# Power System Flexibility Assessment - State of the Art

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***Abstract*—Recent research has led to the development of a number of metrics for the assessment of flexibility in a power system. This paper presents an overview of the tools currently available to those involved in planning and operations to directly incorporate the assessment of the requirements for flexibility, the flexibility resource available in each system and methodologies to assess the overall flexibility of a system including operational and transmission constraints. Current challenges and areas for future development are also highlighted.**

***Index Terms*—power system modeling, power system planning, wind power generation, solar power generation, hydro power generation**

## I. Introduction

Many power systems are currently undergoing fundamental physical and institutional reforms, bringing deregulated power markets, carbon trading and subvention for the development of renewable generation capacity. Consequently, the amount of variable generation (primarily wind and solar generation) installed globally has risen dramatically. The amount of wind generation installed globally has increased by 1100% in the last 10 years [1]; the amount of solar generation has increased by 2700% in the same period [2].

The increase in variable generation (VG) has created new opportunities for interconnection, energy storage, flexible generation, demand side resources, and for advanced system operation tools. Since the output of VG is variable and cannot be perfectly forecast, the integration of large amounts of VG may require additional "flexibility" in the power system in question. Flexibility has been defined in [3] as the ability of a system to use its resources to meet changes in the net load, where net load is the system demand minus the output of variable generation.

A large number of metrics and indicators are currently used in power systems to measure the reliability and efficiency of the system. For example, indicators such as loss of load expectation and expected energy not served are used in a planning context to determine the adequacy of future systems. However, there are few planning metrics currently available which assess a system's flexibility in operational or planning time frames. With system operators and market regulators attempting to determine the necessary level of flexibility for each system, as well as manufacturers promoting new solutions to provide the flexibility required [4], research has begun to focus on the development of power system flexibility metrics.

Flexibility requirements have traditionally been met through reserve provision and generation scheduling. Since the system demand was largely predictable, intra-hour changes could be met by regulation and load following reserve, while contingency reserve was set aside for the unpredictable outage of a production or transmission resource. However, the introduction of variable generation may require a new assessment of the provision of reserve, opening up a larger question concerning the flexibility required and available in a system.

While generation adequacy can be determined with knowledge of relatively few characteristics of generators and the peak load hours of the year, an assessment of flexibility may require significantly increased data, depending on the depth of insight sought. The requirement for flexibility is largely determined by the amount of VG installed, the correlation between VG production and system demand and the failures of conventional generation resources. When compared to the relatively predictable system demand profile used for adequacy calculations, a greater degree of uncertainty surrounds the requirement for flexibility. The number of resources which may contribute to the provision of flexibility are the same as those which provide capacity to meet system demand. However, since the flexibility of a system depends on the state of each resource more detailed information is required for each resource.

Finally, an assessment of the ability of a system to continuously balance demand and generation requires operational modeling followed by statistical analysis, rather than an analytical solution given by the LOLE, for example. The number of degrees of freedom involved with the calculation of flexibility, therefore, is much greater than that for capacity adequacy calculations. NERC [5] and the IEA [6] provide detailed reviews of those factors affecting power system flexibility.

A system's flexibility can be assessed by direct calculation of the likelihood that the system cannot meet changes in net load over a given time horizon, or by a proxy analysis of events which are symptomatic of a system's inflexibility. Current developments have resulted in two distinct classes of flexibility metric based on their targeted applications. Metrics have been developed to provide insight for those involved with real-time operations and for those involved with long-term planning. A further distinction can be drawn between those metrics which measure the flexibility requirements of a system, the flexibility available from its resources, and the overall flexibility of a

This work was conducted in the Electricity Research Centre, University College Dublin, Ireland, which is supported by the Commission for Energy Regulation, Bord Gáis Energy, Bord na Móna Energy, Cylon Controls, EirGrid, Electric Ireland, EPRI, ESB International, ESB Networks, Gaelectric, Intel, SSE Renewables, UTRC and Viridian Power & Energy.

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system including operational and transmission constraints.

Section II reviews current indicators used in an operational time frame to assess the online flexibility of a power system. Section III outlines flexibility indicators for use in long-term planning contexts. Future developments for the assessment of flexibility are presented in Section IV, while Section V concludes.

