants in Japan, are designed as base-load generation for very high efficiency operation. Therefore, it is necessary to distinguish flexible from inflexible CCGT plant to refine the analysis. Also, CHP plant cannot act as a flexible resource without communication links, which are required in several countries, such as Denmark and Germany. It is also difficult to distinguish reservoir hydro and run-of-river hydro from typical hydro data. Therefore, the capacity from hydropower does not always provide flexibility. To refine the analysis, further investigation should be carried out.

Even with the above qualifications, the flexibility chart is a very useful "at-a-glance" tool to select a strategy for how to prepare suitable flexibility resources in the selected country/area.

Using such charts, a comparison of flexibility trends in different countries is discussed in the remainder of the paper. Section II provides a somewhat "microscopic" viewpoint, with analyses at TSO/ISO/utility level and within specific countries (*e.g.* Denmark, Japan, US). In Section III a "macroscopic" investigation of aggregated synchronous areas across multiple countries (*e.g.* Iberian countries, Nordic countries) is presented. Comparison of these results for the above three levels of scale should provide some strategic insights for countries targeting a higher penetration of variable generation. Also, it is hoped that this tool might provide some inspiration and incentive for cooperation and coordination with neighbouring countries/areas.

Table I provides a guide to the flexibility chart analysis results discussed in the following sections.

II. Local to Regional Level Evaluation

In some countries, there are several TSOs/utilities (Germany and Japan), while in others there are several synchronous areas (Denmark, UK and Japan). In this section, the evaluation is focused on the local level, i.e. TSO/ISO/utility area.

A. Denmark

Until the year 2010, Denmark was electrically divided into two parts, each belonging to a different synchronous area. Since then, a DC link connects both systems. Eastern Denmark (Zealand) is still part of the former Nordic synchronous system (NORDEL), while Western Denmark (Jutland and Funen) is part of the continental European synchronous system (former UCTE).

Figure 1 illustrates the Danish flexibility charts including the two divided areas. Both charts show clearly that Denmark has set a high focus on the use of interconnectors to neighbouring countries. (94 and 87% per peak in Eastern and Western Denmark), with a high share of them being HVDC connections. This helps to balance Danish wind with Norwegian and Swedish hydropower A further special Danish feature seen here is that CHP is also a dominant parameter. CHP units work on market signals, which also contributes to increase system flexibility and balance wind power.

Both areas have similar general characteristics (see Fig. 1(b1) and 1(b2)), but the Western system has a higher penetration ratio of wind and more flexibility from interconnection and CHP.

B. Japan

Despite its narrow and long geography, Japan has nine utility companies in its four main islands, all of which are vertically-integrated electric utilities which own generators, transmission lines and distribution lines. Moreover, Japan has a unique electrical environment with three synchronous areas for historical reasons, two of which are Hokkaido Island and the East area operating with a system frequency of 50 Hz, with the third being the Central West area operating at 60 Hz. Interconnectors between adjacent utilities are generally inactive with a relatively small amount of exchange except for emergency situations, despite their significant capacities, especially in Central West Japan.

