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# An Adjusted Weight Metric to Quantify Flexibility Available in Conventional Generators for Low Carbon Power Systems

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**Abstract:** With the increasing shares of intermittent renewable sources in the grid, it becomes increasingly essential to quantify the requirements of the power systems flexibility. In this article, an adjusted weight flexibility metric (AWFM) is developed to quantify the available flexibility within individual generators as well as within the overall system. The developed metric is useful for power system operators who require a fast, simple, and offline metric. This provides a more realistic and accurate quantification of the available technical flexibility without performing time-consuming multi-temporal simulations. Another interesting feature is that it can be used to facilitate scenario comparisons. This is achieved by developing a new framework to assure the consistency of the metric and by proposing a new adjusted weighting mechanism based on correlation analysis and analytic hierarchy process (AHP). A new ranking approach based on flexibility was also proposed to increase the share of the renewable energy sources (RESs). The proposed framework was tested on the IEEE RTS-96 test-system. The results demonstrate the consistency of the AWFM. Moreover, the results show that the proposed metric is adaptive as it automatically adjusts the flexibility index with the addition or removal of generators. The new ranking approach proved its ability to increase the wind share from 28% to 37.2% within the test system. The AWFM can be a valuable contribution to the field of flexibility for its ability to provide systematic formulation for the precise analysis and accurate assessment of inherent technical flexibility for a low carbon power system.

**Keywords:** power system flexibility; flexibility quantification; adjusted weight flexibility metric (AWFM); power system operations; flexibility parameters; renewable energy

## 1. Introduction

In an attempt to reduce our polluting emissions, a large and an accelerated expansion of renewable energy sources (RESs) has been integrated into the current power system. The accelerated integration of RESs in the power grid has posed significant technical challenges [1–4]. Due to the intermittent nature of RESs, persistent fluctuations in their generation impacts and challenges the conventional thermal

generation by bringing new requirements for frequent startups, large ramping and fast sudden power changes [5]. Higher penetration levels of RES are expected in the future power systems. Therefore, there has been an increasing interest and necessity to investigate their impacts on the power system operation and planning [6,7]. Within the integration of intermittent RESs, balancing the generation with load has become a more complex process and has introduced new challenges to maintain system reliability while satisfying the system constraints at the lowest possible cost.

Considering the RESs in the generation mix portfolio has raised the concept of “net-load”. Net-load represents the load that must be provided by the thermal generation if the output of the RES is to be fully utilized. Therefore, the thermal generators output must be skillfully adapted to satisfy the net-load variability. Sudden fall periods in RES output will need running generators with sharp ramp-up rate (RUR) and large operating range. On the other hand, a sharp rise in the RES output creates the need for units with fast ramp down rate (RDR) and low minimum output ( $P_{\min}$ ). This creates the necessity to have more flexible resources in order to match the requirements of the increased ramping in the system [8].

The term flexibility is gaining popularity in the electric power sector. In system operations, the power system flexibility is defined as “the capability of the power system to maintain a balance between generation and load under uncertainty” [9]. Other authors have proposed similar definitions [10–12].

The flexibility requirements have become more severe with the increasing shares of RES integrated in the electric grid. Flexibility requirements can be fulfilled by storage, flexible generation and flexible demand (if applicable). The study presented in [13] proposed a security-constrained flexible demand scheduling strategy for wind power accommodation. The results of the study verified that the presented method could effectively accommodate the uncertainties of wind power output.

Existing conventional generators can effectively compensate higher amplitudes of net-load fluctuations [14]. The generators’ ability to provide flexibility is affected by the constraints that limit how and when a generator can be committed on and off. The presented research in [15] investigates the feasibility, optimality, and the flexibility of the combined heat and power economic dispatch problem. The research presented in [16] highlights the significance of storage which represents an additional flexibility option, as it can smoothen the load pattern and improve system reliability.

The consequences of an insufficient flexibility provision in a power system can be transformed into one or more of the following potential consequences: load shedding and intermittent RES curtailment [17–19], system reliability violation [10,20], increased wear and tear on power system equipment, increased operation and maintenance costs due to cycling effects [20,21] and higher electricity production costs [10,22]. System inflexibility leads to the curtailment of RES output which is an unattractive solution to some stakeholders, thus a wide area of research has initiated the need for higher system flexibility [23–25].

Accordingly, power system operators and planners must guarantee that sufficient flexible resources are accessible on the generation side to reliably enable the power system operation under the future increased share of RES. As a result of that, a great interest in the quantification of the system flexibility has motivated the development of metrics. These metrics should be able to accurately point out to the power system operators the internal flexibility that can be called upon to balance the generation and the net-load at different times of operation.

In the literature, metrics have been presented that evaluate and quantify the available flexibility in power system resources. The complexity of those metrics varies as some metrics are derived based on the physical characteristics of the system while others need comprehensive simulations based on chronological time-series data [8]. The research presented in [26] contributes with an “offline” index to quantify the units and system generation mix flexibility level and also to investigate the flexibility role in the market operation and generation planning. Therefore, system planners can use it in decision-making procedures. It is worthy to note that the proposed index has considered equal weights for both considered flexibility parameters without considering any weighting mechanism to

implement different weights of the flexibility parameters at different scenarios. The research work in [27] provides an accurate analysis of a deterministic metric under different weights of flexibility parameters to assess the available flexibility from an individual generator up to the overall system. The analysis was executed by iteratively varying simultaneously both the capacity and ramping weights as flexibility parameters simultaneously. The results of the research confirmed that prioritizing capacity weight over ramping weight has a higher influence on the system flexibility and on the individual generating unit's flexibility for that case test system. It was also found that the flexibility increment rate is not linear between the test system units. The proposed metric can be used offline and it also gives a simple and fast insight to quantify the power system flexibility.

A visual flexibility chart was proposed by Yasuda et al. [28] which provides a graphical insight in the physical flexibility sources in the power system. The chart is suitable for non-technical stakeholders who are able to use it in order to make quick comparisons of the power systems' relative strengths in flexibility. Conversely, the chart information is limited and should be used prudently. Comparison between different systems is limited to the available capacities of the units which is not a sufficient indicator of flexibility and it also does not consider the power market. One more limitation is that it only takes into account the existing interconnections, without considering the potential future interconnections. On the other hand, it also did not include the calculation of the overall flexibility of the power system. The research presented in [29] has characterized the flexibility requirements and the flexibility provision through dynamical envelopes. An optimal flexibility planning problem was also formulated, but on the other hand, it is more cost-effective than traditional unit commitment assuming constant maximum ramping. The proposed formulations force the system operators to adjust their operational routines to approve the new formulations of flexibility planning.

