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Strategic decision-making support for distribution system planning with flexibility alternatives

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ABSTRACT

The ongoing power system transformation requires rethinking the planning and operation practices of the different segments to accommodate the necessary changes and take advantage of the forthcoming opportunities. This paper concerns novel approaches for appraising initiatives involving the use of flexibility from grid-connected users. This paper proposes a Decision Theory based Multi-Criteria Cost-Benefit Analysis (DT-MCA-CBA) methodology for smart grid initiatives that capture the complexity of the distribution system planning activities in which flexibility competes with grid expansion. Based on international guidelines, the proposed DT-MCA-CBA methodology systematically assesses tangible and intangible impacts, considering multiple conflicting criteria. The DT-MCA-CBA methodology relies on a novel approach that combines MCA and Decision Theory to identify the most valuable option in a complex decision-making problem by modelling the stakeholder perspective with the MiniMax regret decision rule. The proposed DT-MCA-CBA methodology is applied to a comparative case study concerning four different approaches for distribution system planning. A web-based software which implements the proposed decision-making framework and the DT-MCA-CBA methodology is developed to provide a novel decision-making support tool for strategical smart distribution system planning.

1. Introduction

The electrification of final uses of energy (e.g., transportation and heating) represents one of the main actions towards decarbonisation if accompanied by green power generation through renewable energy sources (RES) [1]. The transition from fossil fuels to green electricity makes distribution networks pivotal since new loads and novel generation capacity will be directly installed to this grid, originally designed to be passive and crossed by unidirectional power flows [2]. Consequently, distribution network planning and operation have become increasingly complex due to flow reversals, line congestions, and voltage limit violations [3]. High electricity supply quality and reliability will require significant investments in the distribution system (e.g., more than € 400 billion by 2030) and substantial changes in the value chain of all parts of the distribution sector [4]. However, the required investments could be reduced using active distribution system planning approaches that include the operational flexibility offered by the distributed energy resources (DER), i.e., generators, flexible loads, static storage systems and electric vehicles [5]. The International Energy Agency identifies DER flexibility as a need to accelerate the power ongoing system transformation [6]. Flexibility provision represents a valuable alternative for avoiding or postponing network reinforcement to face the expected operational issues; to illustrate, the technical and economic impacts on distribution network planning of DER flexibility considering a portion of the Italian distribution system are studied in [7], the case of a real Portuguese distribution network is investigated in [8], and the distribution network planning with the use of demand response in typical Chinese distribution networks is addressed in [9]. As shown in the mentioned works, traditional network reinforcement and DER flexibility provision are competitive measures to achieve the distribution network operation goals; therefore, in distribution system planning activities, the two approaches need to be compared on a level playing field to ensure selecting the best option on a case-basis [10]. From the regulatory perspective, DER flexibility provision is considered a valuable alternative for avoiding or postponing network reinforcement to face the expected operational issues, as stated by the Council of European

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Nomenclature

ACER	European Union Agency for the Cooperation of Energy Regulators
AM	Active Management
BCR	Benefit-Cost Ratio
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
CCSD	Correlation Coefficient and the Standard Deviation
CEDEC	European Federation of Local and Regional Energy Companies
CIGRÉ	International Council on Large Electric Systems
CIRED	International Conference on Electricity Distribution
CRITIC	Criteria Importance Through Intercriteria Correlation
DER	Distributed Energy Resource
DG	Distributed Generation
DM	Decision Matrix
DSM	Demand Side Management
DSO	Distribution System Operator
DT	Decision Theory
DT-MCA-CBA	Decision Theory based Multi-Criteria Cost Benefit Analyses
EC	European Commission
E.DSO	European Distribution System Operators association
EV	Electric Vehicle
ENTSO-E	European Network of TSOs for Electricity
EPRI	Electric Power Research Institute
ESS	Energy Storage System
EU	European Union
FF	Fit and Forget
FSP	Flexibility Service Providers
GC	Generation Curtailment
GEODE	European Association of Local Energy Companies
HV	High Voltage
IP	Ideal Point
ISGAN	International Smart Grid Action Network
ISO	International Organization for Standardization
JRC	Joint Research Center
KPI	Key Performance Indicator
LV	Low Voltage
MCA	Multi-Criteria Analysis
MGD	Maximising the Generalized Deviation
MMR	MiniMax Regret
MV	Medium Voltage
NPV	Net Present Value
OPEX	Operational Expenditure
P	Active power
PP	Probabilistic Planning
PQ	Active and reactive power
PV	Photo Voltaic
Q	Reactive power
RES	Renewable Energy Sources
rTOTEX	Reduction of Total Expenditures
SaaS	Software as a Service
SD	Standard Deviation
SE	Shannon's Entropy
SO	System Operator
TOTEX	Total Expenditures
TSO	Transmission System Operator
WG	Working Group

Energy Regulators [11] and acknowledged by the ACER framework guideline for on demand response [12], aligned with the Clean Energy Package [13].

The mentioned regulation emphasises the need for network planning activities to consider on equal footing flexibility and traditional network reinforcement measures. Therefore, decision-making support tools that enable a fair assessment of the impacts of various actions are highly valuable for system operator network planners (at both transmission and distribution levels), regulatory bodies, and policymakers. These tools are especially relevant in planning activities where flexibility competes with traditional network reinforcement measures. Nevertheless, assessing the viability of using DERs to operate distribution networks is challenging since it requires comparing the expected long-term costs and benefits under significant uncertainty. Moreover, the involvement of new players in power system operation (e.g., DERs, flexibility service providers (FSPs), aggregators, EVs) and the strategic goals (i.e., climate and energy security) pursued require a new holistic approach to project appraisal. Thus, the only appraisal of the impacts on the electricity system is not sufficient to measure the socio-economic footprint of the initiatives impacting the entire energy system, economy, society, and earth [14]. However, a broader evaluation approach needs to include the non-monetary impacts (e.g., environmental impacts, impacts on health and the quality of life, social acceptance, technical impacts such as network capacity and connectivity availability, supply security and quality) [15], which traditional financial viability assessment tools, such as the CBA, do not account them adequately [16]. Moreover, exploiting flexibility from third-party resources means involving new stakeholders in the distribution system planning and operation; hence their viewpoint has to be considered in the decision-making process to comply with the customer-centric goals [1].

Different approaches have been proposed to identify, quantify, and account for non-monetary impacts in financial viability assessment tools. However, the equivalent monetary value of a non-monetary impact could be unreliable or even not obtainable for all the impacts due to the impact nature or lack of information [16]. In the context of the electricity sector, several international guidelines have been proposed for project assessment, JRC proposed general guidelines for smart grid projects [15] and specific guidelines for smart metering deployment [17]; which are based on the EPRI's guideline for estimating the costs and benefits of smart grid initiatives [18]; ENTSO-E developed a guideline for CBA to assess the projects, as established by the Regulation (EU) No 347/2013 [19]. These guidelines support the identification of monetary and non-monetary impacts and provide procedures to quantify and monetise the relevant non-monetary impacts. The guidelines recognise that not all non-monetary impacts can be included in the monetary viability assessment. Hence, several non-monetary impacts have to be evaluated aside using KPIs.

However, these guidelines lack a complete framework that systematically considers the outcome of both the monetary and non-monetary impact assessment, although this approach is explicitly recommended [20]. Moreover, the need for a project appraisal covering the widest perspective involving all stakeholder categories requires resorting to approaches that allow collecting the stakeholder preferences without introducing biases that distort the assessment outcomes.

In this context, the MCA methodologies (i.e., decision-making support tools based on systematic assessment approaches that allow selecting the best initiative considering multiple evaluation criteria to appraise the alternatives of a given set) provide a framework to appraise impacts expressed in quantitative and qualitative terms [21]. Therefore, MCA allows combining the assessment of monetary and non-monetary impacts caused by the electricity sector initiatives involving third-parties flexibility service providers [22]. Moreover, stakeholders play a fundamental role in MCA since their perspective is considered in several procedure steps [22]. MCA is also adopted as a planning support tool in various sectors (e.g., transportation, energy, environment) to enhance the representation of the sustainability aspects, as pointed out in [23,24], and [25] for transportation, in [26] for energy policies, in [22], in [27,28] for electric power distribution system and [29] for transmission system, in [29] for the gas sector, in [30] for the maritime sector, in [31] for biosecurity, and in [32] for water supply.

As discussed, CBA and MCA allow appraising investment initiatives. Financial CBA is an acknowledged and reliable tool to estimate the profitability of investments in the private sector [33]. However, it lacks reliability in decision-making problems involving non-monetary impacts, externalities, and multiple stakeholders [16]. MCA systematically evaluates conflicting criteria irrespective of their nature, allowing broadening the assessment [21]; however, it does not respect the Kaldor–Hicks criterion[1] [34,35], and it is not suitable for a strict monetary analysis [21]. Moreover, MCA allows multiple stakeholders' perspectives; nevertheless, if the stakeholder preferences' are not adequately collected and modelled, MCA assessment may lead to biased solutions for the decision-making problem [36].

CBA and MCA are not mutually exclusive; their joint use can relieve the respective gaps [23]. In some joint MCA-CBA approaches, the CBA focuses only on tangible impacts, whereas the MCA on intangible impacts. In other cases, a sequential procedure is used with the CBA or the MCA first filters the initial investment options. The best option is selected using the companion tool as proposed in [37] and shown in [30].

This paper proposes a decision-making framework that joins MCA and CBA to leverage the advantages of combining the two assessment tools. The proposed framework considers the CBA as the economic criterion of the overarching MCA. The proposed joint MCA-CBA decision-making framework is designed for smart grid project assessment since it follows the relevant international guidelines for addressing CBA, criteria selection, and performance quantification. Moreover, to outclass the criticalities of MCA in eliciting criteria relevance, the joint MCA-CBA framework in this paper is complemented by an innovative formulation of the decision-making problem that resorts Decision Theory (DT) to model the stakeholder behaviour. Hence, the proposed decision-support methodology combines the MCA, CBA, and DT decision-making approaches; hence, hereafter this paper refers to the proposed decision-making methodology as DT-MCA-CBA. Based on the MiniMax regret (MMR) rule[2] [38], the proposed DT-MCA-CBA methodology looks for the alternative that determines the least regret for the most sceptical stakeholder. Hence the identified solution represents the compromising alternative determining the lowest regret for the considered stakeholder audience.

The proposed joint MCA-CBA decision-making framework, exploiting the original DT-MCA-CBA methodology, aims to support analysts and decision-makers in the appraisal process. Indeed, in project selection problems, especially in the public sector, identifying the most convincing alternative is key to the success of the planning process. Thus, as recommended by the mentioned regulation, the proposed tool can be used by power system stakeholders (e.g., system operators network planners, regulatory bodies, and policy makers) to compare planning initiatives involving on a level playing field different technological solutions taking into account not only economical aspects but also externalities and smart grid transformation aspects. The research activity presented in this paper contributed to the International Smart Grid Action Network (ISGAN) activities devoted to developing tools for cost-benefit and socio-economic analyses of smart grids. A free-to-use software is available online at https://smartgrideval.unica.it/ to test the methodology and contribute to the design of smart grids. As the mentioned regulation highlights, it is of interest that network development plans ensure transparency and fair comparison of traditional network reinforcement and flexibility measures; making the software available online and free of cost is essential for encouraging the adoption of a common framework for project assessment and strategic decision-making.