Table 1. Evaluation Level by Flexibility Chart

Local level (TSO/ISO/utility area)	Country level	Regional Level (Synchronous area)
Statnett SF	Norway (Fig.4(b1))	NORDEL (Fig.4(a))
Svenska Kraftnät	Sweden (Fig.4(b2))	
Fingrid	Finland (Fig.4(b3))	
Denmark-East (Fig.1(b1), Fig.4(b4))	Denmark (Fig.1(a))	
Denmark-West (Fig.1(b2), Fig.5(b1))		Central Europe (Fig.5(a))
4 TSOs	Germany (Fig.5(b2))	
RTE	France (Fig.5(b3))	
TenneT	The Netherlands (Fig.5(b4))	
Elia	Belgium (Fig.5(b5))	
TERNA	Italy (Fig.6(c))	Italian Peninsula
REE	Spain (Fig.6(b2))	Iberian Peninsula (Fig.6(a))
REN	Portugal (Fig.6(b1))	
3 TSOs	United Kingdom (Fig.7(a))	GB (Fig.7(b1))
SONI (Fig.7(b2))		All Island (Fig.7(d))
EirGrid	Ireland (Fig.7(c))	
Hokkaido	Japan (Fig.2(a))	Hokkaido Island (Fig.2(b1))
2 utilities (Fig.2(c1)~(c2))		East Japan (Fig.2(b2))
6 utilities (Fig.2(d1)~(d6))		Central West Japan (Fig.2(b3))
various ISOs	United States (Fig.3(a))	EI (Fig.3(b1))
various ISOs		WI (Fig.3(b2))
ERCOT	Canada	ERCOT (Fig.3(b2))
Hydro-Québec		Quebec

Fig. 2 shows the unique character of the Japanese grid. Japan is a completely isolated grid without international interconnection to neighbouring countries. Two of the three synchronous areas, East Japan in 50-Hertz operation and Central-West Japan in 60-Hertz operation, have quite similar characteristics.

Hokkaido Island, Fig. 2(b1), is an isolated 50-Hertz area with only a 600-MW interconnector to the Tohoku area and no CCGT capacity at present. To increase the flexible capacity in the short term, it is necessary to improve the usage of hydro power plants, including pumped hydro, and interconnections, as well as to make more effective use of flexibility from conventional coal-power plants, if possible. Construction of additional interconnectors and CCGT plants, as well as distributed CHP plants, would be a long-term target.

On the other hand, the Central-West area in Fig. 2(b3) has surprisingly rich interconnection capacity between the utilities within the area, some of which exceed 100% of peak load. Although it is thought in Japan that there is insufficient interconnection capacity to install a large amount of wind power, this fallacy is exposed after the detailed analysis with the flexibility charts in Fig. 2(d1)-(d6). Discussion of the appropriate usage of interconnectors, including policy and market schemes, is needed to accelerate wind integration.

Tohoku in Fig. 2(c1) and Kyushu in Fig. 2(d6) are some of the most windy areas in Japan. They have some similarities to each other, as well as to Germany and Portugal in Fig.s 5 and 6. This indicates that the two areas have good potential to access more flexible resources to accept more wind capacity.

C. US & Canada

In North America there are 4 interconnections: Western Interconnection (WI), Eastern Interconnection (EI), Electric Reliability Council of Texas (ERCOT), and Quebec. Of these, the first two span portions of the U.S. and Canada. ERCOT is totally contained in the U.S., and the Quebec interconnection is totally contained in Canada. See Fig. 3 for the US flexibility charts.

The Eastern and Western Interconnections are quite large, with peak demands of 760 GW and 118 GW respectively. ERCOT has a peak demand of about 68 GW. Because the Eastern and Western Interconnections are asynchronous, power between them is transferred via AC-DC-AC links. Thus import/export capability is somewhat limited. However, each interconnection spans multiple balancing areas, and each of them has unique transfer capability to neighbouring balancing areas within the interconnection. There are similar links between ERCOT and both the Eastern and Western interconnections. This transfer capability is also quite limited.

ERCOT operates as a single balancing area, which is unique in the U.S. There are approximately 37 balancing areas in the West, in addition to the balancing area operated by the California Independent System Operator (CAISO). In the East there are several large markets that operate as balancing areas, and there are also several smaller balancing areas in the Southeast that are not part of a centralized market. Analysis of the individual areas is beyond the scope of this paper, but other analyses of the flexibility reserve impacts of aggregation of balancing regions have been performed [10].

III. COUNTRY TO REGIONAL LEVEL EVALUATION

A power grid often covers areas wider than those of individual countries. A synchronous area may therefore include several countries combined with many interconnection lines.

