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Quantifying power system flexibility provision

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Abstract

In power systems, flexibility can be defined as the ability to cope with variability and uncertainty in generation and demand. The ongoing energy transition is affecting how much flexibility is required, but also who should provide it: some existing solutions are being phased out, while new solutions' entire business models are based on providing flexibility (e.g. storage or demand response). With the intention of condensing information and rationalising debates, a significant number of methods have been proposed to quantify various facets of flexibility; this paper reviews and classifies them depending on the question they attempt to address. We propose a pair of novel tools to quantify a comparatively unexplored aspect of flexibility: who is providing it. These frequency spectrum analysis based tools separately quantify flexibility provision on the annual, weekly and daily timescales. The tools' effectiveness and versatility is demonstrated through several example applications, analysing both historical and prospective power systems, in several geographical locations with contrasting characteristics. The proposed tools are of particular value to the capacity expansion planner, allowing them to quantify changes in flexibility provision as new solutions are introduced, or as carbon taxes, generation and interconnector capacities evolve.

Keywords: Power system flexibility, flexibility metrics, frequency spectrum analysis, energy transition, renewable integration, network interconnection.

1. Introduction

"Power system flexibility has become a global priority", stated the International Energy Agency in their 2018 report on the status of power system transformation [1], as the Clean Energy Ministerial launched its "Power system flexibility campaign" [2]. The European Network of Transmission System Operators for Electricity roadmap identified power system flexibility as one of 5 clusters of research and innovation challenges from 2017 to 2026 [3]. Power system flexibility generates ample high-level talk, but remains an elusive, complex idea, prompting institutions and academics to propose a vast number of occasionally conflicting definitions.

Beyond merely defining flexibility, there is also a need for tools that can delve into it, quantifying related notions. There are two main motivations for such tools: (i) condensing large amounts of power system data, extracting that which relates to flexibility, and (ii) providing a neutral basis on which discussions can be held, leading to social welfare maximisation decisions. This is a key issue considering the magnitude of the investments at stake to ensure adequate provision of power system flexibility in the future.

A significant number of metrics have been proposed, quantifying different facets of flexibility. Despite noteworthy contributions attempting to provide a single framework simultaneously covering multiple aspects [4, 5, 6], it has often been pointed out that flexibility cannot be understood through a single indicator [7, 8, 9, 10]. Faced with numerous metrics with very diverse philosophies, it can be challenging to grasp how they all contribute to understanding flexibility and how or when they should each be used.

The contributions of this paper are threefold. (i) Scrutinising proposed definitions, we will start by discussing the historical evolution of what has been understood by the term "power system flexibility", before providing our own view on the matter (section 2). (ii) Structuring existing knowledge, we will then present the results of an extensive review of existing flexibility quantification methods, classifying approaches depending on the question they address (section 3). (iii) We will then propose a pair of novel tools (FSMS, for Flexibility Solution Modulation Stack, and FSCD, for Flexibility Solution Contribution Distribution, section 4), which quantify a comparatively unexplored aspect of flexibility: who is providing it. Example applications of the methodology will then be provided (section 5), closed off by a summary of key findings (section 6).

2. Defining power system flexibility

2.1. Literature review

Institutions and academics alike have been proposing definitions of "power system flexibility" for some time; the idea behind the term has evolved with the changing context and perceived challenges¹. Early mentions of the term can be found in the 1990s, when power system planners were faced with great uncertainty due to deregulation and the introduction of competition. This caused a paradigm change: the system planner would no longer search for the minimal cost solution, but for a flexible one, that could adapt quickly and withstand a great variety of situations with reasonable additional cost [11]. In the early 2000s, in a world where transmission and generation were no longer co-optimised, Bresesti *et al.* discuss the need for flexible transmission planning when the timing, location and size of generation expansion is uncertain [12]. Still, flexibility was understood as a long-term uncertainty issue.

A few years later, when Variable Renewable Energy (VRE) began integrating power systems, the term "flexibility" took on a new meaning and started to thrive. Some definitions even limit its breadth to this sole issue, referring to flexibility as the ability "to balance rapid changes in renewable generation and forecast errors" [13], to "cope with the variability and uncertainty that VRE generation introduces into the system" [14], or a system's "readiness for high shares of variable renewables" [10].

Different phases of VRE integration have been identified, characterised by different issues [1, 15]. Early integration concerns tend to be short-term focussed: meeting changes in supply-demand balance on timescales of minutes to hours. As VRE penetration increases however, balancing on longer timescales (days, weeks or years) also becomes problematic. This evolution in perceived challenges can again be seen in evolving definitions of flexibility. When VRE penetrations in advanced economies were still low, flexibility was often considered to be a short-term concept only [13, 16, 17], while later definitions explicitly state flexibility to be a multi-timescale issue [7, 14, 18, 19, 20].

While recent definitions have been gradually converging towards something along the lines of "the ability to cope with variability and uncertainty

¹All definitions referenced in this section are provided in full in Appendix A.

in generation and demand", some subtleties can still be found. One might adopt the point of view of a flexibility solution provider [17, 21] or that of a power system [1, 20, 22]. One might refer to flexibility purely for supply-demand matching [7, 20], also mention network congestion management [17] or be much more general and simply define flexibility as the ability to adapt to changing conditions [23].

2.2. Definition proposal

Given our analysis of the state of the art, we define flexibility as the power system's ability to cope with variability and uncertainty. In power systems, these can be found in demand, generation and power flows resulting from their geographical spread. This implies that flexibility is required for both key tasks of a system operator: matching generation with demand and ensuring that power flows do not exceed network thermal and voltage limits. This paper, along with the majority of existing literature, will focus on the former.

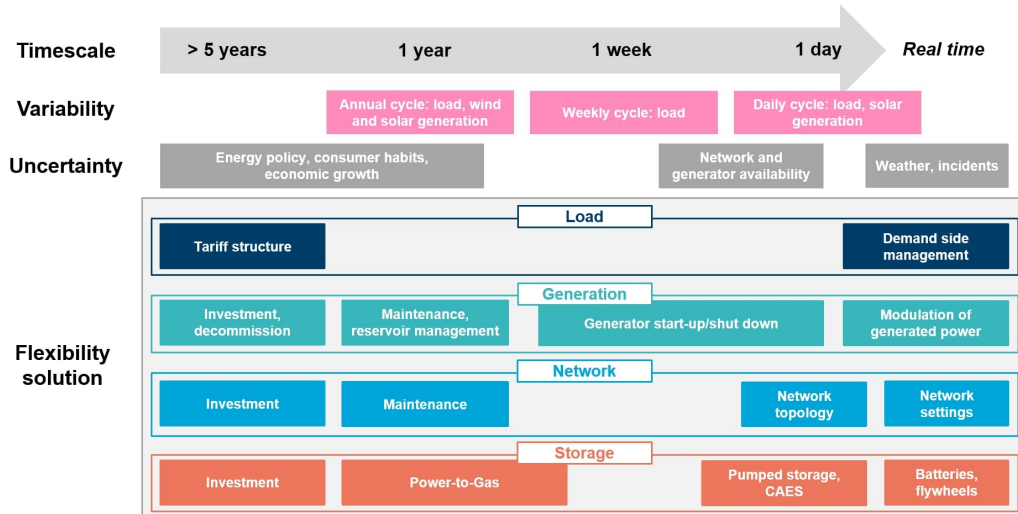


Figure 1: Different sources of variability and uncertainty generate a need for flexibility, which can be dealt with by a set of flexibility solutions. These are shown over a range of different timescales.