The authors in [11,30] proposed an insufficient ramping resource expectation (IRRE) metric for the system flexibility measurement. The proposed IRRE is also able to determine the time intervals at which the system will most likely face a shortage of flexible resources. The main disadvantage of the proposed metric is that it only considers the ramp rate to characterize the power system flexibility requirement. The Electric Power Research Institute (EPRI) introduced a more comprehensive flexibility assessment tool called "InFLEXion" [31]. "InFLEXion" is a multi-level flexibility assessment tool which can be used to support and validate power system planning. It enables decision-makers to understand the flexibility needs and future power system performance.

This work focuses on thermal generation flexibility, it is supposed that the flexibility requirements in this sense are only met by thermal generation. Therefore, an offline quantitative metric to assess the inherent level of available flexibility of the generating units and the overall system is highly desirable.

This paper contributes to the developing research area of flexibility metrics by proposing an adjusted weight flexibility metric (AWFM). Compared to the existing work, in this paragraph, we explain the major contribution pillars of the present research work.

- i. The developed metric employs a new adjusting weight mechanism based on correlation analysis (between flexibility parameters) and applying analytic hierarchy process (AHP) based on adopting a participatory approach.
- ii. A new ranking technique by incorporating the flexibility ranking of thermal units to overcome the hidden power system inflexibilities imposed by traditional unit commitment solution for optimal generation scheduling at a higher share of RES with the minimal possible cost.
- iii. The presented metric in this article provides a more realistic and accurate quantification of the available technical flexibility from individual generating units and the overall system without performing time-consuming multi-temporal simulations.
- iv. It can be used 'offline' to evaluate the provided flexibility. Additionally, it facilitates comparisons, in terms of available technical flexibility, between different scenarios.
- v. It can be used as a tool for power system operators to provide insightful and quick information about the inherent system flexibility (between different importance weights of the flexibility parameters in different scenarios).

To accomplish the stated goals of this study, the rest of the paper is organized as follows, Section 2 describes the selected flexibility parameters, Section 3 provides details about the development of the framework, the methodology adopted for the selection of the flexibility parameters, the weighting mechanism and scenario creation and a brief description of the test system. The results and discussion are presented in detail in Section 4, and finally the conclusion is stated in Section 5.

## 2. Description of Selected Flexibility Parameters

The power system flexibility is recognized as a significant parameter to manage the variability in electric loads and the uncertainty in generation due to the RES integration. Flexible generators increase the power system stability by ramping up or down as the load and generation vary. Thus, in this section, a definition of the flexibility parameters of thermal power plants is provided.

### 2.1. Ramp Rates

Ramp rate is the average speed at which the generator can increase its RUR or decrease its RDR between the minimum and maximum generation levels. It is expressed as megawatts per hour (MW/h). Rapid ramping leads to changes in the temperature of power plant components which reduces the power plants lifetime due to the thermal stress [32]. The ramp rate depends on the generation technology, operating conditions and unit's capacity. Ramping can be formulated based on the following conditions [16], ramping up and ramp down are given by Equations (1) and (2), respectively:

$$P_{n,t} - P_{n,t-1} \leq UR_n, \text{ if generation increases} \quad (1)$$

$$P_{n,t-1} - P_{n,t} \leq DR_n, \text{ if generation decreases} \quad (2)$$

where  $UR_n$  and  $DR_n$  are the ramping up and ramping down of the  $n$ -th unit, respectively.

### 2.2. Generation Capacity

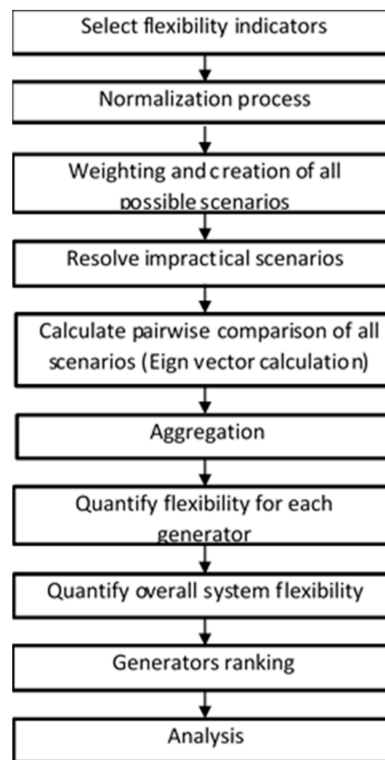
A thermal generator is designed to deliver a reliable power output within a definite range and under the generator's normal operating conditions. This range is constrained by the minimum possible stable generation level ( $P_{min}$ ) and the maximum power output ( $P_{max}$ ). Running the generating unit at its  $P_{min}$  is usually not cost-effective but due to the minimum uptime constraint of the generator, it must run at a minimum baseload. On the other hand, running at this level gives the advantage of calling upon the unit to match the variation in the net-load at any time. The generation capacity of the thermal unit is formulated as follows by Equation (3):

$$P_n(min) < P_n^t < P_n(max) \quad (3)$$

where  $P_n(min)$  and  $P_n(max)$  are the minimum and maximum real power output, respectively [33].

## 3. Development of the Proposed AWFMM Framework

The development of the proposed metric has gone through a sequence of steps starting from the selection of flexibility parameters. Normalization, weighting, correlation analysis, and aggregation are the most important steps in the framework development for the proposed metric. The proposed framework for the metric development ensures that suitable and practical decision weights and scenarios are employed while the impractical ones are resolved. Furthermore, robustness and sensitivity analyses are then performed to investigate different weights on the final accumulated value of the AWFMM. Figure 1 summarizes the sequence of the steps in the development process of the AWFMM.



**Figure 1.** The framework of the proposed adjusted weight flexibility metric (AWFM).

### 3.1. Normalization

Technical flexibility parameters of generation units are stated in different measurement units and inconsistent scales. For the sake of comparison and aggregation, these scales must be normalized. Normalization is also executed to provide for the correlation analysis of individual flexibility parameters to be evaluated. Many normalization methods have been presented in the literature to date. The min–max normalization process is chosen in this study as it converts all parameters into an identical range between 0 and 1 using Equation (4) [8,34]:

$$I_{ji} = \frac{x_{ji} - \min_i(x_j)}{\max_i(x_j) - \min_i(x_j)} \quad (4)$$

where  $I_{ji}$  is the normalized value of  $x_{ji}$ , and represents the value of the parameter  $j$  for the generating unit  $j$ ,  $\max_i(x_j)$  and  $\min_i(x_j)$  are the maximum and minimum values of parameter  $j$  across all generating units  $i$ .

