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Conference Paper

Indices to Assess the Integration of Renewable Energy Resources on Transmission Systems

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The continuous increase on the penetration levels of Renewable Energy Sources (RESs) in power systems has led to radical changes on the design, operation, and control of the electrical network. This paper investigates the influence of these changes on the operation of a transmission network by developing a set of indices, spanning from power losses to GHG emissions reduction. These indices are attempting to quantify any impacts therefore providing a tool for assessing the RES penetration in transmission networks, mainly for isolated systems. These individual indices are assigned an analogous weight and are mingled to provide a single multiobjective index that performs a final evaluation. These indices are used to evaluate the impact of the integration of RES into the classic WSCC 3-machine, 9-bus transmission network.

1. Introduction

European Union countries have a set of specific targets to promote the use of energy from Renewable Energy Source (RES) in accordance with the Directive 2009/28/EC of the European Parliament [1]. These *National Action Plans* (NAPs) consider and set targets for the final use of energy for heating and cooling, electricity generation, and transportation. In particular, electricity generation is of great interest as it requires the liberalization of the electricity markets.

The 16% of global final energy consumption comes from renewable sources during 2012, with 10% coming from traditional biomass, which is mainly used for heating and 3.4% from hydroelectricity. New renewable sources (small hydro, modern biomass, wind, solar, geothermal, and biofuels) accounted for another 2.8% and are growing very rapidly [2]. The share of renewable sources in electricity generation is around 19%, with 16% of global electricity coming from hydroelectricity and 3% from new renewable sources [2].

Nevertheless, RESs have not been a significant part of the energy mix for the vast majority of countries around the world, fact which has led governments to provide incentives to entities that are interested in investing in RES electricity generation, in most cases using wind and solar power. Consequently, it is of crucial importance to investigate how RES generation affects the network's operational ability and which potential configurations could prove beneficial. Hence, a series of technical aspects must be considered by the planners in order to evaluate the pros and cons of such penetration. In particular, the minimization of power losses has so far been the most important issue for the planners [3, 4]. However, other grid related technical aspects have to be considered, since they are significant as well. Such aspects are voltage profile improvement, short-circuit level alteration, and relief of the network's line capacity usage [5, 6]. In addition to these, the *greenhouse gas* (GHG) emissions' reduction is increasingly becoming more important as it reflects on the environmental side of the energy problem. Moreover, the system's reliability is of great significance, since access to reliable, cheap electricity relates to the quality of life of a society. Table 1 shows a brief summary of the relevant

Table 1: Index-relevant literature references.

Reference	Power losses	Voltage	Line capacity	SCL	Emission reduction	Spinning reserve
[3]	Yes	No	No	No	No	No
[4]	Yes	Yes	No	No	No	No
[5]	Yes	Yes	Yes	Yes	No	No
[6]	No	Yes	No	Yes	No	No
Present work	Yes	Yes	Yes	No*	Yes	Yes

*Due to software limitations.

existing literature regarding indices used to evaluate the integration of RES.

There are several aspects to be considered in order to integrate RES into traditional networks. However, there are two parameters that have high impact on the integration of RES plants in the network: the selection of the size (rated capacity) and the installation's location of such plants. This paper investigates these effects by developing a series of indices, spanning from power losses to GHG emissions' reduction, which quantify this impact and provide a tool for assessing the RES penetration in transmission networks, mainly for isolated systems.

The paper is organized as follows; Section 2 introduces the indices that are used and they are being thoroughly described. Section 3 presents the test network that is used in this paper together with the results obtained for each index evaluated. Finally, in Section 4 a multi-objective assessment is carried out to investigate the overall impact of RES generation on the system's performance.

2. Description of Assessment Indices

In this section, the assessment indices are presented. Six individual indices are considered in this paper to evaluate the steady-state performance of the network, each one relating to a specific technical aspect. Table 2 tabulates the indices' description and acronyms.

In particular, ILp and ILq relate to power losses, active and reactive, respectively. IVD is used to define the voltage deviation. IC is related to the system's line capacity usage; IEm relates to the GHG emissions reduction and ISR to the spinning reserve of the system, meaning the total synchronized capacity, minus the losses and the load [7]. All these indices are explained in the next subsections. For clarification purposes, the term *configuration* relates to the scenario under study while the term *base scenario* relates to the scenario without any RES penetration.

