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Multi-objective planning tool for the installation of renewable energy resources

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Abstract: This study examines how environmental and socioeconomic criteria affect renewable energy resources (RES) distribution strategic plans regarding national energy policies. Four criteria are introduced with respective coefficients properly formulated to quantify their capacity. Moreover, these coefficients are properly normalised to combine the effect of each criterion under a uniform formulation. The base case scenario in this work considers an initially available capacity of RESs to be equally distributed among the candidate regions. Six scenarios about different prioritisation are examined. The results prove that different prioritisation criteria yield significant variations regarding the assigned regional RES capacity. The proposed algorithm defines optimisation only by terms of predefined prioritisation criteria; each solution could be considered optimal given that the respective installation strategic plan is subject to specific weighted criteria. The advantages of the proposed algorithm rely on its simplicity and expandability, since both coefficients formulation and resizing procedure are easily performed, as well as additional criteria could be easily incorporated in the resizing procedure. Thus, this algorithm could be considered as a multi-objective planning tool regarding long-term strategic plans for nationwide RES distribution.

1 Introduction

Power systems are experiencing tremendous changes regarding their structure and infrastructure as long as their management under real-time operating conditions, basically because of the installation of renewable energy resources (RESs) and the establishment of the smart grid concept. The former has mostly influenced traditional conceptions concerning the grid's sending and receiving points while the latter has raised several challenging aspects about the available capabilities for on-line interferences to the grid's management and operation [1–3]. On the other hand, RES penetration in power systems remains on top of the energy policy agenda in developed countries because of environmental and sustainability issues. Therefore RESs installation incentives are still being given while ambitious targets for global greenhouse gas emissions decrease are tried to be fulfilled [4–7].

Initially, the implementation of large-scale RES installation projects was mostly focused on estimating the energy production by such units [8, 9] (e.g. photovoltaic (PV) and wind power (WP) units) to estimate the benefits arising from covering a proportion of the energy demand by 'eco-friendly' power units. Soon enough, engineers and researchers faced several technical aspects concerning the RES installation, such as protection coordination, islanding, harmonics and short-circuit levels [10, 11], while at the same time additional benefits resulting by both the dispersed nature of the RESs and the renewable energy production itself, such as loss reduction, reliability improvement, peak shaving, environmental benefits etc., have been analysed [12–14].

On the other hand, the RES penetration in power systems imposed initially the investigation and thus the determination of the optimal siting and sizing taking in account target functions, such as loss reduction, reliability improvement, voltage stability and others [15–17]. In various research studies, financial parameters considered usually via feasibility studies along with environmental and social aspects of high RESs penetration [18–20], as well as uncertainty handling [21, 22] have been investigated. The uncertain parameters are introduced in RESs planning by the technical and economic factors and among the common tools for the handling of the above uncertainties are the Fuzzy modelling, the Info-Gap decision theory, the Point Estimation and the Monte Carlo method [23–26]. In more detail, the technical uncertainties of the RES's operation could be severe in terms of short-term power curve (i.e. daily and weekly), nevertheless they can be considered negligible in terms of long-term (i.e. yearly) energy prediction. Secondly, the decision of the aggregated RES capacity could be affected by economic uncertainties; however it could also be predefined when the planner has to meet specific targets such as '20-20-20' goals [27]. In this work, a multiyear meteorological database is required to evaluate long-term RES's yield prediction along with a predefined aggregated RES capacity.

In this paper, the optimisation regarding both siting and sizing of a predefined aggregated RES capacity is faced through four different perspectives which are all combined in a multi-objective planning tool for the distribution in regions with different socioeconomic, environmental and natural resources characteristics. Although solar irradiance (SI) and wind speed (WS) constitute the key-parameters that prioritise specific RES installation points, additional issues such as potential environmental restrictions, the implementation of a development policy regarding the investments related with RES installation and the exploitation of these usually small or medium sized power units towards the implementation of a new energy planning with dispersed characteristics should also be taken into account. Therefore in this work the four aforementioned criteria are properly expressed and quantified through respective coefficients that in turn are processed subject to suitable normalisations to be combined to a final coefficient. This final coefficient represents the proportion of the initially considered RES capacity to be hosted by the respective assumed region, subject to simultaneous consideration of all aforementioned criteria. Moreover, respective weight factors are assigned to each coefficient/criterion and thus different scenarios with various combinations of weighted coefficients are examined. Finally, for each scenario the available RES capacity is distributed to the considered regions based on the weight factor values, and the annual energy production is estimated via appropriate simulations.

This work aims in explaining how the RES siting and sizing is implemented under strategic plans that emphasize on technical, social, environmental and economic parameters. Thus, based on different prioritisation, various alternatives regarding the RES allocation could be evaluated. Moreover, the analysis in this work aims to show the impact of the aforementioned parameters, especially when they are not equally weighted.

This paper is organised as follows: in Section 2 the four coefficients are explained and their quantification formulas are presented. Moreover the algorithm that combines all the coefficients to a final unified one is discussed, and the examined scenarios concerning different prioritisation criteria are explained. In Section 3, a brief analysis about the utilised software simulations for the annual energy production of PV and WP units is presented, along with the siting and sizing results for the selected scenarios are analysed. Finally, Section 4 is devoted to conclusions.