### 3.2. Analytic Hierarchy Process

The analytic hierarchy process (AHP) is a method used to set the priorities in a complex situation. AHP is one of the multi-criteria decision-making methods to derive ratio scales from paired comparisons [35]. The comparisons can be taken from a fundamental scale or actual measurements which reflect the relative importance of preferences. In every comparison, a preference score of 1–9 as per Table 1 is used. The AHP decomposes the problem into a hierarchy of sub-problems which can be subjectively evaluated and easily comprehended. AHP has found its widest applications in planning and resource allocation, multi-criteria decision making, power engineering and applied sciences [36,37]. Table 1 presents the intensity of the importance of individual parameters as compared to each other.

**Table 1.** The fundamental scale (scale of pair-wise comparisons of two criteria) [35].

Intensity of Importance on an Absolute Scale	Definition	Explanation
1	Equal importance	The two criteria contribute equally to the objective
3	Moderate importance	Experience and judgement strongly favor one criterion over the other
5	Strong importance	Experience and judgement strongly favor one criterion over the other
7	Very strong importance	Very strongly favors one criterion over the other. Its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one criterion over another is of the highest possible order of affirmation
2,4,6,8	Intermediate importance between two adjacent values	When compromise is needed

### 3.3. Correlation Analysis

Correlation refers to the strength of a relationship between two variables. In this regard, caution must be applied when assigning weights to the flexibility indicators as if two indicators are highly correlated, which may lead to one of them to be duplicated. To this end, the statistical correlation among each pair of flexibility parameters  $x$  and  $y$  was calculated using their Pearson correlation coefficient and is expressed as in Equation (5) [34]:

$$r_{xy} = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{(n-1)\sigma_x\sigma_y} \quad (5)$$

where  $n$  is the number of values for each indicator  $x$  and  $y$ .  $\bar{x}$  and  $\bar{y}$  represent the means while  $\sigma_x$  and  $\sigma_y$  are the standard deviation of both indicators  $x$  and  $y$ , respectively. As the correlation coefficient reaches a higher value than a predefined value, the weights assigned to the pairs are revised downward and the intensity of importance is reduced by one level so that the common components of the metric is not duplicated or over-represented.

### 3.4. Consistency Ratio Calculations

In a problem with  $N$  criteria, the possible combinations of pairwise comparisons are presented in a  $N \times N$  pairwise comparison matrix. This matrix gives the relative importance of each criterion by solving the normalized principal eigenvector [38].

It could happen that the experts' judgement becomes inconsistent due to the increasing number of criteria and comparisons. To sustain the integrity of the judgments, the consistency ratio (CR) is calculated by using Equation (6). A CR of equal to or less than 0.10 is generally accepted; otherwise, the judgements must be revised [35]:

$$CR = \frac{\lambda_{max} - 1}{n - 1} \quad (6)$$

where  $\lambda_{max}$  is the principal eigenvalue and  $n = N(N-1)/2$  is the number of pairwise comparisons.

### 3.5. Weighting Mechanism and Scenarios Creation

Trying all possible combinations and scenarios of the AHP scales for the aforementioned flexibility parameters would not only be computationally intensive but it is also illogical. Therefore, developing a worthwhile methodology to combine the flexibility parameters of thermal generating units is the most crucial and challenging phase in the development of the AWF. Thus, an accurate weighting

mechanism must be chosen to assign weights to the flexibility parameters to represent their relative importance in the flexibility supply. Weighting mechanisms are categorized as participatory or statistical. This depends on whether the mechanism is based on expert opinions or it is data driven, respectively [8]. The absence of a reliable database leads to fundamental statistical relationships between the generators' technical characteristics, and based on [8], a participatory approach was adopted in this study. The AHP is believed to be the most appropriate method for such an application.

As stated in Section 3.3, the *RUR* and *RDR* are highly correlated,  $P_{min}$  and  $P_{max}$  are strongly correlated as well. Therefore, it is unreasonable to assume that  $P_{min}$  and *RUR* are extremely important or even more important than  $P_{max}$  or *RDR*, respectively.

Taking the example that *RUR* and *RDR* are highly correlated, upgrading the assigned importance weights of either of them over the other will lead to favor the generating units with a big *RUR* or *RDR*, but will reach low scores in time-related indices. Therefore, duplicating the importance of *RUR* or *RDR* will penalize small generating units such as Oil/Steam (O/S-12) and Oil/CT (O/CT-20). The same justification is also valid for the second example where  $P_{min}$  and  $P_{max}$  are strongly correlated too. Reducing or increasing the importance of any of these parameters over the other will result in favoring the generating units with a large  $P_{min}$  or  $P_{max}$  while achieving low scores in time-related indices. Consequently, the largest units in terms of these indicators will be preferred at the expense of the smaller units. It is noteworthy that the generating units, namely Coal/3 Steam (C/S-350) and Nuclear (N-400), are the highest two units in terms of capacity. Therefore, duplicating their importance will result in them being the most influential in ranking and hence raising their value over the small units. These observations and analysis justify the judgements made during the creation and assumption scenarios applied to the methodology development.

### 3.6. Scenario Creation: Tree Diagram

In this section, a tree diagram is structured for the scenarios' creation and selection. Table 1 presents a preference score to judge the intensity of importance between two variables and the scale is presented from 1 to 9. It is noted that the intensity of importance 2, 4, 6 and 8 are of intermediate importance between two adjacent values, so here they are assumed not to be included in the scenario creation. Therefore, as presented in Figure 2, a mechanism is utilized to form and present a tree diagram which assigns all the possible weights (relative importance) for each flexibility parameter as compared to other parameters. Equal weights are assigned to the highly correlated parameters, e.g.,  $P_{min}$  and  $P_{max}$  and *RUR* and *RDR* where *RUR* is the ramping-up rate and *RDR* is the ramping-down rate. By this way, it is guaranteed that all the practical scenarios are considered, which prevents favoring any parameter over the other. It is also clear that the intensity of the importance of a single flexibility parameter is adjusted by one level/step-up starting from the equal weight scenario which satisfies the judgment in Table 1.