The main contributions of this paper are summarised as follows:

a. The formalisation of a joint MCA-CBA decision-making framework inspired by international guidelines on smart grid project assessment,
b. The proposal of an innovative formulation for multicriteria decision-making based on Decision Theory that complements the joint MCA-CBA decision-making framework: the DT-MCA-CBA methodology,
c. The application of the proposed joint MCA-CBA decision-making framework with DT-MCA-CBA methodology to the planning activity of a realistic distribution network with a level playing field comparison of traditional network reinforcement and flexibility service provision measures, and
d. The development of the software version of the joint MCA-CBA decision-making framework with the DT-MCA-CBA methodology, under the aegis of ISGAN.

The paper is organised as follows. Section 2 introduces the problem of decision-making for power distribution system planning by describing the novel planning approaches and the relevance of decision-making tools, such as joint MCA-CBA frameworks, for identifying the best planning alternative. Then, Section 3 describes the DT-MCA-CBA methodology proposed in this paper. The formalised joint MCA-CBA decision-making framework with the DT-MCA-CBA methodology is applied to a case study considering a distribution network typical of the Italian distribution rural ambit in Section 4. Final remarks are provided in Section 5.

[1] The Kaldor–Hicks criterion [34,35] assumes that an initiative is desirable if the generated gains can compensate and outclass the losses; it states that an initiative is favourable if creates a net gain.

[2] The MiniMax regret rule is a decision-making approach assuming that decision makers choose the alternative that minimise the maximum regret from a suboptimal decision [38]. Regret is defined as the difference between the payoff received if the best alternative would have been chosen and the payoff received from the actual chosen alternative.

2. Decision-making for power system planning

2.1. Novel distribution system planning approaches

The traditional approach for distribution system planning, known as *Fit and Forget* (FF), aims at solving at the planning stage all possible network's limits violation (e.g., overvoltage or undervoltage conditions, cable thermal limit violation) using only network solutions (i.e. resizing of existing conductors and substation transformer and construction of new connections and substations) [3]. The FF network design is usually based on the deterministic assessment of the worst-case scenario (*maximum load demand* or *maximum generation - minimum demand* scenario). Therefore, FF leads to extreme network oversizing since it reduces the risk of network constraint violation to zero. In recent years, the deployment of DG, mainly fed by RES, characterised by an intrinsic uncertainty, and the increasing presence of energy-intensive loads (e.g., electric vehicles and heat pumps) changed the scenario in which the FF was formalised. Thus, the deterministic FF approach is not suitable due to the high costs it would lead [3].

Generally speaking, the distribution system's most severe scenarios (i.e., high generation with low peak consumption) are infrequent; therefore, huge network oversizing is avoided by accepting a relatively low risk of constraint violation. Expert working groups of technical associations and communities (e.g., CIGRÉ, CIRED) agree on the adoption of a modern approach in which the scenarios of generation and demand are characterised by a distribution probability that can be combined to obtain the probability of constraint violation [3]. Additionally, a minimum level of violation (residual risk) is accepted [7]. Also, they promote to abandon the idea of fixing all network issues at planning level by integrating progressively operational solutions exploiting the smart grid technologies improvement. Among the operational solutions, the use of DER flexibility (i.e., the capability of a generator to increase/decrease production or the availability of a load to reduce or postpone its energy demand) is considered a cost-effective alternative to network reinforcement that allows network investments reduction or deferral under increasing uncertainty. The importance of the integration of flexibility in distribution system planning is demonstrated by the noticeable documents released in the last few years [6,10,39]. The topic is analysed from different perspectives; in [39], four European distribution system operators DSOs associations (CEDEC, E.DSO for Smart Grids, Eurelectric, and GEODE) discuss how DSOs can use flexibility and contribute to the transition towards a more sustainable energy sector, also presenting a tool to operate their grids in a cost-efficient way. In [10], flexibility employment from the DSOs' point of view is analysed, investigating flexibility assessment procedure and regulatory approaches, and presenting some case studies from demonstration projects. In particular, in [10,39] possible schemes for the coordination of transmission and distribution system operators (TSOs, DSOs respectively) are discussed. In [6], particular attention is given to policies, regulatory frameworks and strategies to mitigate challenges to unlock system flexibility.

The introduction of flexibility requires the active operation of the distribution network; therefore, operational practices have to include, besides the traditional actions, the active management (AM) of the flexibility available from DG, loads, and energy storage systems (ESS) [3]. Recently DSOs, thanks also to the Clean Energy Package, have recognised the potential of such approach and started cooperating with the scientific community for developing suitable procedures and tools for innovating their distribution system planning approach, able to consider the abovementioned aspects [40]. This paper presents the assessment of the distribution system planning alternatives obtained by applying one of the new planning tools proposed in [41].

2.2. Decision-making for power system planning

Investment evaluation is a pillar of strategic management; ex-ante project appraisal aims to support the design of actions that best allocate scarce resources (e.g. capital, labour, land, water) [42]. The laws of economics are pivotal in determining the profitability of project initiatives [42]. However, the assessment of projects of social interest has to consider a range of impacts beyond the financial profitability [42], as also pointed out in JRC guidelines [15]. In general, the approaches for project appraisal can be classified considering the assessment perspective and the evaluated impacts, as shown in Fig. 1. The most restrictive assessment is the financial analysis that considers the investors' profitability only by contemplating monetary impacts [42], CBA is the most acknowledged tool for financial analysis [33]. The economic analysis broadens the scope by considering the national or societal viewpoint and assessing both direct and indirect monetary and monetisable impacts. Generally, a tool for economic analysis is known as Economic or Societal CBA [42]. MCA approaches represent a useful tool for simultaneously assessing quantitative and qualitative project impacts [15], MCA can be used for the widest project assessment, including soft effects and intangible non-monetisable impacts.

This paper proposes a decision-making approach combining CBA and MCA for assessing distribution expansion projects. The joint use of CBA and MCA aims to relieve the respective gaps by emphasising the strengths of each tool. Economic or Societal CBA is the assessment approach based on CBA in which non-monetary impacts are accounted for by relying on an ad-hoc procedure for calculating the monetary equivalent [21]. However, even if some corrective is adopted, CBA shows fundamental flaws in appraising initiatives with relevant externalities and societal impacts not always possible to quantify, monetise and discount with accuracy [16]. In recent years, the European Commission (EC) Joint Research Centre (JRC) developed a smart grid project appraisal framework based on CBA and a set of dedicated KPIs [15]. The JRC guidelines aim to support the local context analysis and the identification and monetisation costs and benefits [15], an example of local context analysis is provided in [43]. Furthermore, the JRC guidelines support identifying the relevant externalities and social impacts [15]. The JRC CBA guidelines represent a structured set of suggestions and a checklist for appraising the impact of smart grid initiatives [15]. At the European level, the relevance of an approach that broadens CBA, also considering non-monetary impacts, is recognised by the associations of TSOs of electric [19] and gas systems [29]. The guidelines released by these associations, in line with the relevant EU Regulation, devise a project assessment for planning initiatives concerning the transmission system that combines CBA and MCA. Several 'project level indicators' are defined to include non-monetary impacts (e.g., system safety and environmental impacts).

This paper's proposed decision-making framework relies on the JRC guidelines, the joint MCA-CBA decision-making framework proposed follows and completes the JRC recommendations formalising a comprehensive assessment approach that includes a mathematical model based on DT for identifying the solution to the decision-making problem.

3. Decision-making problems addressed using decision theory rules

3.1. Decision-making with MCA

Complex decision-making processes aim to identify the option that best satisfies several conflicting evaluation criteria. Problem complexity increases with the number of alternatives and

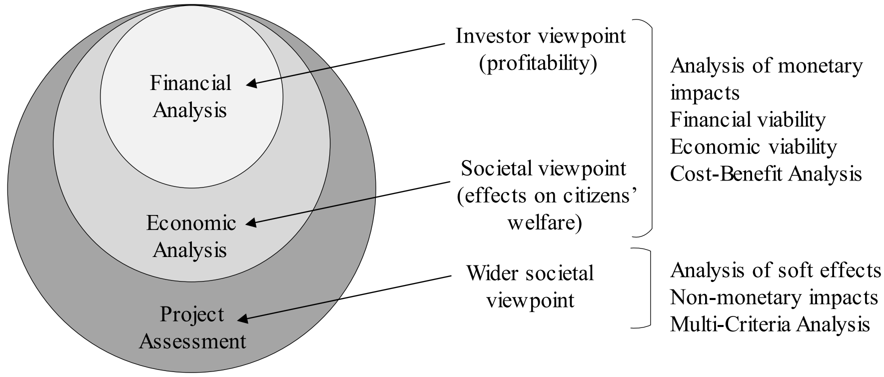

Fig. 1. Classification of project appraisal approaches.

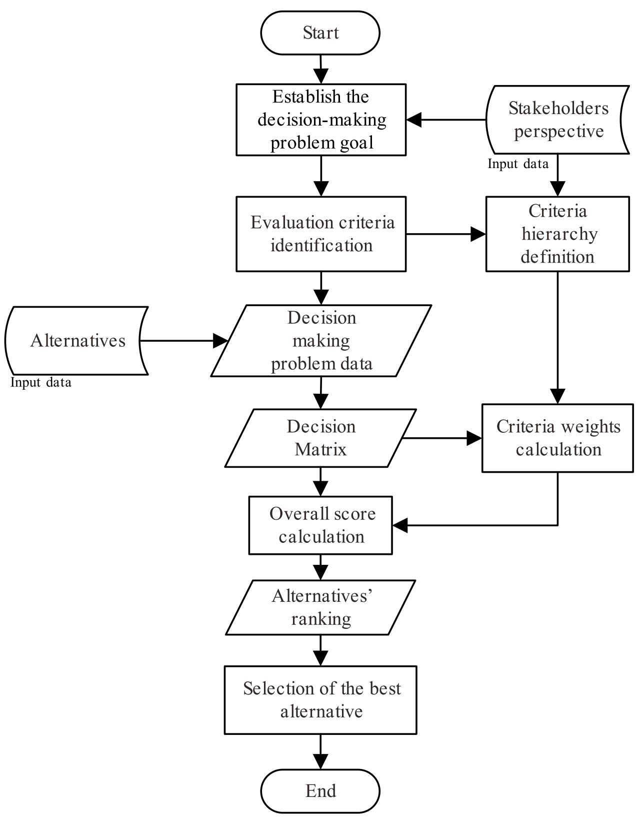

Fig. 2. Generalised process of MCA methodologies for decision-making.

criteria. MCA represents the systematic approach to decomposing decision-making problems into elementary problems that can be easily managed. Several methodologies have been proposed to support decision-makers in identifying the best option in an explicitly known set [21]. Different decision-making philosophies inspired the different MCA methodologies; hence, different methodologies applied to the same decision-making problem may provide different outcomes [21]. Fig. 2 depicts the flowchart of a generalised process of MCA methodologies for decision-making. A detailed description of the fundamentals of the MCA methodologies is available in [21,44]; however, for completeness, the key aspects of MCA methodologies are mentioned in this section. As shown in Fig. 2, the information required as input for the decision-making process is formed by the set of alternatives to be assessed and the stakeholders' perspective to set up the decision-making goals and the related evaluation criteria. The key process of a decision-making addressed with MCA methodologies are:

1. Identification of evaluation criteria and criteria hierarchy definition.
2. Collection of information on the options and decision matrix building.
3. Definition of the criteria relevance and calculation of criteria weights.
4. Calculation of the overall score of the alternatives.

