FLEXIBILITY IN POWER SYSTEMS

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ABSTRACT

Planning for variability in power systems is becoming more and more important as penetrations of variable generation increases worldwide. Flexibility, or operability of portfolios has previously been implicitly delivered in planning approaches. This paper seeks to make explicit a system's flexibility needs and resources. A metric is also proposed to measure the flexibility offered from conventional generating units.

INTRODUCTION

Power system flexibility describes the ability of a system to meet the changes in demand during an interval. Portfolio operability and flexibility are synonymous. The demand for flexibility has traditionally been fulfilled by reserves, split into categories depending on the time scale of the flexibility required. This paper aims to develop a paradigm to help explain the needs for and the provision of flexibility in power systems and to develop a method to determine generation portfolios which are both adequate and operable.

The need for a method to evaluate the operability of planning portfolios has increased due to the demand for flexibility from the introduction of variable generation

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resources (VG) in power systems. Flexibility requirements were historically dominated by a system's load duration curve which, after a century of operational experience, was typically well understood. With fundamental changes in the shape of the net load (load – variable generation) ramp characteristic with higher penetrations of variable resources, system planners need new tools to understand the volatility in the net load and to map that to a requirement in the generation fleet for flexibility.

The effect of VG on power systems has been examined in reports such as the IEA Wind Task 25 [1] and NERC integration of Variable Generation Task Force's report [2]. Assessing the requirement for reserve arising from VG has been examined in Doherty [3] and Morales [4]. Integration studies have been carried out for many power systems to understand the changes that are necessary to facilitate the integration of large amounts of variable generation. The All Island Grid Study [5], Western Wind and Solar Grid Integration Study [6] and the Eastern Wind Integration and Transmission Study [7] all outline solutions to the provision of flexibility for their respective target penetrations.

Generation planning previously aimed to meet capacity adequacy but did not explicitly consider the operability of the future system at the planning stage. However, planners were implicitly mindful for the need for flexibility which was delivered through cost minimising optimisation. Billington [8] previously used the terminology "adequacy" and "security" to describe a portfolio's ability to meet the load and to be able to move from state to state reliably. The security term is developed here into the concept of flexibility. Planning for flexibility makes explicit the requirement for flexibility and flexible resources available to a power system. The result is a new adequacy criterion to ensure that planned generation portfolios operate reliably and economically. Future portfolios planned to meet both load adequacy and operational adequacy will provide more realistic outcomes.

The proposed metric is a measure of the contribution of conventional generating units to system ramping needs. This is of interest from a planning point of view since planners

want to deliver generation portfolios which are capable of being operated as well as meeting load demands. It is also of interest in an operational setting to evaluate the security of a system to ramp events explicitly, similar to the requirement for reserve provision.

A metric is sought that could with some alteration fulfil both roles and extend on well known existing methods. Specifically, a variation of the Expected Load Carrying Capability (ELCC) is sought due to its widespread acceptability in determining the contribution a unit or a variable resource makes towards generating adequacy. Garver [9] and Billington [8] detail a calculation method for the ELCC which is adapted here. The ELCC method has also been used more recently to measure the capacity credit of wind generation.

FLEXIBILITY ASSESSMENT

FLEXIBILITY PARADIGM

Flexibility can be assessed in a three part paradigm. Flexibility is essentially "created" in the sources and is "consumed" by sinks such as load changes, forecast errors, generator and transmission outages, and the operation of variable and resource constrained generation. The matching of flexible resources to needs is affected by factors such as market and transmission design, interconnection, grid codes, electricity storage, scheduling and the accuracy and implementation of forecasting. A set of properties which can categorise ramping events is proposed to facilitate the matching of the need for flexibility to a combination of resources. Each of part can be analysed under the following headings:

- Magnitude describes the size of a net load or resource output change in MW/minute or MW/period.
- Frequency of changes in the net load are also used.
- Quality describes the reaction time the system operator or generation unit is afforded to respond to a ramp in net load.
- Ramp intensity is a combined result of the magnitude and the quality.

FLEXIBILITY SINKS

Flexibility is consumed by changes in either load, variable generation or both simultaneously. In systems with little variable generation, load is the dominant factor. Each system's load curve will follow various patterns: seasonal, weekly and diurnal. A feature of the diurnal pattern is that every morning a positive ramp in demand is expected and that in the evening demand declines. On a weekly scale it is known that demand on the weekend is normally less then working weekdays. On an annual scale, system demand is usually correlated with meteorological conditions and so e.g. can peak in summer for systems with large air-conditioning load, or in winter where light is a substantial portion of electrical demand.

These changes in load require the provision of flexibility from a source which is consumed over different timescales and magnitudes. For example in the Irish system, morning ramps may require 300MW in 15 minutes while the difference between summer and winter load may require 0.5–1 GW, but over the space of a number of months. Figure one illustrates the requirement of flexibility by the load over 15 minute periods.