2 Proposed methodology

2.1 Criteria selection

In this section the coefficients that constitute quantified formulations of the four basic criteria are analysed. These criteria are related with respective oriented strategic plans that concern the determination of the capacity and the RES installation locations. Therefore each of these criteria is considered to constitute the core parameter that defines the respective strategic plan. The first criterion expresses the capacity of the regional natural resources (i.e. SI and WS) and thus, it clarifies that the respective strategic plan aims to exploit the capabilities for the maximum possible RES energy production. The second criterion refers to the regional load density, to exploit the RES dispersion benefits. The third criterion quantifies the existent capacity of power units in candidate regions to denote that more RES should be installed in regions with no or negligible power units. This criterion describes strategic plans which aim to face the problem through a socioeconomic perspective since it implies that specific regions should be benefited for reasons related to investments and economic growth. Finally, the fourth criterion embeds environmental concerns since it is considered to link the availability for RES installation in one region with its total area.

2.2 Criteria formulation

The first criterion is related to the natural resources capacity of each candidate region for RESs installation which is in direct proportion to the energy efficiency of such units. In this analysis the RESs under investigation are considered to be PV and WP units and thus, the respective objective for this criterion relies on ranking each candidate installation point based on both the mean annuals SI and WS. Therefore the first coefficient for PV units is defined as the normalised regional annual mean SI. In this work 42 regions have been examined that compose the Interconnected Greek Transmission System (IGTS), while for WP units the coefficient is defined correspondingly as the normalised annual mean WS of IGTS. The coefficients are formulated as follows

$$c_i^{1\mathrm{PV}} = \frac{\mathrm{SI}_i}{\mathrm{SI}_{\max}} \text{ and } c_i^{1\mathrm{WS}} = \frac{\mathrm{WS}_i}{\mathrm{WS}_{\max}}$$

where, i is the candidate region, $i = 1, \ldots, 42$, SI_i and WS_i are the annual mean SI and WS values of region i, $\mathrm{SI}_{\max}$ and $\mathrm{WS}_{\max}$ are the annual maximum SI and WS values of region i.

The second criterion is related to the dispersion of these units towards the implementation of a distributed generation (DG) approach. By that sense, the proposed planning tool should consider the regional load density to assign increased RESs capacity in high load demand areas. Therefore the primary objective embedded in this criterion constitutes in regional ranking based on energy demand. This coefficient is formulated as a joined formulation by the following two coefficients

$$c_i^{2a} = \frac{p_i}{p_{\mathrm{tot}}} \text{ and } c_i^{2b} = \frac{\mathrm{PL}a_i}{\mathrm{PL}a_{\mathrm{tot}}}$$

where, p_i is the population region i, p_{tot} is the total IGTS population, $\mathrm{PL}a_i$ is the annual peak load (*PLa*) for region i, and $\mathrm{PL}a_{\mathrm{tot}}$ is the total *PLa* for the IGTS.

The population magnitude p_i or the $\mathrm{PL}a_i$, as individual metrics, could yield misleading results regarding the load density mainly because they provide a relative perception about the regional energy demand since they ignore the consumer types. On the other hand, annual Peak Load reflects more properly the load density but still is not adequate enough since several parameters such as the particular regional climate conditions, or short-term consuming behaviours could also cause deceiving conclusions about the annual regional energy demand. In this work both coefficients c_i^{2a} and c_i^{2b} are utilised simultaneously under a unified formulation to adequately describe the load distribution across the IGTS. The final coefficient is expressed as follows

$$c_i^2 = \frac{c_i^{2a} + c_i^{2b}}{2} \tag{1}$$

The third criterion is related to the economic growth prospects and the social impact caused because of the investment characteristics imposed by the installation of new PV and WP units. The respective objective relies on determining the RES siting and sizing through a socioeconomic perspective aiming to ensure that regions with poor natural resources would not be excluded from the RESs distribution procedure. Although there could be several different ways to express this criterion, the one in this analysis utilises the existent regional capacity before the RES installation. Hence, the algorithm assigns high priority for RESs installation to regions with no or negligible existent conventional power units (carbon and hydro units) based on the following two considerations: the spatial power production should be balanced among all regions while the RES investments could contribute in economic regional growth, for example, via job offers during the construction and operation, enhancement of the local economy because of the income of the energy production etc. The coefficient that quantifies the third criterion is formulated as follows

$$c_i^3 = \left\{ \begin{array}{lll} 1 & \text{if } \mathrm{EC}_i & \rightarrow \quad \leq 100\,\mathrm{MW} \\ 0.9 & \text{if } \mathrm{EC}_i & \rightarrow \quad 100 \leq 500\,\mathrm{MW} \\ 0.8 & \text{if } \mathrm{EC}_i & \rightarrow \quad 500 \leq 1000\,\mathrm{MW} \\ 0.7 & \text{if } \mathrm{EC}_i & \rightarrow \quad 1000 \leq 2000\,\mathrm{MW} \\ 0.6 & \text{if } \mathrm{EC}_i & \rightarrow \quad 2000 \leq 3000\,\mathrm{MW} \\ 0.5 & \text{if } \mathrm{EC}_i & \rightarrow \quad >5000\,\mathrm{MW} \end{array} \right\}$$

where, EC_i is the existent capacity in region i. As easily observed in c^3 formulation, no region is excluded from the RESs installation even for high (above 5 GW) capacity of existent power units since for these regions the RESs installation could be considered as an offset to environmental burden from CO_2 emissions.

Finally, the fourth criterion is related to restrictions, regarding the regional capacity of potentially RES installations, which could be imposed by environmental issues. The objective takes in account the regional morphology and any other environmental specificities such as mountains, forests, lakes or rivers and especially areas included in Natura 2000 network of nature protection areas. This criterion is quantified by coefficient $c4$ which in turn is formulated as follows

$$c_i^4 = \frac{A_i}{A_{\mathrm{tot}}}$$

where A_i is the area of region i and A_{tot} is the total IGTS area.

