Network development alternative analysis based on Analytic Hierarchy Process

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***Abstract*— In the framework of energy transition, transmission network expansion planning process arises the need of effective and flexible tools to evaluate development options and their mutual influence, accounting for heterogenous though significant information. This paper aims to propose a new methodology developed by the Italian Transmission System Operator to identify and select the transmission network developments of higher importance for investment planning strategies. The presented approach involves the definition of alternatives by combination of network developments, by using a multi-criteria analysis involving technical and economic aspects. The method is tested on the Network Development Plan of Italian Transmission Network.**

***Keywords*— transmission network planning, network development, multi-criteria analysis, decision making.**

I. INTRODUCTION

The growing diffusion of variable renewable sources, the progressive thermal power plants decommissioning and the consumption electrification, together with the technological innovations related to the world of energy, are making the transmission expansion planning increasingly complex [1]. New methods and approaches are needed to make the planning process more effective and flexible towards sudden changes in the energy sector [2], [3].

Transmission expansion planning must involve both economic and technical impacts on a competitive energy market [4], considering the evolution of generation mix, load trend, policy directives, investments costs and commodities. In practice, the Transmission System Operators (TSOs) adopts the Cost-Benefit Analysis (CBA) for network development assessment in different energy scenarios. Starting from a defined reference network (or base case), the "Put IN one at Time" (PINT) approach [5] is generally used: the network developments are added one at time to the reference grid and the benefit indicators variation evaluated by difference from benefits related to the base case.

The optimization methods for development strategies identification in different energy scenarios are of interest for network planners and regulators and able to combine methodological rigor and practice-oriented applications. However, mathematical optimization methods such as Linear Programming (LP) [6], [7], mixed integer linear programming ("MILP") [1], [8], and robust optimization [9], [10], require high computational efforts and are applicable to simplified systems under market competition simplifications.

In this context, the assessment of different investment options requires the definition of some significant judging criteria in order to provide cost-effective indications on the implementation planning maximizing the benefits for the entire system. In fact, the Multi-Criteria Decision Making (MCDM) methods are often used in different sectors to help the Decision Maker (DM) to solve a complex decision-making problem composed of heterogeneous variables, uncertainties and with many alternatives evaluated according to different criteria [11]. A weight reflecting its relative importance in the decision process is associated to each criterion, often in a judgmental manner on the basis of the expert decision makers subjective assessment [12].

Among the MCDM methods, the Analytic Hierarchy Process (AHP) adopts the 9-point scale defined by Saaty [13] to the relative preferences between pairs of criteria definitions and applies a consistency criterion to the preferences expression verification. A novel approach for the comparison of different candidate project on the basis of merit indicators compared by the AHP method is presented in [4] and applied to the NREL-118 system. Whereas, the Ordered Weighted Averaging (OWA) [14] orders the weights on the basis of their relative importance and realizes a modification of the weighted values of the criteria by means of a transformation function, obtaining a multi-criteria combination procedure guided by a single parameter. Moreover, the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) allows to evaluate the criteria depending on their distance to the reference ideal solution [15] – [18].

In this paper, a new methodology is proposed for the selection of the transmission network developments of higher importance in the study of differentiatied strategies for investment planning. The method involves the definition of alternatives by combination of network developments, and most significant ones are pointed out by using a multi-criteria analysis involving technical and economic considerations based on cost-benefit assessment of each project, and the analysis is solved with the AHP method. The methodology is applied to the study of a relevant set of planned reinforcements included the National Network Development Plan (NDP) by Terna, the Italian TSO.

The rest of the paper is organized as follows: the methodology is illustrated in Section II; the case study and results are provided in Section III; lastly, the Section IV concludes the paper.

II. Methodology

Starting from a specific perimeter of network developments identified by the TSO, a classification of alternatives based on decision-making criteria through AHP is performed. The entire workflow of the proposed method is depicted in Figure 1. In the following, the aforementioned phases are detailed.