2.1. Power Losses Related Indices ILp and ILq. The following indices are used to evaluate the changes on the total active and reactive power losses:

$$\mathrm{ILp}^k = 1 - \frac{\mathrm{Re}\left\{\mathrm{Losses}^k\right\}}{\mathrm{Re}\left\{\mathrm{Losses}^0\right\}},$$
$$\mathrm{ILq}^k = 1 - \frac{\mathrm{abs}\left(\mathrm{Im}\left\{\mathrm{Losses}^k\right\}\right)}{\mathrm{abs}\left(\mathrm{Im}\left\{\mathrm{Losses}^0\right\}\right)}, \quad (1)$$

Table 2: Indices' acronyms.

Index acronym	Acronym meaning
ILp	Active power losses index
ILq	Reactive power losses index
IVD	Voltage profile index
IC	Line capacity index
IEm	Emissions' reduction index
ISR	Spinning reserve index

where Losses^k refers to the total power losses of the kth configuration of the network, whereas Losses^0 refer to the total power losses of the base scenario (scenario without RES generation).

Near unity values of these indices imply a maximization of the positive effect of RES integration on losses.

2.2. Voltage Related Index IVD. Voltage issues are of critical significance as they are an indicator of the network's condition. The following index evaluates the maximum voltage deviation of the configuration under study:

$$\mathrm{IVD}^k = 1 - \left(V_{\max}^k - V_{\min}^k\right), \quad (2)$$

where $V_{\max}^k$ refers to the maximum bus voltage level while $V_{\min}^k$ refers to the minimum bus voltage level of the network for the kth configuration. Near unity values of the index mean small deviation of voltage levels.

2.3. Line Capacity Index IC. One important aspect of RES integration is the altered branch power flows, meaning the different power flow allocation through the lines of the network. A key parameter to optimally introduce RES plants in a network is the relief in the network's line flows. In other words, the introduction of RES in the network should help in reducing the transmission line exploitation and lead to greater tolerance in demand growth.

The IC index is used to evaluate how the configuration under study affects the total branch flows of the network:

$$\mathrm{IC}^k = \frac{\mathrm{Scap}^k}{\mathrm{Scap}^0}, \quad (3)$$

where Scap^k refers to the remaining line capacity for the kth configuration while Scap^0 refers to the remaining line capacity for the base scenario. Values greater than unity

reflect a positive influence on the line capacity usage while values less than unity reflect a negative influence.

2.4. Emissions' Reduction Related Index IEm. CO_2 emission production is maybe the most important environmental factor that RES integration has to tackle. This is to be achieved through minimization of the use of conventional, fossil-fuelled plants. At first sight it seems that the larger the RES penetration, the less the need for conventional plant use. However, this is only partially true since RES effects on the system's reliability due to their variability and unpredictability have to be accounted as well in order to correctly evaluate the conventional generation requirements.

Hence, the following index was developed in order to appropriately calculate the CO_2 emissions' reduction for every possible network configuration. The planner can include this information when assessing the system before reaching to a decision. Near unity index values represent nullification of the emissions produced:

$$\mathrm{IEm}^k = 1 - \frac{\mathrm{Emissions}^k}{\mathrm{Emissions}^0}, \tag{4}$$

where $\mathrm{Emissions}^k$ refer to the emissions produced for the kth configuration while $\mathrm{Emissions}^0$ refer to the emissions produced for the base scenario.

2.5. Spinning Reserve Related Index ISR. Large RES integration radically alters the system's reserve requirements, both short-term and long term [8, 9]. The following index is useful for observing the system's operating spinning reserve status for every configuration under study, meaning the total synchronized capacity, minus the losses and the load [7]:

$$\mathrm{ISR}^k = \frac{\mathrm{SpinRes}^k}{\mathrm{SpinRes}^0}, \tag{5}$$

where $\mathrm{SpinRes}^k$ refers to the spinning reserve of the kth configuration while $\mathrm{SpinRes}^0$ refer to the spinning reserve of the base scenario. Over unity values in this index suggest that the available online capacity is larger compared to the base scenario whereas less than unity values imply the opposite. This helps the planner to quickly assess the system's ability to supply the demand thus providing an estimate of its security of supply.