Variability and uncertainty occur on several timescales [24], as shown in figure 1. On the long-term (more than a year), matching supply and demand

is made uncertain by the difficulty to predict VRE development, the evolution of consumer habits, economic growth etc., with implications on capacity expansion planning. On the medium-term (annual, weekly and daily horizons), power system operators must face cyclical variations in residual load (load minus VRE generation), with implications on the Unit-Commitment and Economic-Dispatch (UC-ED) of dispatchable assets. On the short-term (intraday), power system operation is constrained by uncertainty through incidents and forecastability of demand and VRE generation, with implications on reserve sizing and activation.

As depicted in figure 1, there are a number of ways one can cope with these sources of variability and uncertainty, i.e. provide flexibility (see [8] for a review of solutions). Broadly speaking, one can either (i) modulate generation output (including VRE curtailment), (ii) modulate demand, (iii) store energy in a different form to smooth out variations through time, (iv) interconnect with another system to smooth out variations through space (see figure 1). To cope with long-term uncertainty, one can build, mothball or decommission these flexibility solutions (FS). To cope with medium-term variability and short-term uncertainty, one can activate existing FS.

Note that this discussion has focussed on the sole power system. Sector coupling (strengthening the links between energy vectors) has been shown to be an interesting way of providing flexibility to the power system [25]. Depending on the technology linking energy vectors together, from the power system point of view, this can be considered either as a modulation of generation or demand.

3. Review of flexibility quantification methods

As can be seen from the sheer number of proposed definitions (see section 2.1), power system flexibility remains an elusive, complex idea, grasping its physical meaning is not that straightforward. There is a need for tools that can delve into flexibility, quantifying related notions.

A significant number of metrics have been proposed, exploring different facets of flexibility². As shown in figure 2 and loosely based on the categorisation proposed by Tuohy *et al.* [23], we classify quantification methods depending on the question they address: *how much flexibility does my system*

²All papers cited in this review of flexibility quantification methods are further described in the tables of Appendix B.

need? (section 3.1), *how flexible is my flexibility solution?* (section 3.2), *how flexible is my power system?* (section 3.3), and *who is providing flexibility in my power system?* (section 3.4).

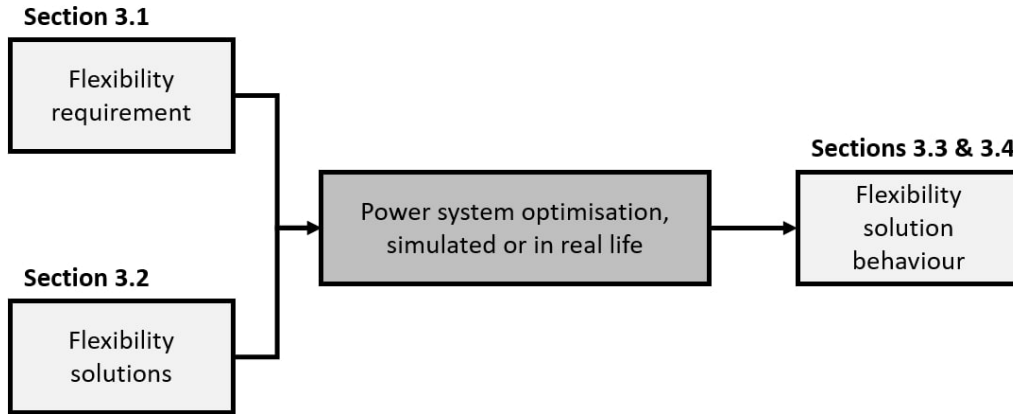


Figure 2: Structure of the review of flexibility quantification methods.

3.1. How much flexibility does my system need?

As a general rule, a power system's flexibility requirement is dictated by the amount of variability and uncertainty in residual load (load minus VRE generation). Kondziella and Bruckner [26] classified methods quantifying short-term FS potential as defined by the Intergovernmental Panel for Climate Change [27]: theoretical, technical, economic and market potentials. FS theoretical potential can be equated to flexibility requirement. Various metrics have been proposed, generally focussing on the short-term (intra-day): one or multiple hour ramps, expressed in MW or as a percentage of maximum power output [22, 28, 29], ramp acceleration and volatility [29], standard deviation of VRE output and residual load, forecast error statistics [9]... Tracking intra-hour deviations between scheduled and actual residual load has also been proposed, describing these deviations in terms of their magnitude, ramp rate and ramp duration [30]. In their "flexibility envelope" framework, Nosair *et al.* [5] identify flexibility requirement as 95% of the probability distribution function of VRE intra-hourly deviation from forecast.

As discussed in section 1, flexibility is a multi-timescale issue. With that in mind, in previous work, we proposed a method going beyond short-term aspects, using a frequency spectrum analysis based method to quantify flexibility requirement on annual, weekly and daily timescales [24]. Olsen *et al.* [31] extended this idea to also include shorter timescales, while making their source code available online [32].

Other studies have also tried to quantify storage required to cope with a subset of flexibility [33, 34, 35, 36, 37, 38, 39] (see Appendix B for further details, or Zerrahn and Schill [40] for a review of such work). Curtailment and mismatch between hour ahead forecast and reality are examples of flexibility requirement subsets. Note that storage is one of several means to a common end: coping with variability and uncertainty in generation and demand (i.e. provide flexibility). Hence "storage requirement" could be argued to be a flawed approach, or at least a poor choice of words.

Energy resource complementarity is a field of study closely related to the concept of flexibility requirement. Metrics have been proposed to quantify the degree of complementarity between energy resources, essentially providing an indication of how flexibility requirement can be reduced by carefully choosing the size and location of renewable generation (see Jurasz *et al.* [41] for a review of such metrics).

3.2. How flexible is my flexibility solution?

In their simplest form, metrics quantifying a solution's ability to provide flexibility are input parameters of UC-ED models. Typical examples include minimum power output, operational range (the difference between maximum and minimum power output), up/down ramping capability, start-up and shut-down times, response time, and minimum up and down times [42]. Some FS's may require additional metrics to express distinctive constraints, e.g. energy capacity, rebound effect and recovery period for storage or flexible load [40]. The ability to provide reserve has also been mentioned [9].

Composite metrics have been proposed to condense this information. Ma *et al.* [18] proposed a flexibility index composed of a weighted sum of operational range and ramping ability, normalised by maximum power output. Oree and Hassen [42] extended this idea, with an index combining 8 metrics mentioned in the previous paragraph, weighted using an analytic hierarchy process. This approach was also employed by Wu *et al.* [43]. A different way of condensing this information was suggested by Nosair and Bouffard

[5]: for individual time steps, they maximised a FS’s upward and downward deviation from a scheduled output, subject to maximum and minimum power output, ramping and energy constraints.

Another approach consists in simulating power system behaviour and analysing outputs. Ulbig and Andersson [6], for example, evaluated, for a given point in time, the ability to provide up/down regulation, energy storage and ramping.

3.3. *How flexible is my power system?*

This category of metrics is the most varied in terms of approaches. One option is simply to aggregate flexibility indices of individual FS’s. This has been performed in various ways by several aforementioned studies [5, 6, 18, 42, 43].