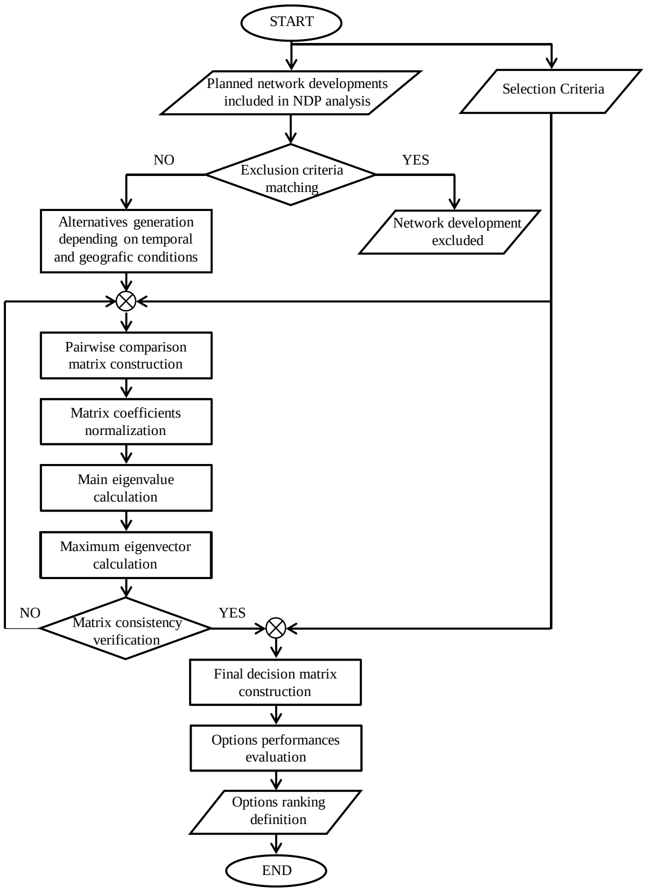

Fig. 1. Workflow of the proposed approach.

Each phase of the method depicted in the workflow is described in the following sub-sections.

A. *Planned network developments, exclusion criteria and alternatives generations*

Starting from a set of network developments, since the aim of the study is to point out the possible positive correlations among them, alternatives are defined as combination of two network developments. In order to avoid a huge computational effort and identify the most significant interdependencies, temporal and geographical exclusion criteria for the alternatives are adopted together with investment cost and voltage level thresholds and foreseen date of entry into service.

B. *Selection criteria*

The first step of the AHP analysis is the transformation of a decision problem into a hierarchical structure [19]. A three-level hierarchical structure has been identified for this study:

- *First level – objective*: classification of alternatives to be evaluated with NOA methodology;
- *Second level – criteria*: techno-economic impacts and interdependence;
- *Third level – alternatives*: combination of development interventions.

The criteria in the AHP constitute the references through which the considered alternatives are evaluated and classified. The application of the Saaty method requires the consistency verification of results and a limitation occurs with remarkable number of alternatives and criteria. For this purpose, fixed degrees of alternatives interaction for each judgmental criterion are defined, leading to simple binary comparisons. This approach allows to avoid subjective and arbitrary assessments, guaranteeing the consistency.

For this application, three evaluation criteria have been identified: the technical-functional interdependence, the temporal interdependence and the Net Present Value (NPV) as cost-benefit analysis outcome. A different value of the Saaty scale is associated with each type of interdependence and NPVs. The technical-functional interdependence allows to define the mutual influence between network developments from the technical and operational point of view. Within the AHP, the alternatives are evaluated through pairwise comparison matrices, based on four levels of interdependence:

1. Technical interdependence (strong): a network development cannot come into service before the completion of another reinforcement. In these cases, constraints in terms of anticipation of the year of completion must be added in the decisional problem;
2. Intermediate interdependence: when a development action could have influence on another in terms of full exploitation of the capacity associated with the new infrastructure, although the two interventions could enter in service independently of each other;
3. Functional interdependence (low): when the reciprocal influence between two network developments concerns only possible effects on the benefits for the system;
4. Zero interdependence: when no reciprocal influence is encountered.

The temporal interdependence takes into account the correlation of interventions based on their completion date expected in the NDP. Combinations of network development with similar years of completion will be considered with higher priority in the study over more distant in time ones. For this aspect, four levels of correlation are identified according to the difference between the years of completion:

1. Strong temporal interdependence: development actions have the same year of completion in the NDP;
2. Intermediate temporal interdependence: the difference of completion years is within 2 years;
3. Low temporal interdependence: the difference in the years of completion is in the range 2-5 years;
4. Zero temporal interdependence: when the difference in the years of completion is beyond 5 years.