2.6. Auxiliary Indices. Three auxiliary indices are introduced in this section. These indices are not a part of the evaluation process, but they are very helpful for observing the system's status.

The first and most commonly used of these is the *Load Level Penetration index* (LLP) [3]:

$$\mathrm{LLP} = \frac{P_{\mathrm{res}}}{P_{\mathrm{demand}}}, \tag{6}$$

where P_{res} refers to the RES rated capacity while P_{demand} refers to the active power demand of the system. This index is essentially the percentage of the demand that is supplied by RES plants.

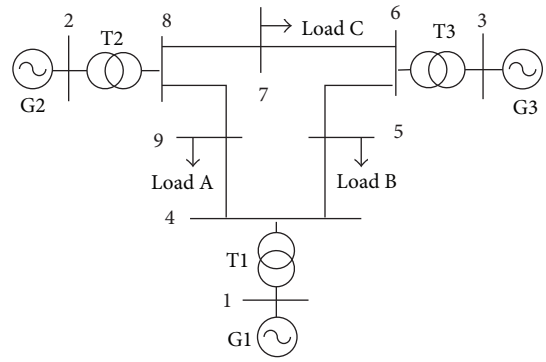

Figure 1: One-line diagram of the test network: WSCC 3-machine, 9-bus system [10].

Furthermore the other two indices developed are similar to each other and regard the RES rated capacity in relation to the system's capacity.

These two indices are the ratio of the RES rated capacity over the capacity that existed *before* the addition of RES (PEC) and the capacity that exists *after* the addition of RES (NEC), that is, without and with taking into account the RES rated capacity to the previously existing capacity. In (7) the two indices are expressed in mathematical forms:

$$\mathrm{PEC} = \frac{P_{\mathrm{res}}}{P_{\mathrm{existing}}}$$
$$\mathrm{NEC} = \frac{P_{\mathrm{res}}}{P_{\mathrm{existing}} + P_{\mathrm{res}}^{\mathrm{rated}}}. \tag{7}$$

3. Test Case: Assessment of RES Integration

3.1. Test Network. The assessment indices presented in the previous section of this paper are used on a classical test network: WSCC 9-bus system which is depicted in Figure 1. The network's data is properly adjusted to suit the objectives of this work (see Tables 3 and 4) and the generators data used in this test system are shown in Table 5.

It should be noted that the minimum active power generation is set to 30% of the maximum generation of every generator in order for the system to be more realistic. The fuel type and efficiency selected for each generator are generic but realistic. Furthermore, the reader can find the analytical methodology of emissions production calculation that was utilized for this work in [11].

A special MATLAB code was developed to obtain the solution of the optimal power flow problem using routines provided by MATPOWER [12]. In this paper, indices related to short circuit level are not included. It is well known that the integration of RES may increase short circuit level; however, since there is no available equipment data for the network under study, it is assumed that no rating violation occurs at any scenario. In future endeavors, this index could also be

Table 3: Bus data.

Bus	Type	P_{demand} (MW)	Q_{demand} (MVAr)
5	PQ	90	30
7	PQ	100	35
9	PQ	125	50
Total		315	115

Table 4: Branch data.

From bus	To bus	R (pu)	X (pu)	B (pu)	Rated ampacity (MVA)
1	4	0.000	0.0576	0.000	250
4	5	0.017	0.092	0.158	250
5	6	0.039	0.170	0.358	150
3	6	0.000	0.0586	0.000	300
6	7	0.0119	0.1008	0.209	150
7	8	0.0085	0.072	0.149	250
8	2	0.000	0.0625	0.000	250
8	9	0.032	0.161	0.306	250
9	4	0.010	0.085	0.176	250

Reactance values are in pu on a 100-MVA base.

Table 5: Generator data.

Bus	P_{max} (MW)	P_{min} (MW)	Q_{max} (MVAr)	Q_{min} (MVAr)	Fuel type	Efficiency [pu]
1	250	75	300	−300	Diesel	0.4
2	300	90	300	−300	Coal	0.34
3	270	81	300	−300	Lignite	0.38

added by modifying MATPOWER or by utilizing a different power system simulator.

The MATPOWER data file has been edited in order to assign plant type and efficiency values to each generator. The algorithm caters for several other fuel types.