### 3.7. Aggregation

Aggregation is the last step in the development of the proposed AWFM framework. The normalized flexibility index proposed by [12] is given by Equation (7):

$$flex(i) = \frac{\frac{1}{2} [P_{max}(i) - P_{min}(i)] + \frac{1}{2} [Ramp(i) \cdot \nabla t]}{P_{max}(i)}, \forall i \in A \quad (7)$$

where  $\frac{1}{2} Ramp(i)$  is the average of  $Ramp_{up}(i)$  and  $Ramp_{down}(i)$  and can be calculated by Equation (8):

$$\frac{1}{2} Ramp(i) = \frac{ramp_{up}(i) + ramp_{down}(i)}{2} \quad (8)$$

Now, substitute  $\nabla t = 1$  and apply the weighting mechanism using AHP. Then, the proposed flexibility index for the AWFEM is obtained by Equation (9):

$$flex(i) = \frac{\frac{1}{2} \cdot (w_{RC}) [P_{max}(i) - P_{min}(i)] + \frac{1}{2} \cdot (w_{RC}) [RUR(i) + RDR(i)]}{P_{max}(i)} \quad \forall i \in A \quad (9)$$

where  $w_{RC}$  is the intensity of the importance of ramping in relation to capacity and  $1/w_{RC}$  the relative weights of capacity to ramping.

The flexibility index of the whole system  $A$  to be calculated as the summation of the weighted sum of the flexibility indices  $flex(i)$  of each generator as shown in Equation (10):

$$FLEX_A = \sum_{i \in A} \left[ \frac{P_{max}(i)}{\sum_{i \in A} P_{max}(i)} \times flex(i) \right], \quad \forall i \in A \quad (10)$$

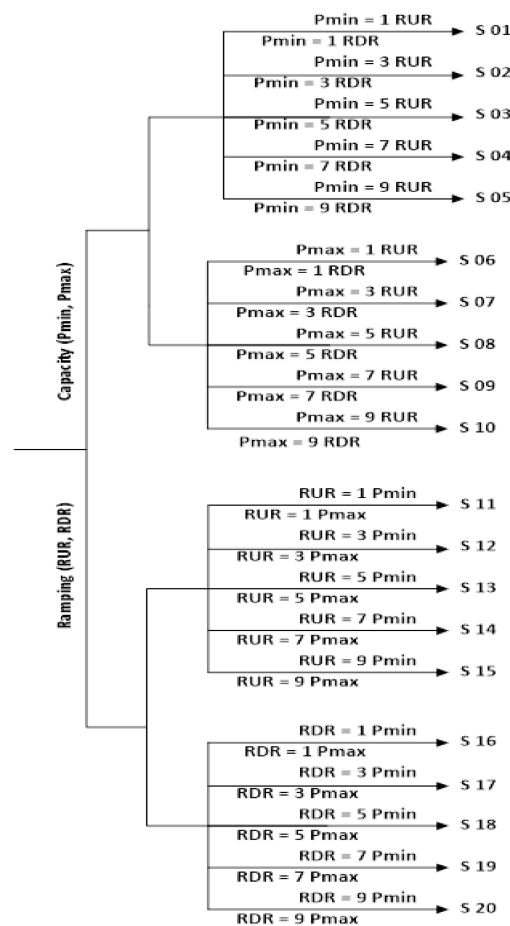


Figure 2. Illustration of a probability tree to construct weighting scenarios.

### 3.8. Test System

The developed flexibility metric is verified on a generation system based on a single-area version of the IEEE RTS-96 test system. This system has been chosen due to the following reasons: (1) it is well recognized in literature, (2) the availability of the number of generation units of each type and the system’s technical parameters, (3) the flexibility characteristics of its units have been defined in literature and (4) it has diverse type of units. This consists of 26 generators with eight different types of units and it has total maximum generation capacity of 3105 MW. The system’s number of units,



their type and their technical parameters are summarized in Table 2 [39–41]. It is also worthy to note that the selected flexibility parameters for the developed metric are clearly presented in Table 2.

**Table 2.** IEEE RTS-96 generating units technical characteristics.

Unit Type	Unit Size (MW)	Units Range	No. of Units	$P_{min}$	RUR (MW/h)	RDR (MW/h)	OR (MW)	SUT (h)	SDT (h)	MUT (h)	MDT (h)
Oil/Steam	12	1–5	5	2.4	9.6	9.6	9.6	4	0	0	0
Oil/combustion turbine(CT)	20	6–9	4	15.8	4.2	4.2	4.2	0	0	0	0
Coal/Steam	76	10–13	4	15.2	38.5	60.8	60.8	12	2	3	1
Oil/Steam	100	14–16	3	25	51	74	75	7	4	4	2
Coal/Steam	155	17–20	4	54.25	55	78	100.75	11	3	5	2
Oil/Steam	197	21–23	3	68.95	55	99	128.05	7	6	5	2
Coal/3 Steam	350	24	1	140	70	120	210	12	5	8	3
Nuclear	400	25–26	2	100	50.5	100	300	NA	5	8	4

where  $P_{min}$  is the minimum output power, RUR is the ramping-up rate, RDR is the ramping-down rate, OR is the operating range, SUT is the start-up time, SDT is the shut-down time, MUT is the minimum-up time and MDT is the minimum-down time.

## 4. Results and Discussion

### 4.1. AWFMI Indices of Generators and Overall System

The proposed AWFMI indices for the eight different types of generating units in the IEEE RTS-96 are presented in Table 3 with their rankings based on their flexibility index. The results are based on the baseline case where the relative importance amongst the flexibility technical parameters of generators is based on [8]. The ranking obtained by [12] is also provided. The overall power system flexibility index is determined by the summation of the AWFMI indices of all its units, as stated by Equation (10).

**Table 3.** AWFMI indices and rankings for the individual generators in the IEEE RTS-96: Baseline Case Scenario.

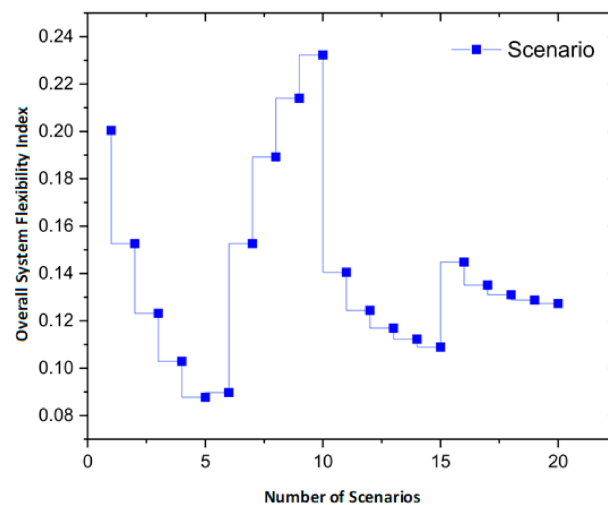
Unit Type (Size—MW)	AWFMI		
	Flexibility Index	Ranking	Ranking by Ma et al. [12]
Oil/Steam (O/S-12)	0.2000	1	1
Oil/CT (O/CT-20)	0.0525	8	8
Coal/Steam (C/S-76)	0.1906	2	2
Oil/Steam (O/S-100)	0.1796	3	3
Coal/Steam (C/S-155)	0.1486	5	4
Oil/Steam (O/S-197)	0.1463	6	5
Coal/3 Steam (C/S-350)	0.1294	7	7
Nuclear (N-400)	0.1523	4	6
Overall (26 units System)	0.1526	–	–