Another intuitive approach involves analysing historical or UC-ED simulation data to identify times when flexibility is lacking. Traditional adequacy metrics already provide some information: Expected Unserved Energy, Loss Of Load Probability and Duration [5, 44]. Curtailment and use of interruptible load, common last resort FS’s in power system models (slacks), are other regularly used indicators of a flexibility deficit [5, 9, 45]. Lannoye and Tuohy [23, 46] proposed a set of metrics identifying flexibility deficiency: Periods of Flexibility Deficits, Insufficient Ramping Resource Expectation, and Expected Unserved Ramping. These can be used to identify particularly challenging lead times for power system operation. With a similar goal in mind, Zhao *et al.* [4] track the evolution over time of upper and lower boundaries of residual load uncertainty that can be accommodated for a given cost.

Instead of identifying flexibility deficits, another possibility is to simply check, typically for a single point in time, whether FS’s can cover flexibility requirement. Ulbig and Andersson [6] represent this graphically, in terms of up/down regulation, energy storage and ramping. Zhao *et al.* [4] propose a Boolean metric indicating whether or not a system’s largest variation range is within a target range. Menemenlis *et al.* [47] develop an index measuring the probability that a balancing reserve strategy might satisfy various scenarios.

Identifying limits to flexibility is another way of measuring a power system’s degree of flexibility. For example, Deane *et al.* [48] extract a ramping shadow price, in their study of the impact of sub-hourly modelling of a power system. This is also carried out by Vithayasrichareon *et al.* [49] when they quantify the cost implications of various flexibility constraints: ramping, minimum power output, start-up costs and minimum synchronous

generation. In broader terms, Morales *et al.* [50] recommend, as a measure of the value of flexibility, analysing the sensitivity of a UC-ED problem's optimal value, primal and dual variables to input parameter values.

Two indices stand out by their consideration of flexibility for network congestion rather than for supply-demand matching. Bresesti *et al.* [12] compare the flexibility of different network configurations, which can be used both in expansion and operational contexts. With a similar understanding of flexibility, Cappaso *et al.* [51] quantify the additional generation a transmission system can accommodate, based on an Optimal Power Flow algorithm.

Lastly, Papaefthymiou *et al.* [10] take the stance that assessing the degree of flexibility of a power system requires both technical and non-technical metrics. They therefore provide a list of 80 key performance indicators scanning a broad range of flexibility issues, from assets to market design.

3.4. Who is providing flexibility in my power system?

A comparatively unexplored question one might ask when quantifying flexibility is who is providing it. Yasuda *et al.* [52] propose a "flexibility chart" (also see [15] for an example application), which gives a quick overview of the installed capacities of a few assets that could provide flexibility in a given power system. The number of start-ups of various generating units has also been used for flexibility provision quantification [48, 49].

However, as pointed out by Cochran *et al.* [53], capacity is not a proxy for flexibility. Start-up limitations are only one of many ways FS behaviour is constrained, as expressed by metrics covered in section 3.2. We need a way of quantifying flexibility provision while simultaneously accounting for all technical and economic constraints facing FS's, that can equally treat all four FS categories (flexible generation, flexible load, storage and interconnection), that is able to express how the role of a FS varies with the considered timescale, and that can be applied both real and simulated power systems. The tools presented in the following section fulfil each of these objectives.

4. Methodology

Based on frequency spectrum analysis, we introduce two graphical tools, (i) the Flexibility Solution Modulation Stack (FSMS), which shows how FS's provide flexibility on annual, weekly and daily timescales, (ii) and the Flexibility Solution Contribution Distribution (FSCD), which quantifies contributions to flexibility on the same three timescales. These tools simultaneously

consider flexibility provided by all solutions: flexible generation, flexible load, storage and interconnection. FSMS and FSCD can be derived both from historical data and power system simulation data.

Condensing significant amounts of information, FSMS’s and FSCD’s ability to describe the relative roles of flexibility on different timescales is of significant value to highlight differences between countries or illustrate the impact of evolving conditions on power system operation (changes in carbon tax, increase in generation or interconnector capacity, introduction of new FS’s such as Power-To-Gas, or even temporary conditions such as low nuclear availability due to planned outages).

As described in figure 3, after discussing input data (both its nature and its preprocessing by feeding it through frequency filters), the methodology used to build Flexibility Solution Modulation Stacks (FSMS) will be covered, detailing the stacking rules specific to flexible generation, storage, interconnection and flexible load. Lastly, we will discuss how this graphical information can be further condensed to more of a metric, using the Flexibility Solution Contribution Distribution (FSCD).

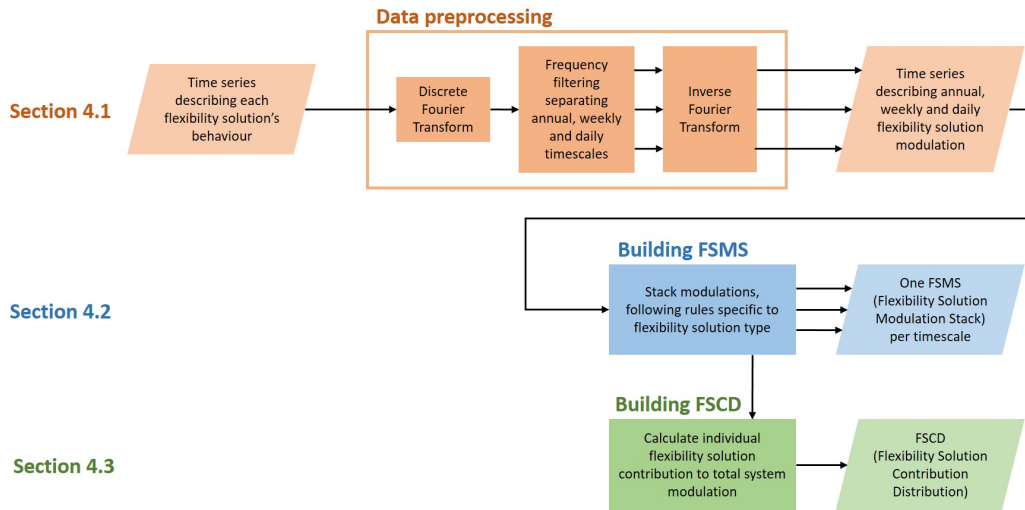


Figure 3: Overview of the methodology used to build FSMS and FSCD.

4.1. Input data description and preprocessing

The only inputs required for both FSMS and FSCD are time series of system load, generation per source, storage in/out flows, and interconnector

flows (historical or simulated data). Installed capacities are not required, nor are FS technical and economic parameters. For a flexible electricity use, load curves of both the flexible and the inflexible version of this use must be provided. Time series should be one year long and typically have hourly resolution. Any system size will do, however, note that FSMS and FSCD will only consider flexibility provision for supply-demand matching, i.e. they will ignore flexibility provision for congestion management purposes.