Table 1 Criteria, objectives and coefficients of the proposed algorithm

Algorithm conceptual framework for RESs siting and sizing		
Criterion	Objective	Quantification – coefficient
natural resources	define best points for PV and WP units installation	normalised SI and SW
load density	siting and sizing of RESs through the perspective of DG	population and annual peak load demand of each candidate region for RESs installation
capacity of existent power units	benefit regions for economic growth and social impact by new investments	normalised predefined coefficient values in respect to the existent capacity
environmental constraints	rank each region based on the availability regarding the capacity of RESs	area of each region normalised to total area of IGTS – in respect to increased possibility for availability about RESs installation

In Table 1 all considered criteria along with their respective objectives and quantified coefficients are summarised.

2.3 *Proposed algorithm*

The base case scenario assumes that given an initial RES capacity to be installed in i regions with different characteristics, all regions would host the same RES capacity.

The multi-objective nature of the proposed approach regarding the RESs installation has the following meaning: each criterion quantifies specific regional characteristics that embed information about how the initial capacity of the base case scenario should be resized. By that sense, the regional coefficient values provide a prioritisation list that quantifies the siting aspect. Moreover, since these aforementioned values are properly normalised, they also express the deviation of the new capacity to be installed in comparison with the base case scenario that considers the same regional capacity.

The proposed algorithm consists of three levels. The first performs the computation of each coefficient that quantifies the respective criterion. The second detects any possible outliers based on the Chauvenet criterion to exclude from the solution process regions that result in unrealistic solutions. Finally, the third performs the normalisation of each coefficient and subsequently, the resizing of the regional RES capacity is implemented.

2.3.1 First algorithm level – coefficients computation: The first level is implemented by four parallel subroutines that provide quantified coefficients for the four criteria that are considered during the siting and sizing of the initial RES capacity *cap*. It should be mentioned that the expressions provided in Section 2 about the criteria quantification by the respective coefficients are suitable only if only one criterion is considered to the algorithm since all normalisations are not implemented to a common base. To consider the simultaneous effect (i.e. parallel subroutines) of all criteria, different formulations about the criteria quantification have been utilised. More specific, the first level of the algorithm calculates the average value for each coefficient as follows:

1. Criterion related to natural resources:

Calculate for PV units $c_i^1 = (\mathrm{SI}_i/\mathrm{SI}_{\max})$ and $c_{\mathrm{av}}^1 = \left(\sum_{i=1}^{n} c_i^1/n\right)$ where, c_i^1 is the first coefficient for region i, SI_i is the annual mean SI for region i, $\mathrm{SI}_{\max}$ is the annual maximum SI among all regions, c_{av}^1 is the average value of the first coefficient, n is the number of the considered regions.

Calculate for WP units $c_i'^1 = (\mathrm{WS}_i/\mathrm{WS}_{\max})$ and $c_{\mathrm{av}}'^1 = \left(\sum_{i=1}^{n} c_i^{1\prime}/n\right)$ where, $c_i'^1$ is the first coefficient for region i, WS_i is the annual mean WS for region i, $\mathrm{WS}_{\max}$ is the annual maximum SW among all regions, $c_{\mathrm{av}}'^1$ is the average value of the first coefficient, n is the number of the considered regions.

2. Criterion related to load density – a and b:

(a) Calculate $p_{\mathrm{tot}} = \sum_{i=1}^{n} p_i$ and $p_{\mathrm{av}} = (p_{\mathrm{tot}}/n)$ where, p_i is the regional population, p_{tot} is the total IGTS population, p_{av} is the average regional population, n is the number of the considered regions.
(b) Calculate $\mathrm{PL}a_{\mathrm{tot}} = \sum_{i=1}^{n} \mathrm{PL}a_i$ and $(\mathrm{PL}a_{\mathrm{av}} = (\mathrm{PL}a_{\mathrm{tot}}/n)$ where, $\mathrm{PL}a_i$ is the annual Peak Load of region i, $\mathrm{PL}a_{\mathrm{tot}}$ is the annual IGTS Peak Load, $\mathrm{PL}a_{\mathrm{av}}$ is the average annual regional Peak Load, n is the number of the considered regions.

3. Criterion related to existent regional capacity but RES:

Calculate $c_{\mathrm{tot}}^4 = \sum_{i=1}^{n} c_i^4$ and $c_{\mathrm{av}}^4 = (c_{\mathrm{tot}}^4/n)$ where, c_i^4 is the coefficient value based on the EC of region i, c_{tot}^4 is the total coefficient value for the IGTS, c_{av}^4 is the average value for the coefficient for the IGTS, n is the number of the considered regions.

4. Criterion related to environmental constraints:

Calculate $A_{\mathrm{tot}} = \sum_{i=1}^{n} A_i$ and $A_{\mathrm{av}} = (A_{\mathrm{tot}}/n)$ where, A_i is the area of region i, A_{tot} is the total IGTS area, A_{av} is the average regional area, n is the number of the considered regions.

The different regional values for each coefficient denote that, based on the respective criterion, the initial uniform distribution of the total capacity is not justified when this criterion is considered to participate in the siting and sizing procedure. Hence, the deviation from the regional coefficient's mean value describes how the initial capacity of the base case scenario should be resized.

2.3.2 Second algorithm level – outliers detection: The second algorithm level is proposed as a means of assessing whether a coefficient value for some regions deviates extremely from the mean value. The concept relies on detecting too high or too low values (i.e. outliers) that are expected to overestimate/underestimate the respective criterion's influence to the resizing procedure. Therefore during the second level, the Chauvenet criterion [28] is applied to estimate possible outliers. The Chauvenet criterion is implemented as follows:

- Consider that the regional data series follow a normal distribution.
- Compute the mean value μ of the data series and the standard deviation S.
- Based on the number of data points N, define the value of the ratio d/σ from Table 2 (d/σ – deviation/std. deviation of distribution). For N not provided in Table 2 extrapolate between adjacent values (in this work since the number of candidate regions is 42 the extrapolation was performed between numbers 40 and 50 of Table 2 regarding the data points N).
- Compute deviation (cd) by: $\mathrm{cd} = S \cdot (d/\sigma)$.