A. NORDEL

Fig. 4 shows the flexibility charts of the former NORDEL area and participant countries/areas (Norway, Sweden, Finland, and East Denmark).

From the comparison between the charts, it becomes clear that two of the NORDEL countries (Norway and Sweden) have rich hydro capacity, while the rest have CHP-dominated flexibility. Also, it can be seen that all countries/ areas have adequate interconnection capacity to exchange flexibility with each other.

As the aggregated chart of the NORDEL area has less interconnection capacity, it is natural that such an aggregated wide area operates as a large isolated system itself, with few connections to neighbouring areas. However, it is clear that sufficient capacity from hydro and CHP are already deployed to provide significant flexibility in Nordic countries, which suggests more wind generation could be installed in this area and more flexibility could be exported to neighbouring areas.

B. Central Europe

The wide region of Central Europe (here, we consider "Central Europe" with five countries/areas; West Denmark, Germany, France, Netherlands and Belgium) is a part of the former UCTE area. The results of the flexibility chart analysis can be seen in Fig. 5.

From the analysis for this region, it is seen that Germany, Belgium and the Netherlands have a similar combination of flexibility that includes moderate CHP and CCGT capacities as well as significant interconnection capacity. France, as shown in Fig. 5(b3), seems to have the least flexibility.

The aggregated flexibility chart of this region suggests that comparably little capacity from various sources remains to provide flexibility. Appropriate strategies should be taken through the installation of CCGTs and CHPs in the mid-term. However, note that the present approach using flexibility charts can take neither transmission line bottlenecks within the area nor the geographical spread of wind sites into account. New interconnection lines to neighbouring regions are also very important in the long term. As part of the European strategy and policies, an increasing number of interconnections between European countries will be built, to complete the internal energy market (IEM).

C. Iberian Peninsula

The two Iberian countries, Portugal and Spain, both have similar tendencies (see Fig. 6), with relatively rich hydro and PHS, as well as CCGTs, helping to provide flexibility. There is a smaller CCGT ratio in Portugal than Spain, and a smaller ratio of interconnection capacity in Spain than in Portugal.

The aggregated chart of this (sub-)synchronous area has, as expected, less interconnection capacity, like an isolated system, but it still has a similar tendency to that of the two individual countries. This is because they have similar strategies to support renewables, including wind generation. In the Iberian Peninsula, a well-balanced combination of hydro and CCGTs is realised, and a higher penetration of wind capacity can be expected.

For reference, Fig. 6(c) shows the chart of another (sub-) synchronous area, the Italian Peninsula. It is interesting to note that both areas in the two peninsulas lying in southern Europe share similar flexibility characteristics, although the Italian grid has higher interconnection capacity to Central Europe.

D. UK & Ireland

The UK & Ireland also provide unique environments from the international power system viewpoint, where the UK is divided into two synchronous grids (Great Britain and Northern Ireland), while Ireland and Northern Ireland together constitute the All Island grid. The two systems are, however, asynchronously linked together by two distinct HVDC links. Both systems have high penetrations of CCGT generation. While GB has significant hydro and off-shore plus on-shore wind generation, in Ireland, on-shore wind-based renewables dominate, but also with some run of river hydro and even tidal stream. Pumped storage is an important flexibility source in both systems.

As can be seen from the charts in Fig.7, both countries (and also each sub-region) display a similar shape, due to the major influence of CCGT generation. HVDC interconnection has the potential to offer flexibility solutions, but due to economies of scale, the much larger GB power system tends to export power to the all-island Irish system. A range of new ancillary service products are being proposed in Ireland (including fast frequency response, synchronous inertial response, ramping margin) in order to enhance the flexibility of existing and new build generation [22]. Also, in GB much of the existing generation is in the north, while the load is mainly in the south, leading to transmission bottlenecks, a situation not helped by the (wind, hydro, wave) renewable potential in the north (Scotland).