Comparing the individual unit's flexibility index with the overall system flexibility index, the units O/CT-20, C/S-155, O/S-197, C/S-350, and N-400 were classified as inflexible generation units due to the fact that their individual flexibility index was lower as compared to the overall system index. Meanwhile, the units O/S-12, C/S-76 and O/S-100 were categorized to be flexible because of their flexibility index being higher than the overall system flexibility index. Compared to the results presented by [12], four units were categorized to be flexible while the other four units were inflexible using the same judging criteria as before. The results indicate that using adjusted weight rather than equal weight has improved the accuracy of the systems flexibility quantification. This is a significant improvement by considering an adjusted weight to the flexibility parameters and separates the ramping into *RUR* and *RDR* rather than considering it as one term fixed weight, presented in Equations (7) and (9), respectively. In a practical system, this improvement is translated to less load shedding, less RES curtailment or lower electricity production costs. Based on this, it is critical to define a generation

unit as flexible or not, based on its flexibility parameters, while it is in an isolated mode because the flexibility provision of a single generation unit varies from system to system.

In the comparison between the flexibility index presented in [12] and the proposed AWFM, it can be inferred that the Oil/Steam (O/S-12) is the most flexible unit while Oil/CT (O/CT-20) is the least flexible unit in both cases. The Oil/CT (O/CT-20) is the least flexible unit due to the fact that it has the smallest normalized flexibility index (NFI) scores in the flexibility indicators accounted in this solution under all scenarios, as clearly appears in Figure 3. The reason for this result is that, the aforementioned unit has the minimum values of the flexibility parameters ( $P_{min}$  and  $P_{max}$  and  $RUR$  and  $RDR$ ) considered in the calculations of the proposed metric.

The system flexibility index changes with the variation of flexibility parameters weights, the distribution of the overall 26-unit system flexibility index under all scenarios is provided in Figure 3.



**Figure 3.** Distribution of the overall system flexibility index under all scenarios.

From Figure 3, it can be observed that scenario 5 had the lowest system flexibility index while scenario 10 had the highest system flexibility index. That was due to the variation in priority weight of the flexibility parameters. The justification for that is, in scenario 5,  $P_{min}$  weight is considered to be extremely more important than the  $RUR$  weight, while in scenario 10, the  $P_{max}$  weight is considered to be extremely more important than the  $RUR$  weight.

In Figure 3, it is noticed that the system flexibility index increases from the scenario (6 to 10) which confirms the relationship between the flexibility parameter weights. With the increment of the  $P_{max}$  weight, the values of the whole system index increases, while on the other hand, scenarios (1 to 5), scenarios (11 to 15) and scenario (17 to 20) have seen a decrement in the overall system flexibility index. The justification for such decrement is that the normalized values of  $P_{min}$ ,  $RUR$  and  $RDR$  are less than the value of  $P_{max}$ .

By these indices, the system operator is able to compare the provided flexibility from different generation units, technologies and the overall systems flexibility and will be able to categorize each individual generating unit as a flexible or non-flexible unit. The unit is flexible if its NFI is higher than the overall system's NFI; on the contrary, non-flexible units are those that have a flexibility index lower than the overall system's index.

#### 4.2. Weighting Mechanism

Four flexibility parameters are identified in Section 2 and listed in Table 4. They are compared in pairs in the relation of their relative importance which contributes to the system flexibility. The baseline case is based on the participatory approach adopted from [8]. The level of intensity of importance of the flexibility parameters is presented in Table 4.

Table 4 shows the resulting pair-wise comparison matrix. The element  $a_{xy}$  appoints the intensity of importance of the indicator  $x$  in relation to the indicator  $y$  in flexibility provision. An element 1 indicates that the related two flexibility indicators are equally weighted, which means that they have the same importance. The relative weights of the flexibility indicators are calculated using the right eigenvector method [38] and presented in the priority vector column of Table 4. It should be observed that the relative weights presented by the eigenvector are scaled such that their summation is equal to one.

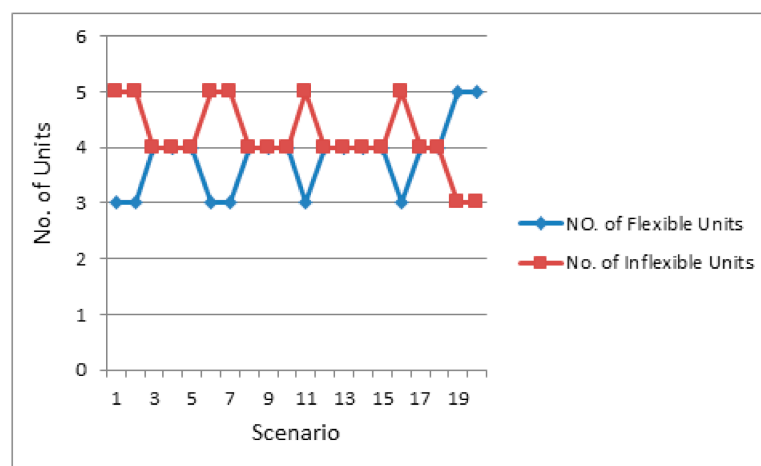
**Table 4.** Pair-wise comparison matrix of flexibility parameters and their alternative priority vector.

Flexibility Indicator	$P_{min}$	$P_{max}$	RUR	RDR	Priority Vector (PV)
$P_{min}$	1	1	3	3	0.375
$P_{max}$	1	1	3	3	0.375
RUR	0.333333	0.333333	1	1	0.125
RDR	0.333333	0.333333	1	1	0.125
	CI = 0	CR = 0	$\lambda_{max} = 4$		$\sum PV = 1$

The priority vector presents the relative weights between the parameters. The results presented in Table 4 show that  $P_{min}$  and  $P_{max}$  are the most preferable parameters followed by RUR and RDR. Therefore, it can be seen that  $P_{min}$  and  $P_{max}$  are preferred three times more than RUR and RDR.