Table 2 Maximum deviations for Chauvenet criterion –probability adjusts with *N*, the number of observations, by 1/(2*N*)

N (number of data points)	*d*/*σ* (deviation/std. dev. of distribution	*N* (number of data points)	*d*/*σ* (deviation/std. dev. of distribution
5	1.65	30	2.39
6	1.73	40	2.49
7	1.81	50	2.57
8	1.86	60	2.64
9	1.91	80	2.74
10	1.96	100	2.81
12	2.04	150	2.93
14	2.10	200	3.02
16	2.15	300	3.14
18	2.20	400	3.23
20	2.24	500	3.29
25	2.33	1000	3.48

- Compare deviation d with cd

$$\left\{\begin{array}{l}\text{if}\,|d| \le \text{cd accept the value}\\ \text{if}\,|d| > \text{cd reject the value (outlier)}\end{array}\right\}$$

Whenever an outlier is detected, the algorithm rejects that value and the respective region is excluded from the siting and sizing procedure. The excluded regions are proposed to be handled by some alternative resizing approaches presented as follows:

(a) Increase the critical deviation cd of the Chauvenet criterion to include more outliers, if not possible all, to the procedure. For those that are still excluded, one of the following alternatives should be applied.
(b) Define the capacity for the outlier regions by excluding from the algorithm the coefficient that defined these regions as outliers. Thus, these regions should be considered to host a resized RES capacity without the influence of the outlier criterion. That means that the initial total RES capacity is updated by $\text{cap}_{\text{new}} = \text{cap} - \sum_{i=1}^{m} \text{cap}_{i(\text{outliers})}$ (m is the number of outlier regions) within an updated number of regions $n_{\text{new}} = n - m$.
(c) Define a percentage, from the initial available capacity, to be distributed in outliers and execute the algorithm based on the expression provided in (b).
(d) Perform a fictitious increase of the regions n by cutting up the outlier regions to a number of sub regions so that for each sub sub-region $|d| \le \text{cd}$ (no outlier).

2.3.3 Third algorithm level – resizing procedure:

At the third level the four criteria are reformulated to express their resizing effect on the initial equal distributed capacity. This procedure consists of three steps presented as follows:

- Compute the coefficient deviations from their mean value: $c^1_{i(\text{dev})} = \left((c^1_i - c^1_{\text{av}})/c^1_{\text{av}}\right)$ where $c^1_{i(\text{dev})}$ is the deviation of the first coefficient (PV) for region i, $c'^1_{i(\text{dev})} = \left((c'^1_i - c'^1_{\text{av}})/c'^1_{\text{av}}\right)$ where $c'^1_{i(\text{dev})}$ is the deviation of the first coefficient (WP) for region i, $p_{i(\text{dev})} = ((p_i - p_{\text{av}})/p_{\text{av}})$ where $p_{i(\text{dev})}$ is the deviation of the first utilised expression of the second coefficient for region i, $\text{PL}a_{i(\text{dev})} = ((\text{PL}a_i - \text{PL}a_{\text{av}})/\text{PL}a_{\text{av}})$ where $\text{PL}a_{i(\text{dev})}$ is the deviation of the second utilised expression of the second coefficient for region i, $c^3_{i(\text{dev})} = \left((c^3_i - c^3_{\text{av}})/c^4_{\text{av}}\right)$ where $c^3_{i(\text{dev})}$ is the deviation of the third coefficient value for region i, $A_{i(\text{dev})} = ((A_i - A_{\text{av}})/A_{\text{av}})$ where $A_{i(\text{dev})}$ is the deviation of the fourth coefficient for region i.
- The computed deviations from the first step express whether the initial regional capacity should be either increased or reduced. A positive deviation implies that the RES capacity should be increased while a negative value implies the opposite. Therefore all five coefficients are computed as follows

$$c_i^{1(\text{new})} = 1 + w_1 \cdot c^1_{i(\text{dev})} \tag{2}$$

$$c_i'^{1(\text{new})} = 1 + w_1 \cdot c'^1_{i(\text{dev})} \tag{3}$$

$$c_i^{2(\text{new})} = 1 + w_2 \cdot p_{i(\text{dev})} \tag{4}$$

$$c_i^{3(\text{new})} = 1 + w_3 \cdot \text{PL}a_{i(\text{dev})} \tag{5}$$

$$c_i^{4(\text{new})} = 1 + w_4 \cdot c^4_{i(\text{dev})} \tag{6}$$

In (2)–(6), the respective weight factors range between 0–1 and it is expected to define the criteria prioritisation. By that sense, numerous scenarios could be examined regarding different strategic plans based on whether the RESs distribution embeds social, economic, environmental or other orientations.