3.2. Results and Analysis. In this section, the results for each individual index of the previous section are presented. The MATLAB script that was developed executes a series of simulation scenarios. For this particular test network, the scenarios investigated are for 10 MW up to 150 MW of RES rated capacity (i.e., from LLP = 3.17% to LLP = 47.62%) with a 10 MW step. Every RES rated capacity scenario is examined for every potential installation bus. It should be mentioned that RES plants are considered to operate at a constant power factor pf = 1.0.

3.2.1. Power Losses: ILp and ILq. The results obtained regarding the power losses of every configuration are presented in Figures 2 and 3, where ILp and ILq are plotted for several cases. As can be seen, bus 9 presents the most encouraging results as in all cases the active power losses are reduced.

Another interesting aspect of the results obtained is the behavior of the network when a generator shut-down takes place. This occurs at the 70 MW (LLP = 22.2%) scenarios.

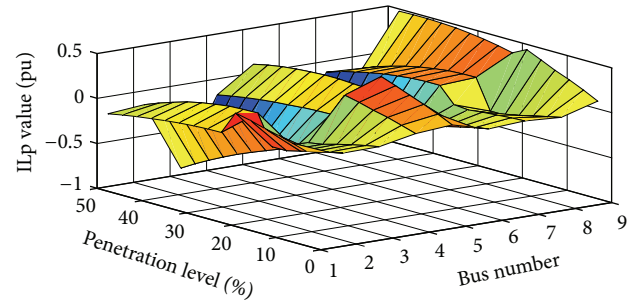

Figure 2: Active power losses (ILp) versus location of RES power plant and load level penetration.

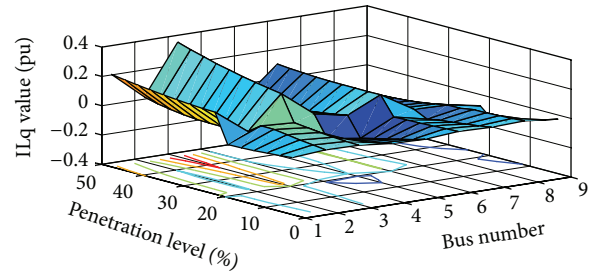

Figure 3: Reactive power losses (ILq) versus location of RES power plant and load level penetration.

The results acquired reflect radical changes in the ILp value for almost every bus of the system (see Figure 2). The changes can be either positive or negative, depending on the new topology of the system (power injections' buses, flow path from generation to demand, etc.). The same effect appears for ILq (see Figure 3) as well. However, it is rather limited in comparison to ILp.

3.2.2. Voltage Profile: IVD. Figure 4 shows the results obtained for the voltage related index, IVD. As can be seen, the maximum IVD value is 0.9885 and is presented for bus 9. All buses provide an acceptable voltage profile, since optimal power flow caters for voltage improvement. However, it is important for the planner to know which configurations lead to smaller voltage deviations as this could lead to less reactive power support investments. The acceptable regulation voltage is assumed 1.00 ± 0.05 p.u, thus leaving a 0.1 p.u margin for acceptable voltage deviation.

3.2.3. Line Capacity Index: IC. IC index is a way to measure the potential benefit of RES penetration in terms of branch power flow alteration. If a configuration leads to a relief of the power flows through the network's transmission lines, then the network becomes more tolerant to load growth. As can be seen in Figure 5, most configurations present a positive effect on the line capacity usage. In Pareticular, when RES generation is located at load buses or close to load buses, then the benefit tends to be greater. This, of course, is subject to the network's topology (existing generators, transmission lines, etc.) that defines the power flows. For this particular network,

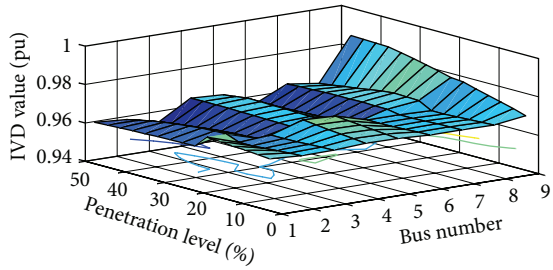

Figure 4: Voltage profile (IVD) versus location of RES power plant and load level penetration.