The *evaluation criteria identification* depends on the decision-making problem scope and the relevant aspects for evaluating the options. The principles of discrimination, confidence, and uniqueness must guide the criteria selection and definition. The *Criteria hierarchy* is the structure that organises the criteria of the decision-making problem. The *decision matrix* contains the relevant information on the options; its entries are the attribute values of each option concerning the evaluation criteria. The *Criteria weights* are the numerical values that model the relevance of each evaluation criterion in the context of the specific decision-making problem. The definition of criteria weights is momentous since the strong influence on the analysis outcome. Calculating the overall evaluation of project alternatives requires as input *decision matrix* and *criteria weights* calculated based on the *criteria hierarchy* [21]. The result indicates the best option among the set or a complete options rank. Several calculation techniques have been proposed in literature classified into three families: (i) full aggregation approaches, (ii) outranking approaches, and (iii) goal, aspiration, or reference level approaches [44]. Typically, most MCA methodologies provide the outcome based on a single set of criteria weights. Several techniques have been proposed to address criteria weighting systematically. Criteria weighting techniques are classified into three families: subjective, objective (or synthetic), and integrated (or hybrid) [45]. *Subjective* techniques define criteria weights on stakeholder preferences collected explicitly (e.g., Saaty's method [46], trade-off method [47], swing method [47], resistance to change method [47]) or implicitly (e.g., ordinal ranking [36], rank sum, rank reciprocal, rank exponent methods [48], rank order centroid method [48–50]). The main advantage of subjective techniques is the direct involvement of the stakeholder in the decision-making problem. However, subjective techniques have a high cognitive burden and introduce high subjectivity; personal biases can negatively influence the decision-making problem solution. Moreover, partial or incomplete information in verbal, sorting or numerical form allows to deduce the criteria relevance given a share of uncertainty [51]. To reject the subjectivity from criteria weight elicitation, the objective of synthetic techniques (e.g., Shannon's entropy method [50,52], standard deviation method [53], statistical variance method [54], CRITIC method [53]) is to determine criteria weights from the entries of the decision matrix. However, the exclusion of stakeholders may lead to unsatisfactory and disappointing solutions. Integrated, or hybrid, techniques calculate criteria weights using optimisation models that integrate subjective and objective information (e.g., correlation coefficient and the standard deviation (CCSD) method [55], Ideal Point (IP) method [56], method of maximising the deviation of attributes [57], maximising the generalised deviation (MGD) method [58]. They relieve the shortcoming of objective techniques; however, integrated techniques may lead to unsatisfactory and disappointing solutions since they are not designed to model the stakeholder perspectives but to maximise or minimise a numerical feature of the options set (e.g., distance, standard deviation).

To outclass the shortcomings of the traditional methodologies discussed in this section, this paper proposes a novel approach for MCA that models the stakeholder audience behaviour by an objective function based on the MMR rule [38]. The MMR rule is suitable for risk-averse decision-makers to avoid the worst-case scenario, it makes the MMR rule appealing for decision-making in power system planning activities.

3.2. The proposed joint MCA-CBA framework and DT-MCA-CBA methodology for decision-making

The proposed joint MCA-CBA decision-making framework follows the general approach of MCA in Fig. 2, having the goal of facing the decision-making problem of identifying the most valuable smart grid planning initiative considering climate goals and the path established for the transformation of the energy and electricity sectors; moreover, the proposed framework relies on the JRC guidelines for decision-making problem formulation [15] and criteria selection [20]. Moreover, this paper complements the proposed joint MCA-CBA framework with an MCA methodology based on a decision rule from DT to model the stakeholder audience behaviour with the aim of outclassing the shortcomings of traditional weighting techniques in MCA methodologies. Among the examined DT rules available in the literature [59,60], the MiniMax Regret (MMR), proposed in [38], has proven to fit with decision-making based on MCA [45]; thence, it is exploited for the optimisation model of the proposed DT-MCA-CBA methodology. Therefore, the DT-MCA-CBA methodology proposed in this paper aims to identify the alternative that minimises the maximum regret the stakeholder audience feels due to a suboptimal decision. The MMR is an acknowledged approach widely applied in industrial decision-making [61]. MMR identifies the option leading to the least maximum regret for the stakeholders in the worst possible scenario, as proposed in [62] and complemented [63] and adopted in [64]. Given a scenario, a stakeholder feels regret when the action that has been selected brings fewer benefits than those that an alternative action in the initial set would have produced. The MMR approach aims at identifying the alternative that minimises the maximum regret that could be felt considering all possible scenarios. In this paper, to provide the proof of concept of the proposed DT-MCA-CBA methodology, the decision-making problem formalised according to the MCA-CBA framework is studied by applying the proposed DT-MCA-CBA methodology and MCA-CBA methodologies based on traditional MCA techniques. Fig. 3 depicts the flowchart of the procedures for the decision-making methodologies adopted in this paper, Fig. 3 particularises the procedure in Fig. 2 for the case of decision-making problems formalised according to the joint MCA-CBA framework. Fig. 3a depicts the procedure of the MCA-CBA methodology based on traditional MCA techniques based on subjective, objective (or synthetic), or integrated (or hybrid) weighting, as described in Section 3.1. Fig. 3b depicts the procedure of the DT-MCA-CBA methodology proposed in this paper. As shown in Fig. 3b, the DT-MCA-CBA methodology is characterised by the absence of a weighting stage and the use of the MMR optimisation algorithm instead of the overall score calculation stage. Hence, in comparison to the MCA-CBA methodology in Fig. 3a, the original DT-MCA-CBA methodology in Fig. 3b proposed in this paper is characterised by the blocks “Boundaries for criteria weight value”, “MMR optimisation algorithm”. Additionally, the DT-MCA-CBA methodology utilises an ascending sorting order based on the maximum regret value to rank the alternatives and select the one with the lowest value. Therefore, the best alternative is selected considering the one with the lowest maximum regret value instead of considering the one with the highest overall score. The processes concerning those blocks are part of the MMR optimisation model and algorithm described in Section 3.3.

Differently from traditional MCA methodologies as the ones that can be adopted for the procedure in Fig. 3a, the proposed DT-MCA-CBA methodology in Fig. 3b does not rely on a single weight vector that misrepresents the stakeholders’ viewpoint, but it adopts an optimisation model that reflects a common stakeholder attitude. The solution is obtained using the MMR optimisation model which explores the weight space of the decision-making problem defined by the stakeholder audience’s preferences. These preferences represent information that can be collected with a low cognitive burden, as it is boundaries for weight values instead of exact values for each criterion weight.

The presented joint MCA-CBA decision-making framework with the related DT-MCA-CBA methodology is a support tool for analysts, policy makers, Regulators, and TSO and DSO planners that need to assess by comparison different planning initiatives. The decision support tool is designed to be applied to any initiative involving power system planning; hence, it is replicable to different contexts by identifying the relevant goal, stakeholders, evaluation criteria, and alternatives. Moreover, it implements an output-based assessment that ensures its scalability. In fact, the definition of adequate criteria allows the fair assessment of any technology. Moreover, in principle, there is no limit to the number of evaluation criteria or alternatives that can be identified. Additionally, the presented decision-making support tool can be applied to planning initiatives of any scale, from local to regional, making it a truly scalable solution.

3.3. MMR optimisation model and algorithm for the DT-MCA-CBA methodology

In this section, the proposed correlation between MCA and Decision Theory formulations and the DT-MCA-CBA mathematical formulation are described using a lowercase italic type font for variables, parameters, running numbers as scalars (i.e., $x_{i,j}$ or x), lowercase bold italic type font for vectors (i.e., $\boldsymbol{x_i}$), uppercase italic font for sets (i.e., X), and lowercase italic font for functions without a space between the function symbol and the parenthesis containing the argument, as defined in the ISO 80000-2:2019(en) standard [65].

MCA and DT involve the decision matrix as an element of the decision-making problem modelling [59]. Considering a generic decision-making problem, characterised by a set S of scenarios, in the DT, the decision matrix describes the finite set A of feasible actions in terms of the corresponding elementary consequences to the state of nature [59]. The utility of an action is the overall effect related to the corresponding consequences in a scenario belonging to the set S. Hence, the utility $u_{i,k}$ of the ith action $\boldsymbol{a_i}$

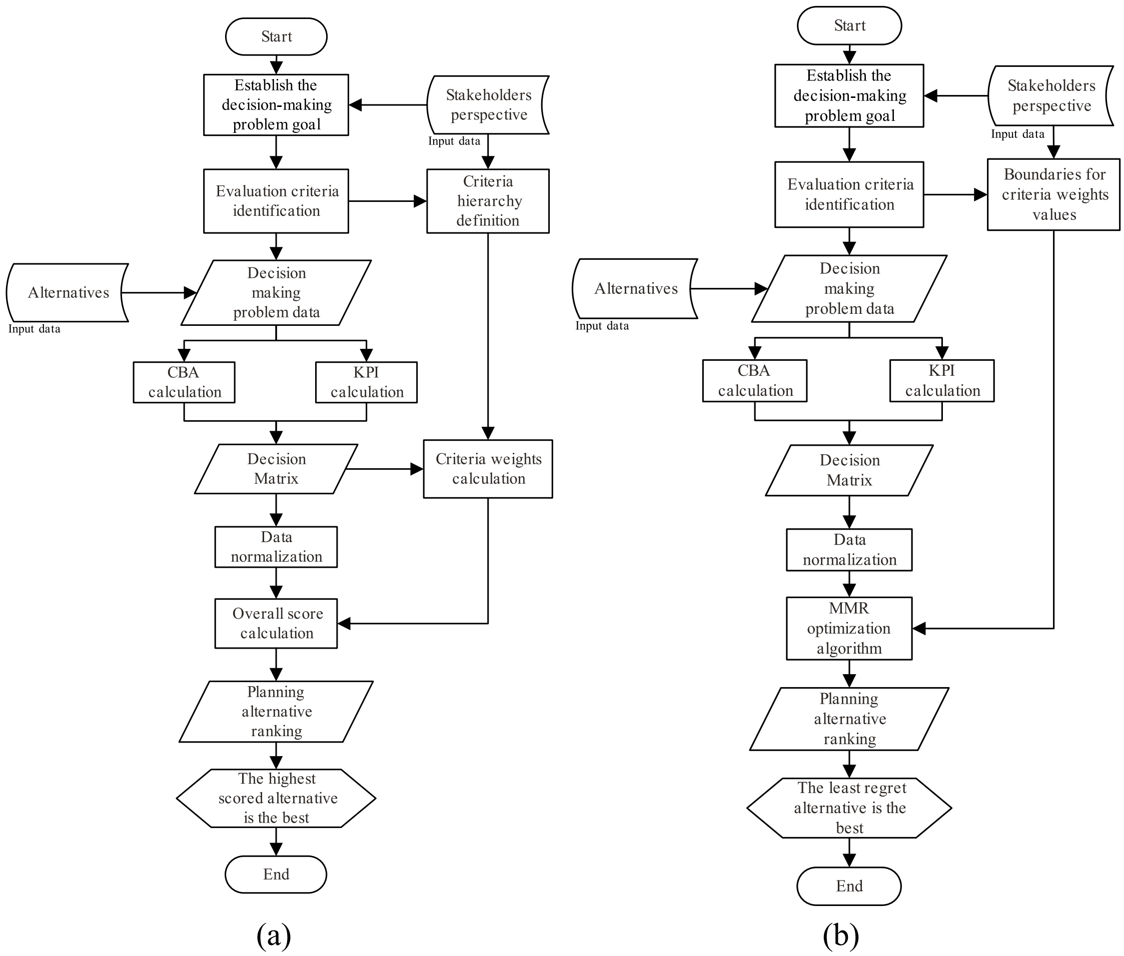

Fig. 3. Process of MCA methodologies for the joint MCA-CBA decision-making framework. (a) MCA-CBA methodology; (b) proposed DT-MCA-CBA methodology.