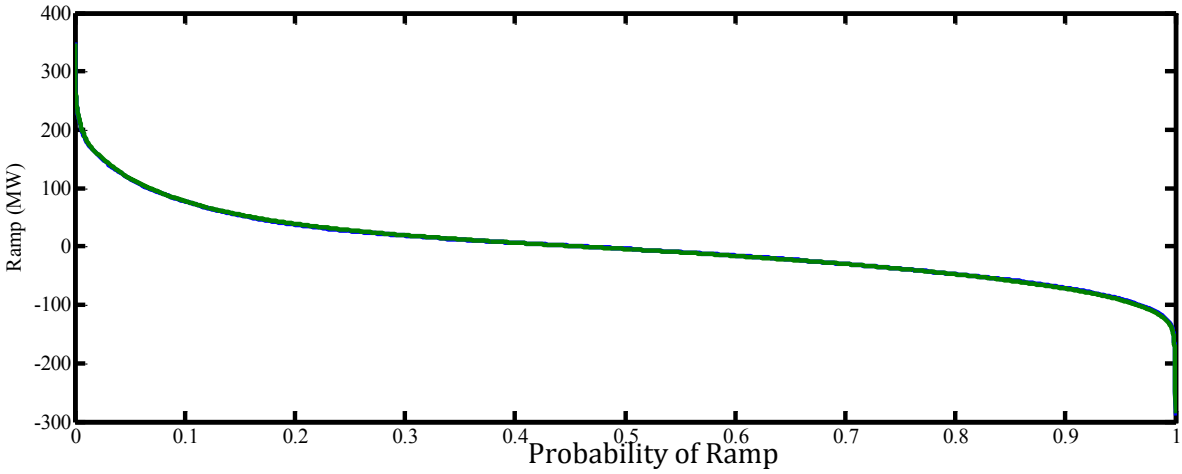

FIGURE 1: 15 MINUTE NET LOAD DELTA DURATION CURVE

The requirement for flexibility also increases with the addition of VG units, as previously mentioned. Resources such as wind, marine and solar power are dependent on the availability of the resources which are variable. In the example of solar, intermittency is caused at a unit level due to passing clouds, the daily cycle of the sun and the seasons. This

requires different flexibility over different time periods. For example, fast start units will be needed for less predictable ramps (clouds), while predicted ramps (diurnal and seasonal) can be met with more inflexible plant. This is true across most of the types of variable generation. This is captured in the quality of a ramping event. An unpredicted event such as passing clouds will be a require high quality, fast acting units, but will be small in magnitude. The loss of a generator or high speed cut out of a large number of wind farms will be require high quality flexibility and be larger in magnitude

The frequency of large ramping events in the system will increase as the distribution of net load ramps becomes more extreme. This has implications for the provision of flexibility since the largest unforecasted ramping events to date are generation outages which occur relatively infrequently. If units are expected to ramp more frequently, this will have consequences for the service life of existing system assets.

In areas where VG is highly correlated due to poor geographical dispersion or climactic conditions, variability will affect all VG units at the same time. This gives rise to high quality and magnitude ramps acting over a short period of time. This is a high intensity event. Systems with well dispersed resources are less likely to witness high intensity events since the effect is delayed throughout the system.

Ramping events from VG will not necessarily consume the same amount of flexible resource due to correlations with the load and other variable generators. A positive ramp in a single wind farm might occur at the same time as the morning load ramp up or at the same time as another wind farm's production ramps down. For example, both solar and to a lesser degree wind power tend to produce more during the day then the night, correlating well to the load profile's flexibility requirements. Tidal devices will operate predictably, but according to the tidal flows which may be in or out of phase with changes in net load. A summary of the flexibility assessment characteristics with the associated properties of the net load sink is given below.

TABLE 1: NET LOAD PROPERTY ASSESMENT

Characteristic	Net Load Property
Magnitude	The net load ramp rate in MW/min or MW in a given time step, correlation of VG with the load.
Frequency	The net load delta distribution.
Quality	Predictability of net load changes, time of day variability.
Intensity	Duration of net load delta events.

FLEXIBILITY SOURCES

Generators' ability to ramp up and down provides the majority of flexibility to a system. Different plant types will have different abilities according to the specific design of the unit. For example, nuclear and coal units typically have high up and down times, long start up times, high minimum operating points relative to rated capacity and slow ramping rates. This type of plant would give large quantities of flexibility but of a low quality.

Due to the high capital costs invested in the unit, such plants are designed to have high capacity factors and are designed to meet system capacity rather than flexibility adequacy. In addition, these units are unsuited to deal with a high intensity event as the units' ramp rates are relatively small over a small time period.

In contrast, plant with high operational costs operate in the few hours of the year of greatest need such as high load, generator outages, or during hours where inflexible generation is committed and changes in the net load occur. These plants have fast start-up times, fast ramping capabilities and low up and down times. Plants such as OCGT[2] and pumped hydro units offer the system a highly flexible resource. Such plant would be high quality, low quantity flexible plant. Mid merit plants strike a balance between meeting capacity and flexibility adequacy by offering plant designs which maximise efficiency subject to a flexibility requirement. Resource constrained generators such as storage devices can offer high quality flexibility but can contribute less to high magnitude and frequency events. A table of synchronisation times, up times, minimum stable level as a % of rated

[2] Open Cycle Gas Turbine

capacity and positive ramp rates for different plant types is shown below to illustrate the above discussion.

TABLE 2 UNIT TYPE CHARACTERISTICS

Increased Capacity

Plant Type	Synch. Time (hrs)	Up Time (hrs)	Stable Level as % of Rated Cap.	Ramp Rate as % of Rated Cap.
PF Coal[3]	15	8	48%	1%
CCGT	5	4	50%	3%
Hydro	0.3	0	55%	27%
Peaking Oil	0.1	0	10%	10%
P Storage	0.1	0	7%	288%

Increased Flexibility

When considering traditional models of flexibility provision, different reserve products served different purposes. Regulation products tended to be focused on small, frequent changes in the load over relatively a short period. Operating reserves focused on large scale changes in load during short periods and were less frequent then regulation. Replacement reserve reacted to bring large amounts of resources online, but over an even longer time period. Table three characterises generators' properties in the assessment paradigm.

TABLE 3: GENERATOR PROPERTY ASSESMENT

Characteristic	Generator Property
Magnitude	The unit ramp rate in MW/min or MW in a given time step
Frequency	The ability of a plant to cycle, given by a metric such as the minimum cycle period which is physically possible.
Quality	Synchronisation time, minimum up and down times, unit availability to ramp
Intensity	Reservoir size for energy constrained units

The rated MW/min ramp rate offered by a unit is described by the magnitude. Temporal and operational constraints on the unit such as minimum and maximum up and down times, synchronisation time and likely output level are described by quality. The position of a unit in the merit order dictates the probability that the unit will be available to

[3] This is based on a PF coal unit in the ROI system. This is perhaps more flexible then coal units designed for use in other systems.

ramp in either direction. High merit units are more likely to be ready to ramp up, while low merit units are more likely to be ready to ramp down.