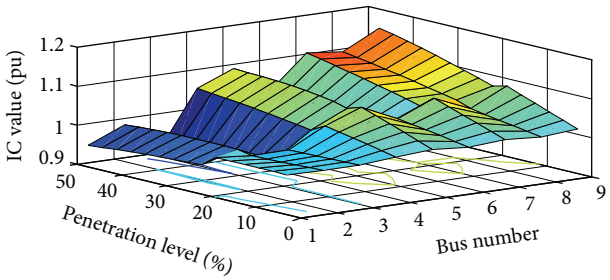

Figure 5: Remaining Line Capacity (IC) versus location of RES power plant and load level penetration.

the most beneficial bus for RES installation in terms of line capacity usage is bus 9. Also, buses 5, 7, and 8 are of similar benefit.

3.2.4. Emissions Reduction Index: IEm. As can be seen in Figure 6, the emissions reduction index IEm is increasing linearly as RES generation gets larger. This is logical, since RES is substituting conventional generation, thus leading to less emission production.

3.2.5. Spinning Reserve Index: ISR. In Figure 7, the results for the ISR index are shown. It should be noted that the ISR index has a lot in common with the IEm index. In a way, they act as complementary to each other. This is due to the fact that when a conventional generator is decommitted and substituted by an RES plant, the security of the system decreases whereas emissions are reduced. It is logical that the security of the system increases as RES generation increases, since more generation becomes available. However, when RES generation becomes so large that leads to a decommitment of a conventional plant, a rapid decrease of the synchronized on-line capacity takes place. Consequently, this leads to a decrease of the security of the system. This is reflected in Figure 7 for the 70 MW (LLP = 22.22%) scenarios.

4. Multiobjective Assessment

In order to create a general index that allows evaluating the performance of the network considering all the previously defined indices (except from the auxiliary), a new approach

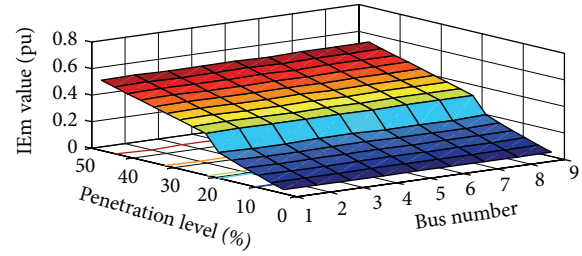

Figure 6: Emissions' reduction (IEm) versus location of RES power plant and load level penetration.

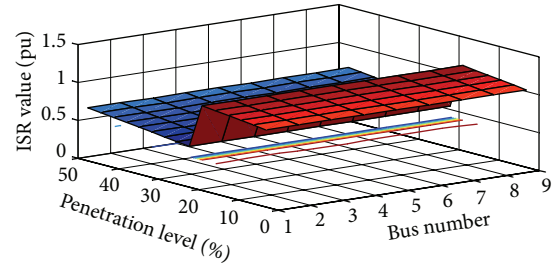

Figure 7: Spinning reserve (ISR) versus location of RES power plant and load level penetration.

is presented in this paper combining the aforementioned indices into a single multiobjective index (IMO).

This multi-objective index is defined as

$$\mathrm{IMO}^k = \sum_{i=1}^{n} w_i \Psi_i^{(k,0)}, \tag{8}$$

where w_i is the weight for the ith index while $\Psi_i^{(k,0)}$ is the absolute change of the ith index between the case base (0) and the kth case. In this paper, six indices are considered ($n = 6$):

$$\Psi_1^{(k,0)} = \left(\mathrm{ILp}^k - \mathrm{ILp}^0\right), \tag{8a}$$

$$\Psi_2^{(k,0)} = \left(\mathrm{ILq}^k - \mathrm{ILq}^0\right), \tag{8b}$$

$$\Psi_3^{(k,0)} = \left(\mathrm{IVD}^k - \mathrm{IVD}^0\right), \tag{8c}$$

$$\Psi_4^{(k,0)} = \left(\mathrm{IC}^k - \mathrm{IC}^0\right), \tag{8d}$$

$$\Psi_5^{(k,0)} = \left(\mathrm{IEm}^k - \mathrm{IEm}^0\right), \tag{8e}$$

$$\Psi_6^{(k,0)} = \left(\mathrm{ISR}^k - \mathrm{ISR}^0\right). \tag{8f}$$

It is important that all weights are normalized and their sum equals one. This is done by dividing each absolute weight value of every index with the sum of all the indices' absolute weight values:

$$\sum_{i=1}^{6} w_i = 1. \tag{9}$$

The weight value reflects the importance of each index and is subject to the planner's interests. However, an unbiased

Table 6: Indices' weight selection.