can be modelled as a real function measuring the value of the action's consequences in the kth scenario, as defined in (1).

$$u_{i,k} = f_k(\boldsymbol{a_i}) \tag{1}$$

Given the kth scenario, given two actions $\boldsymbol{a_i}$ and $\boldsymbol{a_h}$, the regret $r_{i,h,k}$ between them is quantified as the difference between their respective utilities $u_{i,k}$ and $u_{h,k}$ (2) [59].

$$r_{i,h,k} = u_{i,k} - u_{h,k} \tag{2}$$

The decision-making methodology presented in this paper considers the set A of feasible actions coinciding with the set of MCA-CBA alternatives. The mathematical model of the proposed methodology is described as follows. The decision-making problem comprises a set A of n alternatives and a set C of m criteria. The generic ith action is represented by the vector $\boldsymbol{a_i} = (a_{1,i}, \ldots, a_{m,i})$ of the attributes (i.e., the consequences) concerning the m criteria of the multicriteria problem. Hence, each alternative is described by a row vector $\boldsymbol{a_i}$ which the generic entry $a_{i,j}$ is the attribute of the ith alternative considering the jth criterion. The decision matrix of the decision problem is formed by the row vectors of all the alternatives. To ensure commensurability of the attributes corresponding to different criteria, the decision matrix is normalised to obtain the normalised decision-matrix in which all the entries belong to the interval [0, 1], the entry $z_{i,j}$ is the normalised attribute of the ith alternative concerning the jth criterion [52]. The decision-making model defined according to the MCA methods typically requires the explicit definition of the evaluation criteria weights [22]; a weigh vector defines a scenario that model a specific stakeholders' points of view. Therefore, for generality, the proposed decision-making methodology considers the decision-making problem characterised by a set of S scenarios, in which the vector $\boldsymbol{w_k} = (w_{1,k}, \ldots, w_{m,k})$ of criteria weights models the kth scenario in terms of the evaluation criteria relevance, $w_{j,k}$ is the weight of the jth criterion in the kth scenario, each kth weight vector has to satisfy (3).

$$\begin{cases} \left\{\forall w_{k,j} \in \mathbb{R} | w_{k,j} \geq 0\right\} \\ \displaystyle\sum_{i=1}^{m} w_{i,k} = 1 \end{cases} \tag{3}$$

A linear additive model is considered a utility function of alternatives, as proposed in [44]; hence, $u_{i,k}$ is the utility of the ith alternative in the kth scenario as defined in (4).

$$u_{i,k} = \sum_{j=1}^{m} w_{j,k} z_{i,j} \tag{4}$$

Finally, the proposed optimisation model based on the MMR decision rule is defined by (5). The optimisation model in (5) identifies the alternative of set A that minimises the maximum regret considering the feasible weight space.

$$\min_{\substack{i \\ i=1,\dots,n}} \max_{\substack{k \\ k=1,\dots,s}} \left\{ r_{i,k} \right\} = \min_{\substack{i \\ i=1,\dots,n}} \max_{\substack{k \\ k=1,\dots,s}} \left\{ \left[\max_{\substack{t \\ t=1,\dots,n}} \left(\sum_{j=1}^{m} w_{j,k} z_{t,j} \right) - \sum_{j=1}^{m} w_{j,k} z_{i,j} \right] \right\}$$
$$\text{such that} \begin{cases} \forall w_{k,j} \in [0, 1] \\ \sum_{j=1}^{m} w_{k,j} = 1 \\ \forall w_{k,j} \in Q \end{cases} \tag{5}$$

$r_{i,k}$ is the maximum regret of the ith alternative in the kth scenario, and Q is the set of additional constraints for the values of criteria weights. This set of constraints represents the peculiar viewpoint of the stakeholders involved in the decision-making problem.

The decision-making problem modelled by the decision rule in (5) allows identifying the alternative that achieves the least regret in the stakeholder audience considered in the decision-making problem. Hence, it represents the compromise solution that least displeases all involved stakeholders. In the context of the decision-making for project assessment applied to the smart grids, it is of the greatest interest to identify the alternative that achieves satisfactory acceptance for all stakeholders. On the contrary, identifying an alternative suitable only for a niche is of little interest. To this aim, the proposed DT-MCA-CBA methodology models the stakeholder audience behaviour using a DT rule; the MMR rule used reflects a risk-averse behaviour that can be adopted in strategic decision-making where overly pessimistic and optimisation attitudes need to be mitigated.

In this paper, the proposed DT-MCA-CBA methodology based on the MMR decision rule in (5) assumes as unknown variables the criteria weights; therefore, the set of possible stakeholders' scenarios is not *a priori* known.

The objective function (5) of the DT-MCA-CBA methodology is not linear in the weight space due to the first term; however, it is continuous within weight value intervals in which the alternative with the highest utility score does not change; and the problem constraints are linear. The algorithm used to solve the optimisation model involves three main steps: initialisation, maximisation, and selection. The initialisation process identifies the starting point for the optimisation process, the maximisation process maximises the inner term of the objective function, and the selection process selects the alternative achieving the minimum value of maximum regret as the solution to the optimisation problem. The Interior Point method has been used to solve the minimisation problem within the Python environment [66]. A software implementing the joint MCA-CBA decision-making framework and the DT-MCA-CBA methodology has been developed using a Software as a Service (SaaS) architecture for maximum interoperability, with a modular structure comprising the front-end, back-end, and calculation engine. The software is available at: https://smartgrideval.unica.it/.

4. Case study

The proposed case study provides the proof of concept of the joint MCA-CBA decision-making framework proposed in Section 3. Moreover, the case study described in this section aims to validate the application of the DT-MCA-CBA methodology by means of a decision-making problem containing a clear superior alternative. The presented case study uses as input the planning approaches comparison and results in [41]. In the following, the main hypothesis and the result are briefly proposed for the reader's convenience.

4.1. The network under analysis

In [41], a Medium Voltage (MV) distribution network representative of the rural Italian context, connected to the transmission system through a 25 MVA HV/MV transformer is analysed. As represented in Fig. 4, the MV grid is formed by 7 feeders and 102 busses to feed 16 MV loads and 175 LV networks through MV/LV secondary substations. The MV network is characterised by medium-length overhead power lines with modest cross-sections, especially in the lateral branches. More details on the network characteristics are provided in Appendix. A planning horizon of 10 years is assumed for calculations. As described in [41], the expected future scenario, based on the Italian National Energy and Climate Plan, estimates a 150% growth in generation (only PV are considered) and an average of 2% per year in consumption.

The high presence of PV generators, in combination with a low load density, leads to daytime overvoltage and power congestion (peak of PV production). On the contrary, at the peak of demand in the evening, frequent voltage drops are frequent due to the combination of electrification and weak overhead lines. In case of faults, when back-end supply is used, lines can be as long as 40 km exacerbating the voltage regulation issues.

4.2. Devised planning options

The case study compares four realistic planning options (defined in [41]) considering different distribution system planning methodologies, starting from the more traditional approach (based on worst-case scenario analysis and considering only network reinforcement solutions) to the modern one (considering the exploitation of DERs flexibility and the evaluation of risk) according to CIGRÉ WG C6.19 [3]. More in detail, the planning options considered in [41] are:

(A1) Traditional Fit and Forget philosophy (FF case):
Only traditional network reinforcement measures are considered with a deterministic approach (worst-case analysis).

(A2) Probabilistic approach with passive network management:
Only traditional network reinforcement measures are considered but the probabilistic network calculation and the assessment of technical constraints violation risk is performed.

(A3) Active management of ESS (500 kW, 4000 kWh) without control of any DG:
Traditional network reinforcement measures and EES operation are included according to a probabilistic network calculation approach, as in A2 option.

(A4) Active management of DERs (both active and reactive power):
Traditional network reinforcement measures and active management of DG and demand (i.e., generation curtailment and load shedding) are included using a probabilistic network calculation approach, as in A2 option.

Table 1 summarises the main characteristics of the planning methodologies considered in this paper as defined in [41].

This paper focuses on the assessment of a set of already formalised planning alternatives according to the proposed joint MCA-CBA decision-making framework and the DT-MCA-CBA

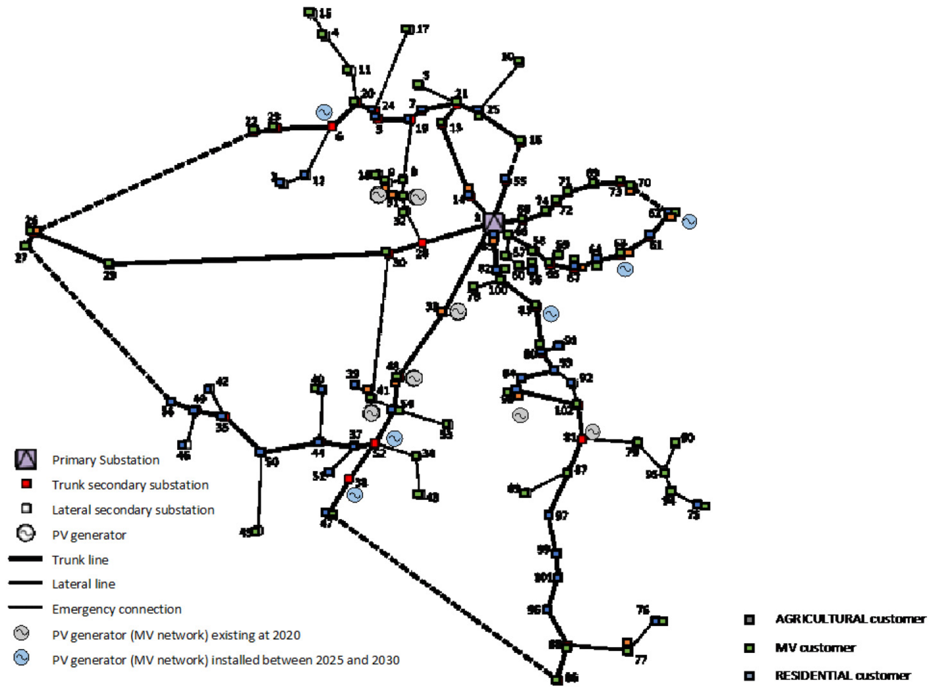

Fig. 4. The rural distribution network of the case study [41].