Load curves show clear cyclical patterns of various time periods: demand is higher during the day than during the night, higher during weekdays than the weekend, and either higher in summer or winter depending on geographical location. These patterns are sufficiently deterministic that, using a Fourier series based model, Yukseltan *et al.* [54] were able to predict Turkish national load within 3% Mean Absolute Percentage Error. The behaviour of a FS mix is dictated by cycles in residual load, it hence shows the same annual, weekly and daily patterns. As can be seen in figure 4, solutions play different roles on each timescale. Baseload generation such as nuclear modulates mostly on the annual timescale (1 cycle per year), while pumped hydro storage modulates mostly on the daily and half-daily timescale (365 and 730 cycles per year). Mid-merit generation such as coal and gas shows an intermediate behaviour.

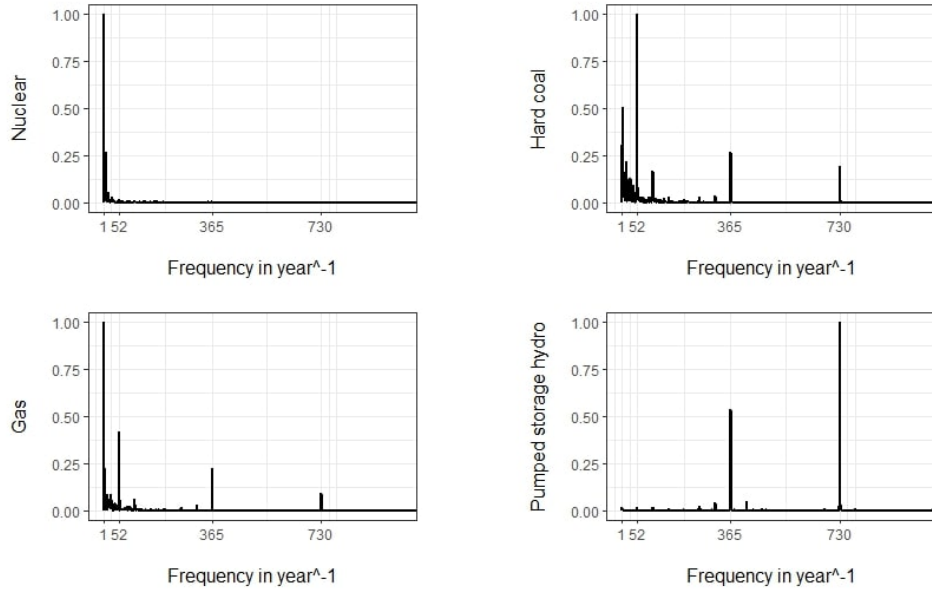


Figure 4: How different are the roles of flexibility solutions over different timescales? Normalised power spectral densities show the timescales over which behaviour is modulated, for nuclear, coal, gas and pumped storage hydro time series, on the German power system in 2018 (data from [55]). Marked out frequencies correspond to periods of a year, a week, a day and half a day.

To analyse these timescale specific behaviours separately, frequency filtering is applied to FS time series. Cut off frequencies are set at 20 and 180 year^{-1} i.e. periods of about 18 and 2 days. Note that different or even additional cut off frequencies may be used, however, following extensive testing, these were judged to be the most appropriate to investigate flexibility.

The filtering process consists of three steps. First, each time series is fed through a Discrete Fourier Transform (see equation 1), the DC offset (annual mean) having been removed. Then, as was done in previous work [24], band pass filters with unit magnitude within the band and zero magnitude outside the band are applied. Finally, the three resulting signals are passed back into time domain using the inverse Fourier Transform, thus obtaining three time series each containing a fragment of the initial signal’s information, respectively annual, weekly and daily modulations.

$$X_f = \sum_{t=0}^{N-1} x_t e^{-i2\pi ft/N} \quad f = 0, \dots, N-1 \quad (1)$$

As expressed in figure 3, this filtered data constitutes the input to FSMS. This process works well for historical data. For simulated data however, FSMS and FSCD will only be as good as the power system model: the poor representation of technical constraints or lead times might lead to unrealistic behaviour of flexibility solutions, which FSMS and FSCD will reflect. This issue may appear in an inflexible power system, most likely on the daily timescale.

Note that frequency based approaches have been used for a variety of other reasons in power system planning, e.g. to integrate a flexibility constraint in a unit commitment problem [56], for storage sizing [33, 34, 35, 57, 58], for short-term VRE forecasting [59, 60, 61] or simply as a visualisation tool to complement the time domain vision [62, 63].

4.2. Stacking flexibility contributions: FSMS

As discussed in section 2.2, a power system copes with variability and uncertainty (i.e. provides flexibility) by adjusting the behaviour of its FS's. The aim of FSMS is to help its user understand how individual FS's modulate over time to provide flexibility in order to match generation with demand, on the annual, weekly and daily timescales.

By tracking how each FS modulates around its mean value (each signal's integral is equal to zero), this is exactly what is expressed by the signals resulting from the preprocessing. To show FS's relative roles, these modulations can then be stacked in a plot (FSMS), as one would stack generation time series to see how electricity demand is covered. By construction, at any point in time, the sum of FS modulations is equal to the variations of residual load (here, load minus wind, solar and run-of-river hydro). The following paragraphs describe the rules to follow when stacking each FS's signal, depending on the FS type.

Flexible generation modulations simply express to what extent a technology generates more or less than on average. In figure 5, this translates to the following: if a generator's ribbon is above that of the previous FS ribbon, this generator's output is above its average annual value. Conversely, if under, its output is below its average annual value. The majority of the time, flexible generator modulations neatly add up i.e. all generators contribute

towards coping with residual load variation. However, in some cases, flexible generators may be forced by technical or economic factors to contribute negatively to flexibility, modulating "with" residual load rather than "against" it. An example of such a case is that of hydro in the month of June, snow melts causing abundant water supply. FSMS expresses this by overlapping the hydro and gas ribbons (see figure 5).

For *storage modulations*, the input time series corresponds to the hourly sum of inflows and outflows. Due to round trip efficiencies, inflows are greater than outflows, therefore a storage modulation above the previous FS ribbon does not necessarily mean that this storage technology is supplying power to the grid.

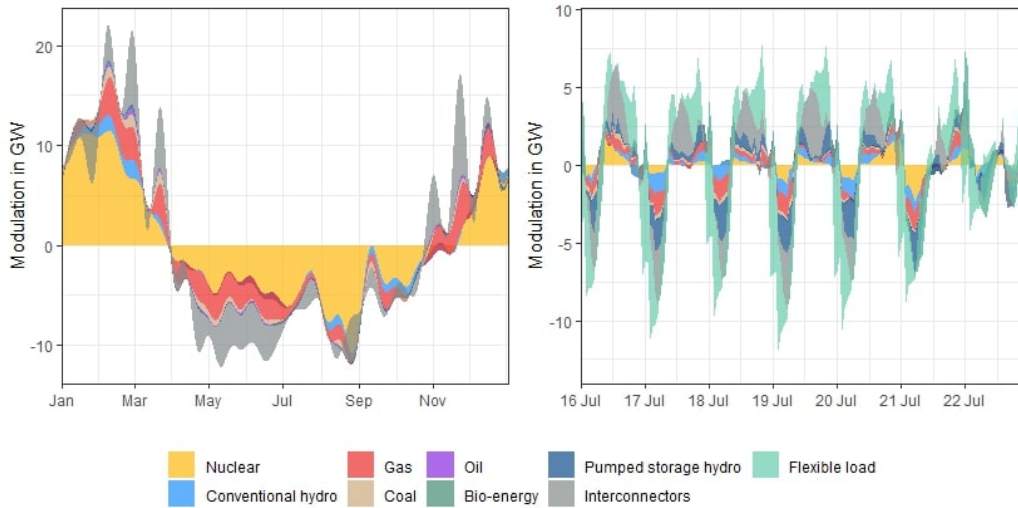


Figure 5: Who currently provides flexibility? Annual (left) and daily (right) flexibility solution modulation stacks, on the French power system in 2018. Generation and interconnector flow data from [64], flexible load data was generated by an unpublished RTE (French Transmission System Operator) model based on consumer panels.