## II. Operational Metrics

Flexibility is not a new problem. System demand has varied and generation outages have occurred for as long as power systems have existed. A range of indicators for the instantaneous power balance and reserve provision have traditionally been available to system operators. While the introduction of the term flexibility may be a new one, many of the constituent parts of power system flexibility have been measured for many years. These existing metrics have been complemented by new metrics which assess the flexibility of a power system. The following sub-sections distinguish between those metrics which measure the flexibility required, the flexible resources available and the overall flexibility of a system.

### *A. Flexibility Requirements*

System demand is currently the single largest consumer of flexibility in power systems and, therefore, the prediction of changes in system demand is critical to an understanding of the flexibility of a system. The system demand forecast, and importantly, the confidence interval associated with the predicted system demand may indicate the level of flexibility required by the system. In the first instance, predicted changes in net load are likely to have been incorporated in the day-ahead unit commitment and dispatch of the generation resources. However, deviations from the predicted system demand must be met by the remaining flexible resources. When the confidence interval of the forecast system demand is relatively large, it can be expected that increased flexibility from reserve may be required and the utilization of that flexibility is less predictable. Heretofore, this problem has been adequately managed with load following reserve.

With the introduction of high penetrations of variable generation, a system's flexible assets must now meet the changes in net demand. While forecast errors for system demand remain low, forecasts of net load must now consider VG production and the corresponding confidence intervals. As with system demand, the net load poses two challenges. Depending on the correlation of the VG output to the system demand, the magnitude of changes in the net load may increase. Without curtailing VG production, it is conceivable that the existing flexible resources (generators, demand side resources (DSR), storage devices, interconnectors, etc.) may be insufficient to meet the upward, or downward, changes in net load at certain times, even with perfect foresight. Furthermore, the output of VG will displace conventional generation and reduce the amount of online flexibility, while the stochasticity of VG output will result in wider confidence intervals, indicating that additional flexibility may be required.

Consequently, net load forecasts provide system operators with two insights; the magnitude of forecast changes in net load indicates the flexibility required which may be met by slower acting resources and, secondly, a forecast's confidence interval, which indicates the increased risk that additional fast acting flexibility may be required.

### *B. Resource Flexibility*

Many power systems perform an online assessment of the available ramping capacity. This may be given as a system ramp rate or energy available in a certain time frame. With the assumption that no outages of resources will occur in the near future, this is the most basic indicator of the flexibility available from a system's resources, before constraints related to the transmission network and system operation are included.

In most cases, systems have organized their flexible resources into various categories of reserve. The amount of reserve capacity provided for in operations represents the amount of flexibility that has been deemed to be economically viable, and that system operators may wish to engage, if necessary. Metrics such as those in [7], [8] highlight the ability of a system to provide for the reserve which has been determined. Risk indices which show that a reserve constraint is frequently not being met indicate an inflexible system, or a system with a large requirement for flexibility.

While metrics which concentrate on the flexibility requirements and the availability of flexibility separately offer some insight into the flexibility of a system, transmission and some operational constraints are not included. Since these system constraints can play a large role in determining the flexibility of a system, their inclusion is critical to assessing the overall flexibility of a system.

### *C. System Flexibility*

The following metrics represent a system's overall ability to deploy its resources to meet changes in the net load and generation outages over various time horizons. The resources available to manage a 15 minute ramping event differ greatly from those available to meet ramps which last 6 hours, and should be considered separately as a result. While the majority of the indicators previously mentioned are currently calculated for various purposes, development has focused on dedicated flexibility metrics at the system level.

The most fundamental measure of the instantaneous balance between demand and generation is the system frequency. The deviation of system frequency from nominal for prolonged periods during net load ramping events indicates the inability of a system to organize its resources to meet the net load ramp rate. However, while the system frequency is a useful indicator in real-time operations it cannot predict the state of a system's flexibility in the immediate future. Instead, it only indicates the instantaneous flexibility of a system. Other metrics are applied for day ahead scheduling and are often unique to each power system.

The Midwest ISO [9] has introduced a market ramping product based on the expected scarcity of ramping resources in the short-term (e.g. day ahead and intra-day). The appropriate ramping reserve in this case is determined by a number of considerations, including the aforementioned system demand

and VG production forecasts, and the associated confidence in those forecasts.