The dominance intensity values assigned for the first and the second criteria are listed in Table I, and if two alternatives have the same interdependence level the pairwise dominance is set to 1. In this way, the consistency with transitivity of the dominance values is verified, since the following relation holds:

$$d_{kp} = d_{kq} \cdot d_{qp} \tag{1}$$

where d_{kp} is the is the dominance value between the alternative A_k and A_p, d_{kq} is the is the dominance value between the alternative A_k and A_q and d_{qp} is the the dominance value between the alternative A_q and A_p.

TABLE I. DOMINANCE SCALE FOR TECHNICAL-FUNCTIONAL AND TEMPORAL INTERDEPENDENCE

Alternative I	**Alternative II**	**Dominance I-II**	**Dominance II-I**
Strong	Intermediate	2	1/2
Strong	Low	4	1/4
Strong	Zero	8	1/8
Intermediate	Low	2	1/2
Intermediate	Zero	4	1/4
Low	Zero	2	1/2

The third criterion is related to network developments' benefits, giving priority to the combinations with higher NPVs. The order of preference of an alternative over the others is evaluated through the difference between the NPVs of the compared alternatives in five levels with odd dominance values from 1 to 9 in the Saaty scale.

C. *Pairwise comparison matrices construction*

After defining the evaluation criteria, it is possible to construct the pairwise comparison matrices. In this step, two alternatives are compared for each of the three criteria and a dominance intensity value is assigned according to the Saaty scale, depending on the preference of one alternative over the other. This standardization in the assignment of values allows the construction of three pairwise comparison matrices.

D. *Normalization, main eigenvalue and maximum eigenvector calculation and final decision matrices construction*

After binary comparisons, the Saaty eigenvalue method is employed to derive the elements of the final decision matrix. The eigenvector associated with the maximum eigenvalue of the normalized pairwise comparison matrix of a criterion constitutes the column of the decision matrix associated with that criterion, as in Table II.

TABLE II. DECISION MATRIX

	C₁(w₁)	***C₂(w₂)***	***C₃(w₃)***
A_1	$a_{1,1}$	$a_{1,2}$	$a_{1,3}$
A_2	$a_{2,1}$	$a_{2,2}$	$a_{2,3}$
…	…	…	…
A_n	$a_{n,1}$	$a_{n,2}$	$a_{n,3}$

E. *Matrices consistency verification*

The technical and temporal interdipence levels standardization allows to obtain, in a simple and automatic way pairwise comparison matrices as:

$$\boldsymbol{D} = \begin{bmatrix} 1 & d_{12} & \dots & d_{1n} \\ d_{21} & 1 & \dots & d_{2n} \\ \dots & \dots & \dots & \dots \\ d_{n1} & d_{n2} & \dots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \frac{u_1}{u_2} & \dots & \frac{u_1}{u_n} \\ \frac{u_2}{u_1} & 1 & \dots & \frac{u_2}{u_n} \\ \dots & \dots & \dots & \dots \\ \frac{u_n}{u_1} & \frac{u_n}{u_2} & \dots & 1 \end{bmatrix} \tag{2}$$

Where $u_1, u_2, \dots, u_n$ are the alternatives' weights and the decision-making matrix elements researched. In our case $d_{ij} = u_i/u_j$ values are perfectly known and if the relation (1) is satisfied, $\boldsymbol{D}$ is a consistent matrix and its rank is one because each row is a constant multiple of a given row. Consequentially, all its eigenvalues are zero except one with value equal to n and $u = (u_1, u_2, \dots, u_n)^T$ is the eigenvector associated with it. In a general decision-making problem, it may be difficult to provide exact values of u_i/u_j.

In these cases, it is possible to calculate a *consistency index* (*CI*) that measures the deviation of the judgment from the consistent approximation:

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{3}$$

This value is compared with a *random consistency index, RCI*, obtained as an average estimated based on a large number of pairwise comparison matrices of the same order. In this way, it is possible to calculate a *consistency ratio, CR*, as:

$$CR = \frac{CI}{RCI} \tag{4}$$

If this ratio is significantly small, the estimates of *u* can be considered reliable. In [20] is proposed an approach that allows to analyze the stability of a hierarchy when the judgments are randomly generated around a mean value. This study also shows that a consistency ratio of 10% is an acceptable upper bound.