For *interconnector flow modulations*, the input time series corresponds to the hourly sum of exports and imports to and from neighbouring systems. In most results shown in this paper, all borders are considered simultaneously; treating each border independently is also possible but may hinder readability and give a biased representation of Kirchhoff's laws. One should keep in mind that interconnector flow modulation implies modulation of another

FS (generation, demand or storage) in a neighbouring system. Depending on a system’s annual exporting or importing status, an interconnector flow modulation above the previous FS ribbon may reflect a higher export or a lower import than on average. The interconnector ribbon may overlap other ribbons, as an optimal dispatch on the European system may imply adjusting a FS’s behaviour to balance a neighbouring country. As can be seen from figure 5, this is only occasionally the case in France due to significant base load capacity. In countries with FS’s that are cheaper to modulate, the interconnector ribbon will likely overlap other ribbons more often.

For *flexible load modulations*, the input time series corresponds to the difference between flexible and inflexible load curves. As a result, the ribbon expresses the additional variability the power system would have to cope with, were load not flexible. Depending on data availability, flexible load can be aggregated to a single ribbon, or split by use. In France, flexible load consists mostly of residential and commercial hot water boilers, which only provide flexibility on the daily timescale.

Note that all these modulations do not express a flexibility solution’s deliberate intent to provide flexibility, nor its ability to provide flexibility (for this purpose, see metrics in section 3.2), but rather the flexible aspect of its behaviour, defined while considering the entire power system’s capacities, technical and economic constraints.

4.3. Summarising this information further: FSCD

While FSMS provides a graphical representation of what is going on in a power system regarding flexibility, it isn’t a quantified metric. Such a metric could be argued as artificial, as a flexibility solution’s contribution cannot be boiled down to a single figure: it may vary considerably over the course of a year (this is particularly true on the daily and weekly timescales), it might occasionally contribute negatively, or modulate beyond variations in residual load. Expressing the distribution of modulations, FSCD is more of a metric, condensing the information held in FSMS further but without distorting or losing too much of it.

As detailed in equation 2, for each time step, a FS’s contribution to total modulation of a power system’s FS set is recorded, as a percentage. Time steps where the absolute value of this total system modulation is smaller than 20% of its maximum are removed, to avoid spuriously giving credit to a FS because of asymptotic behaviour when residual load modulation is close to zero. The primary interest being FS contributions when flexibility is a

constraint for power system operation, this has a limited impact on results, as confirmed by extensive tests with different thresholds.

$$\forall t = [1, 8760] : \left| \sum_{FS} M_{FS}(t) \right| \geq 0.2 * \max\left(\left| \sum_{FS} M_{FS}(t) \right|\right)$$

$$C_{FS}(t) = \frac{M_{FS}(t)}{\sum_{FS} M_{FS}(t)} * 100\% \quad (2)$$

where: C_{FS} Contribution time series (%)
 M_{FS} Modulation time series (MW)

This whole process is performed separately for the annual, weekly and daily timescales. FSCD is defined as the set of three distributions of $C_{FS}(t)$ (one per timescale), and can be represented as a box plot, as shown in figure 6. Note that a contribution can exceed 100% in some cases, when a FS modulates beyond variations in residual load.

5. Example applications

5.1. Potential future role of flexibility solutions

By applying the FSMS methodology to the outputs of a UC-ED model, one can quickly get an idea of how a fictional system is expected to cover its flexibility requirements. This is of particular value when performing long-term adequacy or capacity expansion studies. Figure 7 shows an example application of FSMS on the daily timescale, for a prospective 2035 French power system. Results are from a study analysing the future role of electric vehicles in the power system, based on the French government's latest multi-annual energy plan [65]. The results shown are for a scenario considering 11,7 million electric vehicles, 60% of which are smartly charged (see [66] for full study details). For clarity, electric vehicle smart charging is the only form of demand side management which is represented.

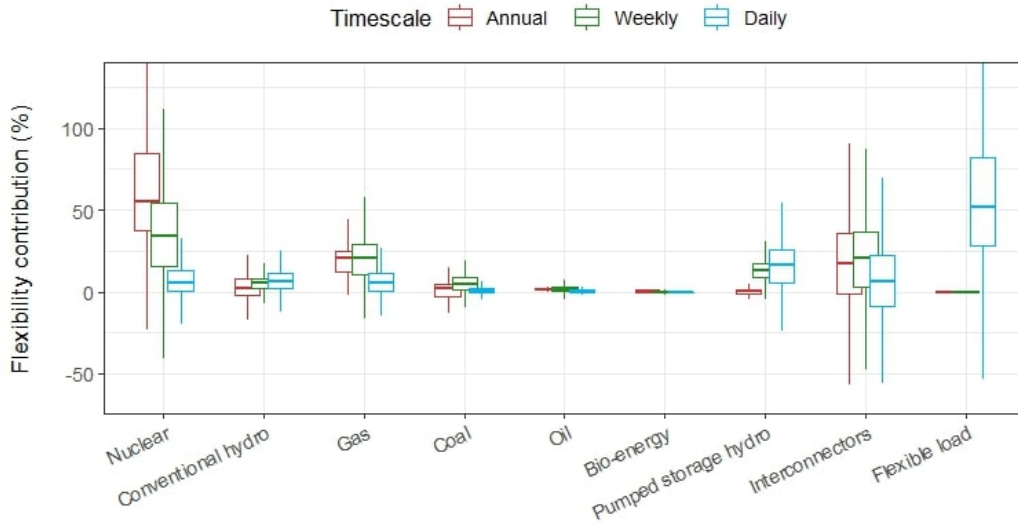


Figure 6: How do solutions currently contribute to flexibility? Flexibility solution contribution distributions on annual, weekly and daily timescales, on the French power system in 2018. Generation and interconnector flow data from [64], flexible load data was generated by an unpublished RTE (French Transmission System Operator) model based on consumer panels.