IV. Conclusions

This paper described an international study on comparative analysis of flexibility in various countries/ areas/regions using the proposed *Flexibility Chart*. The flexibility chart is useful to illustrate the potential to provide flexibility for higher wind penetration for selected TSO/utility areas, countries, and aggregated synchronous areas.

From comparative analysis using the flexibility chart, the following conclusions can be made;

(1) The larger an aggregated area is, the less the (relative) amount of interconnection capacity becomes. This is natural and predictable, as a large synchronous area is similar to an isolated system with less interconnection towards the exterior. As larger areas can benefit from the smoothing effect of variability and uncertainty, many aggregated areas still have sufficient flexibility capacity from their dominant component, such as hydro or CCGT units. This suggests that there is sufficient room to install more variable renewable generation (VRG), including wind and solar in those areas in the short term, provided that the internal grid has enough capacity and connectivity, as the US interconnections and Nordic system illustrate.

(2) In the Nordic countries, the flexibility chart showed a sharply hydro-dominated character, which suggests that more wind generation could be installed in this area and more flexibility could be exported to neighbouring areas.

(3) Larger areas such as Central Europe show quite well-balanced flexibility chart components. Note that the flexibility charts cannot recognise a transmission bottlenecks. New interconnection lines to neighbouring region are important in the long term.

(4) In Southern European countries, namely Portugal, Spain and Italy, where the grids are effectively isolated systems because of their geographical peninsular configuration, it is clear that they have prepared themselves to operate as flexible power systems, as they rely on the combination of hydro, energy storage (e.g. PHS) and CCGTs to provide flexibility. It is therefore expected that more wind generation can be installed in the near future.

(5) As island systems, GB and Ireland present a different strategy to prepare for flexibility, with CCGTs being the dominant generation technology. In particular, the ambitious target by the Ireland government of 40% renewables generation by 2020 (≈37% wind generation) is set against the background of a small, isolated system with comparatively large generating units, and hence system flexibility is not a recent, or entirely wind-focused, concern.

(6) Although Japan has no international connections, it is clear that significant interconnection capacity has been installed between some Japanese utilities. There appears to be sufficient flexibility to install more VRE in the grid if the effort is made to change the policy and market schemes to handle variable generation.

Diversity is one of the keywords when one discusses the components of flexibility in highly developed wind countries/areas and how to plan for increased flexibility in those countries/areas that have the potential to have higher wind penetration in the future. In other words, there must be multiple appropriate approaches that can be suitable for each geopolitical environment to accept an increased amount of wind power in its grid. The authors hope that the approach in the present paper will help further detailed analysis regarding sources of flexibility in existing and planned systems.

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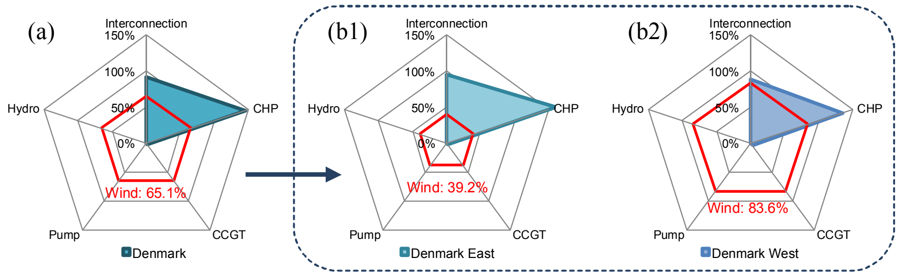

Figure 1. Flexibility charts of Danish grid with wind penetration ratio (% of GW per peak as of the end of 2011). (*All data from [5]. Note that the maximum value in each axis is different from the other charts in this paper.*)