In recent years, the Irish power system has frequently experienced instantaneous wind penetrations of between 40% and 50% of system demand. The system operator, EirGrid, has deployed an array of new tools to manage the consequent variability including the implementation of an operational flexibility metric. The system operators calculate the available flexibility over the next hour and compare this to a range of net load forecast values [10]. This essentially compares the system ramp and load forecasts, as discussed in previous sections, and determines whether the current resources could meet the net load ramp if there was a large forecast error. The forecast errors are estimated from historical wind forecast error data. While this is a conservative approach, computational effort is minimized and the result is an intuitive outcome. Such measures are more likely to be included in market products to provide flexibility.

Menemenlis *et al.* [11] propose a flexibility metric based on a comparison of balancing reserves provided by feasible unit commitment and dispatch solutions to a set of system demand and VG production scenarios. By determining the sum of the probabilities for all the scenarios met by the solution to the unit commitment problems calculated for each scenario, a flexibility index can be determined for each solution. Such an approach pre-supposes the calculation of more than one unit commitment scenario for each trading period. While most systems do not currently employ a stochastic unit commitment algorithm, the resulting flexibility may be increased, and at low cost, [5], as well as enabling the calculation of the proposed flexibility metric. However, the introduction of stochastic unit commitment will greatly increase the computational effort required.

A further development for operational metrics will be consideration of the flexibility required by the outage of generation resources and changes in the net load. One possible methodology to achieve this is an adaptation of the planning methodology proposed in [12]. At each instant, the state of each flexible resource can be represented as a two state Markov process. For upward ramping and in the 'available' state, the resource may provide the calculated available flexibility, with the probability that the unit remains in service for the time period in question (e.g. a generator can provide 100 MW in the next hour with a probability of 0.99). In the 'unavailable' state, the resource will require additional flexibility equal to the resource's current production, with a probability of failure during the time period in question (e.g. -300 MW in the next hour with a probability of 0.01). Similarly, a model can be developed for downward ramping, including resources which can consume as well as generate. The convolution of all state models for each resource results in the cumulative distribution function of available flexibility at that instance, including the possibility for resource outages. Using the forecasted net load and error statistics, the probability that the system would not be able to meet the change in net load can be calculated for a range of net load scenarios. Subsequently, by assigning appropriate weighting factors, an expected value of the risk to the system in a given time frame can be calculated.

## III. Planning Metrics

While operational type metrics tend to look ahead for potential flexibility issues in the immediate future, planning metrics concentrate on the design of a system and may depend on the results of integration study simulations. The majority of new metrics to date have been dedicated to system planning and investment with increasing penetrations of VG. Similar to operational indicators, a number of existing metrics are relevant when considering power system flexibility.

### A. Flexibility Requirements

Historical system demand and VG output data offer an immediate insight into the potential for future flexibility requirements. Variability statistics, such as those outlined in [13], offer a starting point when developing forecast VG production and system demand time series. While some uncertainty may arise from the scaling of VG output, the prediction of system demand, or the translation of weather data to VG production, the characteristics of the forecast net load time series are a first indication of the resources which will be required.

The magnitude and temporal distribution of changes in net load are important indicators of the type of flexible resources which may be necessary. For example, a high penetration of solar generation capacity may result in a reduced morning ramp for conventional generation for certain periods of the year. This may not be the case with high penetrations of wind generation. However, localized, sudden drops in output may affect PV production as clouds pass, similar to high speed cut-out for wind generation. The aggregation and production characteristics for each VG technology will determine the frequency of occurrence and the predictability of large variations in VG output. Metrics such as the standard deviation of VG output and net load, the maximum change in net load over given time horizons (e.g. 10 minutes, 4 hours) and the maximum change in net load at a given time of day are important indicators of the kind of flexibility which may be required in future. Furthermore, a trend towards including operational constraints in long-term planning is now developing. With newer planning tools, the metrics available in the operational time frame, such as load and VG forecast error statistics, may also contribute to the body of information available for planning decisions.

The impact of generation outages on the requirement for flexibility is highlighted by the forced outage rate of each resource. A system containing resources with high outage probabilities will have more difficulty meeting the demand due to capacity shortages, but may also experience more frequent outages, depending on the time to repair of that unit. Since generation outages require additional flexibility from the remainder of the system's resources, the number of resources and the forced outage rates of those resources are important from both a capacity and a flexibility perspective.