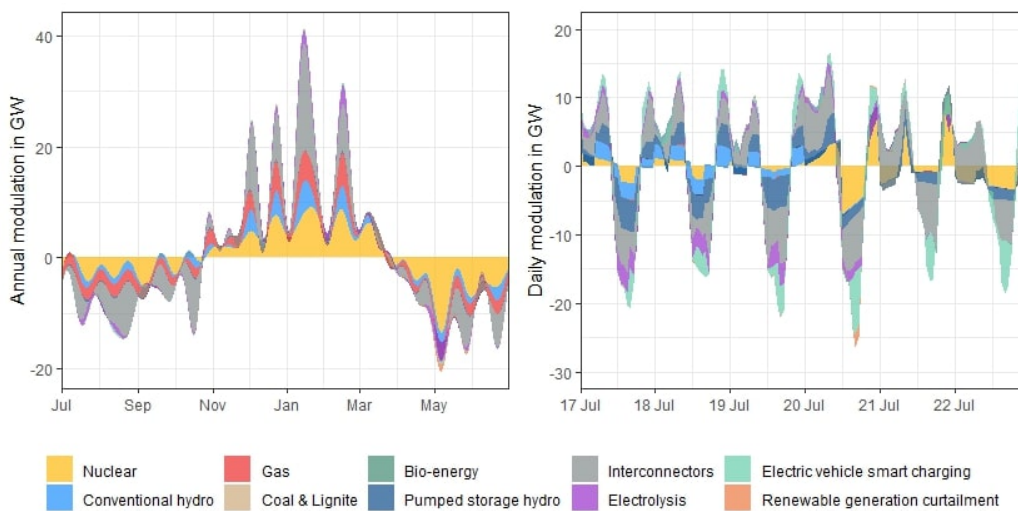


Figure 7: Who could be providing flexibility in the future? Annual (left) and daily (right) flexibility solution modulation stacks, for a prospective 2035 French power system (study described in [66]).

Note that in 2035, particularly in the summer, troughs in residual load no longer correspond to nighttime but to midday hours. By comparing figure 5 to figure 7, one may note that residual load variability greatly increases between 2018 and 2035. In previous work [24], a quantification of this increase was performed, along with a sensitivity analysis to identify the long-term variables at play.

5.2. Potential evolution of the role of flexibility solutions

By applying the FSCD methodology, one can also quantify and visualise the evolution of the respective roles of flexibility solutions. Example results of such an analysis are shown in figure 8, for the period running from 2021 to 2036 on the French power system. Results are from a study based on the French government’s latest multi-annual energy plan [65], that has been used as a reference scenario in several recent RTE (French Transmission System Operator) reports [66, 67]. Note that no form of demand response has been considered in this figure.

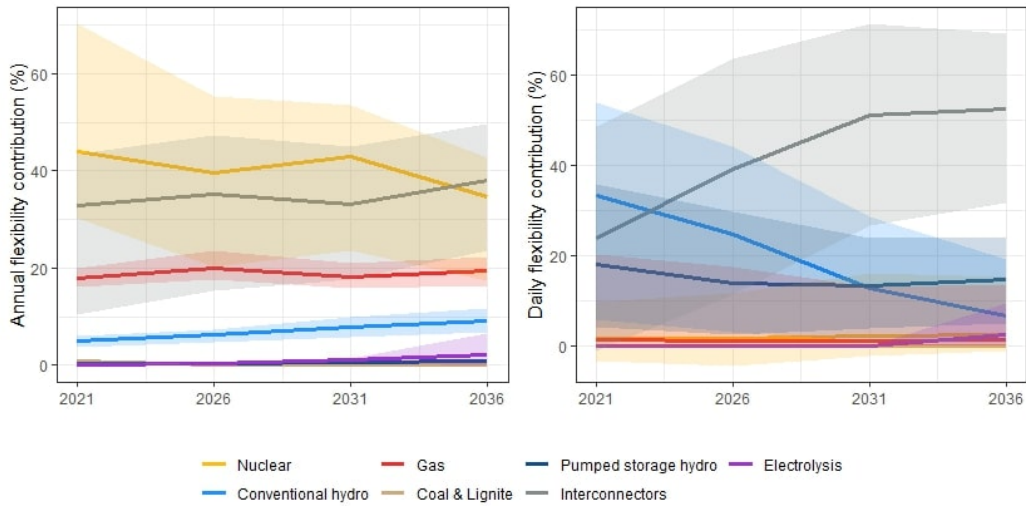


Figure 8: How could the roles of flexibility solutions evolve in the coming years? Evolution of flexibility solution contribution distribution between 2021 and 2036, on the French power system (data from the reference scenario used in [66, 67]). Uncertainty bounds correspond to the 25th and 75th percentiles of FSCDs, full lines correspond to the median.

5.3. The case of highly interconnected systems

Applying FSMS and FSCD to power systems with high interconnection relative to peak load can give very different and interesting results, in which case considering borders separately rather than simultaneously can add significant value to the analysis. Figure 9 illustrates such a situation through box plots of FSCDs for the Western Denmark power system in 2018. All interconnectors but that with Germany being Direct-Current, the representation does not violate Kirchhoff’s laws. For clarity, not all FS contributions were represented, but coal and gas were still included to provide context. The limited contribution of generation highlights the role of Western Denmark interconnection in European electricity balancing.

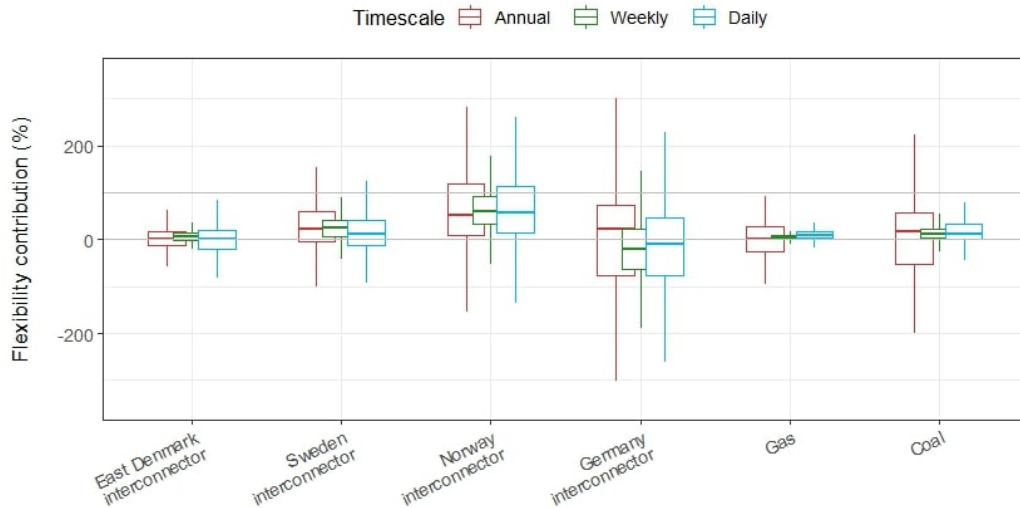


Figure 9: How do interconnectors contribute to flexibility in highly interconnected systems? Flexibility solution contribution distribution on annual, weekly and daily timescales, for the western Denmark power system in 2018 (data from [55]).

One may note the significant width of FS contribution distributions, single FS’s often contributing far beyond modulations in Western Danish residual load (represented by the 100% line). Of particular interest is the German interconnector, which very frequently contributes negatively to local flexibility requirement, particularly on the weekly and daily timescales. This is to

be expected as, on these timescales, German residual load is highly correlated to that of Western Denmark. Closer inspection using FSMS shows that this is compensated by modulations in Norwegian plants' power output, as suggested in figure 9 by the contribution of the Norway interconnector.

5.4. Varying the size of the considered system

As previously mentioned, modulation in interconnector flows implies modulation of another FS (generation, demand or storage) in a neighbouring system. To understand the cost, environmental and social implications of a flexibility mix, it would be helpful to know what hides behind these interconnector flow modulations. To this end, we can change the size of the considered system, and apply FSMS and FSCD to geographical aggregations of FS time series. One should keep in mind that these methods ignore any modulation for internal congestion management purposes, which may become more significant as the size of the considered system grows.

