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Power System Flexibility Tracker
Indicators to track flexibility progress towards high-RES systems

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Power System Flexibility Tracker: Indicators to track flexibility progress towards high-RES systems

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A B S T R A C T

Variable renewable energies (VRE), in particular wind and solar PV, constitute a key option to reduce global greenhouse gas emissions. Future policy scenarios therefore propose a dominant role for VRE. However, relying almost entirely on the stochastic weather-determined output of VRE will require a transformation of the way power systems are planned and operated: a growing amount of flexibility will be needed to match variable demand with increasingly variable supply.

Due to the complexity of power systems as well as their long investment cycles, it is crucial to prepare the strategic development of flexibility now. The key question for the transition to energy systems based on variable renewables becomes: “How can we ensure that future power systems have the flexibility needed to match demand and variable supply?” Power system operators and regulators need to assess the current flexibility level in their system, analyze all possible flexibility options, and clearly prioritize the needed actions.

This paper presents the Flexibility Tracker, an assessment methodology developed to monitor and compare the readiness of power systems for high VRE shares. The Flexibility Tracker builds 14 flexibility assessment domains, by screening systems across the possible flexibility sources (supply, demand, energy storage) and enablers (grid, markets), via 80 standardised Key Performance Indicators (KPIs) scanning the potential, deployment, research activities, policies and barriers regarding flexibility.

The methodology allows monitoring the progress made in individual power systems with respect to their potential for integrating VRE, comparing and ranking of different systems, and identifying best practices, common challenges and needed actions to enable and advance flexibility. It ensures that the complex flexibility question has a clear reference which looks at all relevant flexibility options, without being restricted to a single technology scope. As such it provides a useful instrument for market actors operating in multiple countries, as well as policy makers. As case study, the paper presents a comparative assessment of key European systems using this methodology. The results show that the although flexibility deployment depends on the specifics of each system, a coordinated approach would be beneficial as there are clear no-regret options that face barriers in some systems.

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1. Introduction

Mitigating climate change is a key challenge of our time. One of the necessary steps to keep the increase in the global mean temperature within acceptable bounds is reducing greenhouse gas emissions, which translates into the decarbonisation of the power sector. In this context, variable renewable energy (VRE) constitutes a key option to reduce global greenhouse gas emissions [1–3]. VRE sources are wind, solar PV, run-of-river hydropower, wave and tidal energy. As wind and solar PV are the predominant technologies, the term VRE is used to refer mainly to these two technologies. They are the fastest-growing source of electric power generation today and, in many circumstances, have already become cost-competitive with fossil-fuel-based generation [4,5]. In this respect, a dominant role of VRE in the future energy mix is expected, e.g. the

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scenarios of the Energy Roadmap 2050 of the European Commission consider that the share of renewable energy sources (RES) in future electricity consumption rises substantially, achieving at least 55% up to 97% in gross final energy consumption in 2050, from today's level at around 10% [6]. As RES become a cheap and reliable source of electricity, the key question arising in order to shift to VRE-dominated systems is related to the variable nature of these resources: “how to match variable demand with increasingly variable supply?”

In contrast to dispatchable conventional power plants, variable renewables have a stochastic nature, i.e. they are (directly) dependent on natural sources and weather. This makes their output variable over time and their exact output level uncertain until realisation. Relying almost entirely on such resources requires a transformation of the way power systems are planned and operated: a growing amount of *flexibility* will be needed. There are different ways to define power system flexibility in the literature, linking it primarily to system balancing: power system flexibility is the extent to which a power system can adapt electricity generation and consumption to maintain system stability [7]. The non-storability of electrical energy has dictated balancing as key design parameter of power systems. Flexibility is therefore an inherent feature of the planning and operation of power systems, which are designed to ensure spatial and temporal balancing of electricity generation and consumption at all times [7]. Flexibility comes in different forms and is relevant for various aspects of power system operation and planning as well as several time frames (from short term balancing of resources to long-term seasonal planning of the system).

Traditionally, power system flexibility has been provided primarily by conventional power plants at the supply side to the system. Introducing VRE in the system results into what we can call the “flexibility gap” due to two reasons. Firstly, VRE push conventional power plants out of the market as they take over a market share. This leads therefore to a reduction of the existing supply-side flexibility. Secondly, VRE increases the need for flexibility in the system due to the variable nature of these resources (the variability of net load is higher than the variability of load). The resulting flexibility gap needs to be filled by new sources of flexibility as schematically depicted in Fig. 1. Potential new sources of flexibility are demand-side flexibility, energy storage and new supply flexibility, which should be supplemented by the two key flexibility “enablers”: grid and markets. This reveals the tight relationship between VRE and flexibility: for the transition to higher VRE shares, VRE and flexibility options must come together, be perfect complements [8]. In this respect, we will here adopt an alternative notion of power system flexibility, linking flexibility directly to variable renewables, as “the readiness of systems to integrate higher VRE shares”.

Measuring the flexibility of a system and the adequacy of flexibility options is a non-trivial task. Instead of measuring flexibility, we often rely on signs of inflexibility which are visible today already, such as recurring severe frequency excursions, structural RES curtailment, high levels of re-dispatch, area control errors, negative market prices, price volatility, loss-of-load, subsidized overcapacity. The adequacy of flexibility options on the other hand depends on the nature and technical characteristics the different options, as well as the generic framework defined by the “flexibility enablers” (grid, market framework and policy). In general, as options and enablers are very different, their comparison is difficult. On the other hand, as they are highly interrelated, they directly compete for the provision of flexibility in the system, which creates situations where adopting one option could make other options obsolete.