Table 1
Summary of the characteristics of the planning approaches adopted.

Planning option ID		A1	A2	A3	A4
Description		FF	PP	A2 + ESS	A2 + PQ control and DSM
Management of uncertainties		Deterministic	Probabilistic	Probabilistic	Probabilistic
Risk of network constraint violation accepted		No	Yes	Yes	Yes
Planning actions	Network reinforcement	Yes	Yes	Yes	Yes
	DSO's ESS	No	No	Yes	No
	Generators (i.e., generation curtailment and reactive power support)	No	No	No	Yes
	Flexible demand (i.e., load shedding)	No	No	No	Yes

methodology. Hence, a detailed description of the planning methodologies used to design this set of alternatives and the characteristics of the resources involved is out of this paper's scope; further details are available in [41]. However, it is worth mentioning that all the planning options devised in [41] are obtained considering an objective function involving the minimisation of network investment costs, discounted at the beginning of the planning period. Network losses are calculated afterwards on the obtained final network. Moreover, the planning alternatives, devised in [41] and used in this paper as input for the joint MCA-CBA decision-making framework and the DT-MCA-CBA methodology, do not include awards and penalties related to service quality. Also, the considered investments do not include those related to the ageing of components, but only those attributable to technical constraints violation due to load growth and/or the emergence of generation in the study period. In calculating discounted values, for simplicity, economic rates are assumed constant throughout the study period.

For simplicity, the planning activity in [41] focus only on the distribution system; hence the planning alternatives with flexible loads and generators only consider their contribution to solve the distribution network constraint violations; therefore, no value-staking (e.g., due to the additional provision of other services, as the balancing service) is considered. Since the set of alternatives is a piece of input information for the joint MCA-CBA decision-making framework and the DT-MCA-CBA methodology presented in this paper, value-staking impacts are not included in the alternatives' assessment. However, the decision-making support tool presented in this paper can consider value-staking impacts by defining appropriate criteria in all the cases in which the planning alternative includes this aspect.

The reference case A1 (the traditional FF approach) lead to the most expensive solution since new lines are needed to connect some nodes directly to the primary substation, allowing a better distribution of power flows in the grid and limiting currents and voltage regulation issues.

With the probabilistic approach (alternative A2), accepting the risk of a constraint violation, a 70% CAPEX reduction is allowed (compared to A1). There is a relatively low residual risk, equivalent to the possibility of overvoltage events for a maximum of 4.5 h/year, that does not jeopardise the performance of the electricity system since the most extreme operating conditions have a low probability.

Table 2
Expected capital and operating costs of the planning options.

CAPEX, OPEX and Benefits		Only traditional network reinforcement	Traditional network reinforcement and flexibility		
		Deterministic	Probabilistic with the accepted risk of constraints violation		
		A1 (Reference)	A2	A3	A4
$CAPEX_{MV}$	CAPEX for MV reinforcements [k€]	32 062.1	9579.8	7930.5	3169
$CAPEX_{LV}$	CAPEX for LV reinforcements [k€]	323.9	136	166	69.6
$CAPEX_{ESS}$	CAPEX for ESS [k€]	0	0	20 403.2	0
CAPEX	CAPEX for network investments [k€]	32 386	9715.8	28 499.7	3238.6
$OPEX_{MV}$	OPEX for flexibility in MV [k€]	0	0	0	980.1
$OPEX_{LV}$	OPEX for flexibility in LV [k€]	0	0	0	963
TOTEX	Total expenditures ($CAPEX + OPEX_{MV} + OPEX_{LV}$) [k€]	32 386	9715.8	28 499.7	5181.7
rCAPEX	Reduction of *CAPEX* with respect to Reference [k€]	0	22 670.2	3886.3	29 147.4
rTOTEX	Reduction of *TOTEX* with respect to Reference [k€]	0	22 670.2	3886.3	27 204.3
$OPEX_L$	Cost of Losses [k€]	1151.1	1556.1	1598.8	1725.9
COST	Total planning costs ($TOTEX + OPEX_L$) (Monetary Costs) [k€]	33 537.1	11 271.9	30 098.5	6907.6
$rOPEX_L$	Reduction of $OPEX_L$ with respect to Reference [k€]	0	−405	−447.6	−574.8
rCOST	Reduction of *COST* with respect to Reference (Monetary Benefits) [k€]	0	22 265.2	3438.6	26 629.5
BCR	Benefit-Cost Ratio ($rCOST/COST$)	0.00	1.98	0.11	3.86
NPV	Net Present Value [k€]	−33 537.1	11 803.3	−5361.3	22 814.6

However, the network issues fixed with a high investment with A1 and A2 approaches can be addressed by exploiting the DER flexibility [41], as shown by A3 and A4. The A3 option is characterised by 12 ESS positioned in the trunk nodes (Fig. 4). In the design of A3, [41] considers all ESS owned by the DSO, hence there are not payments related to the procurement of flexibility from ESS. Also, the OPEX related to the energy exchange and the corresponding losses, since considered of relatively small entity, are neglected. The active management of ESS reduces the contingencies (mainly overvoltage) by absorbing the energy produced by the local PV generation in the central hours of the day and injecting reactive power. Consequently, despite the ESS's high investment cost, the network planning CAPEX decreases, the amount of the avoided network investments is larger than the ESS CAPEX, due to the design assumption in [41], the cost of procurement flexibility from ESS is expected negligible since considered as a fully integrated network component (as prescribed in [13]); hence, such cost would be equivalent to the energy losses incurred due to the charging and discharging of the ESS and the possible residual net value of the energy exchanged by the ESS. The A4 planning option admits using DERs flexibility (still adopting a probabilistic network calculation approach). Control of the DG active (i.e., generation curtailment) and reactive power exchange allows for eliminating some voltage regulation problems and power congestion that occur at times of maximum irradiation, particularly when back-end reconfigurations are used due to faults. The need for flexibility is limited to infrequent operational situations (i.e., particular grid emergency configurations due to power lines' maintenance during the central hours of the day).

4.3. CBA results

The monetary impacts of the four planning alternatives are assessed through a financial CBA that complies with the Italian Regulator's guidelines for distribution system planning, as described in [41]. According to the assumptions adopted in [41] to design the planning alternatives, this paper considers only the expenditures caused by network constraint violations, neglecting those related to the ageing of components and awards and penalties related to service quality. Table 2 presents the financial CBA of the planning alternative devised in [41] considering 10 years for the planning horizon, 40 years of asset service life, and a 4% discounting rate.

4.4. DT-MCA-CBA results and discussion

In this section, the results of the extension of the CBA using the joint MCA-CBA decision-making framework presented in Section 3 are discussed. The monetary impacts in Table 2 assessed through the financial CBA consider only the DSO point of view [41]. The proposed joint MCA-CBA decision-making framework extends the financial CBA appraisal, including tangible and intangible impacts relevant to the societal perspective. The CBA extension is addressed using different MCA methodologies: the proposed DT-MCA-CBA methodology (described in Section 3.2) is compared to MCA methodologies based on subjective, objectives, and integrated weighting techniques. The relevant evaluation criteria selected for applying the joint MCA-CBA decision-making framework to the case study of this paper are economic, smart grid transformation, and externalities. The criteria for evaluating the impacts of the smart grid transformation and externalities have been defined according to JRC guidelines [15]. Concerning externalities, the preliminary set of possible criteria applicable to the decision problem was analysed considering the information on the impacts of each planning alternative to select the most representative set of externalities criteria to be included in the analysis. The criteria selected for this paper's case study and their formulas are reported in Table 4, all quantities in the formulas are real numbers, and definitions are reported below Table 4. Moreover, Table 4 provides information on the criterion direction considered in this study: "Maximizing" means that the option that achieves the highest value better performs for the corresponding KPIs, contrariwise, "Minimizing" means that the option that achieves the lowest value better performs for the corresponding KPIs. Table 4 is the decision matrix of the decision-making problem; while Fig. 5 depicts the its structure. The hierarchical structure in Fig. 5 is obtained by selecting the criteria proposed by the JRC guidelines relevant to the case study as proposed in [15] and updated in [20]. Different colours are used to distinguish the three branches (light blue for the economic branch, light orange for the smart grid branch and light grey for the externalities) and the nine KPIs considered.

In Table 3, *rTOTEX* is the reduction of the *TOTEX* related to network investments and acquisition of flexibility as defined in Table 2. n_y is the number of years in the planning period, n_{DG} is the number of controllable distributed generators, n_h is the number of time intervals of 1-h length in the planning period, n_L is the number of controllable loads, n_{ESS} number of controllable ESS, n_c

Table 3
Description and formulation of the KPIs of the decision-making problem.

KPI	Description	Evaluation metric	Criterion direction	Formula
rTOTEX	Reduction of TOTEX	Reduction of TOTEX [k€]	Maximising	$rTOTEX_i = TOTEX_{REF} - TOTEX_i$
KPI_{A1}	Energy not withdrawn from DERs	Total energy curtailed from DERs during the planning horizon [GWh/y]	Minimising	$KPI_{A1} = \frac{1}{n_y}\sum_{i=1}^{n_{DG}}\sum_{h=1}^{n_h} e_i^{(h)}$
KPI_{A2}	CosPhi	Average power factor ($\cos\phi$) at the HV/MV interface [–]	Maximising	$KPI_{A2} = \frac{1}{n_h}\sum_{h=1}^{n_h} \cos\phi_I$
KPI_{B1}	Operational flexibility	Power capacity of controllable DG, loads, and ESS [kW]	Maximising	$KPI_{B1} = \sum_{i=1}^{n_{DG}} p_i + \sum_{j=1}^{n_L} p_j + \sum_{k=1}^{n_{ESS}} p_k$
KPI_{C1}	System stability risk	Residual risk of network constraints violation [h/year]	Minimising	$KPI_{C1} = \frac{1}{n_y}\sum_{i=1}^{n_c}\sum_{h=1}^{n_h} c_i^{(h)}$
KPI_{C2}	Voltage quality	Average voltage value in the network [pu]	Maximising	$KPI_{C2} = \frac{1}{n_b + n_h}\sum_{i=1}^{n_b}\sum_{h=1}^{n_h} v_i^{(h)}$
KPI_{D1}	Network losses	Energy losses [MWh]	Minimising	$KPI_{D1} = \sum_{j=1}^{n_e}\sum_{k=1}^{n_h} e_{L_{j,k}}$
KPI_{D2}	Demand side participation	Users involved in DSM [%]	Maximising	$KPI_{D2} = \frac{n_L + n_{DG}}{n_U} 100$
KPI_{E1}	Market Dynamism	Possibility of aggregation services (yes, no) [–]	Maximising	$\begin{cases} \text{if yes } \overrightarrow{K}PI_{F1} = 1 \\ \text{if no } \overrightarrow{K}PI_{F2} = 0 \end{cases}$