### B. Resource Flexibility

While forced outage rates may indicate the flexibility required by the outage of a resource, the ramp rate, start-up time and minimum stable output level relative to the maximum capacity for each resource indicate the potential for flexibility to be offered by that resource. A system containing many resources with high minimum output levels relative to their maximum capacity (e.g. 60+ % of rated capacity) and small upward or downward ramp rates would be less flexible than a system containing resources with a wide output range and high ramp rate capability. Furthermore, if the offline resources cannot be brought online without significant notice (i.e. the resource would have to be started in the unit commitment), the system becomes very reliant on the flexibility from online resources.

While the key criterion for each resource from a capacity adequacy perspective is the maximum output of that resource, other characteristics, such as the start-up time, now become important from a flexibility perspective. The amount of demand side resources which are available, whether the system is interconnected to other systems, the market arrangements for interconnection and the interconnection type (i.e. AC, VSC HVDC or LCC HVDC) all indicate the additional active power which can be drawn upon in a given time interval.

Finally, metrics exist which assess the flexibility enabled by transmission designs [14]. While internal transmission systems do not provide flexibility, inadequate transmission capacity may reduce the amount of the technically available flexibility which may be called upon by system operators. A perfectly flexible transmission system is one which allows a resource at any bus to increase production to its maximum output in response to a change in net load or the outage of a generator at any other bus in the system. The consideration of outages and changes in net load can be implicitly accounted for in traditional transmission design methodologies, subject to cost considerations. However, the metric proposed in [14] allows flexibility to be explicitly considered at the transmission design stage.

### C. System Flexibility

The largest number of flexibility tools recently developed have concentrated on assessing the overall system flexibility in the long-term planning time horizon. A selection of methodologies have been proposed to meet the needs of those involved in planning for the integration of VG, both for systems with little or no experience with the integration of VG and those achieving higher penetrations of installed VG.

The International Energy Agency's Grid Integration of Variable Renewables (GIVAR) project has sought to provide a high level flexibility assessment methodology to systems with little experience of VG, and without the need for extensive system data and computationally intensive system simulation [6]. The Flexibility ASsessment Tool (FAST) calculates the potential VG penetration in a system by estimation of the amount of flexibility available from a stylized representation of a system's resources. The estimated potential VG penetration is based on a number of qualitative and quantitative inputs and operational assumptions which may not hold true for certain systems, and a more detailed analysis would be required before definitive investment or policy decisions are undertaken.

Production cost simulation of a power system offers the most valuable insight into the potential ramping issues in a proposed power system. Notwithstanding the uncertainty surrounding the resources available, the characteristics of those resources, the need for dispatch procedures, the timing of outages, the forecast operating costs and the future demand profile, simulation of the resource dispatches highlights whether a system is sufficiently flexible to meet the changes in net load. Only by dispatching each resource, can the instantaneous amount of ramping capability available in a system be compared to the ramping requirement for every time step in the dispatch, rather than estimating the likely periods of maximum variability and the state of each resource during those periods. The use of production cost simulation enables analysis of those periods which may have typically been well understood in a capacity planning context, but may now be important in a flexibility context (e.g. ramping events during periods of low demand).

Given all the information obtained by the simulation of a power system, a simple count of the number of periods per year when the net load cannot be met due to a lack of ramping capability is the most basic planning indicator of the flexibility of a system. However, the value of that number is dependent on the treatment of net load forecasting. When perfect forecasting is assumed, the number of periods when the system is likely to have insufficient flexibility may be lower than in practice. When the production cost simulation results in a few hours of insufficient flexibility, the amount of flexibility which is not deployed may be calculated at each time step for each time horizon of ramping. A time horizon is the duration of net load ramps in question. Instances which indicate a potential shortage of ramping capacity may be vulnerable given different VG production or resource outage profiles. Therefore, further analysis of a system's flexibility may be required.

The unit commitment and dispatch solution highlights the scarcity or otherwise of flexibility in a system. For example, in a system with insufficient flexibility, inflexible nuclear and coal generation units may be required to cycle their output or to increase the number of times they are started or shut down in a year. An increased number of start-ups may be attributed to increased net load variability, lower average net load as a result of the installed VG, or relatively high minimum stable generation levels from those units.