Designing policy pathways for the development of the needed flexibility options is a very difficult task, requiring the mapping of existing options in the system and the development of policies to support the growth of new ones. Even though indicators on RES targets for a system are straight-forward (e.g. RES share in primary energy consumption), such targets on flexibility do not exist. A holistic and universal methodology is missing to allow the comparative assessment of all options and the strategic development of policy actions to guide the needed system transformation. This is the focus of the methodology presented in this paper.

The paper proceeds as follows: section two presents a literature review focusing on existing approaches to assess power system flexibility. In section three, the flexibility tracker methodology is introduced, illustrating the general approach, and presenting the specifics of the KPIs. The results of a comparative analysis for Belgium, Denmark, Germany, Italy, the Netherlands, Poland and Spain are presented in chapter four, focusing on the use of the methodology for the identification of best practices as well as common challenges. Finally, section five concludes.

2. Literature review - approaches to assess flexibility

Numerous studies have addressed the issue of an increased need for power system flexibility for VRE integration, among many others [9–14]. Several studies additionally tried to quantify future flexibility requirements [15] provide a review of related research results, while [16] examines the amount and types of flexibility used in 45 studies and the predicted electricity generation cost.

Several studies have an overall system-perspective, while other work focuses on specific aspects [17] examines the effects of

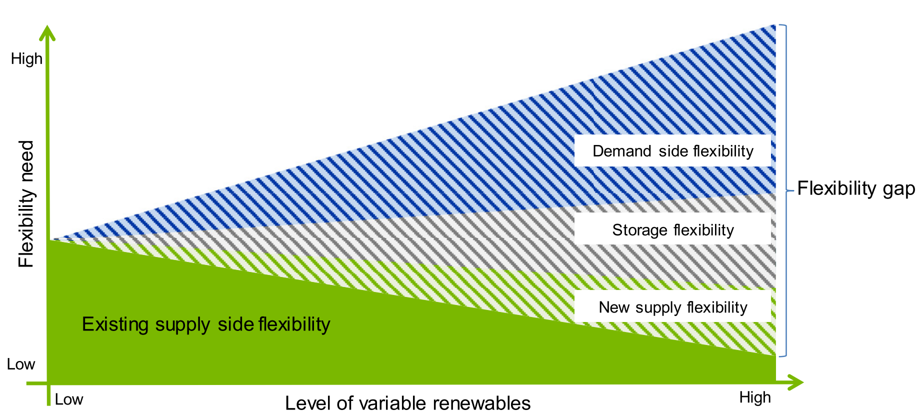

Fig. 1. The emerging flexibility gap. Source: [7].

variable renewables on residual load and derives long-term storage requirements [18] discuss needed backup generation in a 100% renewable scenario for Europe and examine how temporal (storage) and spatial (grid) flexibility options interact. On the demand side [19] analyze how flexible price signals may serve as effective demand control mechanism and find that it can reduce overall demand peaks. The general focus is on identifying options to increase power system flexibility and on defining possible pathways towards very high VRE levels. As key prerequisite, the studies identify that in order to cost-effectively progress to higher VRE shares, methodologies are needed to assess the flexibility of systems and the impact of different flexibility options.

There is no general methodology to measure power system flexibility. In recent years, however, a number of assessment concepts have been developed. They vary in approach as well as in complexity [20] provide an overview of some recently introduced frameworks. The flexibility chart by Ref. [21] is designed to provide an "at a glance" overview of technically available flexibility potential of a power system. It is a rather simple metric which compares available flexible capacity to peak load [22] have been among the first to propose a metric to assess flexibility for long-term/adequacy planning, the insufficient ramping resource expectation (IRRE), which reflects the expected number of observations when a power system cannot cope with the changes in net load. The authors further built upon this concept and developed further metrics to assess flexibility, e.g. the number of periods of flexibility deficit (PFD) method [23] and the flexibility assessment tool "Inflexion" [24]. The proposed metric is technical, focusing on system operation and planning indicators. The IEA's Flexibility Assessment Tool (FAST; revised version: FAST2) is another example of such a framework, developed by Müller et al. [12]. It measures the maximum upward or downward change in the supply/demand balance that a power system is capable of meeting over a given time horizon. Again, a technical metric is sought to assess the flexibility needs of the system. As discussed in Ref. [10], these assessments constitute important additions to the adequacy planning of systems, which should increasingly consider flexibility, shifting from the concept of "energy adequacy" in traditional systems to "flexibility adequacy" in future, VRE dominated systems.

The established concepts vary in the approach as well as in the adopted complexity, but all share one characteristic: they tend to focus on aspects that can be quantitatively measured, mostly technical characteristics, relevant to the broad topic of power system balancing, but unavoidably leave other aspects aside. However, it is important to assess the different facets of flexibility, on the one side the technical options referring to "hardware" solutions (flexible equipment such as generators, demand side response and energy storage) but also non-technical enablers such as grid, market, regulatory or policy frameworks, as they are highly interrelated. An example of the competing nature of development strategies of flexibility options and enablers is discussed in Ref. [25] for the case of the 'Smart Grid' local infrastructure development versus the 'Super Grids' large scale infrastructure development. The analysis shows that adding grid capacity jeopardizes the feasibility of Smart Grid technology investments and proposes a strategic zoning as a solution to avoid overlap and optimize investments. As discussed in Ref. [26], in the case of Germany, the amount of activated balancing reserves has decreased from 8 TWh to 2 TWh, at a period when the VRE shares increased from 13% to 33%. This seemingly paradoxical development is explained by the market design changes taken during this period, that released existing flexibility in the system. This is a typical example of how in systems flexibility can be available in "hardware" but is blocked due to the "enablers", i.e. inefficient market design.