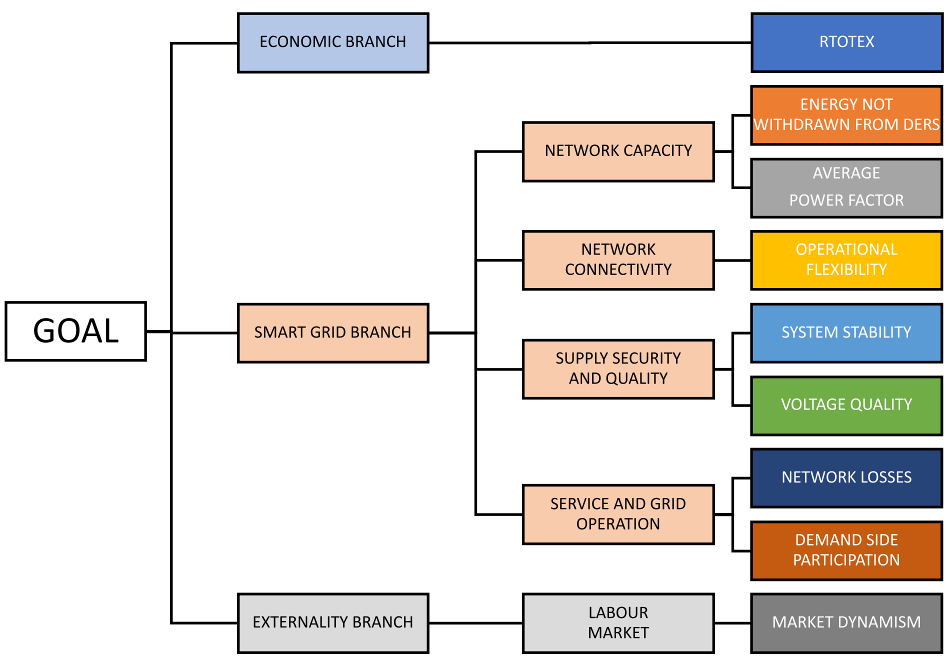

Fig. 5. Decision tree of the decision-making problem. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

total number of constraints violation events, n_b is the number of busses in the network, n_e is the number of elements considered for the assessment of energy losses (HV/MV transformers, lines), n_U total number of users, $\cos\phi_I$ is the power factor at the HV/MV interface, p_i is the power capacity of the ith resource, $v_i^{(h)}$ is the voltage magnitude value in the ith bus at the hth interval; $c_i^{(h)}$ is the occurrence of the ith constraint violation in the hth interval (binary variable); $e_{L_{j,k}}$ is the energy loss of the jth element in the kth time interval.

Table 4 shows, for each considered criterion, the related evaluation type (i.e., quantitative/qualitative) and the values of the performances corresponding to the four planning alternatives (i.e., the decision matrix for the problem under analysis).

The proposed case study's approach is compared to the several acknowledged approaches (i.e., subjective weighting method, Shannon's Entropy, Standard Deviation, Ideal Point objective weighting methods) to demonstrate the capability of the proposed joint MCA-CBA decision-making framework with the DT-MCA-CBA methodology to find the compromise solution that satisfies all the stakeholders' points of view.

The appraisal of the planning options according to the subjective weighting method relies on the decision matrix normalisation addressed with the automated procedure proposed in [22]. The global priorities (or normalised scores) of the options are calculated using Saaty's method [46]. Three different subjective weight schemes are used: WS1 assigns the same relevance to

Table 4
Decision matrix of the decision-making problem.

KPI	Description	Evaluation type	Alternative			
			A1	A2	A3	A4
rTOTEX	Reduction of TOTEX	Quantitative	0	22 670.2	3886.3	27 204.3
KPI_{A1}	Energy not withdrawn from DERs	Quantitative	0	0	0	2
KPI_{A2}	CosPhi	Quantitative	0.844	0.875	0.875	0.881
KPI_{B1}	Operational flexibility	Quantitative	0	0	1500	11 090
KPI_{C1}	System stability risk	Quantitative	0	4.5	12.8	19.1
KPI_{C2}	Voltage quality	Quantitative	0.9972	0.9995	0.9995	0.9983
KPI_{D1}	Network losses	Quantitative	2.88	3.89	4	4.32
KPI_{D2}	Demand side participation	Quantitative	0	0	0	15
KPI_{E1}	Market Dynamism	Qualitative	0	0	0	Yes

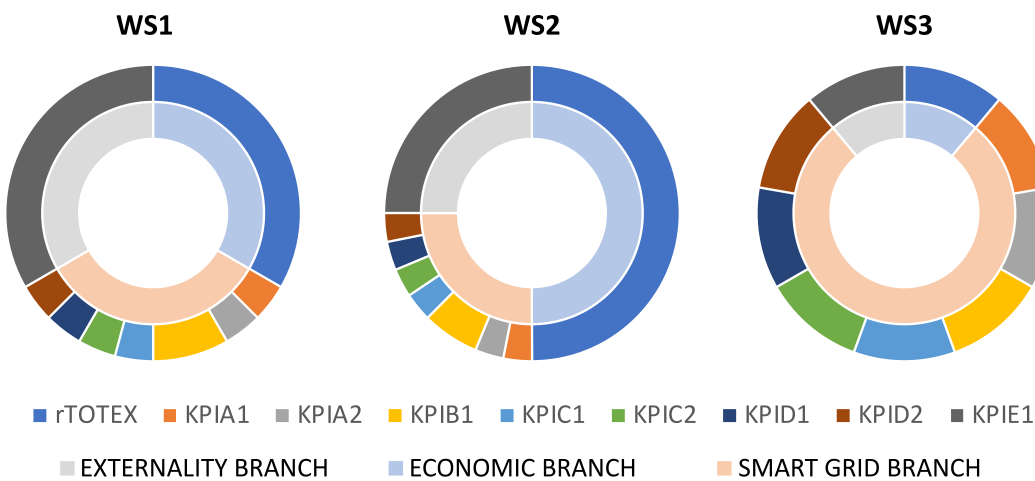

Fig. 6. Weight schemes for subjective weights' evaluation (KPIs global priorities values). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the three branches, WS2 is characterised by the economic branch that accounts for half, and WS3 assigns to all the KPIs the same relevance (and thus a bigger relevance to the smart grid branch). Fig. 6, following the same colour classification as Fig. 5, clearly shows the weights assigned to the three branches and the nine KPIs in the three weight schemes: the bigger the area the bigger the weight assigned to the branch or the corresponding KPIs. The inner circle represents the branch weights, while the external one the weights assigned to the KPIs.

Fig. 7 reports the overall scores achieved by the alternatives considering the three weight schemes. The overall score of the alternatives is calculated using the hierarchical composition principle as applied in [27]. Whatever the weighting scheme, A4 (dark blue bars in Fig. 7) achieves the highest overall score; hence, it is the most valuable alternative according to the appraisal using subjective criteria weights.

Objective methods for weighting Shannon's Entropy (SE) and the Standard Deviation (SD) method require normalising the decision matrix (Table 4) in terms of the relative frequency of the entries [55]. The Ideal Point (IP) method requires normalising the decision matrix to the interval [0, 1] [52].

Fig. 8 reports the criteria weights calculated using SE, SD, and IP methods. The weights in Fig. 8 are obtained by applying the respective methodologies (introduced in Section 3.1) to the DM in Table 4. SE and SD methods produce similar weights for the KPIs since they are based on a similar principle. The KPIs achieving the highest weight are those for which the alternatives show the greatest diversity in attribute values. Therefore KPI_{D1}, KPI_{D2}, and KPI_{E1} (dark red, dark blue and dark grey areas) are the criteria that better discriminate the alternatives. Whereas the IP weights for KPI_{D1}, KPI_{D2}, and KPI_{E1} have less relevance, conversely, the highest importance is gained by KPI_{A1} and KPI_{A2} (orange and a light grey area, respectively).

Fig. 9 shows the overall score of the planning alternatives considering the weight schemes in Fig. 8 calculated according to the normalisation procedures and the application of the hierarchical composition principle, as in [27]. According to SE and the SD Methods, option A4 achieves the highest overall score, almost twice the second-best option's score. The IP method generates an overall ranking in which the alternatives obtain a similar score; nevertheless, the A4 option achieves the highest overall score.

As introduced in Section 3.2, the DT-MCA-CBA methodology does not rely on a single weight scheme. Still, it models the stakeholders' perspectives in terms of an optimisation problem based on the MMR rule which requires defining bounds for the weight value. In this case study, the MMR compares the results obtained using explicit weight schemes related to the subjective and synthetic weights. For each KPI, the minimum and maximum weight value is selected to define the lower and upper bound of the optimisation problem. This way, all possible viewpoints expressed by the different subjective and objective weights within the interval are considered part of the resulting research weight space region. The result of this elaboration is depicted in Fig. 10 which shows the region in the weight space considered for applying the MMR. Fig. 10a and b represent, respectively, the areas in the weight space that corresponds to the subjective (defined in Fig. 6) and objective (defined in Fig. 8) weights. Moreover, as shown in Fig. 10c and d, two additional regions are considered to extend the stakeholder audience of the decision-making problem. The audience of "mild" stakeholders (that is stakeholders with a moderate attitude on all the criteria considered) having for all KPIs values in the interval [0.001; 0.333]; and audience of "extreme" stakeholders (stakeholders that adopted a clear, extreme, position on the criteria) having KPIs values interval [0.001; 0.499]. Extending the weights ranges allows to analyse how the best solution

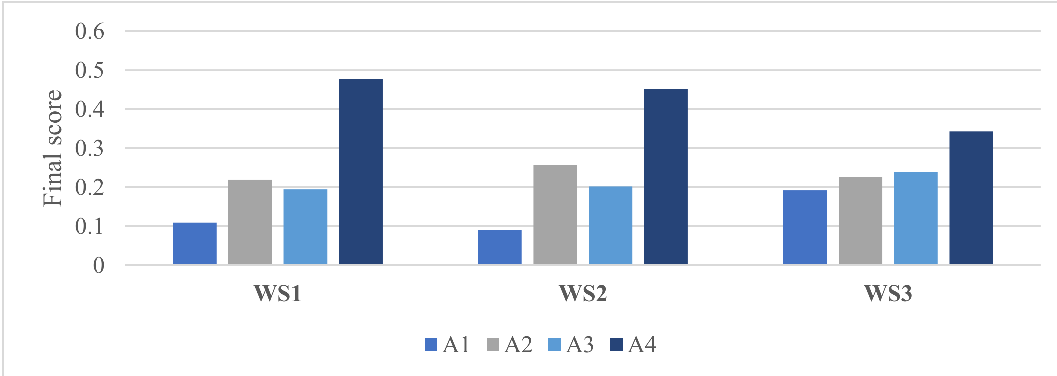

Fig. 7. Evaluation results for the subjective weighting approach. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