- The third step of the third level of the algorithm defines the resized capacity for each region based on the following expressions

$$\text{cap}_i^{\text{new1}} = \text{cap}_i \cdot c_i^{1(\text{new})} \qquad \text{(PV)} \tag{7}$$

$$\text{cap}_i'^{\text{new1}} = \text{cap}'_i \cdot c_i'^{1(\text{new})} \qquad \text{(WP)} \tag{8}$$

$$\text{cap}_i^{\text{new2}} = \text{cap}_i \cdot c_i^{2(\text{new})} \tag{9}$$

$$\text{cap}_i^{\text{new3}} = \text{cap}_i \cdot c_i^{3(\text{new})} \tag{10}$$

$$\text{cap}_i^{\text{new4}} = \text{cap}_i \cdot c_i^{4(\text{new})} \tag{11}$$

Finally, the last step concerns the consideration of all criteria to the resizing problem by computing the final percentage of the initially regional capacity to be installed. Since all resizing factors from (7)–(11) are properly normalised the final distributed capacity D_i is computed as follows

$$D_i = \text{cap}_i^{\text{new1}} \cdot \text{cap}_i^{\text{new2}} \cdot \text{cap}_i^{\text{new4}} \cdot \text{cap}_i^{\text{new5}} \quad \text{for PV units} \tag{12}$$

$$D_i = \text{cap}_i'^{\text{new1}} \cdot \text{cap}_i^{\text{new2}} \cdot \text{cap}_i^{\text{new4}} \cdot \text{cap}_i^{\text{new5}} \quad \text{for WP units} \tag{13}$$

Equations (12) and (13) provide the resized regional capacity, in comparison with the base case, subject to four criteria that are weighted according to different prioritisations. Fig. 1 illustrates the proposed algorithm's flowchart.

2.4 Examined scenarios

In this work six scenarios describing respective strategic plans are examined. Table 3 presents these scenarios based on the assigned weight factors to each considered criterion.

Given the weight factor values presented in Table 3, it is observed that four scenarios (i.e. scenarios 1–4) consider only one criterion at a time to highlight each criterion influence. Scenario 1 refers to a specific strategic plan about RES installation that aims in fully exploiting the capacity of natural resources among the candidate regions. The weight factor in this scenario is equal to one while the other criteria are not considered at all (equal to zero), since this scenario constitutes an energy oriented strategic plan. By that sense, this scenario is expected to be the optimal one in terms of annual energy production in regard to the base. The second scenario embeds technical aspects of the problem since it takes into account the regional load density to promote the DG concept. Thus, the second coefficient is assigned with a weight factor equal to one, while the other three are set to zero. In other words, this scenario implements a DG oriented RES expansion plan. The third examined scenario faces the problem through a socioeconomic perspective. More specific, each region is promoted for RES installation, based on the idea of providing to specific regions with economic growth opportunities and social development through investments for RES installation. Thus, the weight factor for the third coefficient in this case is set to one while for the others are set to zero. The fourth scenario refers to a strategic plan that prioritises environmental benefits of RESs and is a particularly interesting plan since it ignores all technical and economic perspectives. For this scenario, the weigh factor of the fourth coefficient is one while others are set to zero.

Apart from the aforementioned distinct scenarios, two additional scenarios have been examined with hybrid prioritisations. Scenarios 5–6 include all criteria in the resizing procedure and given the selected weight factor values, scenario 5 tend to assign prioritisation to criteria 1 and 4, that is, a strategic plan oriented to fully exploit the regional natural resources subject to environmental constraints. The other two criteria affecting the installation plan are also included with a lower prioritisation level. Finally, scenario 6 assigns the highest prioritisation to criteria 2–3, that is, a strategic plan oriented to face technical aspects of the grid, while lower prioritisation is given to the regional natural characteristics.