F. *Options performances evaluation*

The performance index PI_i for each i-th alternative is obtained with the weighted sum method:

$$PI_i = \sum_{j=1}^{3} a_{ij} w_j \quad i = 1, 2, \dots, n \tag{5}$$

with a_{ij} generic element of the decision matrix and w_j weight of j-criterion.

G. *Ranking definition*

At the end of the procedure, the weighted ranking of the alternatives based on the performance index is obtained, individuating the most significant alternatives for the next steps of the method. In particular, a significance threshold φ is imposed at:

$$\varphi \geq \frac{1}{n} \tag{6}$$

Where *n* is the number of options.

III. CASE STUDY AND RESULTS

A. *Development options under study*

The proposed methodology is applied to the network developments included in the Italian NDP 2020 [21] of Terna, excluding:

1. Network developments under construction (foreseen in service by 2022);
2. Network developments which main infrastructure is yet in service;
3. Network developments on HV grid portions which do not have a remarkable impact on EHV grid connected;
4. EHV new substations involving an investment cost minor than 15 M€ [22], [23].

The application of these conditions leads to the selection of a set of 29 network developments. The binary combination of all the alternatives would determine a total of 406 options to be evaluated by means of the Saaty method, determined as $n \cdot (n-1)/2$, where n is the number of network developments. Such a large number of alternatives to be evaluated by the AHP method would involve a great computational effort and results would be too complex to be assessed by the DM. Therefore, a time constraint is adopted to reduce the number of significant options. In particular, a maximum of 2 years in advance and maximum of 5 year in delay of the network development entry into service date is assumed, as illustrated in Figure 2: only the flagged cells are analysed.

Year	Network Development	A	B	C	D	E	F
2022	A		x	x			
2025	B			x	x	x	
2027	C				x	x	
2030	D					x	x
2030	E						x
2033	F						

Legend
Possible Option: NO
x Possible Option: YES

Fig. 2. Exemple of alternatives selection on the basis of the entry into service date.

A further exclusion condition for the selection of significant combinations is identified according to the network developments' geographic location. The Figure 3 represents the Italian power system market structure configuration, therefore planned network developments affecting distant market zones (i.e. North and South, North and Sicily, etc.) can be considered independent of each other and consequently excluded from alternatives to be studied. Finally, the network developments having a local impact limited to one market zone are excluded from the study. After the application of all conditions mentioned above, the alternatives under consideration are reduced to 193. Therefore, the significance threshold φ is fixed at 0.0052.

Fig. 3. Present market zones configuration of the Italian power system.

B. Scenario under study

The network developments benefits evaluated in the policy scenario "National Climate Energy Plan" (NCEP), adopted in the last edition of the Italian NDP is considered in the application of the AHP method. It is a *development scenario*, or policy-driven scenario, designed to reflect the most recent requirements with regard to climate and energy target. The Figure 4 and the Figure 5 depict the national demand trend and the generation mix in Italy foreseen by the considered scenario [24], where it can be seen that both electrical consumption and renewable generation will significally increase. In Table III the assessment of NPV dominance of alternatives is listed. Since NPV dominance does not respect transitivity, the consistency analysis of relevant pairwise comparison matrices is carried out according to [13], obtaining the satisfactory value of CR equal to 2.6%, well below the maximum value of 10%.

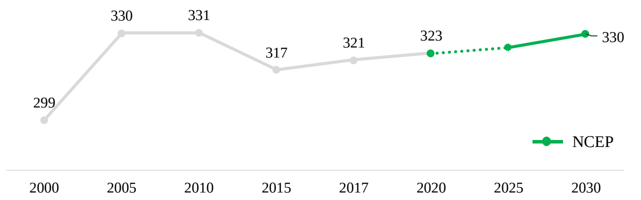

Fig. 4. Demand trend for Italy (TWh) in scenarios under study at 2030 year horizon.

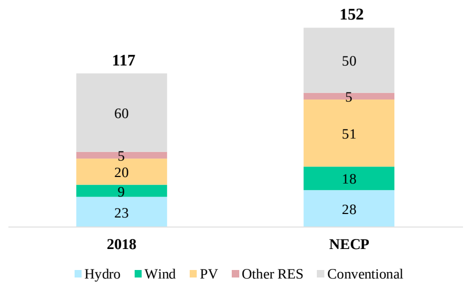

Fig. 5. Generation mix (GW) for Italy in scenarios under study at 2030 year horizon.