Figure 10 shows annual and weekly FSMS for a prospective 2021 European power system³. Results are from the aforementioned study based on the French government's latest multi-annual energy plan [65], used as a reference scenario in several recent RTE reports [66, 67]. Note that interconnectors refer to links to countries beyond the considered system, though they are negligible in this case.

³Modelled countries: Austria, Belgium, Czechia, Denmark (4 zones), France, Germany, Great-Britain, Ireland, Italy (6 zones), Luxembourg, Northern-Ireland, Netherlands, Norway (3 zones), Poland, Portugal, Spain, Sweden (4 zones), Switzerland.

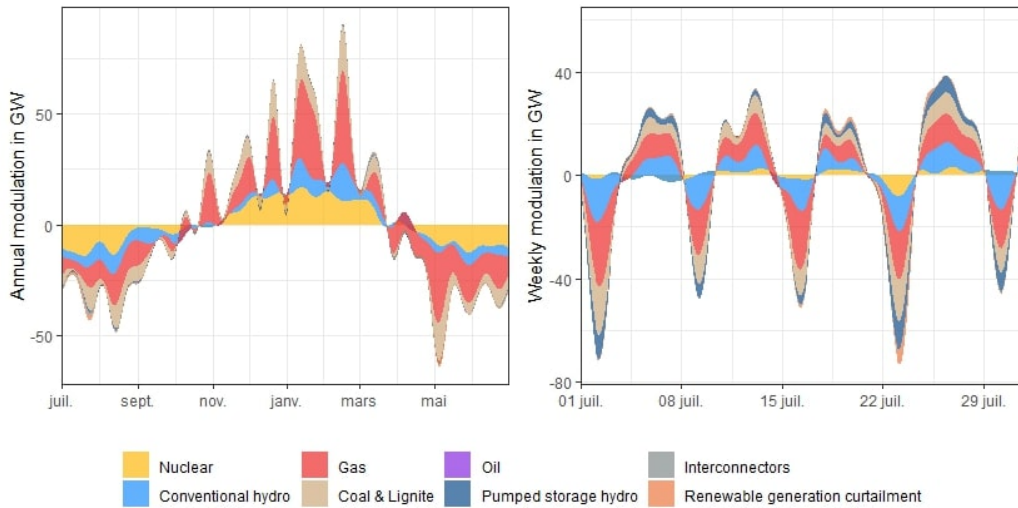


Figure 10: Ignoring congestion management, what are the technologies providing flexibility at the European level? Annual (left) and weekly (right) flexibility solution modulation stacks, for a prospective 2021 European power system.

6. Conclusions

This paper performed a review of definitions of power system flexibility, drawing attention to the historical evolution in the meaning of the term as the context has changed (section 2.1). The authors' own view on the matter was then discussed, defining flexibility as the power system's ability to cope with variability and uncertainty in generation and demand (section 2.2). Sources of variability and uncertainty over different timescales were identified, along with flexibility solutions able to cope with them, which can be grouped in four categories: (i) flexible generation (including variable renewable energy curtailment), (ii) flexible demand, (iii) storage and (iv) system interconnection.

An extensive review of flexibility quantification methods followed, classifying approaches depending on the question they attempt to address: *how much flexibility does my system need?* (section 3.1), *how flexible is my flexibility solution?* (section 3.2), *how flexible is my power system?* (section 3.3), and *who is providing flexibility in my power system?* (section 3.4).

Existing methods addressing this last question were shown to be limited in terms of their number, scope and relevance. A pair of novel tools were

then presented to close this gap in literature: Flexibility Solution Modulation Stack (FSMS) and Flexibility Solution Contribution Distribution (FSCD). These frequency spectrum analysis based tools quantify flexibility provided by all four categories of flexibility solutions, separately considering their roles on the annual, weekly and daily timescales. Note that the proposed tools do not express a flexibility solution’s deliberate intent to provide flexibility, nor its ability to provide flexibility, but rather the flexible aspect of its behaviour, defined while considering the entire power system’s capacities, technical and economic constraints.

Several example applications were provided, for both historical and prospective power systems, in several geographical locations with contrasting characteristics. Condensing significant amounts of information, FSMS and FSCD were shown to be able to support a wide range of narratives, from shedding light on interactions between FS’s, ranking their contributions and analysing the roles of future solutions, to tracking the evolution of a FS’s importance. An extension of this work could involve broadening the analysis beyond the power system to include other energy vectors, such as gas or hydrogen.

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Appendix A. Power system flexibility definitions

Table A.1: Power system flexibility definitions considered in section 2

Authors	Proposed definition	Reference
Van Greet <i>et al.</i> (1993)	The ability to adapt the system (both generation and transmission), quickly and at reasonable cost, to any change in the conditions that prevailed at the time it was planned.	[11]
Bresesti <i>et al.</i> (2003)	The attitude [ability?] of the transmission system to keep up a desired standard of reliability, at reasonable operation costs, when the generation scenarios change.	[12]
IEA (2011)	The capability of a power system to maintain reliable supply in the face of rapid and large imbalances, whatever the cause.	[16]
Bertsch <i>et al.</i> (2012)	The capability to balance rapid changes in renewable generation and forecast errors within a power system.	[13]
Holttinen <i>et al.</i> (2013)	Ability to accommodate the variability and uncertainty in the load-generation balance while maintaining satisfactory levels of performance for any timescale.	[7]
Ma <i>et al.</i> (2013)	The ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons.	[18]
Mandatova <i>et al.</i> (2014)	The modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system.	[21]
Huber <i>et al.</i> (2014)	The ability of a power system to respond to changes in power demand and generation.	[22]
Tuohy and Lannoye (2014)	The ability to adapt to changing conditions while providing electricity safely, reliably, affordably, and in an environmentally responsible manner.	[23]
ENTSO-E (2017)	The active management of an asset that can impact system balance or grid power flows on a short-term basis, i.e. from day-ahead to real-time.	[17]
Villavicencio (2018)	Ability to adjust to changing conditions over different timescales.	[19]
CEER (2018)	The capacity of the electricity system to respond to changes that may affect the balance of supply and demand at all times.	[20]
IEA (2018)	All relevant characteristics of a power system that facilitates the reliable and cost-effective management of variability and uncertainty in both supply and demand.	[1]
IRENA (2018)	The capability of a power system to cope with the variability and uncertainty that VRE generation introduces in to the system in different time scales, from the very short term to the long term, avoiding curtailment of VRE and reliably supplying all the demanded energy to customers.	[14]
Papaefthymiou <i>et al.</i> (2018)	The power system readiness for higher shares of variable renewables.	[10]

Appendix B. Power system flexibility quantification methods

Table B.2: How much flexibility does my system need? Papers considered in section 3.1