It is therefore necessary to develop methodologies that can take a broader view on the assessment of system flexibility and include all options and enablers, combining technical and non-technical metrics. This is the motivation and goal of the flexibility tracker methodology presented in this paper. The methodology adopts a holistic approach, taking into account different aspects that influence the level of flexibility in a power system, in technical, market, regulatory and policy domains. It is based on a set of key performance indicators established on the basis of a top-down approach that enables a horizontal screening of systems keeping a balance between the level of detail and the needed effort to obtain meaningful results.

3. Method: flexibility key performance indicators

The methodology is based on a set of key performance indicators that are established in a top-down approach. The flexibility of a power system is measured by assessing five broad categories of flexibility options: supply, demand, grid, energy storage and markets (incl. regulation). While supply, demand and energy storage constitute actual sources of flexibility, grid and markets are key enablers of flexibility and as discussed are equally important.

The five categories are further divided into a total of 14 domains, see Fig. 2. These domains consist of a mix of quantitative and

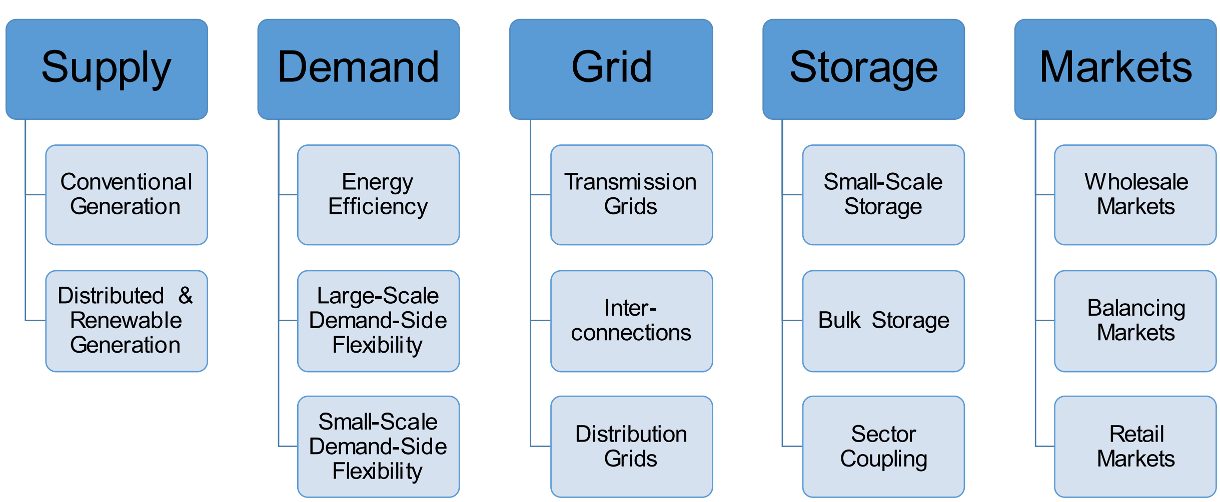

Fig. 2. Categorisation of the 5 flexibility options in 14 flexibility domains.

qualitative KPIs which cover the flexibility aspects related to the topic. These KPIs are inspired by the steps necessary in creating power systems with the flexibility needed to maintain stability and reliability during the transition to higher VRE penetration levels, as outlined in Ref. [8]. The key idea is that the more steps the systems have taken in this direction (the more KPIs fulfilled), the more ready they are to host higher VRE levels. The methodology consists in total of 80 kPIs, which are a mix of quantitative metrics, qualitative assessments and expert judgement that cover all actions needed for the transition to 100% VRE systems. Depending on the depth of the analysis, the KPIs can be obtained by extensive studies, or data analysis. This approach is the basis of rating the system flexibility. Table 1 provides an overview of the 14 flexibility domains, their relevance and the characteristics of the KPIs, showing the variation between qualitative and quantitative indicators. This variation is due to the inherent characteristics of the options.

At the current state of the Flexibility Tracker, KPIs are based on questions of quantitative or qualitative nature and address facts, barriers and incentives related to the respective system, as identified in strategic studies. Concerning the time frame, the questions focus on the current state of the power system, but also include the assessment of established plans. The general structure of the questions that form a KPI is as follows: One or more questions address the share of the available flexibility options of this area in the current system. They are complemented by questions that address future plans for further development and/or incentivization of the individual flexibility options as well as questions related to barriers that could potentially prevent the flexibility options from being harnessed.

This structure ensures a holistic assessment of all flexibility options while still being manageable. To make the assessment measurable the methodology is complemented by a bottom-up scoring system. The aim of the scoring system is to be simple and transparent in order to make the assessments as comprehensive and objective as possible. For each of the 80 KPIs, a score of low (0 points), medium (0.5 points) or high (1 point) can be achieved. In general terms, a higher score equals a better readiness for higher VRE shares. However, a medium score can result from different aspects. It can, e.g., mean that there exists a great potential in the specific flexibility domain and clear policy incentives are in place, but market barriers remain. The score of the individual KPI is then weighted based on expert consultation.