Among the presented flexibility parameters, the correlation analysis results revealed that the correlation was positive and strong between  $P_{min}$  and  $P_{max}$ , i.e., the Pearson coefficient was 0.9477. The RUR and RDR also have a positive and strong correlation with a Pearson coefficient of 0.9704. This analysis is crucial in order to prevent the duplication of any of the values of the parameters in the weighting mechanism.

Based on the provided tree diagram in Section 3.6, a simulation of 20 scenarios under the proposed weighting mechanism was executed. Based on these simulated scenarios, the flexibility index of the individual units and the overall system is changed. Thus, the number of flexible or non-flexible units has also been changed. Figure 4 represents the total number of flexible and nonflexible units for each scenario.



**Figure 4.** Number of flexible and inflexible units for each scenario.

As a result of the units' flexibility index change, the ranking of the units will also change accordingly. The spider diagram presented in Figure 5 reflects the change of the units' ranking based on the proposed AWFM with respect to the baseline case under the 20 proposed scenarios.

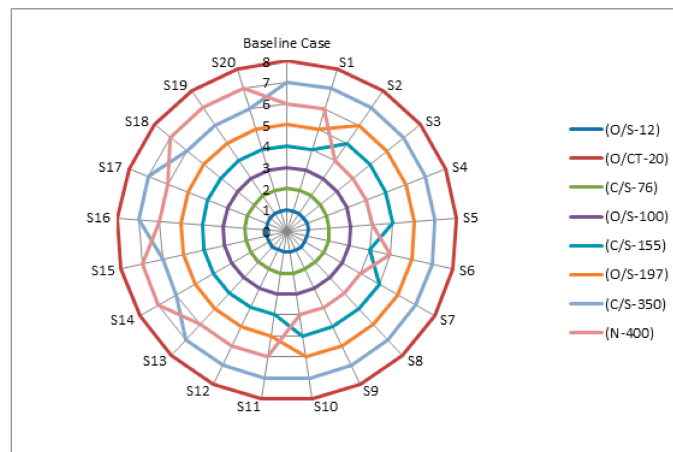


Figure 5. Spider diagram of RTS-26 generation units' flexibility ranking under 20 scenarios.

Despite the trial of combining all the possible and logical scenarios of assigning different weights to the aforesaid flexibility parameters, from Figure 5, it can be observed that half of the units have changed their rank while the other half kept to its rank compared to the base case. For example, Oil/Steam (O/S-12), Oil/CT (O/CT-20), Coal/Steam (C/S-76) and Oil/Steam (O/S-100) are the units which did not change in their rank. This constancy of ranking was expected due to the fact that these units represent the smallest capacities in the RTS-96 test system. Being in this range, this will reflect the lower values of the units that  $P_{min}$ ,  $P_{max}$ ,  $RUR$  and  $RDR$  as compared to the other units in the same test system.

On the other hand, the units Coal/Steam (C/S-155), Oil/Steam (O/S-197), Coal/3 Steam (C/S-350) and Nuclear (N-400) lie in the upper half of the test system value in terms of capacity, and occupy the highest order in terms of ramp rates among the test system units. Therefore, these units have shown a positive response to the assigned weights in terms of changing their rank. The aforementioned discussed results highlight the significance for the power system operators to consider other flexibility parameters such as  $MUT$ ,  $MDT$ ,  $SUT$ ,  $SDT$  when quantifying the generating units or the overall power system flexibility.

### 4.3. Consistency Ratio Calculations

The consistency ratio (CR) is calculated to measure how consistent the judgements are. If the CR is higher than 0.10, the judgements are untrustworthy because they are too close for comfort to randomness and the judgement appears to be valueless or must be repeated.

The calculated CR of the baseline case is equal to zero, indicating a very high level of consistency in the judgment, while the computed CR for the possible 20 scenarios is presented in Figure 6.

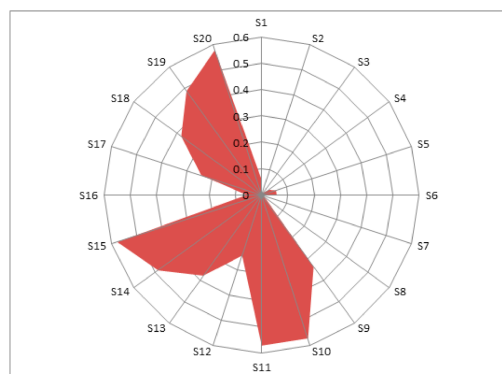


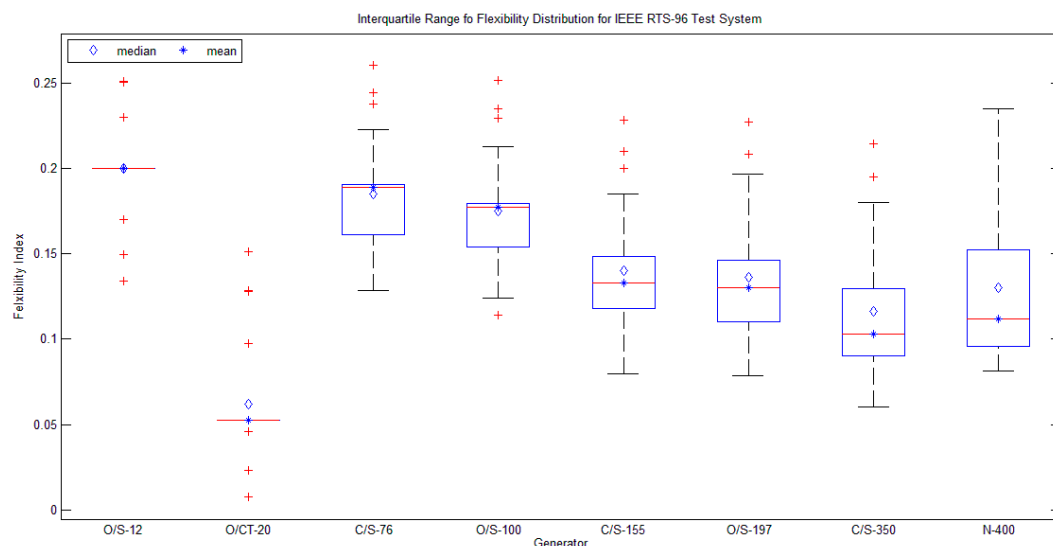
Figure 6. Consistency ratio calculations under all scenarios.