Index weight	Absolute value	Normalized value
w_1	30	0.30
w_2	15	0.15
w_3	20	0.20
w_4	20	0.20
w_5	8	0.08
w_6	7	0.07
Total	100	1.00

evaluation, that is, all indices given the same weight, could lead to erroneous results as the key factors of the system are given the same significance level as others of less importance.

Although the weight selection is decisive for shaping the results of the evaluation, the literature is not very clear on how to define the proper values to each index. It is common, though, that the appreciation of every factor is left on the planner's judgment and personal experience [5]; if the planner cares more about power losses than voltage deviation, then the weights are adjusted accordingly. If on the other hand, considers line capacity or emissions reduction more important during the planning procedure, then the weights given to these parameters would be increased.

4.1. Discussion about the Indices' Weight Selection. It is apparent that the results of the multi-objective assessment employed in this work strongly depend on the weight selection for each individual index. The weight values are of course defined by the planner in respect to his objectives. Consequently, every planner could potentially reach to a different decision with regard to his subjective judgement.

As a first general approach to the weight selection, power losses indices, namely ILp and ILq, are considered the most important factors and, therefore, are given the largest weight values summing up to 45% of the total weight value. Specifically, ILp, which relates to active power losses, has been so far considered the most important factor as it expresses the direct cost of losses that utilities tend to try and minimize. ILq has also received a significant weight value as reactive power support, an ancillary service, is becoming increasingly important to TSOs, as described in [13]. Voltage index IVD and line capacity index IC have been given a 20% weight each; that is to show how significant to the network's performance are both voltage improvement and line capacity as they play an important role in the network's operational profile. Lastly, the emissions index IEm together with the spinning reserve index ISR is given a smaller but essential percentage, summing up to 15%. The individual weight values are given in Table 6.

Utilizing the weight values of Table 6, the multi-objective evaluation of the configurations presents the results that appear in Figure 8.

It comes as no surprise that the best results attained are for bus 9, since it presented the best performance for almost every individual index. It is also the bus with the largest load of the network, which means that the RES generation immediately

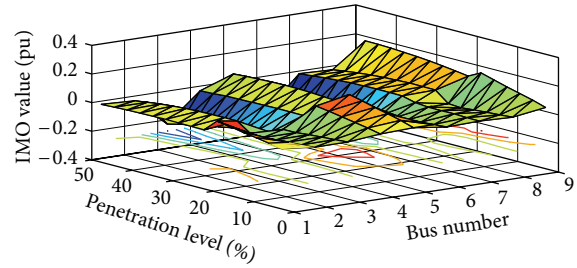

Figure 8: Multi-objective assessment (IMO) versus location of RES power plant and load Level penetration utilizing the weight values of Table 5.

Table 7: Indices' weight limits for the Monte Carlo simulation.

Index weight	Lower limit	Upper limit	Expected value
w_1	20	40	30
w_2	10	20	15
w_3	10	30	20
w_4	10	30	20
w_5	5	11	8
w_6	5	9	7
Total	60	140	100

supplies it, minimizing the need for distant generators to cover the demand. It has to be noted that for bus 9, the IMO index values are relatively close to each other, which leaves the planner with a variety of possible configurations that could prove beneficial for the network's planning process. Bus 5 is proven as the second best in performance, fact which also widens the variety of the planner's choices.

Bus 5 is a load bus as well. This suggests that RES integration is usually more beneficial when located at load buses or buses close to the load. The best case is proven to be the 150 MW (LLP = 47.62%) at bus 9 scenario (presenting an IMO value equal to *0.1677*). However, since the indices' weights have been selected as a set of default values, it is of interest to investigate the way these weights affect the final evaluation outcome.