4. Case study: analysis of seven European systems

The methodology was applied to a set of European systems: Belgium, Denmark, Germany, Italy, the Netherlands, Poland and Spain. The countries were selected in a pragmatic manner to provide sufficient differentiation in size, population, structure of electricity supply, current share of renewables. To allow for some common basis, only countries in the EU, and more specifically the continental part, were selected which have a similar common EU legislative basis, and direct system operation and market integration interaction. While Denmark is very advanced already (60% RES-E) and Italy, Spain and Germany are at advanced stages of 30–40% RES-E, Belgium, Poland and the Netherlands are at lower two digit shares (11–21% RES-E). The analysis was performed in the basis of extensive analysis of data regarding the electricity system in the countries, complemented with dedicated workshops with country experts. The results of the analysis were collected in the flexibility tracker database and were organised based on the different KPIs and countries. Together with the individual scoring of each KPI, the analysis collected all information necessary to support the scoring decision. This allows to create the “flexibility profile” of each country, and to perform comparative analyses on the potential actions for improvement and key lessons learnt. In this respect, we present below the results across the two main dimensions: first the key learnings per country and second the key learnings per flexibility domain.

4.1. Comparative country analysis

When comparing the country analyses and assessment results, it becomes clear that the seven countries significantly differ from one another. This applies not only to the characteristics of their electricity systems, domestic resources and energy policies, but also to their different ways of managing the flexibility challenge.

Fig. 3 shows a cross-comparison of the flexibility domains for the seven countries in a scale from zero to five. Very different scores are visible, not only between countries, but also among the flexibility domains for the individual countries. In some domains – e.g. distributed generation & variable renewables, transmission grid, interconnections and wholesale markets – some countries are already very advanced and others lack, while in other areas, all countries have room to improve, e.g. in small-scale demand-side flexibility, balancing markets and small-scale storage.

4.1.1. Country analyses

Belgium's system flexibility progress is advanced regarding the implementation of demand response measures and regional grid interconnection. Price responsive demand in scarcity situations has been analysed in detail by the TSO and via grid user surveys (up to 1 GW), and is stimulated to enter reserve markets. Grid expansion plans are ambitious and demonstrate the value of interconnections to the relatively small Belgian system in the meshed European grid (6 GW interconnection on a total peak load 13 GW). Supply flexibility and storage is lagging, on the other hand.

The assessment results show the characteristic strengths of the Danish system. Its integrated approach with a strong grid, high supply-side flexibility and well-developed markets lead to high flexibility levels. To be more specific, **Denmark** is superior in enabling operational flexibility from conventional power plants, but also encourages a system-friendly development and operation of wind power. It utilises unmatched interconnectivity and an uncongested modern internal grid. There is a strong link to the heating sector as most thermal plants are CHP plants, and the coupled Danish wholesale market enables the integration and export of large amounts of wind power when available and the import of electricity when domestic sources are not sufficient. Areas where Denmark could develop further are balancing market, demand-side participation and energy storage.

Regarding the results for **Germany**, it becomes clear that the country's efforts are at an advanced stage in many areas relevant to power system flexibility. This especially applies to wholesale markets as well as to storage, grid, balancing markets and large-scale demand-side participation. In contrast, the flexibility in retail markets and on the supply side as well as the development of small-scale demand-side flexibility and sector coupling are areas in which Germany could increase its efforts and learn from other EU member states, e.g. Denmark. Recent publications by the German government take those shortcomings into account and plan to increase efforts in those directions.

Italy's power system flexibility is mainly provided by gas and hydro power plants at the moment, supported by a modern well-developed grid. Flexibility of the demand side is not developed yet, but there are plans to enable this option is the near future. Energy storage is of growing importance, and tested for grid management applications. The design of the Italian electricity markets is sufficient to meet current flexibility challenges and adapted to EU internal market principles. However, there is room

Table 1
Characteristics of the Flexibility domains and overview of the topics covered by the KPIs.