An alternative to changing the generation to meet the energy balance is to change the load. Load can be changed through a variety of methods; large industrial customers such as furnaces can be taken off the system through interruptible contracts where payment is received for a reduction of load. There are limits to both the amount of this resource in any system and the frequency with which it can be implemented. Repeated load interruption may become uneconomic for the consumer, and the service withdrawn.

Smart metering with time of day pricing may in future provide a system wide resource to control net load variation. These measures are early in development and it is to be seen how responsive consumers will be to real time electricity pricing. Electric vehicles and vehicle to grid technology could potentially provide a very flexible load assuming that a large number of vehicles are grid connected at any one time. DSM is far from mature at the moment leaving control of generation as the main source of flexibility in systems. The flexibility from the load is characterised as follows:

TABLE 4 LOAD PROPERTY ASSESMENT

Characteristic	Load as a Resource Property
Magnitude	The ramp rate in MW/min or MW in a given time step
Frequency	The maximum number of instances when an interruptible contract can be called on. Limits on charge/discharge cycles of a storage device.
Quality	Response time of resource, availability to participate in ramp event
Intensity	Storage size for energy constrained units

FACTORS AFFECTING FLEXIBILITY

While geographical spread and correlation with the load can reduce the requirement for flexibility from VG units, there are a number of factors which can amplify and attenuate the provision of flexibility in a system. These factors include: forecasting, transmission

design, scheduling, operator response, energy storage, grid codes and markets. The role these play in effecting flexibility in a system is described below.

Forecasting allows the system operator to prepare for ramp events. Perfect forecasting does not change the quantity of the flexible resource needed but it does allow the system to be reconfigured to allow less flexible units (lower quality flexibility) provide the required amount to the system. However, imperfect forecasting can increase the quality of flexibility required in the system by underestimating ramps in VG or load. When the ramp event transpires, the system is ready to provide only of a portion of the ramp from flexible generation. This will require more fast start units (higher quality flexibility) to provide a restorative force to the energy balance.

The way in which a system is scheduled can also affect the flexibility of a system in a number of ways. Day ahead scheduling on an hourly resolution will require more flexibility in a system than 6 hour ahead scheduling on a 10 minute resolution. The smaller the time difference between the gate closure and real time operation, the smaller the forecast error is likely to be, as demonstrated by the figure two. Forecast error increases with time horizon. Better information can be used as gate closure approaches real time. As previously mentioned, the forecast cannot reduce the quantity of the flexible resource needed, but can reduce the quality of the resource used.

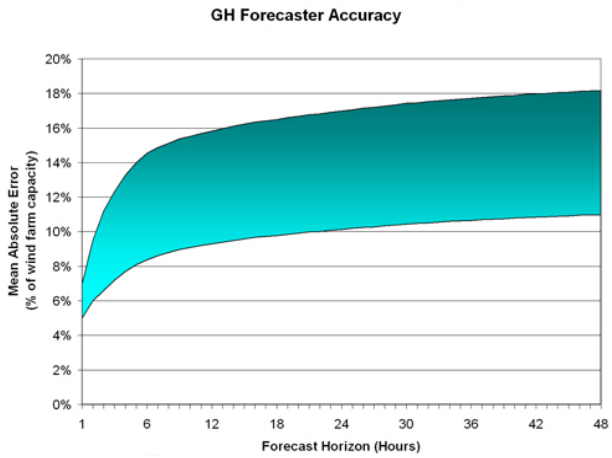

FIGURE 2: GARRAD HASSAN FORECASTER ACCURACY [13]

The design of internal transmission and interconnection are key factors in determining the flexibility of a system and the provision to be made for flexibility. A system with many constrained bottlenecks will require higher amounts of flexible resources situated within each of the areas behind the constraint. This can be viewed on a micro and macro scale. In the

micro scale, a system may internally be made up of several “islands” interconnected weakly to each other. In the instance that a ramping event occurs in one system, depending on the state of each of the connections into and out of the area, the resources needed may not be imported from other areas.

Consequently, each area must have its own flexible resource of sufficient size to meet that island’s needs. At the same time, the island’s neighbours will have the same flexible resources, driving up capital costs. The flexibility available in all islands is unlikely to be required at the same time, leaving the flexible resource for the system as a whole underutilised. The interconnection between larger systems via AC or HVDC links facilitates resource sharing, reducing the system wide need for flexible resources. A limit is often placed on the usefulness of a HVDC link in a situation where a flexible resource is needed through the scheduling policy of the link and the requirement to maintain the power flow on the connector at a certain level. Day ahead scheduling of an interconnection below its rated capacity will reduce the value of interconnection significantly.

Deterministic and stochastic unit commitment algorithms for scheduling a system will also affect the flexibility required. This has been demonstrated by Tuohy *et al* [10]. by showing that stochastic algorithms which prepare the commitments based on the probability of a number of scenarios transpiring. The preparations for such events leave the system in a more robust position, with the ability to make use of lower quality flexible resources to meet ramp events. Deterministic unit commitment prepares the system in a more rigid manner, increasing the reliability on higher quality fast start units.

Energy storage units on a system such as hydro pumped storage, compressed air energy storage, batteries, flywheel systems, fuel cells and vehicle-to-grid enabled electric vehicles provide high quality flexibility over short periods of time. These units can also provide flexibility in both directions at different times.

Policies set out by regulators and system operators can affect the amount of flexibility required. For example, grid codes which stipulate that VG units must have storage capability to smooth their intermittency reduce the need for flexibility in the rest of the system. This exists in parts of Japan where wind plants must provide some sort of storage in order to obtain grid connection. Another example would be a regulation stating that wind units must participate in the electricity market. This way price signals could reduce the number of wind units online during a period of high volatility.

For the flexible resource needed by a power system to exist in reality, markets provide the financial incentive to each player to respond. Markets, like other measures, cannot decrease the amount of flexibility needed but can reduce the quality required. The proximity of gate closure to real time, the resolution of the market and the strength of the ancillary services market are all factors which can affect the provision of flexible resources.