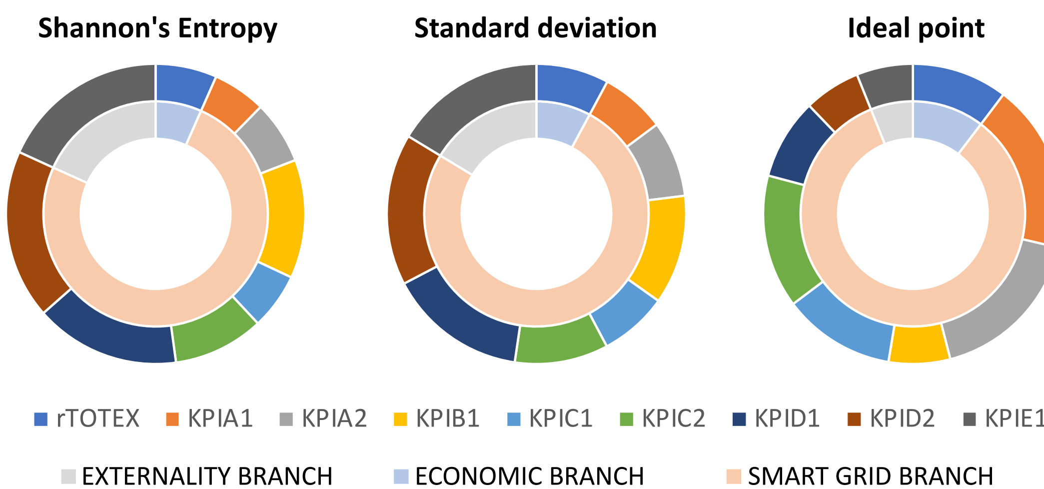

Fig. 8. Weight scheme for KPIs obtained according to the objective weight schemes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

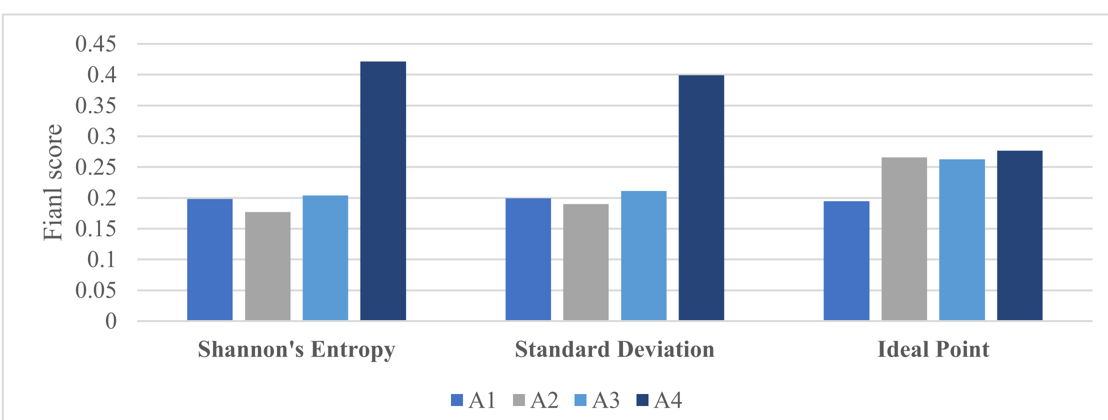

Fig. 9. Overall score of the alternatives according to the objective weight schemes.

identified by the DT-MCA-CBA methodology changes with different stakeholder preferences. In fact, the first extended weights range (Fig. 10c) models a "mild" stakeholder audience where a single criterion can have a maximum relevance of 1/3, while the further extended weights range (Fig. 10d) models "extreme" stakeholders where a single criterion can have a maximum relevance of about 1/2. Hence, for the "mild" stakeholder audience, the performances of an alternative on a single criterion cannot impact more than one third of its overall performance, while for the "extreme" stakeholder audience, this impact can represent almost half of the overall performance.

As a consequence, the comparison of the two stakeholders' models shows that in the weights range of Fig. 10d more than in the one in Fig. 10c the alternatives that perform well on a

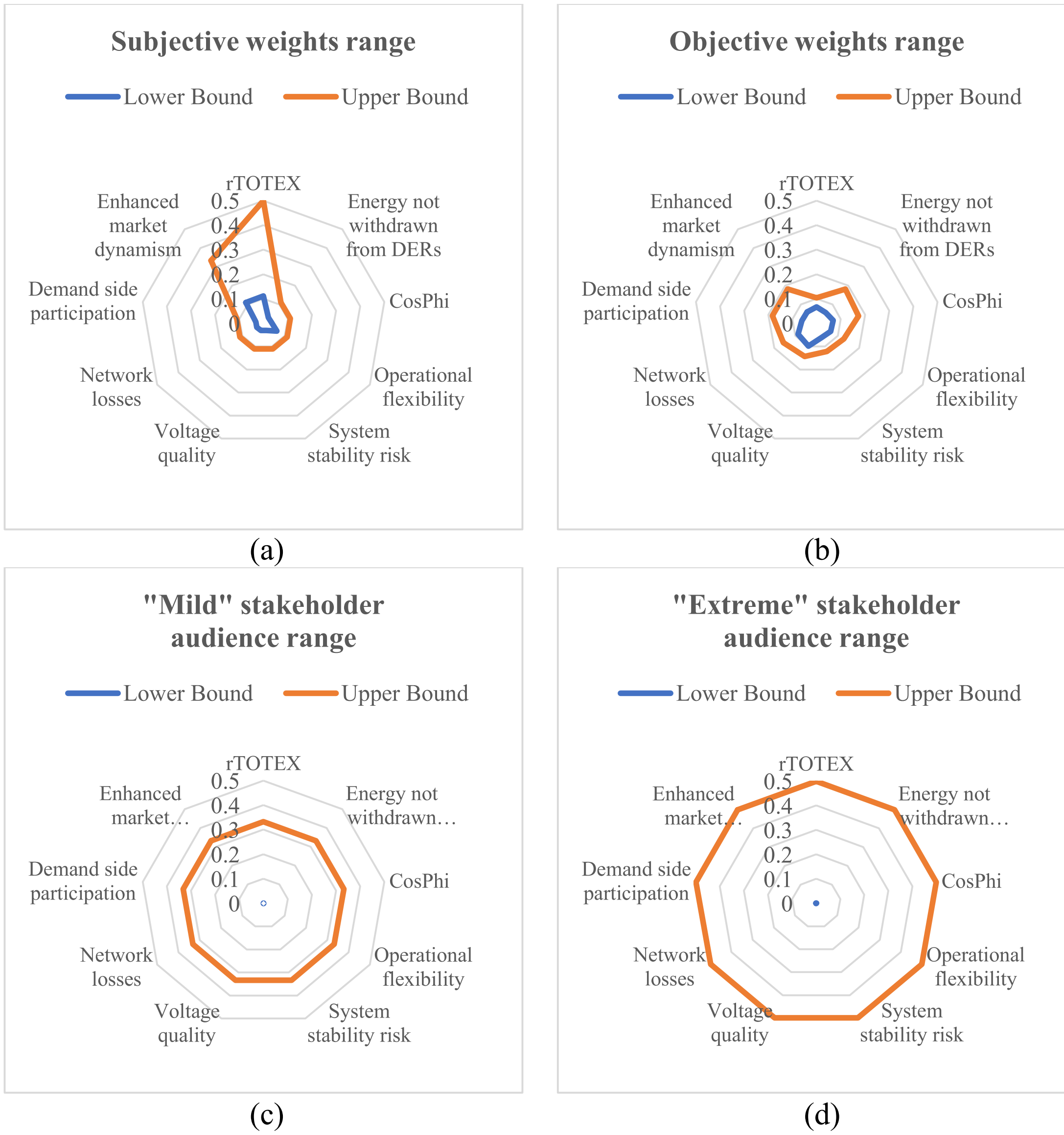

Fig. 10. Weight space regions considered.

single criterion are highly favoured, while the ones that perform poorly on a criterion are highly unwanted. It is important to note that in the "mild" and the "extreme" range, the smallest value is greater than zero to avoid the exclusion of the criterion from the decision-making process (non-exclusion condition). Moreover, in the "extreme" range, the maximum weight that a criterion can reach is lower than 0.5 to avoid its dominance (non-dominance condition); hence, a single criterion always weighs less than the sum of the weights of the other criteria.

The decision-making problem is solved for the four weight regions depicted in Fig. 10. The results in terms of maximum regret caused by the four alternatives are shown in Fig. 11. As described in Sections 3.2 and 3.3, the results of the optimisation problem are the maximum regrets determined by the alternatives in their worst-case scenario. The alternative proposed as a solution for the decision-making problem is the alternative that presents the minimum value of maximum regret.

Considering the weight regions defined on the subjective and objective weights (Fig. 10a, b), the best alternative is A4. In both cases, the maximum regret related to A4 is zero, meaning that A4 is always the best option in the entire weight space region. Hence, no stakeholders prefer adopting another alternative: A4 does not bring any regret.

Considering the "mild" stakeholder audience defined by Fig. 10c, A3 is the option that brings the least maximum regret (Fig. 11, third bar diagram). Differently from the subjective and objective weights ranges, the "mild" stakeholder audience includes a point of view for which the maximum regret determined by A4 is higher than the maximum regret of A3. While, in the case of the "extreme" stakeholder audience, as in Fig. 10d, the best option becomes A4 which achieves the minimum value of maximum regret among the set of the alternative (Fig. 11, last bar diagram). Hence, in this extended weight space region, the maximum regret felt by the stakeholder due to A3 is higher, and the maximum regret related to A3 is higher than the value related to A4, which becomes the alternative proposed solution to the decision-making problem. In Fig. 10d, the A4 minimum value of maximum regret is not zero since A4 is not considered the best option for all the viewpoints that form the weight space region.

A4 is the most valuable solution considering most of the evaluation criteria selected for addressing the decision-making problem. The worst-case scenario for A4 is described by the weighting scheme in which KPI_{A1} (energy not withdrawn from

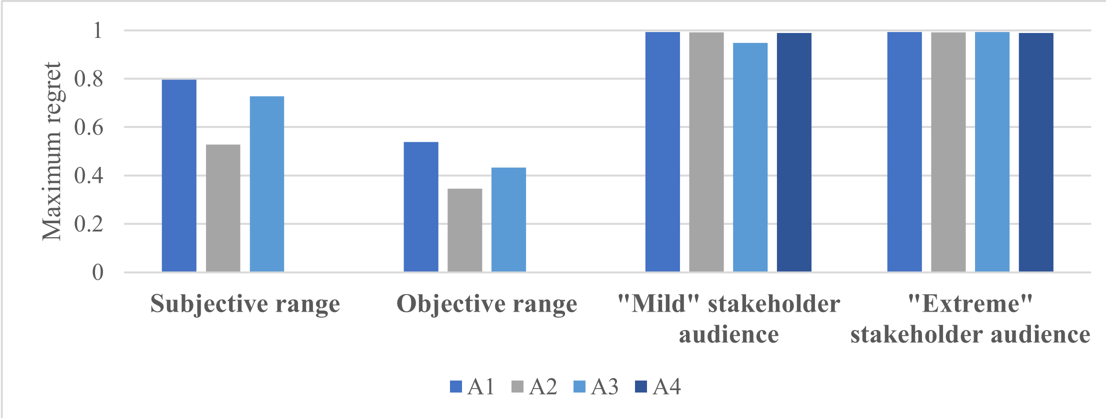

Fig. 11. Maximum regrets for the alternatives in the studied scenarios (the lower, the better).