TABLE III. DOMINANCE SCALE FOR THE THIRD CRITERIION

ΔNPV (Alternative I-II) NCEP Scenario	Dominance
0 ≤ ΔNPV < 2500	1
2500 ≤ ΔNPV < 5000	3
5000 ≤ ΔNPV < 7500	5
7500 ≤ ΔNPV < 10000	7
ΔNPV ≥ 10000	9

C. Results

The application of Saaty method has allowed to identify the set of options to be evaluated throught market simulations. In the analysis, weighting factors w_j are considered equal to: w_1=0.6, w_2=0.3, w_3=0.1. This assumption represents a rational solution for the criteria balancing, in order to obtain a hierarchy in line with the objectives of the methodology. Therefore, it is assigned a higher priority to the level of interdependencies between the network development. In Table IV the analysed options which consist of combinations of development projects (a, b, c, d, e, f) falling within the market zones Sicily, Sardinia and Centre South are listed. The network developments "a" and "m" results the most relevant since the AHP method indicates them in a wide number of alternatives of interest. Moreover, the analysis leads to the selection of 51 alternatives passing the significance threshold.

TABLE IV. SELECTED OPTIONS AFTER MULTI-CRITERIA ANALYSIS

Options	Market Zone Involved	PI
a-b	Sicily – Sardinia – Centre South	0.025284
a-c	Sicily – Sardinia – Centre South	0.017361
a-d	Sicily – Sardinia – Centre South	0.014022
c-e	Sicily	0.013263
c-b	Sicily – Sardinia – Centre South	0.012716
c-f	Sicily	0.012716

Furthermore, the sensitivity analysis about different weights for criteria has been performed in order to evaluate the stability of results obtained. The Table V lists the different weights combinations (P_0, P_1, P_2) considered, while the selected options ranking variation resulting from their application is summarized in Table VI.

TABLE V. DIFFERENT CRITERIA WEIGHTS

	W_1	W_2	W_3
P_0	0.6	0.3	0.1
P_1	0.6	0.2	0.2
P_2	0.33	0.33	0.33

TABLE VI. SELECTED OPTIONS RANKING VARIATION

Option	*Ranking Position*		
	P_0	P_1	P_2
a-b	1°	1°	1°
a-c	2°	2°	2°
a-d	3°	3°	3°
c-e	4°	6°	15°
c-b	5°	4°	13°
c-f	6°	5°	14°

The results obtained using P_1 weights' set instead of the reference one P_0 are substantially aligned. The implementation of P_2 weights' set leads to a significant difference in performance indexes of last three options which decrese in 15°, 13° and 14° position respectively, due to the third criterion increased influence on the ranking, which promotes alternatives containing network developments with high NPVs.

Lastly, a set of 20 alternatives within the case study containing "a" and "m" network development are selected as the most subject to weights variations and relative performance indexes based on different criteria weights represented in Figure 6. It is clear as the performance indexes resulting from P_2 weights combination is mainly due to the economic aspects expressed by the NPV indicator, while the chosen P_0 criteria weights' set gives more relevance to the technical-functional aspects in the options comparison, aimed at meeting future power system needs.