As mentioned previously, the proximity of gate closure to real time operations allow more accurate forecast information to be used. When this is combined with a higher resolution intra-hour market the system can better make use of the slower reacting, lower quality resources. This reduces the need for higher quality, fast acting units which increase system operating costs. Ancillary services markets provide the incentive for flexible resources to be developed. If the ancillary market does not value the service at the appropriate return, developers will not deliver the resources and system flexibility remains low.

METHOD

A method was sought to capture a conventional unit's ability to meet both positive and negative ramps in net load, taking into account the unit's idiosyncrasies. The Expected Ramping Capability method calculates the extra ramp over a specified period in a positive or negative direction that a system can meet to a constant reliability standard when a new unit is added. This is based on the ELCC which measures the extra load which can be added to a system to a constant reliability when a new unit is added. The new ramping reliability

standard can be a variable similar to the Loss of Load Expectation or Probability (LOLE / LOLP) standards used for generation adequacy. Matching variables are proposed for use with these methods which perform identical roles. The Insufficient Ramp Resource Probability (IRRP) is the probability that a system will not have sufficient ramping capability in a given direction over a year. Therefore, the IRRP needs to be specified over different time intervals and in both the positive and negative direction (e.g. $IRRP^{+}_{15\ mins}$, $IRRP^{-}_{60\ mins}$).

Rather than use a rated output capacity for the unit as in ELCC studies, the ERC uses the unit's rated ramping capability over the specific time period but share the same forced outage rates as in ELCC studies. Since the reliability metrics measure the system flexibility resource relative to the ramping requirements, the changes in net load over the specified time period (e.g. 15 mins) are used instead of a load time series. A summary of the equivalent terminology in both methods is shown in figure 3.

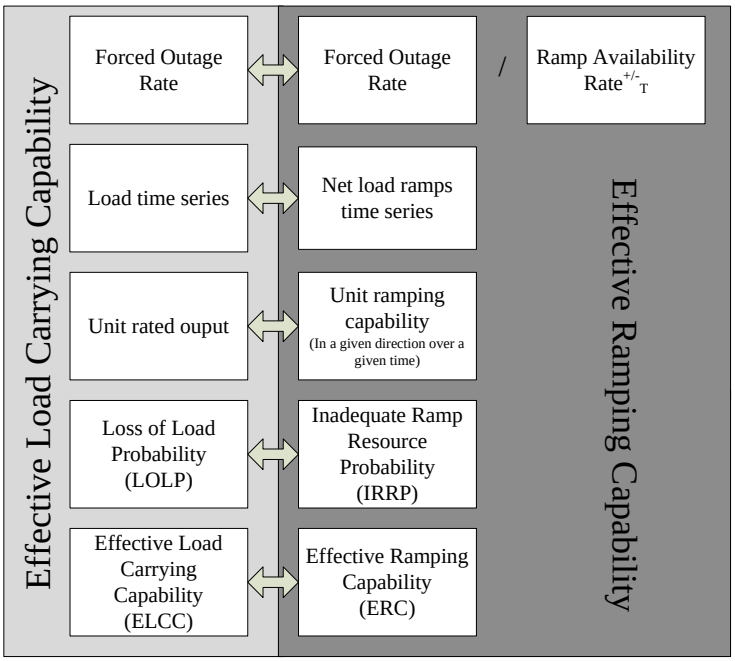

FIGURE 3: COMPARATIVE ERC & ELCC TERMINOLOGY

The unexplained element in figure three is a Ramp Availability Rate (RAR) variable with no direct counterpart in the ELCC calculation. The RAR estimates the proportion of time that a unit is available to offer its full rated ramp in the same direction and time period as the ERC calculation it is being used in. This value can be used to determine the effect of the operational practices on a unit's actual ability to provide its rated ramp. However, as is shown later, the RAR is determined from the unit's historical ability to ramp and is therefore subject to the historical operational environment. This may be useful in ERC calculations where the operational aspect is well known and unlikely to change. In a longer term planning

context, the operational context is likely to change given the large scale integration of variable generation. This will require further research to estimate RAR values and associated risk when operational practices are uncertain.

The RAR can be interpreted in one of two ways; either as the proportion of time the unit is available to give its full rated ramp or as the effective proportion of time that the unit is available to ramp. The first interpretation is shown by the area shaded "1" in figure four and corresponds to the first equation. The second interpretation credits the unit for its availability to ramp less than the maximum rated ramp. The sum of the less than rated ramping is taken and divided by the rated capacity. This gives the number of hours that the unit could effectively ramp at the rated ramp, shown by area "2". The RAR is given by the second equation for this interpretation. A full method for the calculation of the RAR with the first interpretation is detailed later.

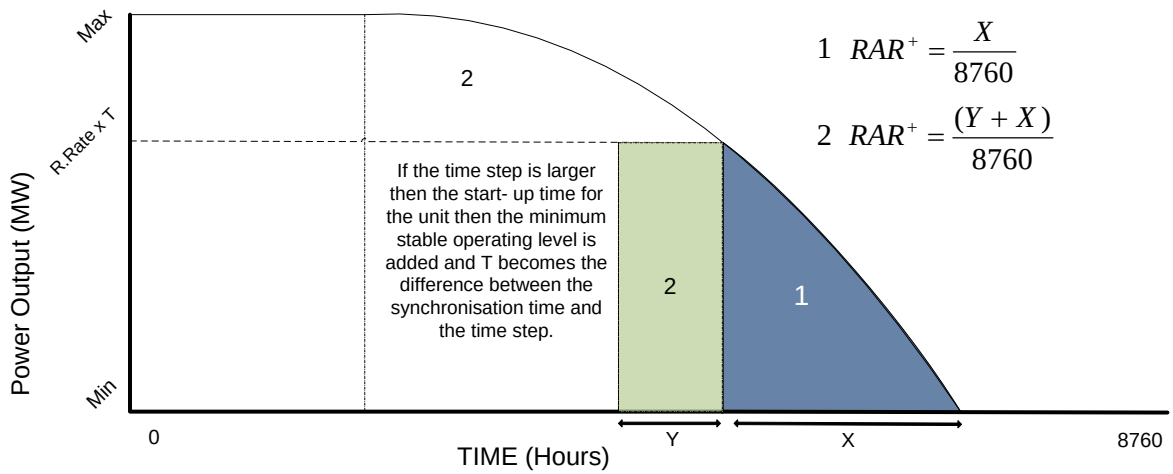

FIGURE 4 RAR DETERMINATION FROM UNIT OUTPUT PROFILE

RAR Method

The use of the Ramp Availability Rate variable in the ERC depends on the context in which the value for the ERC is to be used. The calculation here is for the first interpretation of RAR as discussed in the introduction to this section. The RAR is obtained in a two part process.