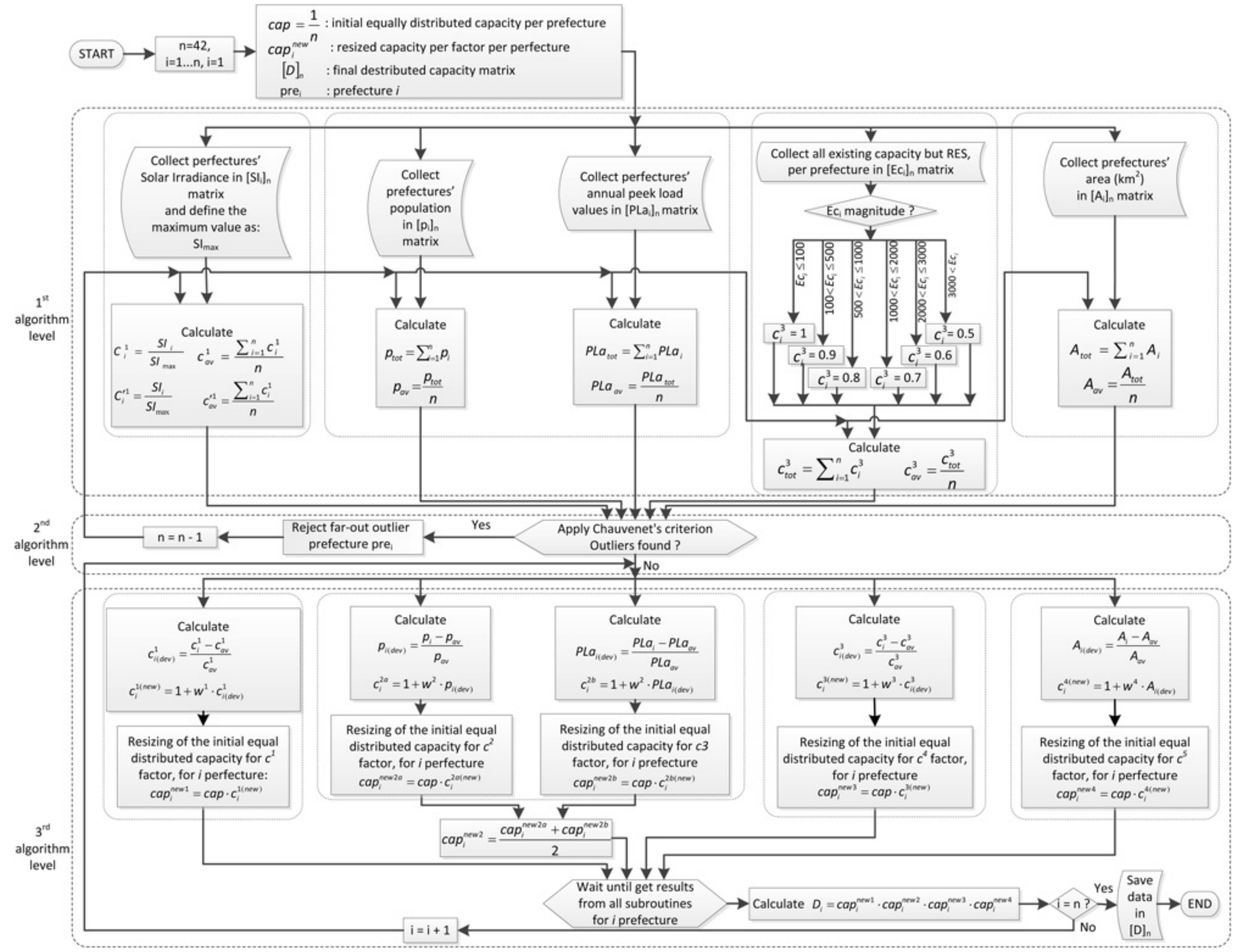

Fig. 1 *Flowchart of the proposed algorithm*

3 Results and discussion

3.1 Annual energy production by RESs – simulation software

The annual energy production for both the PV and WP units has been estimated on an hourly basis with real values regarding the SI and the WS, respectively. More specifically, the data about the regional natural resources have been provided by METEONORM® [29] software package. In this work, hourly values for a time period of one year have been extracted for each region of the 42 in the IGTS concerning the SI and the WS.

The simulations about the energy production of the PV units have been performed via the PVsyst® [30] software package. The total PV capacity resulted for each region has been modelled as an aggregated unit within the region, since it had been found that the spatial distribution of this total capacity within the region under smaller sized PV units would not affect the total annual energy production.

Table 3 Examined scenarios subject to considered criteria and respective weight factor values

Weight factors	Scenario					
	1st	2nd	3rd	4th	5th	6th
Included criterion in resizing algorithm						
	natural resources (1st criterion)	load density-distributed nature of installation (2nd criterion)	existent capacity-socioeconomic impact (3rd criterion)	environmental constraints (4th criterion)	all (emphasize on criteria 1 and 4)	all (emphasize on criteria 2 and 3)
w1	1	0	0	0	1	0.5
w2	0	1	0	0	0.5	1
w3	0	1	0	0	0.5	1
w4	0	0	1	0	0.5	1
w5	0	0	0	1	1	0.5
Prioritisation level of included criterion based on weight factor value						
w1	high	none	none	none	high	medium
w2	none	high	none	none	medium	high
w3	none	high	none	none	medium	high
w4	none	none	high	none	medium	high
w5	none	none	none	high	high	medium

Table 4 Power production in respect to wind speed data for the considered WP unit

WS, m/s	Power, kW	WS, m/s	Power, kW
0	0	11	686
1	0	12	783
2	0	13	891
3	0	14	966
4	24	15	1010
5	64	16	1037
6	111	17	1030
7	197	18	1035
8	314	19	1032
9	454	20	1009
10	582		

Table 5 Base case scenario results

RES type	Installed capacity in each region, kW	Annual energy production in IGTS, GWh
PV	47.62	2576.55
WP	166.67	9402.58

For the WP units, the hourly WS values provided by METEONORM were processed to readjust the data series to the rotor height (i.e. 100 m) since the meteorological database of METEONORM provides values for a typical height of 10 m. Thus, the regional data series have been processed under the (14)

$$\frac{v(z)}{v(z_1)} = \left(\frac{z}{z_1}\right)^{a} \tag{14}$$

where, $v(z)$ is the WS at the rotor height z ($z = 100$), $v(z_1)$ is the WS at the initial height height z_1 ($z_1 = 10$), a is a constant which depends on the roughness of the terrain and the direction of the wind (typical values between 0.07 for ice surface to 0.47 for domestic areas). In this work a was considered as the median of the aforementioned values (i.e. equal to 0.27).

Finally the simulations about the WP annual energy production have been conducted by utilising the power output of a commercially available WP unit provided by RETScreen® [31] software package (with nominal capacity equal to 1 MW) in respect to WS data. Table 4 presents the power output of the considered WP unit in regard to WS values. For intermediate WS values provided from the regional data series, extrapolation between the respective adjacent ones has been performed.

3.2 Results about the examined scenarios

The present analysis considers that the initially available capacity of RESs to be sized and distributed at 42 IGTS's regions, refers to 2 GW of PV units and 7 GW of WP units [32]. The base case scenario (SC#0) adopts the simplest way for allocating the aggregated initial RESs capacity to the 42 regions; each region is

Table 6 Resizing WP units for the examined scenarios in respect to base case scenario (SC#0)