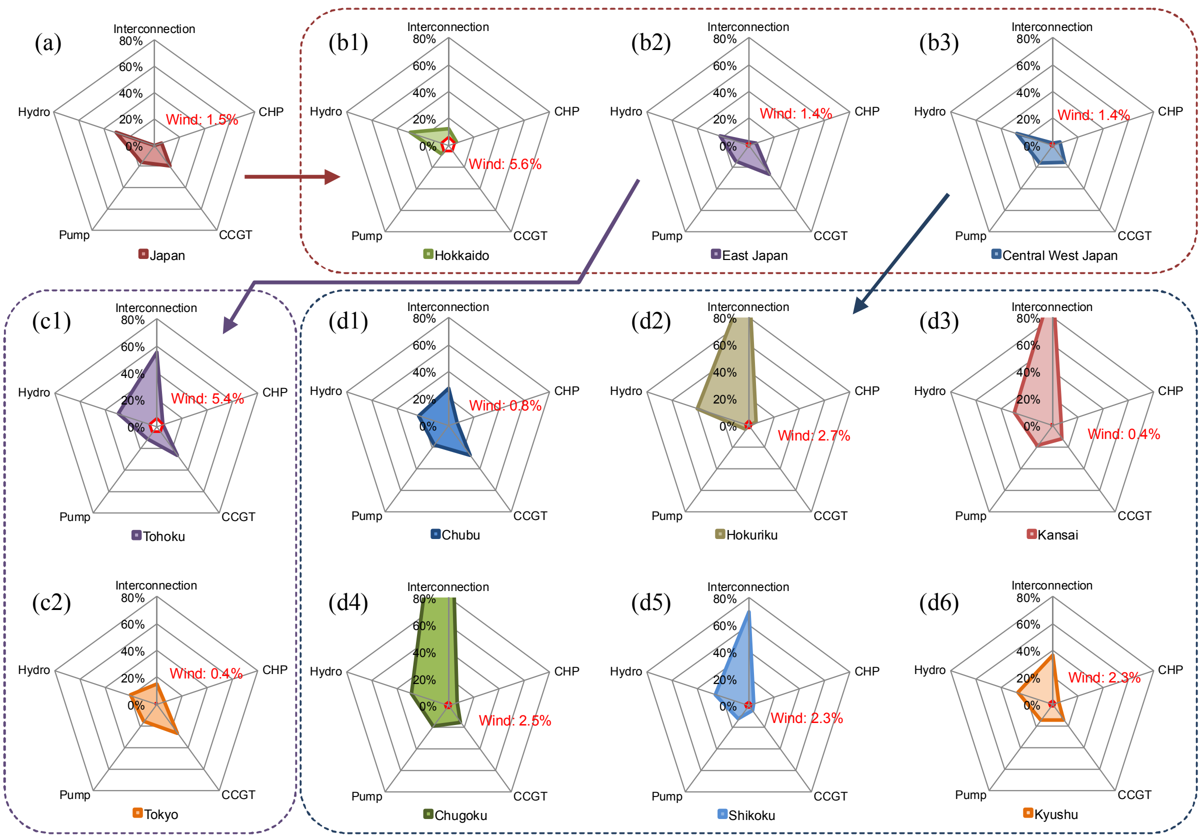

Figure 2. Flexibility charts of Japanese grid with wind penetration ratio (% of GW per peak as of the end of 2011). (*hydro, pumped-hydro, interconnection data from [6]; CCGT from [7]; CHP from [8]*)