The first part of the process is the calculation of the ramp that a unit is able to provide in the time step of interest (e.g. 15 min, 60 min, 2hrs etc.). Data requirements for this part of

the calculation are not intensive and are widely available for most units. Calculation time is minimal for this step in the process. First, the MW/min ramp rate normally specified for a unit is multiplied by the time step for both positive and negative directions. This gives a value in MW which is the theoretical ramp. For the negative ramp the minimum of the theoretical negative ramp rate and the maximum output of the unit are taken as the rated ramp.

The positive ramp rate is more complex since the generator can be in a number of initial states. The first constraint to the theoretical ramp rate is the output range of an online generator. In any generator the maximum ramp possible over any time scale is the difference between maximum and minimum stable operating levels. Therefore, if the theoretical ramp is greater than the operating range, the operating range is used instead.

The second possibility is that a unit is offline at the start of a time step. In some instances the synchronisation times for a unit may be equal to the time step. This is especially true for quick start and hydro units. In this case, the maximum ramp is the minimum stable operating level of the unit. If this is extended to cases where the synchronisation time is less than the time step, the unit is available to ramp for the remaining time. Therefore the ramp is taken to be the minimum stable level plus the product of the remaining time after synchronisation and the positive ramp rate.

Once the rated ramp is found, the RAR is found. This is done separately for the positive and negative RAR values. The exogenous data requirement for this part of the calculation is the unit's historical output time series. The resolution of this data should match the time step of the ERC calculation. The duration of the time series is taken here to be the one year. The sensitivity of the method to the length of the output vector is discussed later.

The left side of the blue shaded area in figure five illustrates the method to determine the positive RAR. If the synchronising time for the unit is longer than the time period, the values where that a unit is offline are removed from the time series. The positive ramp rate is added to all the values in the time series. The resulting vector will now have certain values

which are in excess of the maximum rated capacity of the unit. These are clearly impossible values since the unit cannot exceed its maximum. The number of values less than the maximum output is then recorded. This is the number of values where the unit is available to give its full rated ramp. Dividing this number by the overall length of the original unit output time series gives a value between 0 and 1 for the positive RAR.

The right hand side of the blue part of the diagram shows a similar calculation for the negative RAR. The rated ramp can be seen as the minimum ramp down that should be satisfied since it is easier to ramp down or turn off units then it is to ramp up. The process is the same as the positive calculation with two key differences. First is that no filtration of the unit's output is necessary since negative values indicate the unit is not available to offer its full ramp down. Values greater than zero indicate times when the plant is available to ramp.

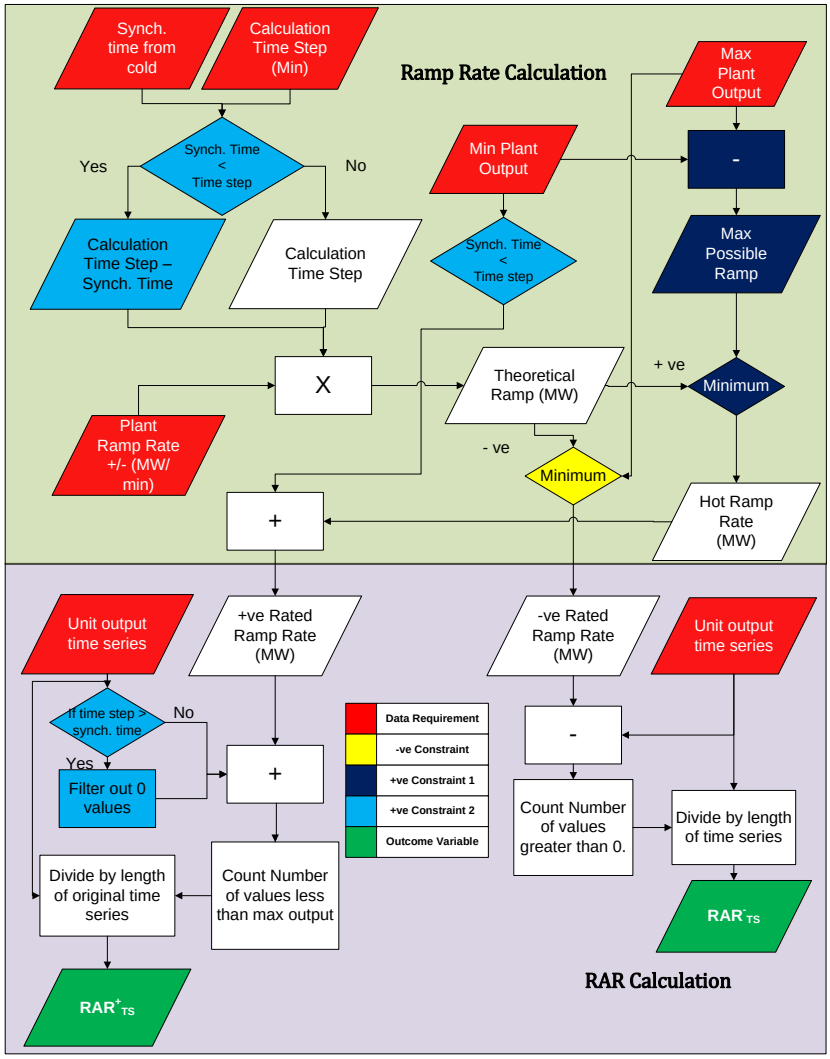

FIGURE 5: RAR CALCULATION ALGORITHM

For units with a storage capability, the threshold is minus the negative ramp. (e.g. -70MW for a hydro pumped storage unit) Dividing the count of these values by the length of the unit's output time series gives the negative RAR.