Region	Examined scenario						
	SC#0 Installed capacity % percentage of the initial 7 GW	SC#1 Resized capacity in respect (%) to SC#0	SC#2 Resized capacity in respect (%) to SC#0	SC#3 Resized capacity in respect (%) to SC#0	SC#4 Resized capacity in respect (%) to SC#0	SC#5 Resized capacity in respect (%) to SC#0	SC#6 Resized capacity in respect (%) to S C#0
1	2.381	+22.09	−22.55	−17.43	+100.92	+80.01	+13.57
2	2.381	+32.55	−37.93	+10.08	−20.75	−18.98	−24.28
3	2.381	+6.72	−63.88	−17.43	+62.58	−2.35	−56.99
4	2.381	+73.54	−71.78	−0.92	−38.85	−38.64	−67.24
5	2.381	+38.98	+1522.39	−44.94	+40.11	+1077.49	+1261.53
6	2.381	+7.56	+31.21	+10.08	+20.33	+42.42	+75.56
7	2.381	+29.78	−16.88	−44.94	+8.61	−9.37	−41.75
8	2.381	−28.94	−85.89	+10.08	−15.71	−67.49	−86.98
9	2.381	−12.89	−61.36	−17.43	+27.59	−36.29	−63.88
10	2.381	−25.91	−42.67	−0.92	+56.07	−18.02	−32.72
11	2.381	+76.10	−9.24	−17.43	+53.30	+112.94	+39.27
12	2.381	+55.40	−91.01	+10.08	−31.25	−44.56	−88.66
13	2.381	−25.28	−80.18	+10.08	−85.05	−93.66	−88.37
14	2.381	−23.14	−36.46	+10.08	−3.70	−42.38	−35.45
15	2.381	−26.17	−35.78	−0.92	−37.42	−65.77	−52.20
16	2.381	−3.32	−83.49	+10.08	−44.27	−70.14	−85.22
17	2.381	−31.04	+323.56	−0.92	+35.49	+120.54	+343.72
18	2.381	−16.97	−37.21	−0.92	+83.58	+11.89	−14.20
19	2.381	−9.70	−40.57	−0.92	−22.34	−49.60	−47.08
20	2.381	−25.28	−47.12	−0.92	−3.02	−50.06	−52.12
21	2.381	−26.17	−82.36	+10.08	−36.71	−73.83	−85.34
22	2.381	−6.09	−58.63	+10.08	−76.44	−85.09	−70.98
23	2.381	+13.57	−82.07	+10.08	−66.74	−78.79	−85.05
24	2.381	−31.50	−59.01	+10.08	−7.35	−57.41	−61.07
25	2.381	−22.93	−40.74	−44.94	+29.36	−44.27	−64.80
26	2.381	−3.11	−17.51	−0.92	−15.75	−32.80	−21.21
27	2.381	+33.39	−56.66	+10.08	+33.77	+21.71	−30.79
28	2.381	−43.85	+54.01	+10.08	+97.94	+34.31	+109.62
29	2.381	+70.77	−91.31	+10.08	−86.90	−88.45	−92.23
30	2.381	−18.23	−5.54	−0.92	−3.02	−30.49	−10.96
31	2.381	+7.35	−35.66	+10.08	+10.04	−7.60	−18.02
32	2.381	−9.49	−57.96	+10.08	−34.02	−59.64	−61.11
33	2.381	+0.13	−33.52	+10.08	−7.81	−26.88	−25.20
34	2.381	−25.70	−46.54	+10.08	−44.23	−69.76	−57.54
35	2.381	+41.75	−79.97	+10.08	−61.91	−69.13	−80.43
36	2.381	−16.34	−47.75	−0.92	−6.43	−46.24	−51.07
37	2.381	−21.46	−9.87	+10.08	+45.99	+3.74	+15.79
38	2.381	−50.69	−36.04	−0.92	+24.49	−54.60	−43.55
39	2.381	+44.52	−22.30	+10.08	+63.38	+100.62	+46.33
40	2.381	−15.67	−77.03	−17.43	−29.23	−69.63	−84.12
41	2.381	−3.95	−84.08	+10.08	−22.01	−58.67	−84.12
42	2.381	−30.41	−42.80	+10.08	+7.35	−44.14	−41.16

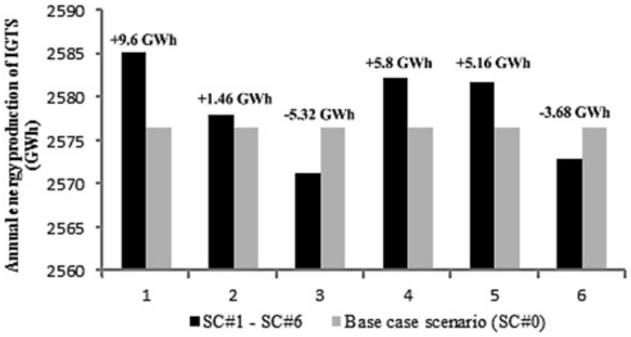

Fig. 2 *Annual energy production for the IGTS regarding the six examined scenarios in respect to equally distributed PV units (SC#0)*

assumed to host a quota of 1/42 of 2 GW regarding PV capacity and accordingly 1/42 regarding WP capacity. Thus, the base case scenario considers none criterion for the RES siting and sizing but implements the simplest possible strategy that refers to an equally distribution among candidate regions. Such a choice does not account the special environmental and socioeconomic characteristics of each region; this gap is expected to be faced by the proposed algorithm. Table 5 summarises the results about the installed regional RES capacity and the annual energy production of the IGTS.

In Table 6 the influence of the proposed criteria on the sizing of RESs because of siting characteristics for the six examined scenarios, is presented.

The results in Table 6 prove that when the proposed criteria are taken into account the sizing of the RESs significantly deviates from the equally distribution approach. The first scenario (SC#1) assigns to each region RES capacity based only on the respective natural resources; this approach is expected to yield the maximum energy production in each region. For the second scenario (SC#2), only the local energy demands of each region are considered, and the results indicate that regions with high population density should be prioritised for RESs installation. It should be mentioned though, that for the IGTS, two outliers result when this criterion is taken into account (i.e. regions 5 and 17). The latter is explained by the following: these two regions host almost the half population of the IGTS which means that in this case RES capacity should be subtracted by most of the regions and in turn it should be ascribed to these regions. The problem of outliers is proposed to be faced through a number of alternatives that are discussed in Section 3.1. For scenarios 5 and 6, the load density criterion is considered in both, the aforementioned outliers seem to be still present but their magnitude is lower because of the influence of the other criteria.