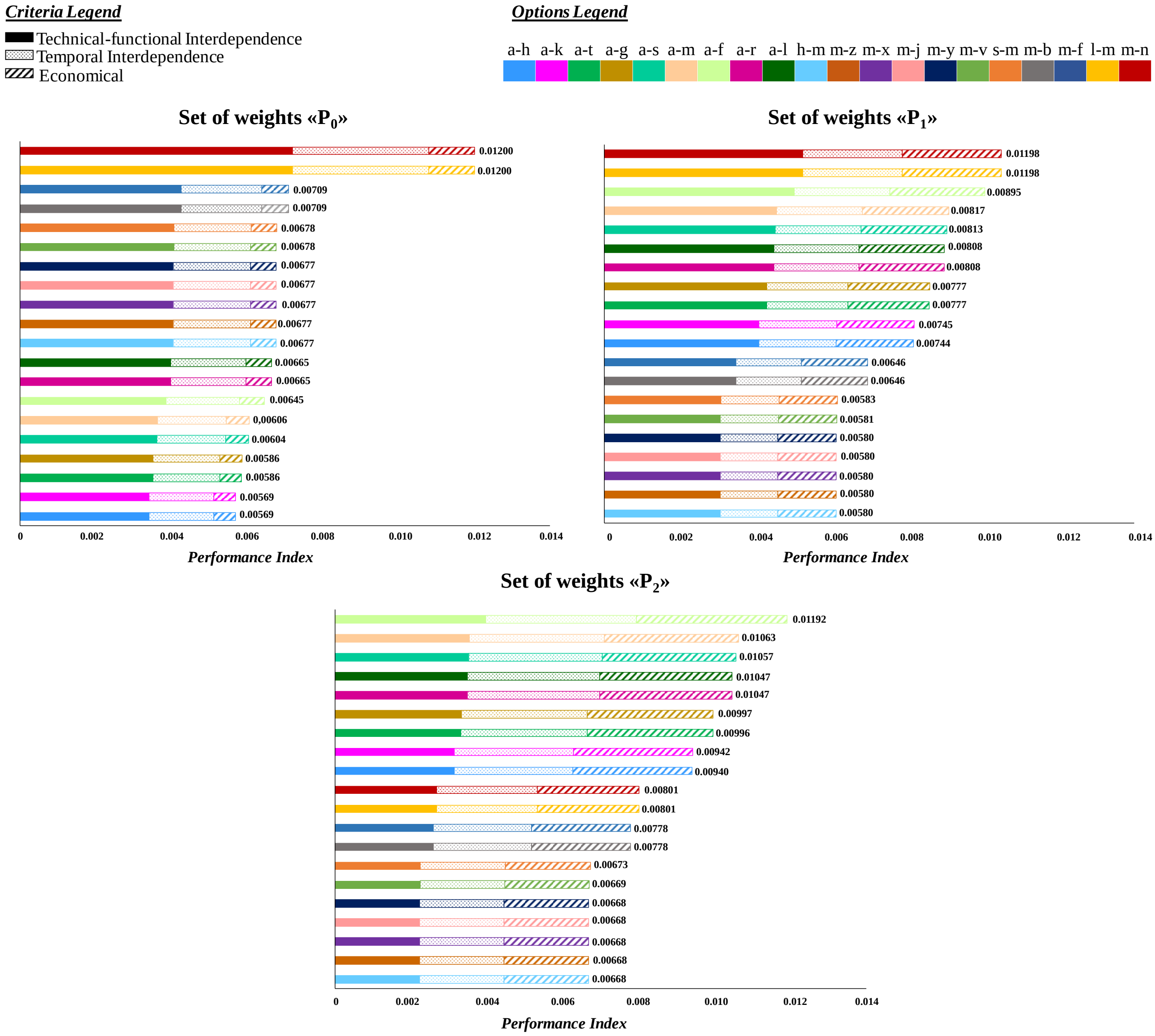

Fig. 6. Most relevant ranking variations in the different weights combinations.

IV. CONCLUSIONS

New methods are needed for an effective investment planning in future energy scenarios. This paper proposes a new methodology to perform a wide, coordinated and cost-effective evaluation of the planned projects. The method is based on multi-criteria selection of alternatives involving technical and economic aspects derived from the single cost benefit analysis; its performance has been tested on the Italian Transmission Network Development Plan considering the policy scenario. Results highlights the importance of some strategic projects, which are present in many significant alternatives, along with the influence that the different criteria weights have on the evaluations. In particular, the options showing the highest performance index involve the South of Italy and the main Islands, testifying the strong temporal, functional and technical interdipendency of relevant network development projects needed to enable a major RES penetration. The sensitivity analysis shows the strength of the first three options, which ranking positions remain unchanged. It also highlights the importance of criteria weights, whose choice by the decision makers is based on the key aspects of the specific transmission planning problem.

The results obtained from the application of the proposed method are relevant for network planners and regulators, enabling the consideration of simultaneous effect given by suitable pairs of network developments in terms of benefits for the entire power system rather than assessing the single projects one at time as required by the present CBA methodology. Robust development investment strategies for the TSO can be derived in the presence of an uncertain environment creating a rational ranking based on most relevant criteria weights.

Future work will focus on the assessment of the benefits of selected alternatives in different future energy scenarios, in order to advise policy makers on possible effects of advance or delay of planned projects.

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