ERC METHOD

The Effective Ramping Capability calculation is substantially the same as that of the Effective Load Carrying Capability. The major change is that this calculation is repeated over various time steps and in both a positive and negative direction for each time step, rather than a single calculation for generation adequacy. The reliability of a system with respect to ramping is measured by the Insufficient Ramp Resource Probability (IRRP). The IRRP for each ramp rate is calculated by completing a Resource Outage Probability Table (ROPT) with the rated ramp used as the capacity in the COPT and the Ramp Availability Rate where the unit availability was previously used (or 1 minus the forced outage rate). The result is a table of the probability that a discreet ramping event is met in a time step. For a system with two identical units with Ramp Availability Rates of 0.8 and rated ramps of 70MW in the time step the ROPT looks as follows:

TABLE 5: 2 UNIT ROPT

Ramp Resource out of Service	Probability
0 MW	0.64
70 MW	0.32
140MW	0.04

Billington [8] demonstrates a method to calculate the COPT table for identical units using a binomial method, which reduces computational time, but is unlikely to apply in practice. Once the ROPT is created, the net load time series is sorted and separated into bins, the edges of which are defined by the system ramp values in the ROPT. The count of entries in each bin is multiplied by the probability for that bin and the summation of that product for each bin results in the IRRP.

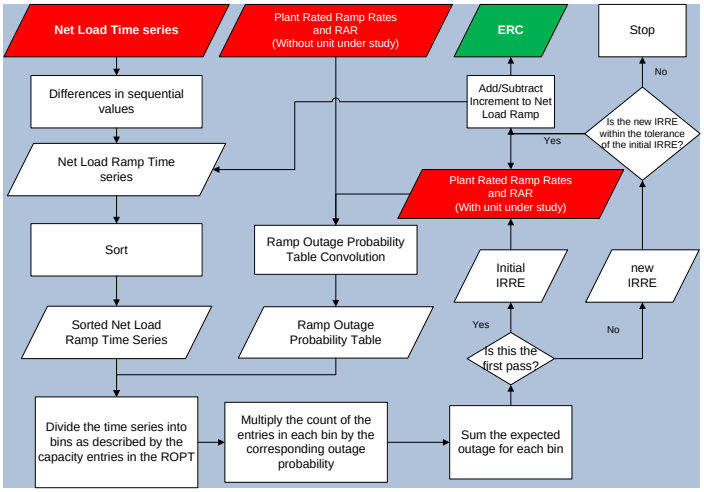

FIGURE 6: ERC CALCULATION ALGORITHM

The ERC is defined as the additional system ramp which can be met, with a constant reliability, by the addition of a new resource. Therefore, the ROPT is recalculated with the new resource included and the IRRP calculation re run. A higher reliability will be achieved by this action. In order to restore the IRRP to the previous value, the ramping on the system is incrementally increased until the new IRRP equals the previous IRRP. The value of the additional ramp added to the original ramp time series is the ERC of the unit added, over the time step and in the specified direction. The method is summarised in the figure six.

Ramping adequacy for a system can be developed by summing the ERC for all the units in a system with the contributions from interconnection and demand side measures. In a similar manner to generation adequacy, the total ERC for the system should be larger than the maximum ramp witnessed plus a planning margin, for each time period and in each direction.

RESULTS

CASE STUDY: IRELAND

The method was tested on the Republic of Ireland (ROI) system using 2009 wind, load and generator data. Dispatch data was used to produce 15 minute resolution production time-series for each unit in the system. Corresponding wind and load data was also available. The assessment for flexibility in 15 and 60 minutes is shown here for the Irish system. Average results for each unit type is shown here.

TABLE 6: 15 MINUTE UNIT TYPE STATISCTICS

Unit type	Avg. type output capacity	Avg. type RAR+ 15	Avg. type ramp rate	Avg.ERC+15
Coal	283.7 MW	0.36	4.3 MW/Min	12.8 MW
Distillate	70.4 MW	0.48	5.4 MW/Min	19.6 MW
Gas	181.3 MW	0.45	5.1 MW/Min	19.3 MW
Gas/Distillate	383.0 MW	0.31	9.3 MW/Min	12.6 MW
Gas/Oil	109.5 MW	0.00	2.4 MW/Min	0.1 MW
Hydro	14.4 MW	0.44	4.7 MW/Min	3.3 MW
Oil	115.1 MW	0.09	1.7 MW/Min	1.9 MW
Peat	103.8 MW	0.57	1.9 MW/Min	13.2 MW
Pumped Storage	73.0 MW	0.95	210. MW/Min	59.5 MW

TABLE 7: 60 MINUTE UNIT TYPE STATISTICS

Unit type	Avg. type output capacity	Avg. type RAR+ 60	Avg. type ramp rate	Avg. ERC+ 60
Coal	283.8 MW	0.35	4.3 MW/Min	12.9 MW
Distillate	70.4 MW	0.49	5.4 MW/Min	19.7 MW
Gas	181.3 MW	0.29	5.1 MW/Min	19.3 MW
Gas/Distillate	383.0 MW	0.31	9.3 MW/Min	12.7 MW
Gas/Oil	109.5 MW	0.01	2.0 MW/Min	0.1 MW
Hydro	14.4 MW	0.55	4.7 MW/Min	3.3 MW
Oil	115.1 MW	0.08	1.7 MW/Min	2.0 MW
Peat	103.8 MW	0.57	1.9 MW/Min	13.4 MW
Pumped Storage	73.0 MW	0.95	210 MW/Min	59.6 MW

These results show that the flexibility available to the system over one hour is almost identical to that available in 15 minutes. This is due to the start up times of fast acting, high quality, flexible units. The physical role these have fulfilled has been to act when generator outages or sudden load changes occur over the space of seconds and minutes. The next fastest synchronising units come online over a 4-5 hour period followed by base loaded units beyond a 12 hour period. 607 MW of ramping can be relied on by the system planner in 15 minutes and 609MW in one hour. The maximum witnessed change in the net load in 15 minutes in 2008 was a 300MW ramp with 830MW of wind installed. This occurred during a morning ramp. Realistically, predictable events have much more flexibility available since the operator can bring offline units online in advance.