Flexibility category	Flexibility domains	Relevance of domain	Topics covered by KPIs
Supply	Conventional Generation	With increasing VRE shares, conventional generation faces lower market shares, lower market prices and needs to adapt to more fluctuations in net demand.	• Operational flexibility of conventional power plant fleet • Plans to phase out inflexible generation • Incentives for flexible generation • Generation and flexibility adequacy from all resources
	Distributed Generation & Variable Renewables	Increasing capacities of VRE and DG units are installed in distribution grids. It is important that policies support their development and diversification, so that their integration does not pose a threat to the system. In this context, they also need to take up responsibility and provide system services themselves.	The flexibility inherent in this domain is influenced by a series of aspects, including: • Shares of DG & VRE achieved • Related development plans • Diversification of VRE • Dispatch rules • Forecasting methods • Incentives for geographical and technological diversification
Demand	Energy Efficiency	Not only do improvements in energy efficiency reduce the need for flexibility as they reduce the total load level, but also the interaction of energy efficiency and flexibility will increase in the future. Due to variability of VRE, the value of efficiency measures obtain a temporal component.	• Assessment of energy efficiency measures and future plans
	Large-Scale Demand Side Flexibility	Industrial DSM potential is the most easily accessible due to already existing controllability, often included storage component, load size, network level and rational behaviour of the end-user.	• Potential • Programmes • Participation in wholesale & balancing markets
	Small-Scale Demand Side Flexibility	Demand side management (DSM) constitutes a key potential of low-cost flexibility when operating a system with increasing VRE shares. Future power systems will not be centred around the task to cover the current demand but around the task to operate the system with the currently available VRE in the most efficient way.	• Share of households with smart meters • Programmes • R&D demos • Aggregators • EV share, eHP share • Incentives for flexible demand
Grid	Transmission Grids	Transmission grids are a crucial asset of power systems, a key flexibility enabler and the only option for the spatial balancing of supply and demand.	• Level of congestion • Grid development plans • TSO/DSO coordination • Advanced control measures
	Interconnections	The interconnection of power systems to larger regional clusters can have great benefits, increase flexibility as well as balance out VRE output, as geographical smoothing effects occur.	• Cross-border transmission capacity • Expansion and optimization plans
	Distribution Grids	Distribution grids will play an important role in future electricity grids as increasing levels of distributed generation and prosumers alter the conditions on low voltage levels and are key to enabling local flexibility.	• Capability for monitoring and controlling network • Smart system implementation • R&D • Allowance to procure local flexibility
Storage	Small-Scale Storage	Small-scale storage installed in distribution grids is an interesting flexibility option on the local level.	• Implementation, plans and incentives for small-scale storage
	Large-Scale Storage	Long-term energy storage becomes a vitally important source of flexibility when VRE reach the highest penetration levels.	• Level and further potential of bulk storage
	Sector Coupling	Sector coupling is a great source of power system flexibility, especially in the context of increasingly frequent situations of surplus energy.	• Status and plans for sector coupling
Markets	Wholesale Markets	Appropriate market design is a key enabler of existing flexibility and future investments.	• Temporal resolution: gate closure times, product lengths • Market coupling • Removal of price caps • Liquidity of markets • Spatial resolution • Market barriers
	Balancing Markets	In addition to wholesale markets, balancing markets are of great importance to enable short-term flexibility.	• Temporal resolution: gate closure times, product lengths • Minimum bid size • Allowance of aggregators • Cross-border exchange • Removal of price caps
	Retail Markets	The implementation of dynamic electricity tariffs for end-consumers are a key element to incentivise demand response. Vice versa, tariff structures with large regulated components offer low incentives to adapt consumption patterns.	• Regulation of prices • Dynamic tariffs

for improvement, which is being tackled by current market reforms.

The Netherlands' system flexibility progress is advanced regarding the implementation of interconnection and electric vehicle usage. The development of VRE-based electricity in the Netherlands remains a challenge, being hindered by inconsistent incentives and policies. As a result, flexibility options and grid infrastructure have not developed very quickly. However, the recent RES auctions might give a boost for further development.

The Polish power system scores lower in most areas compared to Denmark and Germany. It has a drastically lower score regarding energy efficiency, small-scale DSM, its grid as well as the wholesale

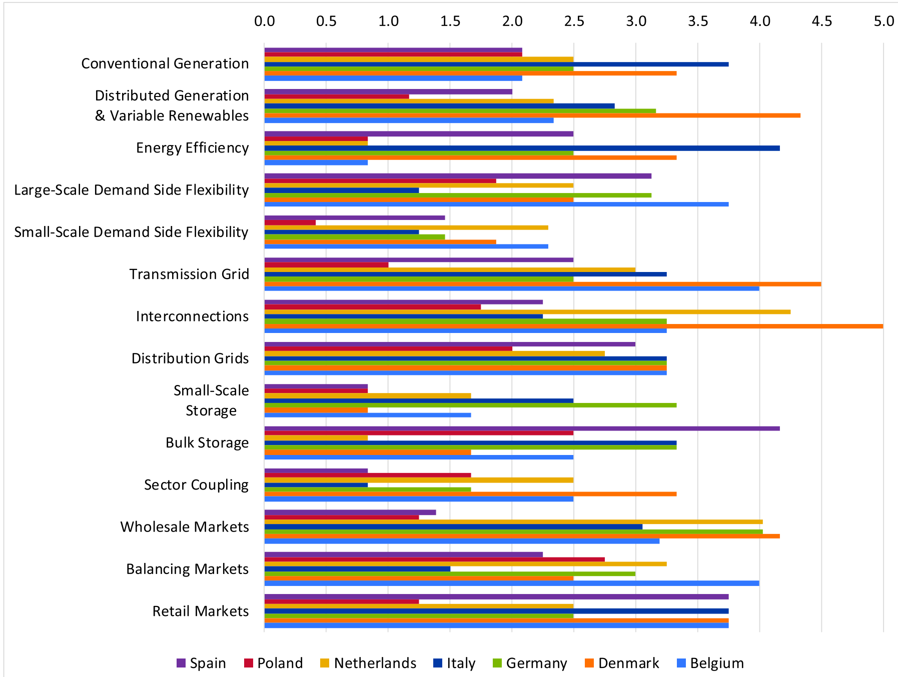

Fig. 3. Comparative country scoring per flexibility domain.

and retail markets. Exemptions to this trend are balancing markets, sector coupling and storage. Of course, **Poland** has a significantly lower share of VRE in the system, too, and therefore might not need as much flexibility as Denmark for instance. However, the scarcity situation in August 2015 shows that systems with low VRE shares also have flexibility needs.

Spain's system flexibility progress is medium with regards to all five categories. In the supply side, there is still a large fraction of inflexible conventional generation and demand response is largely undeveloped. There have been substantial improvements in transmission grids, however, international interconnections are still insufficient. While bulk energy storage is well developed, small-scale distributed storage is negligible so far. The adoption of best practices from other EU countries could improve wholesale market operation design towards enabling greater flexibility.