In order to investigate this, the *Monte Carlo simulation method* is utilized. In a Monte Carlo simulation, a random value is selected for each of the tasks, based on the range of estimates. The model is calculated based on this random value. The result of the model is recorded, and the process is repeated. A typical Monte Carlo simulation calculates the model hundreds or thousands of times, each time using different randomly selected values. In particular, for each of the iterations, the absolute weight values of the indices are assigned a random number between a lower limit and an upper limit, defined by the user, thus exploring a sufficient number of possible combinations. The lower and upper limits for each index are shown in Table 7. These limits have been set accordingly in order for their expected values to match the previous default setting (see Table 6), so the comparison can be essential.

In Figure 9 the IMO values of the Monte Carlo simulation for the 70 MW (LLP = 22.22%) for each bus are shown.

Table 8: Monte Carlo indices' weights For maximum IMO value.

Index weight	Absolute value	Normalized value
w_1	39.31	0.4550
w_2	10.80	0.1251
w_3	10.88	0.1259
w_4	10.01	0.1159
w_5	10.03	0.1161
w_6	5.36	0.0620
Total	86.40	1.0000

Table 9: Monte Carlo indices' weights For minimum IMO value.

Index weight	Absolute value	Normalized value
w_1	20.37	0.2258
w_2	19.03	0.2110
w_3	26.58	0.2947
w_4	10.53	0.1168
w_5	5.24	0.0581
w_6	8.45	0.0936
Total	90.20	1.0000

The results clearly project the need for careful consideration, since, in some instants (i.e., bus numbers), there exist weight combinations which produce both positive and negative IMO values for the same penetration scenario. Furthermore, in Figure 10, the IMO values for the best case scenario (150 MW at Bus 9) are presented. The number of samples was set to 200.000 in order for the method to converge. In Figure 10, the IMO values revolve around an average value of 0.1675. This is logical, since the expected value of each index weight is the same as in Table 5 which presented an IMO value of 0.1677 (a simulation error less than 0.12%). The maximum IMO value obtained from the Monte Carlo simulation of the best case scenario is 0.2545 whereas the minimum IMO value is 0.09. This is achieved for the weight selections that are presented in Tables 8 and 9, respectively. These results point out the importance of the weight selection for each index which can cause a wide oscillation of the multi-objective evaluation outcome that could lead planners to overestimate or underestimate potential configurations of the system. It also proves the dynamic nature of the problem and clarifies the need for careful consideration before reaching to a decision.

5. Conclusion

A number of indices that assess the impact, positive or negative, of RES integration were introduced in this paper. These indices cover a wide spectrum of technical aspects that are crucial to the network's operational procedure, spanning from power losses to emissions' reduction and system security. Thus, an attempt to connect the operational stage with the planning process of a power system has been made. These individual indices are assigned a specific weight and are incorporated into a single multi-objective index that caters for the final evaluation of each configuration under

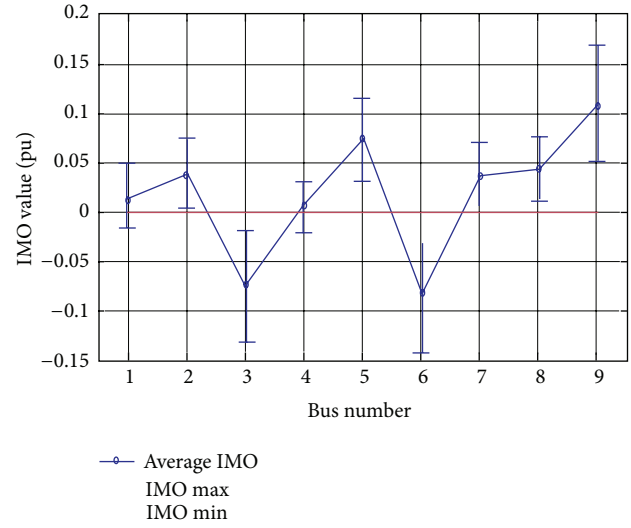

Figure 9: IMO values for the 70 MW (LLP = 22.22%) scenario of the Monte Carlo simulation for each bus.