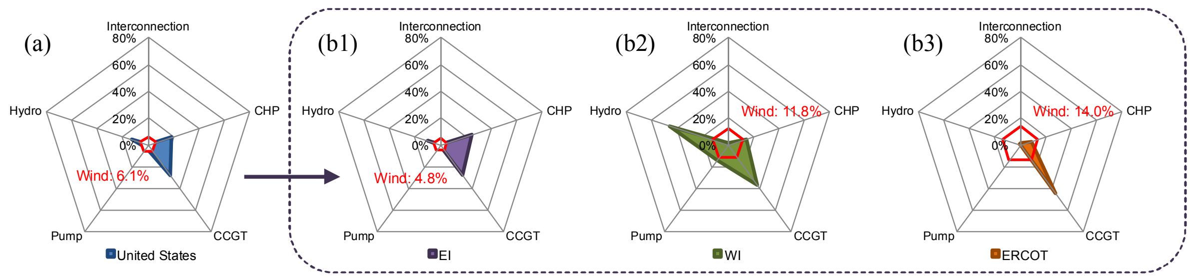

Figure 3. Flexibility charts of US with wind penetration ratio (% of GW per peak). (*All data from [9]*)

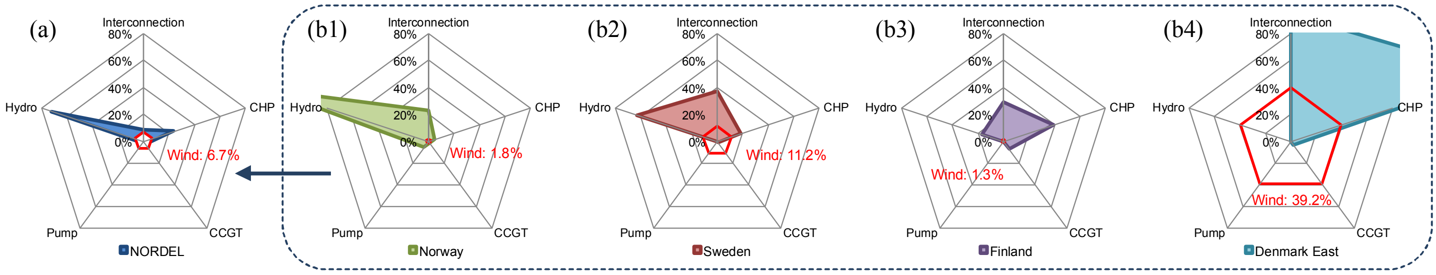

Figure 4. Flexibility charts of NORDEL area with wind penetration ratio (% of GW per peak as of the end of 2011).
(*Norwegian data from [11]; Swedish data from [12]; Finish data from [13] except CCGT data estimated by VTT; Danish data from [5]*)