4.1.2. Comparative analysis

Figs. 4–6 present the results of the comparative country analysis. The results show that no general pattern of flexibility provision can be identified for the set of countries. Instead, all countries are found to pursue individual strategies. Still, it is possible to identify some common trends and similar scores. All seven countries rank similar with respect to distribution grids, conventional generation, balancing markets and demand-side flexibility. These similarities point to structural challenges that do not seem to be so urgent, but will likely become more relevant at higher VRE shares.

Furthermore, in almost all areas there is at least one country that already does very well. This offers potential for an identification and exchange of best practices. While Denmark can be a role model in grid development (especially interconnection) and supply-side flexibility, Belgium could share best practices relating to balancing markets and the deployment of demand-side flexibility.

Other areas, such as wholesale markets, should be subjected to a more differentiated analysis. There are a number of countries that already have established well-functioning wholesale markets, but they still possess very different characteristics and the reasons for their good scores in this analysis differ. This is shown in the detailed country assessments of this analysis, but has also been pointed out by a recent study [27]. In the context of increased regional cooperation and the drive for an internal energy market in the EU, a further harmonisation and optimization of wholesale and balancing markets as well as their opening to new actors, incl. distributed resources across Europe seems to be a promising no-regret option, i.a. to increase the provision of power system flexibility.

In conclusion of the comparative country comparison, it can be said that the countries pursue individual approaches to cover their flexibility needs. Differences are partly due to prevailing conditions in each country, e.g. favourable geographic conditions for the development of pumped-storage plants. In addition, implemented regulation and mechanisms for flexibility provision play a role. These are the areas where countries can learn from one another, identify best practices and adapt them to their own system. The comparative assessment reveals how each flexibility KPI points on a different flexibility pathway. Low priority KPIs can be seen as options which need further development. A low KPI may mean that it simply has not been seriously considered, or that it does not represent a cost-effective pathway. Hence, the interpretation of the comparative analysis should be that high KPIs reveal best practices for other countries, while low KPIs mean that further review is needed on cost effectiveness (and possibly more incentivization).

4.2. Consolidation of results across the 14 flexibility domains

Parallel to the individual approaches towards the flexibility challenge of the assessed countries, the characteristics of the different flexibility domains vary significantly. This section highlights the relevance of the 14 flexibility domains as well as best practices in the areas.

4.2.1. Conventional generation

Conventional generation is the traditional source of power system flexibility. It is still the dominant flexibility source in most

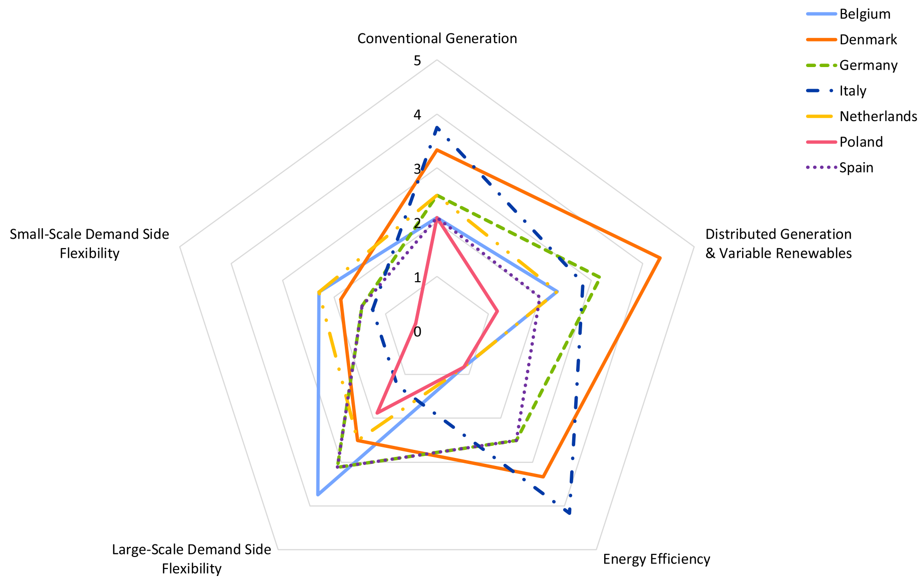

Fig. 4. Comparative country scoring for supply and demand side flexibility domains.