Additionally, when VG curtailment is imposed, the amount of energy curtailed from VG resources indicates that an operational limit has been reached in a system, and that a restriction of VG production has been deemed necessary for either cost or system stability reasons. Fewer occasions of VG curtailment will be necessary in flexible power systems, while inflexible systems may curtail wind production at night so that the start-up or cycling of inflexible base load units can be reduced. The magnitude, timing and duration of VG curtailment highlight those periods during which the system is lacking flexibility, and the cause of the flexibility issue (i.e. insufficient ramping capacity or the high costs of starting units).

Finally, utilization of interruptible load, storage or other demand side resources may provide insight into the scarcity of flexible resources at certain times. While load acting as a system resource may be deployed for either capacity or flexibility reasons, the number of times when such a resource is availed of can be determined by analysis of system dispatches and the associated costs. Demand side resources are actively employed as a viable strategy in the case of net load variation, albeit at a higher cost than generation units [15].

One possible method of assessing the likelihood of insufficient flexibility occurring is by the analysis of the periods when the margin between the flexibility available and the net load changes is smallest. Figure 1 shows the amount of flexibility available and flexibility required by a test system based on the IEEE 118 bus test system using system demand and wind data from the Eastern Wind Integration and Transmission Study [16]. The afternoon periods (15:00 to 17:00) in July and August were identified as experiencing the most challenging flexibility issues. The minimum flexibility available during those hours during each month is shown in Figure 1, compared to the maximum change in net load during those hours.

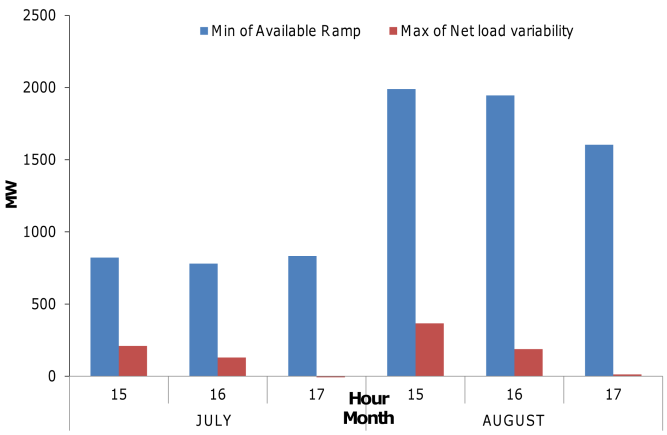


Fig. 1. Worst Case Scenario Analysis. Courtesy of Aidan Tuohy, EPRI

The insufficient ramp resource expectation (IRRE), as outlined in [12], adds an additional level of analysis to production cost simulation. The IRRE is calculated based on a model of the flexibility available during periods of increasing, or separately decreasing, net load and the net load ramping time series. By calculating the cumulative density function of the available flexibility, the probability that each net load ramp can be met by a system's resources can be calculated. The result is an expected number of up or down ramps for which there would be insufficient ramping resources available. Figure 2 shows the IRRE calculated for upward ramps over time horizons between 15 minutes and 24 hours for an example 6 unit test system and for three different scenarios of generator availability and reserve provision. It can be seen that this system has a particular problem in the 4 hour time interval, due to the start-up times of the units in the system. Furthermore, it can be seen that the system is most flexible when reserve is provided, and least flexible when no reserve is provided and generation outages occur.

Since the temporal correlation between the flexibility available and the flexibility required is broken in this process, the IRRE may not represent the precise number of expected periods of insufficient flexibility. Instead, the main value of

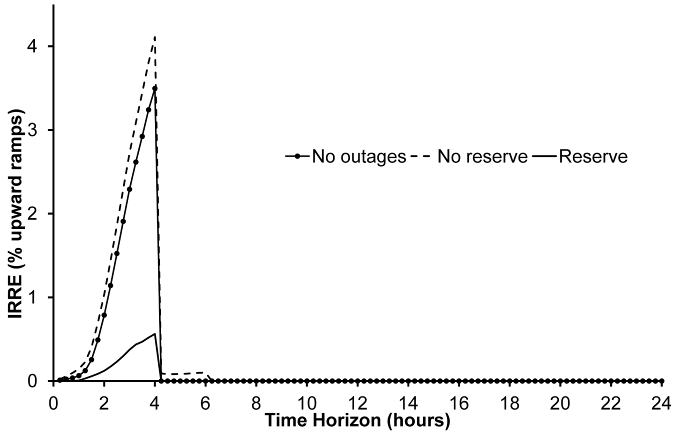


Fig. 2. Test System IRRE

the IRRE is to highlight the time horizons for which ramping events may pose the most risk.