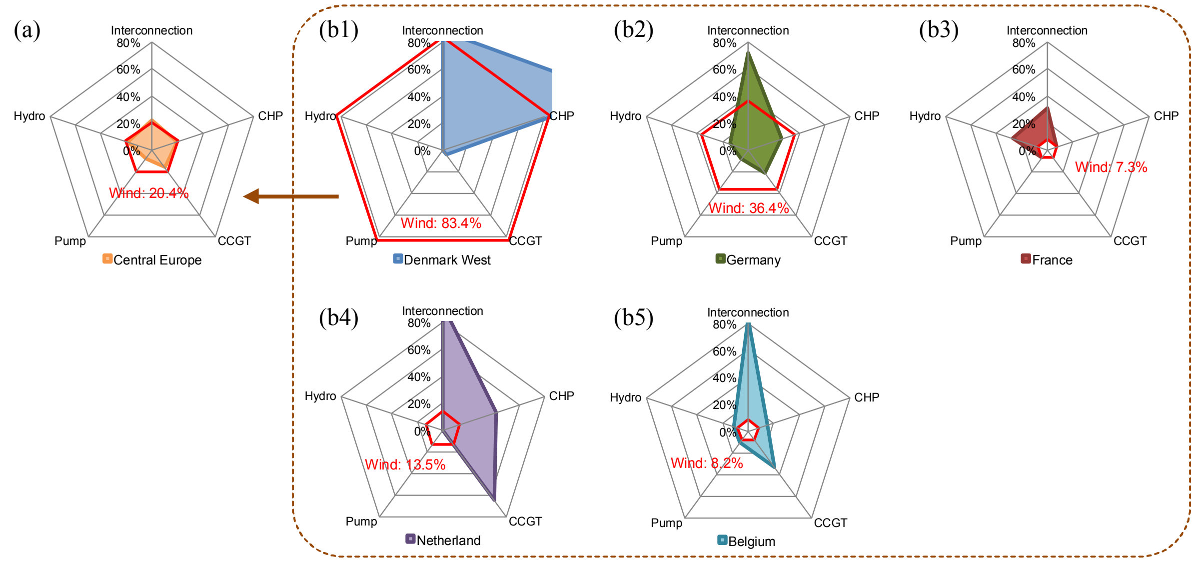

Figure 5. Flexibility charts of Central Europe region with wind penetration ratio (% of GW per peak).
(*hydro, pumped-hydro and CCGT as of the end of 2011 from [14] except German CCGT from [15]; interconnection as of 2008 from [16]; CHP as of 2008 from [17]. Note that French CCGT data is not zero but unavailable.*)

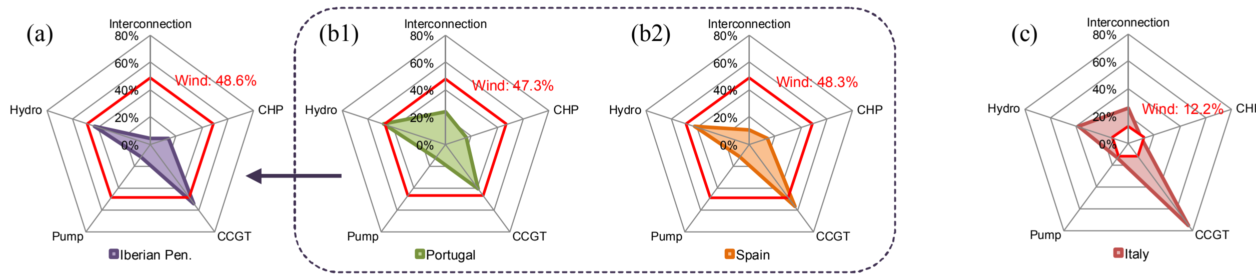

Figure 6. Flexibility charts of Iberian Peninsula as well as Italy with wind penetration ratio (% of GW per peak).
(*Portuguese data from [18], [19]; Spanish data from [14], [17], [20],[21], Italian data from [14],[17]*)

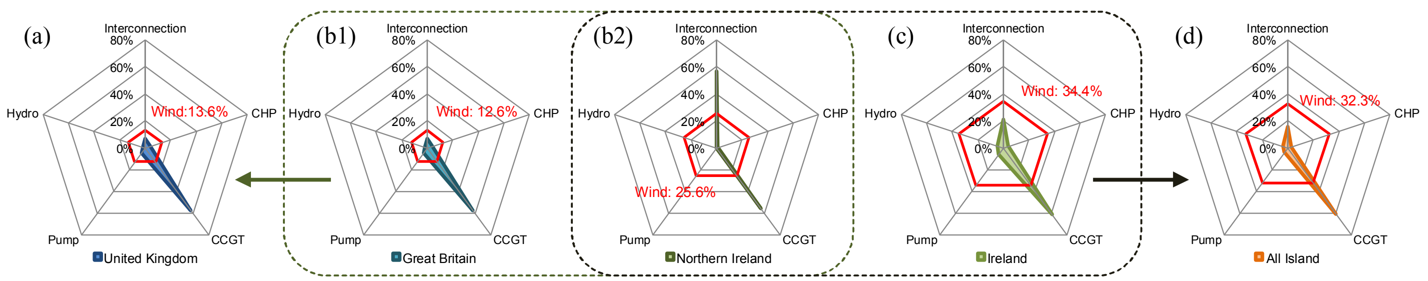

Figure 7. Flexibility charts of UK & Ireland with wind penetration ratio (% of GW per peak as of the end of 2011).
(*UK data from [14]; Irish data from [22]*)