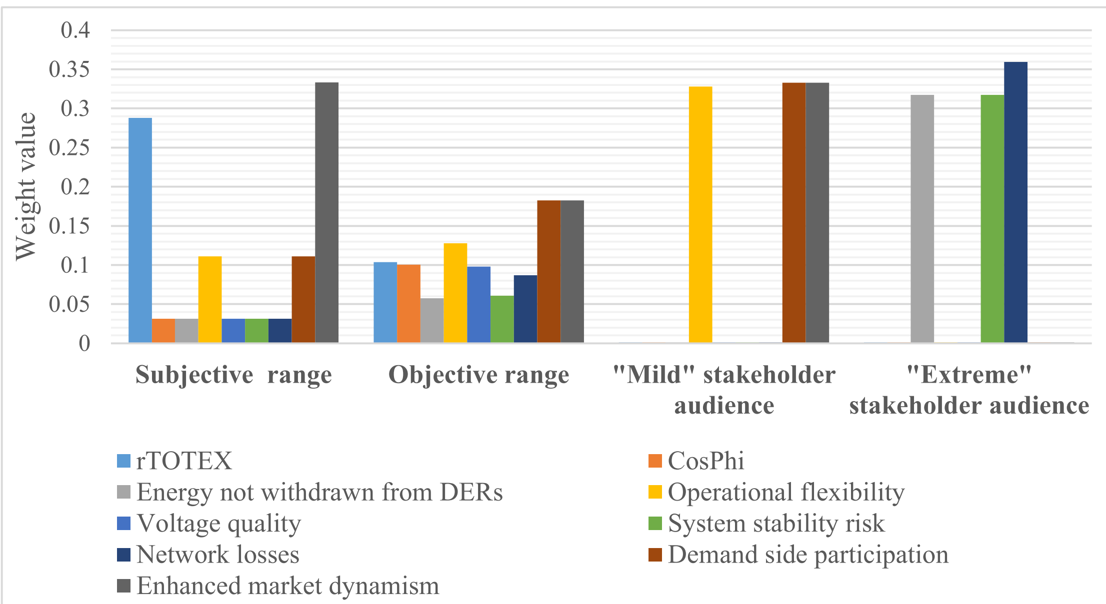

Fig. 12. Solution points for the studied scenarios (the perspective of the stakeholder feeling the highest regret).

RES), KPI_{C1} (system stability), and KPI_{D1} (energy losses) have the highest relevance; these are the KPIs on which A4 is the less valuable alternative of the set. Finally, Fig. 12 shows the criteria weight value related to the solution points; hence, the perspective of the stakeholder feeling the highest regret in each of the four studied scenarios.

The application to the case study of the joint MCA-CBA decision-making framework with the proposed DT-MCA-CBA methodology produces a compromise solution based on the needs of stakeholders, it allows decision-makers to identify the solution that represents a balanced and practical compromise that considers multiple criteria and avoids decision-making to be driven by overly sceptical and optimistic stakeholders.

The presented case study highlights that the MMR rule turns out to be a valid approach to be exploited within the joint MCA-CBA decision-making framework to outclass the highlighted drawbacks of MCA techniques that rely on subjective, objective, or integrated weighting, as described in Section 3. The presented case study illustrates the application of the proposed DT-MCA-CBA methodology to a decision-making problem for realistic distribution system planning. In this paper, the case study provides the proof of concept for the original DT-MCA-CBA methodology presented in this paper. Without loss of generality, the decision-making problem addressed in the case study contains an alternative with a clear superiority to allow us to validate the application of the proposed DT-MCA-CBA methodology. Nevertheless, in all cases where no clear superior option is part of the decision set, applying subjective, objective, or integrated methodologies and using different weight vectors does not lead to the unambiguous identification of the best option. In these cases, the advantage of using the proposed DT-MCA-CBA methodology based on the MMR decision rule becomes substantial since a single best solution is found considering a range for weight vectors which extension tailored to the decision-making problem to solve.

5. Conclusions

This paper proposes an innovative decision-making support tool based on Multi-Criteria Analysis (MCA), Cost-Benefit Analysis (CBA), and Decision Theory (DT) to assess smart grid planning initiatives. The paper presents a joint MCA-CBA decision-making framework to formalise the decision-making problem of smart grid planning and proposes an original DT-MCA-CBA methodology to solve the formalised problem and assists decision-makers in identifying the best solution among the set of analysed options. The key policy implication of this paper is that it provides system operators and regulatory bodies with a decision-making support tool for strategic planning purposes. In line with the relevant regulation, the decision-making support tool presented in this paper allows for comprehensively identifying the most valuable option by fairly comparing initiatives based on different technologies. The output-based framework presented in this paper evaluates monetary and non-monetary impacts, thus broadening the scope of the assessment beyond traditional financial analysis to consider the wider societal viewpoint. The proposed joint MCA-CBA decision-making framework enables the inclusion of externalities and soft-effects that may be disregarded or misrepresented by traditional project appraisal methods. Nevertheless, the proposed support tool is of general purpose and can be extended to be employed in decision-making activities in any sector.

The proposed joint MCA-CBA decision-making framework and DT-MCA-CBA assessment methodology enhance the objectivity of the assessment by rejecting personal biases and outclasses the shortcoming related to the monetisation of all the impacts, as CBA requires. Moreover, the role of stakeholders in the decision-making problem is preserved. Unlike the traditional MCA approaches, the proposed DT-MCA-CBA methodology models the stakeholders' behaviour exploiting the MiniMax Regret (MMR) rule to represent a realistic attitude in strategic decision making, it allows identifying the best compromising solution avoiding biases due to overly sceptical and optimistic stakeholders. Moreover, the stakeholders' view is part of the decision-making problem since they define the boundaries of the weight space for the optimisation problem. The described case study applies the proposed joint MCA-CBA decision-making framework, comparing the proposed DT-MCA-CBA methodology with traditional MCA methodologies in the smart distribution system planning context. The case study highlights the shortcomings related to the definition of the evaluation criteria relevance required by the traditional MCA methodologies.

The proposed joint MCA-CBA decision-making framework for smart grid project appraisal formalises the Joint Research Centre (JRC) guidelines considering the project impacts in three relevant areas of interest: economic, smart grid realisation and externalities. The presented case study proves the capability of the proposed approach in solving complex decision-making problems characterised by mutually conflicting criteria in which the planning options concern the competition between the traditional network reinforcement with flexibility measures. The case study concerns the distribution system planning to assess alternatives based on network and no-network measures; however, the presented decision-support tool can be applied to any planning initiative for the electricity sector involving any criteria and alternatives. However, the analysts have to identify and define the goal, criteria, and alternatives on a case basis.

The proposed DT-MCA-CBA methodology adopted to solve the decision-making problem formalised by the MCA-CBA framework allows a systematic analysis that can be scaled to handle thousands of Pareto optimal planning options produced by multi-objective optimisation planning methodologies. The proposed joint MCA-CBA decision-making framework can be integrated into a unique two-stage planning procedure: (i) design stage for devising the planning options, (ii) appraisal stage using the joint MCA-CBA framework and the DT-MCA-CBA methodology for evaluating them.

The presented case study illustrates the proof-of-concept of the proposed decision-making support tool; in addition, the MCA-CBA framework presented in this paper is tailored for planning initiatives in the electric sector. To outclass those limitations, further work will concern the application of the proposed framework to a larger and more complex decision-making problem and the extension of the decision-making support tool to deal with initiatives regarding technologies characterising multi-energy systems.

The research activity described in this paper contributed to the International Smart Grid Action Network (ISGAN) activities. The presented joint MCA-CBA decision-making framework and the DT-MCA-CBA methodology presented are included in the software available at: https://smartgrideval.unica.it/.

CRediT authorship contribution statement

Matteo Troncia: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Visualisation. **Simona Ruggeri:** Validation, Data curation, Writing – original draft, Visualisation. **Gian Giuseppe Soma:** Validation, Data curation, Writing – original draft, Visualisation. **Fabrizio Pilo:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition, Writing – review & editing. **José Pablo Chaves Ávila:** Supervision, Writing – review & editing. **Daniele Muntoni:** Software, Methodology. **Iva Maria Gianinoni:** Supervision, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix

This Appendix provides the main parameters of the test network shown in Fig. 4. The network is characterised by 100 lines (buried and overhead) for a total length of 157.46 km. Table T.1 reports the conductor parameters (cross-section, resistance, reactance, capacitance, rated current). The whole electric demand – a mix of agricultural, residential and small industrial customers – is about 16 MVA at the peak. Considering the European targets for renewables growth and efficiency improvement at the year 2030, and the following Italian integrated national energy and climate plan, it has been supposed to have a peak load of about 17 MW in 2030. In Table T.2 e in Table T.3, respectively, the data about loads and generators are listed. Table T.4 reports the main parameters of the planning problem. For simplicity, the interest and inflation rates have been assumed constant during the whole planning period.

Table T.1
Main parameters of the conductors of the studied network.

Line type	R [Ohm/km]	L [mH/km]	Rated current [A]	Cross section [mm^2]	Material	Presence in the network
Buried cable 1	0.2540	0.3996	260.0	120	Al	1%
Buried cable 2	0.2034	0.4316	280.0	150	Al	3%
Buried cable 3	0.1655	0.3512	330.0	185	Al	3%
Buried cable 7	0.4000	0.3638	165.0	50	Cu	7%
Buried cable 9	0.1917	0.3448	245.0	95	Cu	4%
Overhead line 1	11.200	13.157	105.0	16	Cu	15%
Overhead line 2	0.7214	12.960	140.0	25	Cu	11%
Overhead line 3	0.5179	12.330	190.0	35	Cu	43%
Overhead line 4	0.3529	12.233	235.0	50	Cu	13%
Overhead cable 5	0.5600	0.4456	156.0	35	Al	1%

Table T.2
Loads main characteristics at the beginning of the planning period.

Load type	Number of loads	Power [MW]
RLV	66	5.066
AGR	108	8.768
RMV_CUST1	1	1.03
RMV_CUST2	6	0.573
RMV_CUST3	9	0.895
Total	190	16.332

Table T.3
Generators main characteristics at the beginning of the planning period.

Load type	Number of generators	Power [kW]
PV	5	35

Table T.4
Main parameters used for the planning calculations.

Planning parameters			Values
Planning period			10 years
Financial rates	Interest Inflation		8.0% 1.0%
Operating limits	Voltage deviations	Ordinary operating condition Emergency operating condition	±5% ±10%
	Overload	Ordinary operating condition Emergency operating condition	0% +10%
Acceptable risks of operating limits violations	Voltage deviations	Any operating condition	5%
	Overload	Ordinary operating condition Emergency operating condition	None (deterministic) 10%

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