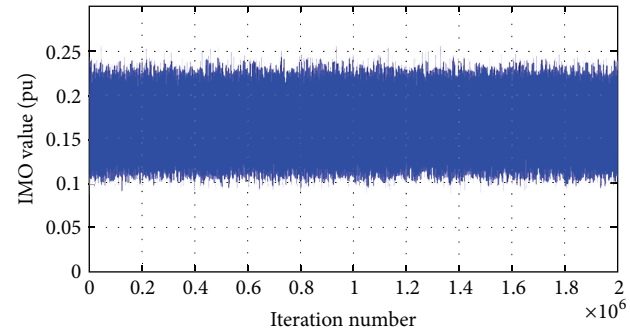

Figure 10: IMO values for the best case scenario of the Monte Carlo simulation.

study. The weight selection is proven to be crucial to the final outcome of the evaluation. This was investigated through a Monte Carlo simulation that pointed out the potential IMO variation of the same network configuration when the weight selection varies between certain limits. Therefore, this work pins out the need for careful consideration of every factor when planning with RES, especially for isolated systems that exacerbate possible contingency situations, since there can be no external support from other interconnected networks that can act as a source or sink of energy. In conclusion, this work examines the impact of RES integration in the system's operational stage in order to determine the technical constraints that directly or indirectly affect the system planning process and, consequently, define the parameters for shaping the National Action Plans of each country.

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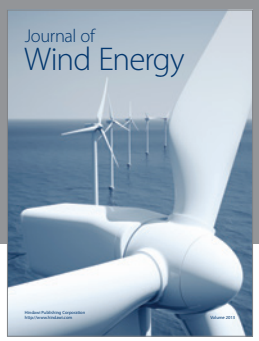

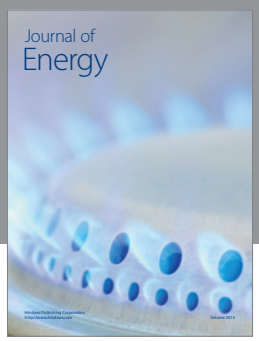

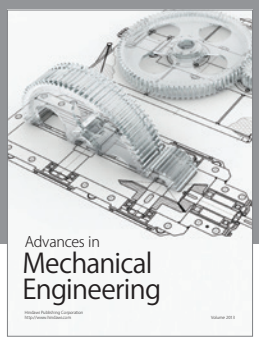

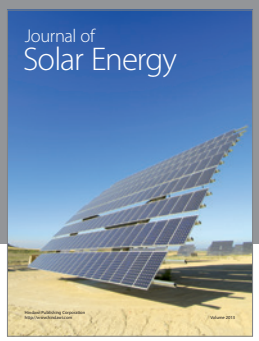

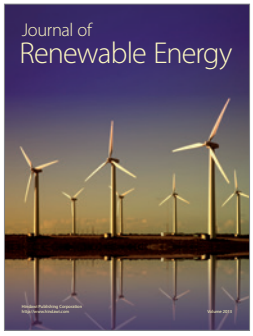

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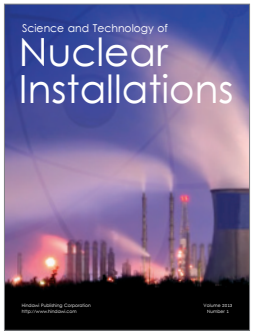

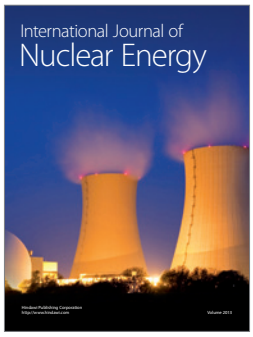

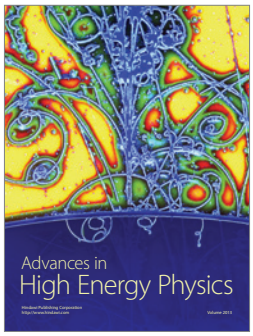

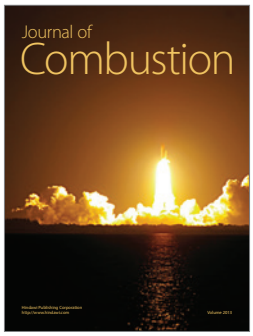

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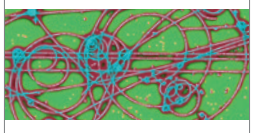

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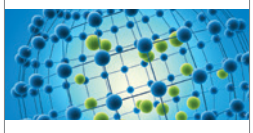

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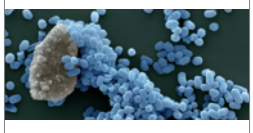

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