Authors	Brief description	Reference
Kondziella and Bruckner (2016)	Review and classification of methods quantifying short-term FS potential. FS theoretical potential can be equated to flexibility requirement.	[26]
Huber <i>et al.</i> (2014)	Study of the impact of wind and solar generation on short-term flexibility requirement by evaluating one and multiple hour ramp rate in residual load.	[22]
Holttinen <i>et al.</i> (2010)	Study the impact of wind generation on residual load variability by evaluating 10-60 minute ramp rates.	[28]
Deetjen <i>et al.</i> (2017)	Study the impact of VRE penetration on flexibility requirement through six indicators: 1 hour ramp-rate, 3 hour ramp rate, ramp factor, ramp acceleration, 1 hour volatility and 1 day volatility.	[29]
Lannoye <i>et al.</i> (2012)	Review of flexibility quantification methods. Proposed the basis for the classification used in this paper. Mention a few metrics that were used back then, such as standard deviation of VRE output and residual load, or forecast error statistics.	[9]
Dvorkin <i>et al.</i> (2014)	Study the impact of wind generation on flexibility requirement, by evaluating the magnitude, ramp rate and ramp duration of deviations between scheduled and actual residual load.	[30]
Nosair <i>et al.</i> (2015)	Present the "flexibility envelope" framework, which covers multiple facets of flexibility. Flexibility requirement is one of the framework's building blocks, and identified as 95% of the probability distribution function of VRE intra-hourly deviation from forecast.	[5]
Heggarty <i>et al.</i> (2019)	Present a set of metrics evaluating flexibility requirement on multiple timescales.	[24]
Olsen <i>et al.</i> (2020)	Extension of method presented by [24], looking at additional shorter timescales.	[31]
Makarov <i>et al.</i> (2012)	Present a methodology to quantify the storage capacity that would be required to manage the mismatch between hour-ahead residual load forecast and reality.	[33]
Oh and Son (2018)	Explore the feasibility of sizing a storage device to reduce penalties from wind forecasting errors.	[34]
Belderbos <i>et al.</i> (2017)	Study the link between storage power and energy sizing and the shape of generation and load profiles.	[35]
Steinke <i>et al.</i> (2013)	Study the roles of storage and network in providing "backup" for 100% VRE systems.	[36]
Heide <i>et al.</i> (2010)	Study the wind/solar balance that minimises the need to store energy.	[37]
Denholm and Hand (2011)	Study how curtailment is impacted by VRE penetration, wind/solar balance and the introduction of storage.	[38]
Weitemeyer <i>et al.</i> (2015)	Study the role of VER curtailment-fed storage in maximising VRE integration.	[39]
Zerrahn and Schill (2017)	Among other things, review storage requirement quantification methods.	[40]
Jurasz <i>et al.</i> (2020)	Review metrics quantifying energy resource complementarity.	[41]

Table B.3: How flexible is my flexibility solution? Papers considered in section 3.2

Authors	Brief description	Reference
Ma <i>et al.</i> (2014)	Present a composite metric based on a generator's operational margin and ramp rate. Aggregation method is also proposed to express the metric at system level.	[18]
Oree and Hassen (2016)	An extension of [18], present a composite metric based on 8 indicators: operational range, minimum power output, up/down ramping capability, start-up and shut-down times, response time, and minimum up and down times. Aggregation method is also proposed to express the metric at system level.	[42]
Wu <i>et al.</i> (2020)	While analysing the link between flexibility and scheduling cost, calculate a flexibility index for generating units following a method close to [42]. Aggregation method is also proposed to express the metric at system level.	[43]
Ulbig <i>et al.</i> (2015)	Based on power system simulation, evaluate power capability for up/down regulation, energy storage capability, power ramping capability, power ramping duration. This is performed at both FS and system level.	[6]
Nosair <i>et al.</i> (2015)	Present the "flexibility envelope" framework, which covers multiple facets of flexibility. As part of this framework, they track upward and downward potential against a constant scheduled output, for both an individual solution and a system.	[5]
Lannoye <i>et al.</i> (2012)	Review of existing flexibility quantification methods. Proposed the basis for the classification used in this paper. Mention a few metrics that were used back then, such as ramp rate, energy available within a certain timescale, or the ability to provide reserve.	[9]

Table B.4: How flexible is my power system? Papers considered in section 3.3

Authors	Brief description	Reference
Nosair <i>et al.</i> (2015)	Present the "flexibility envelope" framework, which covers multiple facets of flexibility. As part of this framework, they track upward and downward potential against a constant scheduled output, for both an individual solution and a system.	[5]
Ma <i>et al.</i> (2014)	Present a composite metric based on a generator's operational margin and ramp rate. Aggregation method is also proposed to express the metric at system level.	[18]
Oree and Hassen (2016)	An extension of [18], present a composite metric based on 8 indicators: operational range, minimum power output, up/down ramping capability, start-up and shut-down times, response time, and minimum up and down times. Aggregation method is also proposed to express the metric at system level.	[42]
Wu <i>et al.</i> (2020)	While analysing the link between flexibility and scheduling cost, calculate a flexibility index for generating units following a method close to [42]. Aggregation method is also proposed to express the metric at system level.	[43]
Ulbig <i>et al.</i> (2015)	Based on power system simulation, evaluate power capability for up/down regulation, energy storage capability, power ramping capability, power ramping duration. This is performed at both FS and system level.	[6]
NERC (2016)	Among other things, discuss probabilistic adequacy metrics.	[44]
Bird <i>et al.</i> (2016)	Review of international experience with VRE curtailment.	[45]
Lannoye <i>et al.</i> (2015)	Propose two metrics identifying flexibility deficiency: Periods of Flexibility Deficits, Insufficient Ramping Resource Expectation.	[9]
Tuohy and Lannoye (2014)	Provide a broad overview of flexibility assessment methods, while also introducing the Expected Unserved Ramping metric.	[23]
Zhao <i>et al.</i> (2016)	Propose a versatile unified framework to define and measure flexibility, allowing the consideration of several of its facets. Among other things, they maximise the uncertainty that a system can accommodate for a given cost, and propose a Boolean metric indicating whether a system's largest variation range is within a target range.	[4]
Menemenlis <i>et al.</i> (2011)	Propose a methodology to evaluate the probability of a balancing reserve strategy satisfying various scenarios.	[47]
Deane <i>et al.</i> (2014)	In their analysis of the impact of sub-hourly modelling of a power system with high wind penetration, calculate the shadow price of ramping.	[48]
Vithayasrichareon <i>et al.</i> (2017)	Quantify the cost implications of various flexibility constraints e.g. ramping, Pmin, start-up costs.	[49]
Morales <i>et al.</i> (2013)	Addresses modelling challenges for VRE market integration.	[50]
Bresemi <i>et al.</i> (2013)	Propose an index comparing the flexibility of different network configurations, for use both in planning and operations.	[12]
Capasso <i>et al.</i> (2014)	From a network congestion point of view, propose a metric quantifying the additional generation that a transmission system can accommodate.	[51]
Papaefthymiou <i>et al.</i> (2018)	List 80 key performance indicators to assess a system's readiness for high shares of VRE.	[10]

Table B.5: Who is providing flexibility in my power system? Papers considered in section 3.4

Authors	Brief description	Reference
Yasuda <i>et al.</i> (2013)	Propose a "flexibility chart" to give an overview of a system's existing FS capacities.	[52]
Deane <i>et al.</i> (2014)	In their analysis of the impact of sub-hourly modelling of a power system with high wind penetration, track the number of generator start-ups.	[48]
Vithayasrichareon <i>et al.</i> (2017)	In their quantification of the cost implications of various flexibility constraints, track the number of generator start-ups.	[49]

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