In Figure 6, it is clear that for scenarios S1 to S8 and S16 are consistent as their CRs are less than 0.10, while scenarios S9 to S15 and S17 to S20 are inconsistent as their CRs exceed 0.10. Based on this, judgement and comparisons must be recalculated. For the scenarios which have a CR of 0.00, the pairwise comparison is considered to be perfectly consistent. Among these consistent scenarios, S2 and S7 are the perfectly consistent scenarios.

#### 4.4. Robustness and Sensitivity Analysis

The results of the flexibility index distribution under all scenarios for every generating unit formulate the basis of sensitivity and uncertainty analysis. The results are synthesized in the box plot presented in Figure 7. The interquartile range for the results is represented by the rectangles for each generating unit accordingly. This indicates the range in which the bulk of flexibility index under the 20 scenarios for each generating unit lies. The small interquartile range indicates that the proposed framework is stable in the presence of uncertainties.

The concentration of the flexibility index value distribution of each generating unit around its baseline value is further verified by its mean being very close to its median as clear in Figure 7. This statistical feature indicates that there are very few values which deviate significantly from the baseline value, therefore confirming the robustness of the methodology to changes in scenario assumptions. The upper and lower whiskers of the box plot represent the worst and best value of flexibility index for the generating unit.



**Figure 7.** Boxplot showing the normalized flexibility index (NFI) distribution of the proposed AWFM of each generating unit under all scenarios.

Different scenarios were simulated within the development process of the AWFM. The final flexibility index largely depends on and reflects the selected scenario. Therefore, in this article, it is significant to conduct a sensitivity analysis to study the impact of different weights on the final flexibility index value of the proposed AWFM. Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system can be apportioned to different sources of uncertainty in its inputs. A number of statistical measures such as the mean, median and standard deviation of the generator ranking under all scenarios are used to describe the uncertainties induced by changes brought to the AWFM development.

#### 4.5. Impact of Adding New Generator on AWFM's Flexibility Indices

The purpose of this section is to investigate the impact of adding a new generating unit to the existing test system on the AWFM's flexibility indices ranking. Therefore, a generator was selected

from the IEEE 10 units generating test system and merged into the IEEE RTS-96 generation mix. The selected unit provided comprehensive technical generation and operation cost function coefficient data. Taking into consideration the flexibility parameters considered in this research, the new unit has a  $P_{min}$  of 20 MW, representing about 15.3% of its maximum capacity as well as 60 MW/h of *RUR* and *RDR*, representing a change with 45.15% of the maximum capacity within one hour. The new ranking of the AWFMs' indices with the new generators' list is presented in Table 5. As expected, the newly merged unit outperforms 6 units out of 8 due to its aforementioned technical characteristics reflecting that it is much more flexible than most of the other units.

In a comparison to the flexibility ranking between Tables 3 and 5, it is worthy to note that the overall system flexibility index changed from 0.1526 to 0.1762, thus the number of flexible units has been changed. The increment in the overall system flexibility is due to the conjunction of a new highly flexible unit to the system.

These results reveal the adaptive feature of the proposed AWFm as it automatically adjusts the flexibility index of a generator to the technical characteristics of all generators in the power system. An additional feature of the developed AWFm is that it is beneficial to quantify the available flexibility in different power systems as compared in Tables 3 and 5.

**Table 5.** AWFm flexibility indices under the extended IEEE RTS-96 test system.

Unit Type (Capacity—MW)	Ranking	AWFM Flexibility Index
Oil/Steam (O/S-12)	1	0.2000
Oil/CT (O/CT-20)	9	0.0525
Coal/Steam (C/S-76)	2	0.1906
Oil/Steam (O/S-100)	4	0.1797
Coal/Steam (C/S-155)	6	0.1487
Oil/Steam (O/S-197)	7	0.1463
Coal/3 Steam (C/S-350)	8	0.1294
Nuclear (N-400)	5	0.1524
Selected IEEE Unit	3	0.1875
Extended RTS-96 test system		0.1762

#### 4.6. Optimal Unit Commitment Solution by Incorporating the Flexibility Ranking of Thermal Units

The presented metric above is implemented to quantify the flexibility of the IEEE 10 units test system [33]. A case study of incorporating the flexibility concept in the priority ranking of the generation scheduling “unit commitment solution” is implemented.

After the quantification of the flexibility of these units, the resulted flexibility ranking is combined with the economical ranking of the generating units based on their thermal characteristics and technical constraints. A new ranking approach is presented for the new generation scheduling.

In solving the unit commitment UC problem of the IEEE 10 units test system and load profile, and using the wind power data as in [33], it was found that the maximum feasible penetration level in this case study is increased from 28.9% to 37.2% wind generation out of the total load demand while satisfying the load and system constraints. This increment of the total wind generation leads to an overall generation cost and emission reduction. Table 6 presents the optimal scheduling of the UC under 28.9% of the integrated wind power generation which was the maximum penetration level before considering the flexibility.

Table 7 presents the optimal UC solution with the highest 37.2% of wind penetration level by incorporating the flexibility ranking approach in this case study.

In the comparison of the results presented in both tables, a difference in the generated amount at different hours was noticed. This difference was due to the new ranking based on the consideration of flexibility. The shaded cells in the presented tables represent the change in the thermal scheduling with different amounts and at different hours comparing both cases (with and without the flexibility incorporation). More flexible units are always committed first while satisfying the system constraints.

**Table 6.** Optimal UC solution under 28.9% of the wind penetration level.

	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
H1	455	177.26	0	0	0	0	0	0	0	0
H2	455	285.50	0	0	0	0	0	0	0	0
H3	455	368.23	0	0	25	0	0	0	0	0
H4	455	455	0	0	30.5	0	0	0	0	0
H5	455	366.54	0	130	25	0	0	0	0	0
H6	455	358.23	130	130	25	0	0	0	0	0
H7	455	408.23	130	130	25	0	0	0	0	0
H8	455	235.50	130	130	25	0	0	0	0	0
H9	455	150	101.21	119.63	25	0	0	0	0	0
H10	455	323.02	130	130	25	0	0	0	0	0
H11	455	290.86	130	130	25	0	0	0	0	0
H12	455	150	75.56	95.32	25	0	0	0	0	0
H13	455	150	21.12	43.72	25	0	0	0	0	0
H14	454.73	150	20	29.98	25	0	0	0	0	0
H15	366.07	150	0	0	25	0	0	0	0	0
H16	175.87	150	0	0	25	0	0	0	0	0
H17	311.70	150	0	0	25	0	0	0	0	0
H18	455	449.65	0	0	25	0	0	0	0	0
H19	455	407.88	0	0	25	0	0	0	0	0
H20	455	415.31	130	130	25	0	0	0	0	0
H21	455	405.66	130	130	25	0	0	0	0	0
H22	371.70	150	20	20	25	0	0	0	0	0
H23	204.47	150	20	20	25	0	0	0	0	0
H24	279.47	0	20	20	0	0	0	0	0	0