Due to the large data requirement and computational effort required by production cost modeling, research is now focusing on methods which avoid the need for detailed simulation. One potential methodology could replace the detailed unit commitment with a simple merit order dispatch at each instance in the time series. This would allow the calculation of dispatches for many years and at high resolution. The IRRE, or other such metric, may then be applied to the resultant dispatches. However, such a dispatch would not include start up times and costs, minimum up and down times, ramp rates or forced outages. Therefore, the impact of removing those constraints remains to be determined.

A further development is the integration of flexibility assessment into generation expansion planning. Ma et al. [17] have developed an enhanced unit commitment and construction methodology to determine an optimum plant portfolio and the appropriate time to commence building each of those resources. The integration of capacity adequacy planning and planning for variability may become critical to the development of integration study tools. Such a tool will avoid the need for analysis of multiple generation portfolios and instead arrive at the optimal portfolio in a single stage. However, the stability of the results against changing fuel prices and technologies may be an issue for further development.

## IV. Future trends

Current markets for VG tend to be in developed countries, with reliable generation portfolios tailored to meet the system demand. Meanwhile, the restriction of nuclear generation in certain countries may necessitate the construction of new generation capacity in the near future. Power systems in developing nations are growing in response to a capacity deficit. As the cost of energy from VG sources decreases, the penetration of VG will continue to increase in a diverse range of power systems around the world. Therefore, flexibility planning and operational tools to meet the needs of a wide audience of end users require further development to create robust planning techniques for capacity expansion planning and to determine the optimal solution to system inflexibility.

In the same way that capacity value calculations establish the effect that a single resource has on a system in a capacity adequacy context, further research is required to develop a methodology to determine the effect that a single resource may have on the flexibility of a system. This effect may be less obvious in future, as units may be required to operate out of traditional merit order and network restrictions. Given an understanding of the benefits offered by the addition of a certain resource, regulation may focus on ensuring that market designs and out-of-market payments result in a reliable system, from both a capacity and flexibility point of view. Furthermore, market participants may examine opportunities for the construction of resources to meet a perceived requirement for flexibility over a certain time horizon.

As is the case in the Midwest ISO currently, and as implied by the Federal Energy Regulation Commission (USA) [18], payments for the availability of flexible resources may become an important market mechanism in future. A clear and robust method of determining a resource's "worth" will be required in order to value the remuneration due to each resource. This is an area which requires significant additional research.

The basis of evaluating the effect of a resource on a system will depend on accurate evaluation of the flexibility of the system, with and without each resource in place. As has been noted, the evaluation of flexibility is in turn dependent on the operational state of each resource in a system. Current methods may need further development to ensure that the resultant metric is sufficiently robust for each observation, and converges to a stable result, given the likelihood for various VG production scenarios, fuel costs and resource outage patterns. This is especially important if standards for the appropriate level of system flexibility are introduced in future.

## V. Conclusion

The assessment of flexibility is a developing practice in power system operations and planning research. This paper has presented a wide range of power system flexibility metrics for operational and planning purposes. Many metrics which currently exist for other purposes may, as a byproduct, indicate the flexibility required by, and the flexibility available in, a system. Newly developed metrics have concentrated on assessing the flexibility of a system as a whole. With the wide range of metrics available, a streamlined process will be required in future to determine the appropriate metric to use in each circumstance.

Each additional metric has tended to fulfill a different purpose for the end user. However, the accuracy of these new metrics, given the considerable uncertainty surrounding long-term planning, which includes operations, is a subject of further research. Finally, the contribution of each resource to the flexibility of a system is a subject of further development and is of significant commercial interest to those involved in market design and operation, and to resource owners and investors.


## VI. Acknowledgements

The authors would like to thank Aidan Tuohy of the Electric Power Research Institute for his assistance with this paper.


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