The following figure shows the correlation of the unit size to RAR^{+}_{15}. Larger units tend to have lower RAR values, given their role as base load units. Some units of all sizes have start up times of greater than 60 minutes which results in those units having close to zero availability. However, a general trend is that smaller units tend to have higher RAR values, matching their physical role and intuition.

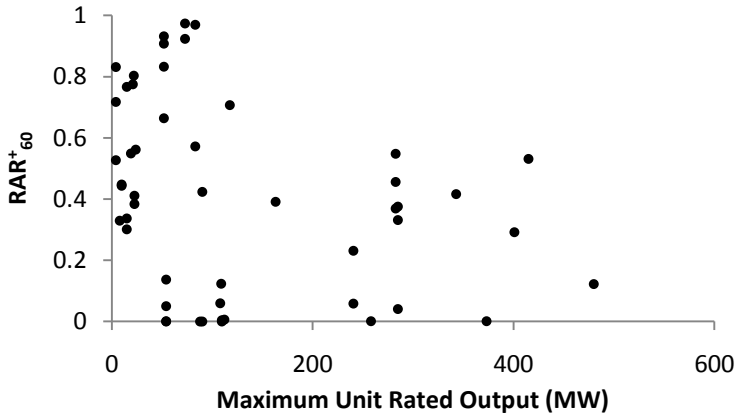

FIGURE 7: RAR VS UNIT SIZE

This brief case study illustrates the ERC method in practice and showing that the ROI system as it exists has sufficient flexibility to manage short duration net load ramp events.

CONCLUSIONS

Flexibility is a nascent concept in power systems planning. By planning for future flexibility needs, system planners can ensure that the integration of VG proceeds as smoothly as possible. Planning metrics will, however, need to incorporate operational practices. The ERC metric incorporates the operational practices through the RAR variable. While this is easily identified from historical unit production, as the net load profile changes the duty cycle of each unit will change. Variables such as the RAR are therefore indirectly a function of the installed VG and the load. When the change in installed VG is incremental, the RAR from the previous period is likely to suffice.

Over longer horizons with larger changes in installed capacity of VG, the net load profile will change significantly. In these situations the RAR will also change and historical data cannot be used. Further work is needed to determine the effect of an error in the estimation of the ERC on system operational security. Some work has been carried out to estimate the impact of certain factors on the RAR such as the presence of interconnection to other systems and the choice of deterministic and stochastic unit commitment algorithms. These initial results are presented in Appendix 1.

Future work will try to determine the relationship between variability in the net load and the RAR values for each unit type. Analysis is also required to determine what planning margin is appropriate for use in planning studies. LOLP criteria are well established current planning studies.

The LOLP measures the probability that the system will not be able to meet the load due to the loss of a unit or inadequate generation capacity. The IRRP is a specific measure of the probability that the system cannot meet the change in the load. This may or may not result in loss of load, depending on the state of the system during the ramping event and the frequency response of the load. Further research is needed to determine the effect of the IRRP on the LOLP and an appropriate value for the IRRP in ERC calculations.

Time of day ERC calculations are valuable since different amounts of flexibility are required at different times of the day. Morning times will be dominated by the increase in load while VG will affect other times of the day. This may be of use in determining critical points of interest when the resource available is close to the requirement.

The effect of two of the input variables on the ERC are shown in Appendix 2. The RAR and the unit size have direct effects on the ERC. The results indicate that as the RAR approaches unity, the unit ERC tends to the rated ramp for that unit. Units with larger rated ramps tend to have a lower normalised ERC due to the effect on system security in the event of their loss.

This paper has presented a high level paradigm to analyse the sources, sinks and factors affecting the provision of flexibility. The ERC was developed to give system planners a tool to plan for variability in a system with increasing penetrations of VG. A case study was presented and further tests shown in the appendices.

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APPENDIX 1: FACTORS AFFECTING THE RAR

Operational aspects such as the unit commitment (UC) type used and the availability of interconnection to other areas affect the system's ability to make ramping resources available for use. To test the effect of these issues on the RAR and consequently on the ERC a test system was used based on Portfolio 5 of the All Island Grid Study [5]. Using the WILMAR [11] system planning tool, production time series were produced for all units under different UC types and with different assumptions about the availability of interconnection.

The RAR for each unit was calculated in three scenarios: deterministic UC with perfect forecasts, stochastic UC with imperfect forecasts and deterministic UC with perfect forecasts and no interconnection to the UK. In order to compensate for the reduced capacity available from the loss of 1GW connection, nine 100GW OCGT units were included. Figure

eight below demonstrates how each of these changes affects the availability of each unit. Deterministic UC operates a system in according to a single forecasted demand while stochastic UC operates a system according to multiple forecasted demand.

The deterministic results here will operate a system based on the perfect forecast for demand. This will operate the system in a way which increases the utilisation of lower quality and less costly flexible resources. Stochastic UC and deterministic UC in reality cannot perfectly forecast demand and will engage the use of higher quality flexibility in instances where forecast errors occur.

The results below reflect this. Perfect forecasting results units being available to ramp for a longer period of time, therefore the RAR values will be higher. Stochastic UC with imperfect forecasting optimises a power system to be able to deal with a number of externalities. This is achieved by having more units online and therefore reducing th0065 availability of units to ramp. The removal of interconnection and replacement with costly OCGT units requires that mid merit units are more often operated to fulfil a base load, reducing their availability to ramp further.