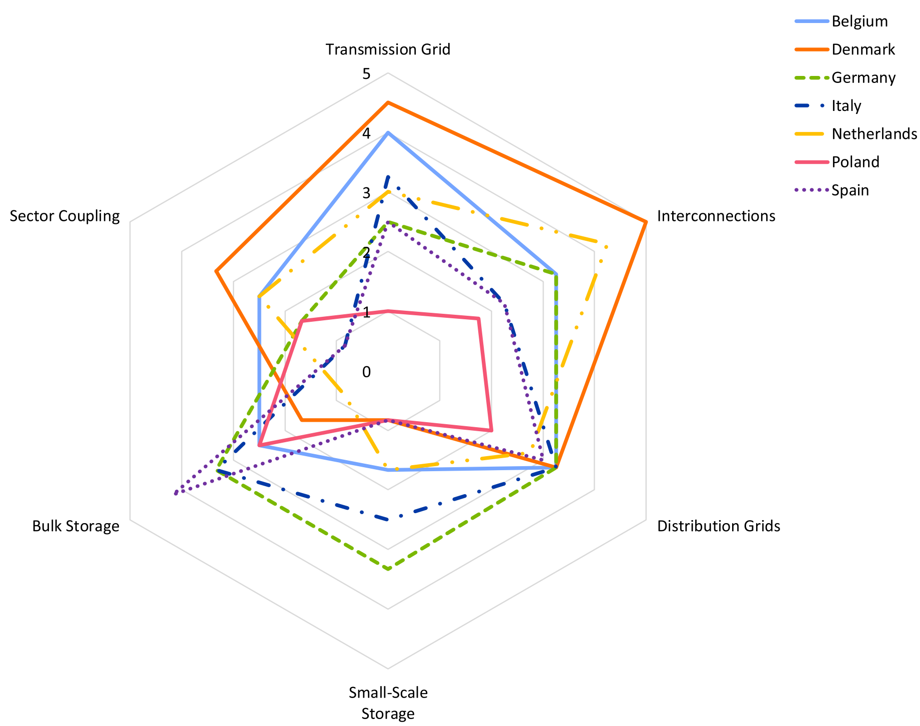

Fig. 5. Comparative country scoring for grid and storage flexibility domains.

systems, yet, its role will change dramatically. Apart from the structure of domestic resources, the flexibility of conventional generation is largely determined by regulation and market design. Italy and Denmark are great examples to highlight these two sides. While Italy is very flexible due to the fuel type of its power plants (i.e. gas), Denmark's coal-dominated power plant fleet is flexible due to political will and visions, coherent regulation and consequential technological and operational improvements over the last decades. The Danish approach is a case of a best practice that is well transferrable to other countries and circumstances and may prove to be attractive for many systems, as it also strengthens the link between the power and heating sector.

4.3. *Distributed generation & variable renewables*

The provision of flexibility by VRE itself will become more important with growing RES shares. VRE have matured over the past years and are increasingly dispatched based on market signals. They begin to provide system services in some places. Again, a positive example is Denmark. Other countries with good practices are, e.g., Germany and Italy, where first pilot projects have been implemented. However, regulatory barriers for a greater participation of distributed generation and especially variable renewables in balancing markets remain in many countries.

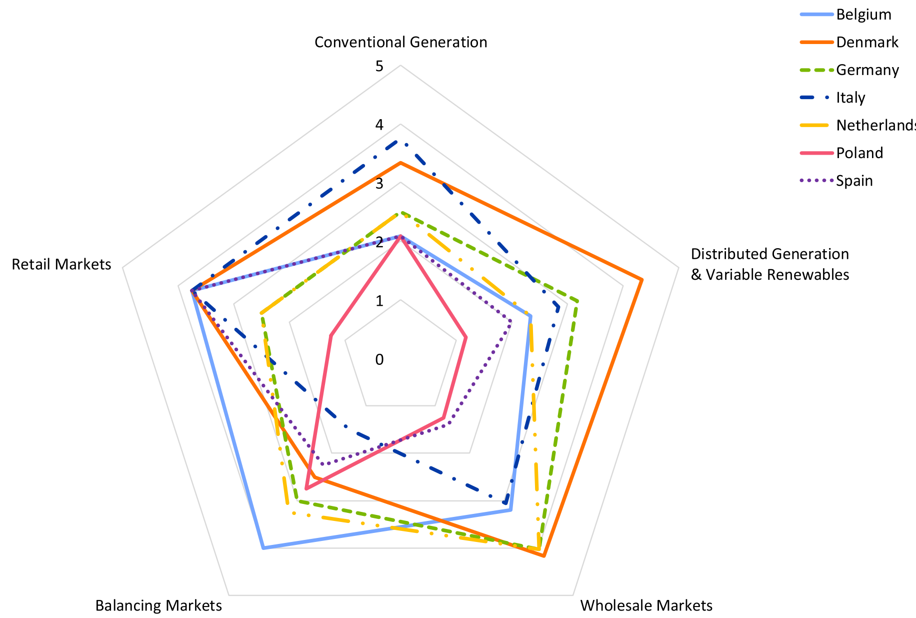

Fig. 6. Comparative country scoring for supply side and market flexibility domains.

4.3.1. Energy efficiency

Although not immediately obvious, energy efficiency influences power system flexibility. Not only do improvements in energy efficiency reduce the need for flexibility as they reduce the total load level, but also the interaction of energy efficiency and flexibility will increase in the future. Due to variability of VRE, the value of efficiency measures obtain a temporal component and turn into flex-efficiency [28]. This will become significantly more important at higher VRE levels.

4.3.2. Large-scale demand-side flexibility

Large industrial consumers, such as steel and aluminium mills, constitute the greatest and often also most cost-effective demand-side flexibility potential [29–31]. Making their potential accessible to the relevant markets can be a great source of low-cost flexibility. However, numerous barriers still exist in most countries that hinder greater demand-side participation. These are mostly technical requirements and low compensation.

Despite the low implementation level of demand side flexibility in many countries, there is significant potential in most countries which will likely be untapped as VRE shares are increasing. Belgium is a best practice example.

4.3.3. Small-scale demand-side flexibility

Households and small applications are another source of demand-side flexibility. The trend towards electrification in the heating and transport sector is leading to additional new demand that can be utilised as flexible load. Given the increasing roll-out of smart meters and the introduction of dynamic electricity tariffs, we will most likely see more small-scale demand-side participation in Europe within the next decade.