**Table 7.** Optimal UC solution under 37.2% of wind penetration level by flexibility ranking approach.

	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
H1	455	157.8046	0	0	0	0	0	0	0	0
H2	455	282.773	0	0	0	0	0	0	0	0
H3	455	382.729	0	0	0	0	0	10	0	0
H4	455	452.773	0	0	0	0	0	10	10	10
H5	455	455	0	0	0	0	0	39.81	10	10
H6	455	455	0	0	0	80	25	55	17.73	10
H7	455	455	0	130	0	52.73	25	10	10	10
H8	455	281.0227	0	130	0	20	25	0	0	0
H9	455	150	0	91.86	0	0	25	0	0	0
H10	455	356.2425	0	130	0	0	25	0	0	0
H11	455	300.4908	0	130	0	0	25	0	0	0
H12	425.0912	150	0	0	0	0	25	0	0	0
H13	342.32	150	0	0	0	0	0	0	0	0
H14	351.5836	150	0	0	0	0	0	0	0	0
H15	201.8323	150	0	0	0	0	0	0	0	0
H16	150.0912	0	0	0	0	0	0	0	0	0
H17	339.289	0	0	0	0	0	0	0	0	0
H18	455	0	130	130	0	80	25	40.72	10	10
H19	455	0	130	130	0	28.24	25	10	10	10
H20	455	0	130	130	162	80	25	55	38.03	10
H21	455	0	130	130	162	80	25	55	54.33	10
H22	374.289	0	20	20	25	0	0	0	0	0
H23	256.4713	0	0	0	25	0	0	0	0	0
H24	156.4713	0	0	0	25	0	0	0	0	0

As can be observed from both tables, units U1 and U2 remain ON continuously in the dispatching cycle to share the major portion of the load demand serving the base load. Due to the new combination of ranking, it was noticed that all the units were utilized through the scheduling time horizon.

Furthermore, in Table 7, it was noticed that the minimum thermal output power occurs during hour 16, with only one unit ON due to the highest generation of wind power at that time. Some units are kept within their minimum generation capacity at peak load hours to fulfil the reserve requirement and generation constraints.

The results presented in both tables show that the net-load is satisfied along the scheduling time horizon. In addition, through satisfying the load profile, satisfying all the system constraints, the generation cost was found to be optimal. The committed units are represented by their real value of dispatch (output power) while the de-committed units are represented by 0 (off).

## 5. Conclusions

Operational awareness has become significant in the modern power system. System conditions fluctuate rapidly due to the stochastic generation output of RESs. Recently, flexibility metrics have been gaining emerging interest in power system operations. In this regard, few metrics have been introduced and proposed. Therefore, this article introduces an adjusted weight flexibility metric (AWFM) to accurately quantify the available technical flexibility of different generating technologies as well as for the overall power system. The proposed metric was also beneficial to quantify and compare the available flexibility in different power systems. The metric was tested and validated on the IEEE RTS-96 test system while the assessment is accomplished by using four technical flexibility parameters. This study found strong correlations between the  $P_{min}$ ,  $P_{max}$ , and the RUR, RDR, respectively. When observing the effects of changing the weight of some flexibility parameters over the others, the ranking of some units changes accordingly. It is worthy to note that the rank of the small unit's capacity is not changed due to the fact that these units represent the smallest capacities among the system units. Thus, this study gives a specific look at how flexibility requirements might be changing in different power systems. The findings also draw some important conclusions about the influence of increasing weights of RUR and RDR on the change in the flexibility indices, generators ranking and flexibility requirements. Results also demonstrate the consistency and coherence of the proposed AWFM. This proposed metric is useful for the power system operators and planners who require a fast, accurate and offline metric to quantify the technical flexibility of the power system.

Based on the presented results, it was clearly shown that the small interquartile range indicates that the proposed framework is stable in the presence of uncertainties. It is also worthy to note that the concentration of the distribution of the mean and the median FI values of each generating unit around the baseline value confirms the robustness of the methodology to changes in scenario assumptions. Within the investigation of the adaptive feature of the developed metric, an addition of a new generating unit has changed the overall system flexibility index from 0.1526 to 0.1762, which reveals that the AWFM is adaptive. This also automatically adjusts the flexibility index of each generator to the technical characteristics of all generators in the power system and hence the number of flexible and non-flexible units is also changed.

The implementation of the developed metric within the UC solution has increased the penetration level of wind generation from 28.9% to 37.2% within the presented case study and test systems, which leads to an overall generation cost and emission reduction while satisfying the net-load along the scheduling time horizon.

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## Abbreviations

$P_{n,t}$	The output power of unit $n$ at hour $t$
$UR_n$	Ramping up of $n - th$ unit
$DR_n$	Ramping down of $n - th$ unit
$P_n(\min)$	Minimum real power output
$P_n(\max)$	Maximum real power output
$I_{ji}$	Normalized value of $x_{ji}$
$x_{ji}$	Value of the parameter $j$ for the generating unit $i$
$\max_i(x_j)$	Maximum values of parameter $j$ across all generating units $i$
$\min_i(x_j)$	Minimum values of parameter $j$ across all generating units $i$
$n$	Number of values for each of indicator $x$ and $y$
$\bar{x}$	Means of indicator $x$
$\bar{y}$	Means of indicator $y$
$\sigma_x$	Standard deviation of indicators $x$
$\sigma_y$	Standard deviation of indicators $y$
$\lambda_{max}$	Principal eigenvalue
$n = N(N - 1)/2$	Number of pairwise comparisons
$flex(i)$	Flexibility of unit $i$
$\frac{1}{2} Ramp(i)$	Average of $Ramp_{up}(i)$ and $Ramp_{down}(i)$
$w_{RC}$	Intensity of importance of ramping in relation to capacity
$1/w_{RC}$	relative weights of capacity to ramping
AWFM	Adjusted weight flexibility metric
RES	Renewable energy source
RUR	Ramp up rate
RDR	Ramp down rate
IRRE	Insufficient ramping resource expectation
EPRI	Electric Power Research Institute
AHP	Analytic hierarchy process
CR	Consistency ratio
MW	Mega watt
NFI	Normalized flexibility index

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