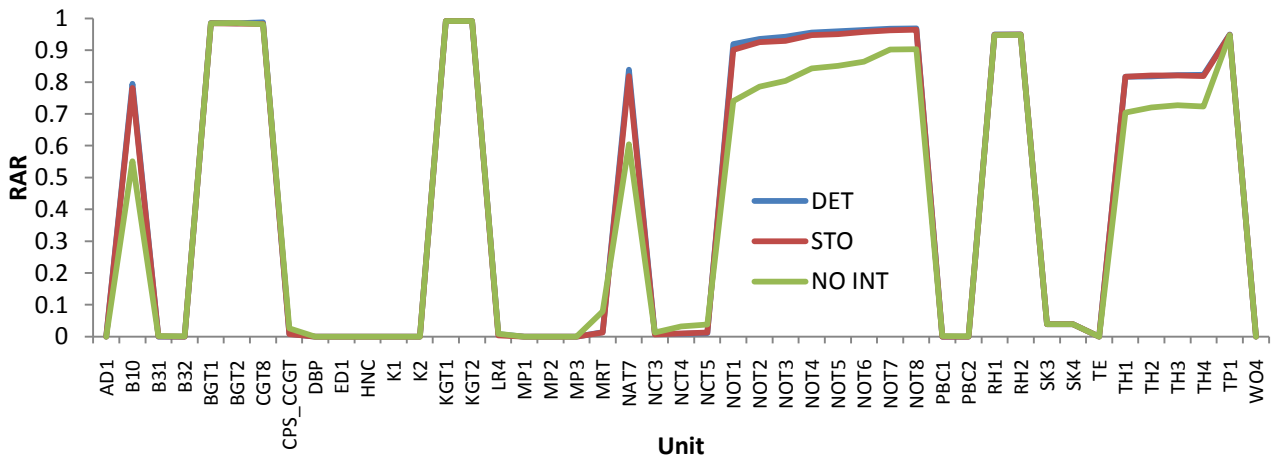

FIGURE 8: UNIT RAR FOR NO INTERCONNECTION, STOCHASTIC AND DETERMINISTIC UNIT COMMITMENT

Unit data is taken from the all island grid study [5] and all island modeling project [11].

APPENDIX 2: FACTORS AFFECTING THE ERC

The ERC was calculated for an additional unit to the 30 unit test system, the details for which are outlined in [5]. Figure eight shows the per-unit ERC for four units of different rated ramp with RAR values from 0.1 to 1. This was calculated for positive 15 minute ramps. Smaller units tend to have a higher per unit ERC then larger units since the loss of that unit to a system is comparatively less of a threat to system security. The behaviour is as expected since as the availability of the unit tends to one, the full rated ramp becomes available to the system.

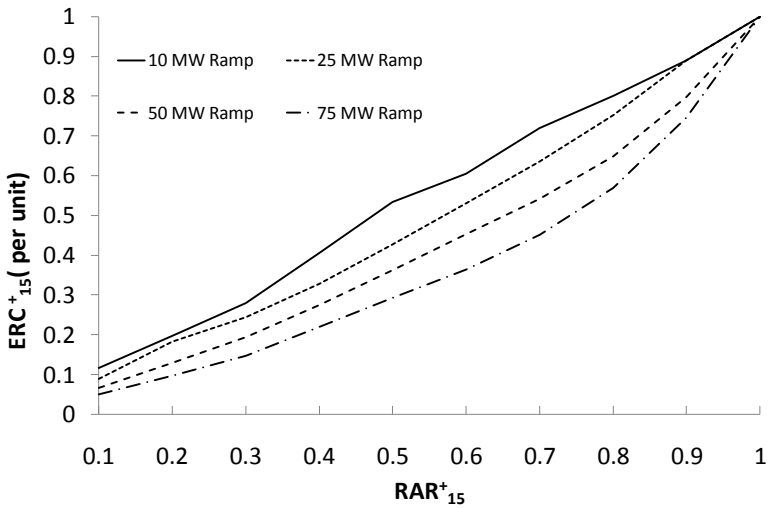

FIGURE 10: ERC AS A FUNCTION OF RAR

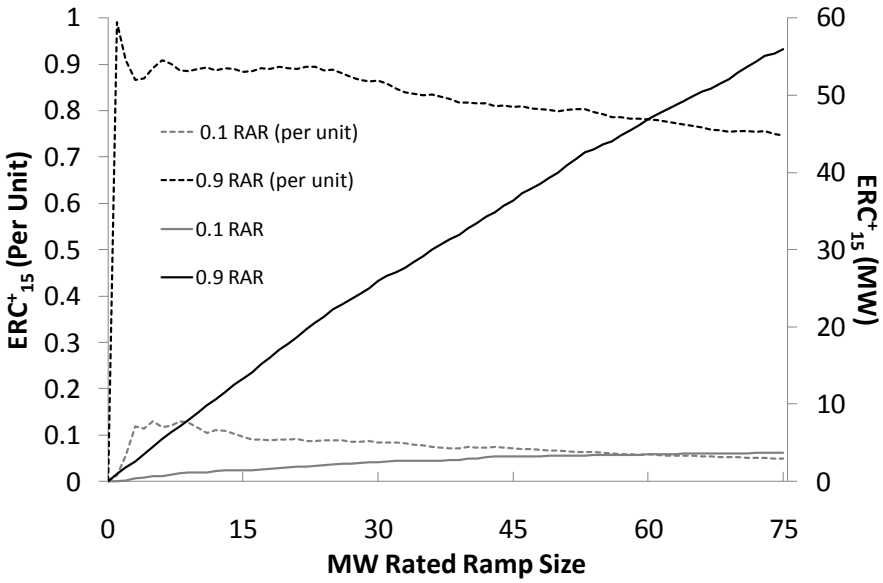

FIGURE 9: ERC AS A FUNCTION OF UNIT SIZE

Assuming a constant RAR value, the impact of the unit size on the ERC is examined. Figure ten shows that for increasing unit size, the per-unit ERC decreased after peaking initially. This indicates that for each RAR value there is an optimal unit size to maximise the usefulness of the unit to the system for ramping. It also reinforces the point made previously that the loss of larger units have larger consequences for a system and ERC reflects this.