Fig. 2 illustrates the annual IGTS energy production regarding PV installation for all examined scenarios.

It has to be mentioned that the results in Fig. 2 do not include the outliers presented in Table 6. The latter means that the IGTS is considered to be constituted by 40 and not 42 regions. Nevertheless, the results indicate that SC#1 yields the maximum annual energy production; this is rational since this scenario resizes the PV units based on each region's real SI data series. The latter means that SC#1 could be considered optimal only by terms of maximum exploitation concerning the natural resources variations among the regions. For the other scenarios (SC#2–SC#6), optimality is defined only under the assumption that the considered respective weighted criteria compose the strategic plan. By that sense, every examined scenario could be assumed to be the optimal one given that the selected weight factor values define the policy and the targets about the respective strategic plan. On the other hand, the stochastic influence of each criterion affects the resizing procedure regionally as presented in Table 6, and it could not necessarily present a clear trend in aggregated level as in Fig. 2.

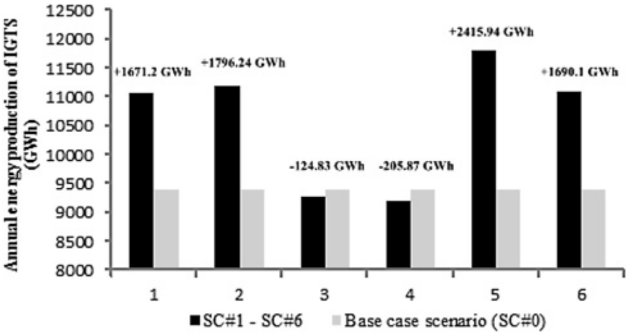

Fig. 3 *Annual energy production for the IGTS regarding the six examined scenarios in respect to equally distributed WP units (SC#0)*

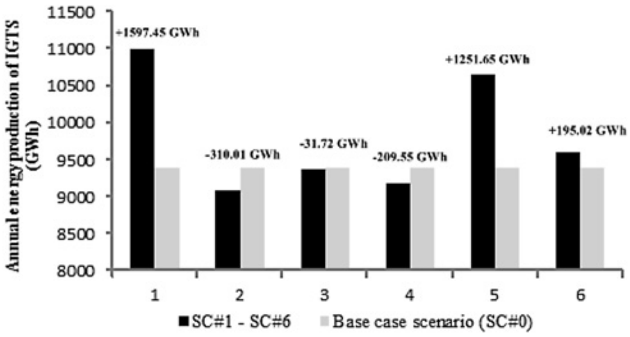

Fig. 4 *Annual energy production for the IGTS regarding the six examined scenarios in respect to equally distributed WP units (SC#0) – outlier problem faced with alternative (b)*

In Fig. 3, the annual energy production for the IGTS because of the WP capacity allocation for the six examined scenarios is presented.

In Fig. 3 both outliers presented in Table 6 are included in the resizing procedure. As a result, the scenarios that include the criterion which provided these outliers (i.e. SC#2, SC#5 and SC#6), prove to be more efficient concerning the annual energy production of the IGTS in respect to SC#1 that sizes the WP units based on the regional WS data. The latter is explained as follows: the two included outliers refer to regions with high wind capacity and the algorithm assigns to both almost 60% of the available WP capacity. Thus, the remaining 40 regions are expected to host too small WP units while for the two outliers the computed WP capacity installation could be in conflict with technical and environmental constraints (i.e. the other criteria). Therefore in Fig. 4 the results are updated by facing the outlier problem with alternative (b) as explained in Section 2.3.2. As easily observed in Fig. 4, SC#1 is now the most efficient about the annual energy production. All other scenarios either do not consider the natural resources of each region or perform a compromise between the natural resources and other targets/criteria.

4 Conclusion

In this paper the problem of RESs siting and sizing is faced through a long-term perspective with environmental and socio-economic orientations. A simple multi-objective planning tool is proposed aiming to combine different objectives that define the distribution of RESs and are usually in conflict. The presented analysis shows how a uniform distribution of RES capacity among a specific number of regions, could be greatly influenced when the special regional characteristics, that is, natural resources capacity, energy demand, growth potentials and environmental constraints are taken into account. The present methodology proposes a simple way to formulate respective coefficients that quantify the capacity of each considered criterion. Moreover, appropriate data process is proposed to commonly normalise these coefficients aiming to develop a joined and simple final coefficient that embeds each criterion's influence.

The proposed algorithm could be considered as a simple planning tool that could guideline long-term strategic plans regarding the installation/distribution of RESs. A significant advantage of this methodology is that is expandable since additional criteria should also be easily included in the resizing procedure of the RESs. Thus, numerous scenarios could be examined in a simple way to analyse the effect of multiple criteria to the RES installation policy. The effect of the proposed criteria in this work is evaluated by terms of annual energy production for both at regional and aggregated level but other alternatives could also be utilised, such as the economic growth at each region because of the expected investments or the socioeconomic impact because of job offers by such investments.

Six scenarios have been examined in this work with different weighted factors for the proposed four criteria: the first four scenarios consider the consideration of one criterion at a time while the last two refer to strategic plans with all criteria included under different prioritisation. The results indicate that the simple approach with equally distribution of RESs is significantly influenced when the proposed criteria are taken into account, thus the user could decide the best policy based on predefined criteria prioritisation.

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