4.3.4. Transmission grids

Transmission grids are a crucial asset of power systems and a key flexibility enabler. A well-developed uncongested grid can be a great enabler of flexibility, as experience e.g. in Denmark shows. A congested grid with delays in development, in turn, can lead to serious problems and RES curtailment, as can be seen e.g. in Germany.

4.3.5. Interconnections

The interconnection of power systems to larger regional clusters can have great benefits, increase flexibility as well as balance out VRE output, as geographical smoothing effects occur. The significance of this flexibility option is visible in the Benelux countries as well as in the Danish context. In both regions, interconnections are of key importance in electricity supply and several countries form a well-integrated power market area.

4.3.6. Distribution grids

Distribution grids will play an important role in future electricity grids as increasing levels of distributed generation and prosumers alter the conditions on low voltage levels and are key to enabling local flexibility. Once a one-way electricity distributor from higher voltage levels to end-consumers, future distribution grids will need to become “smart” to monitor and control the bidirectional power flows from increased distributed generation.

4.3.7. Small-scale storage

Small-scale storage installed in distribution grids is an interesting flexibility option on the local level. Often fast and accurate, e.g. batteries, it is an ideal option to provide ancillary services. Although other flexibility options such as demand side flexibility are considered to be cheaper, there currently is a trend towards installing batteries, e.g. in the US and Germany.

4.3.8. Bulk storage

The current deployment of large-scale storage depends largely on local geographical circumstances (which largely determines the potential for pumped hydro storage) and market conditions. However, large-scale storage capacities will play a central role in power systems with very high VRE levels.

4.3.9. Sector coupling

Sector coupling is a key element for a successful energy transition across all sectors and a potentially great source of power system flexibility, especially in the context of increasingly frequent situations of surplus energy. Up to date there is little sector coupling in most power systems. A positive exception is Denmark, where the power and heating sectors are strongly connected by flexible CHP plants and district heating networks.

4.3.10. Wholesale markets

In the light of ever-increasing VRE shares, appropriate market design is essential to exploit already existing flexibility sources and set incentives for investments in additional flexible capacity. Respective discussions have been going on for some time now and several studies on the topic have been published. The common understanding is to further expand and liberalise electricity markets. This can be done, among other things, by an ongoing harmonisation of market rules and further market coupling (allows for greater exchange of flexibility and balances VRES variability), the removal of entry barriers for new actors (to ensure a level playing field for all sources of flexibility) as well as the reduction of gate closure times (to increase VRES forecast accuracy) and shortening of product lengths (to allow more precise adaptation to the fluctuation of VRES output). In addition to the temporal resolution of power markets, the spatial resolution is gaining significance in the European context, too. Regarding wholesale markets, the short-term markets (day-ahead and intraday market) are especially interesting for the provision of flexibility.

4.3.11. Balancing markets

The common trends described for wholesale markets generally apply to balancing markets too. A special focus with regard to balancing markets should, however, be placed on the removal of barriers as most European countries are still characterised by substantial barriers preventing greater participation of new actors. Besides ensuring a level playing field, studies have shown that improved coordination between TSOs can reduce reserve requirements [32], which also applies to the establishment of larger balancing areas and faster market operations [14], as well as the dynamic determination of reserve requirements. However, institutional “inertia” has been a major barrier to the introduction of advanced balancing regulations, e.g. in Germany, and will be needed to overcome.

4.3.12. Retail markets

The implementation of dynamic electricity tariffs for end-consumers is a key element to incentivise demand response. Vice versa, tariff structures with large regulated components offer low incentives to adapt consumption patterns. Studies suggest that appropriate market frameworks can incentivise greater demand-side participation [19,33]. Finding an optimal combination of flexible energy and power price signals, including dynamic fees and levies, is one of the great challenges in this area.

5. Conclusions and policy implications

More flexibility is needed in power systems accommodating ever higher shares of variable renewables to ensure reliability and cost-effectiveness for the overall energy system. This is not just an operational planning aspect, but needs long-term planning to ensure incentives exist for all market players (incumbent, new actors, system operators) to deploy flexibility solutions. Planning and timely development of flexibility will allow avoiding technical or economic barriers for RES deployment in the future.

However, flexibility is a complex topic spanning across a multitude of options, from “hardware” solutions (flexible generation, demand, energy storage) to flexibility enablers (grid and markets). In order to properly plan solutions that address the emerging flexibility gap, proper assessment of the flexibility of systems is needed. Many studies address part of the issue (e.g. only single technology or timeframe based), but a holistic approach is lacking so far. The methodology presented in the paper covers the full scope of flexibility and highlights which areas (flexibility options) have progressed well in a specific system, and which have more potential left. The approach is based on a set of 80 KPIs across 14 flexibility domains, and allows to compare progress across different power systems. This can be used to gain understanding, set benchmarks or promote knowledge sharing. This paper shows an application to seven relatively diverse European countries.

It is not expected that all systems will follow the same flexibility approach. Regions have their specific legacy system and different intrinsic potential for RES, storage and load flexibility. However, some solutions would benefit from a coordinated approach, some are clearly no-regret options (but face a barrier in some countries), and systems can adapt best practices from each other. The presented methodology allows market actors and policy makers to understand the different pathways taken in different countries, monitor progress and prioritize actions. It also gives valuable information for market actors who often focus on a specific technology and need to prioritize market entrance. The approach allows all to highlight priority actions on short- medium- and long-term to prepare for higher shares of renewables in the system.

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