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ISGAN INTERNATIONAL SMART GRID ACTION NETWORK

Power Transmission &
Distribution Systems

SmartGridEval User Guide

User Guide v.03

ISGAN WG 3

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About ISGAN Discussion Papers

ISGAN discussion papers are meant as input documents to the global discussion about smart grids. Each is a statement by the author(s) regarding a topic of international interest. They reflect works in progress in the development of smart grids in the different regions of the world. Their aim is not to communicate a final outcome or to advise decision-makers, but rather to lay the ground work for further research and analysis.

Disclaimer

Preface

This document is the User Guide for the ISGAN SmartGridEval software. An overview of the features of the web-based software is provided. An example assessment is explained step by step. By means of this User Guide the end-use will be able to fully exploit the ISGAN SmartGridEval software capability.

Acknowledgments

The smart grid evaluation toolkit and related activities are part of the International Smart Grid Action Network (ISGAN) WG 3 initiatives (**http://www.iea-isgan.org/**).

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Nomenclature or List of Acronyms

AHP	Analytic Hierarchy Process
CBA	Cost-Benefit Analysis
CBR	Cost Benefit Ratio
CR	Consistency Ratio
DM	Decision Maker
EC	European Commission
FAA	Full Aggregation Approach
GHG	Greenhouse Gas
GUI	Graphical User Interface
IEA	International Energy Agency
IRR	Internal Rate of Return
ISGAN	International Smart Grid Action Network
JRC	Joint Research Centre
KPI	Key Performance Indicator
MADM	Multi-Attribute Decision Making
MCA	Multi-Criteria Analysis
MC-CBA	Multi-Criteria – Cost-Benefit Analysis, combined analysis framework
NPV	Net Present Value
PM	Performance Matrix

Table of Content

1 Introduction

The *SmartGridEval* software helps decision makers in identifying the best smart grid initiative. The tecno-economic assessment of the alternatives integrates the Cost-Benefit Analysis (CBA) within a Multi-Criteria Analysis (MCA) framework. The web-based application that can be used by any governmental and private entity as an aid for decision-making in the field of Smart Grids. The *SmartGridEval* software integrates the *ISGAN CBA toolkits* within a multi-criteria analysis (MCA) framework, the overall assessment framework is defined as MCA-CBA. The *ISGAN CBA toolkits* have been devised for conducting a simplified cost-benefit analysis (CBA) on development plans of specific smart grid assets. The aim is improving the assessment framework by combining the monetary and non-monetary appraisals of the project impacts.

The SmartGrideEval software and its fundamentals are developed within the ISGAN WG 3 activities. The *SmartGrideEval* is a cross-platform web-based tool.

1.1 Evolution of the SmartGridEval Toolkit NEW !

The SmartGridEval toolkit has undergone a structured and progressive development since its inception, reflecting the evolving needs of smart grid planning and evaluation. The following summarizes the main releases and associated enhancements:

- **Version 1.0 (2019):**

  The initial release of SmartGridEval introduced a unified platform that integrated Cost-Benefit Analysis (CBA) and Multi-Criteria Analysis (MCA) methodologies. This first version aimed to support decision-making processes for smart grid projects by combining monetary and non-monetary evaluation criteria into a structured assessment framework.

- **Version 2.0 (2021):**

  The second release brought substantial improvements, particularly in terms of information technology security and user experience. Enhancements were made to both the front-end and back-end components, providing a more robust graphical user interface and strengthening the software's resilience against cybersecurity threats, ensuring safer and more efficient evaluations.

- **Version 2.1 (2024):**

  The 2024 update introduced revisions to the internal calculation engines and processes, improving the computational efficiency and reliability of the assessment outputs. This version focused primarily on technical optimizations to support more complex planning activities without compromising performance.

- **Version 3.0 (2024–2025):**

  The new release is designed to further expand the toolkit's functionalities. It includes **CBA functionalities** for calculating economic indicators. Additionally, weighted **scenario analysis** is introduced, enabling users to conduct more detailed and structured evaluations across multiple planning alternatives. **New Key Performance Indicators** are integrated to address sector coupling aspects.

Looking ahead, SmartGridEval is expected to continue its development trajectory by incorporating new features based on user feedback, technological advancements, and emerging industry requirements. The evolution of the toolkit reflects a commitment to maintaining state-of-the-art support for the techno-economic evaluation of smart grid initiatives.

1.2 Studies performed NEW !

The SmartGridEval toolkit has been applied in a variety of case studies and internal analyses to support structured decision-making for smart grid investments. Below is a selection of key applications:

- **Smart Metering Infrastructure Evaluation:**
  The MC-CBA methodology was used to compare 1G and 2G advanced metering infrastructure (AMI) systems in Italy. The analysis integrated ISGAN's CBA toolkits within a multi-criteria framework to evaluate economic impacts, grid intelligence, and externalities, using the Analytic Hierarchy Process (AHP) for decision support.
- **Distribution System Planning with Flexibility Alternatives**
  A systematic MC-CBA approach was adopted to assess the role of DER flexibility in comparison with traditional network reinforcement. This included four planning options (from deterministic Fit and Forget to full Active Management) applied to a rural Italian MV network.
- **Techno-Economic Assessment of Hydrogen Electrolysis Technologies:**
  The tool was used to evaluate different electrolyser technologies (PEM and AE) integrated with renewable energy sources (RES) and battery storage. Multiple configurations were analysed in terms of hosting capacity, RES utilization, and economic viability.
- Multi-Energy Planning for Territorial Decarbonization
  SmartGridEval was used to perform MC-CBA of planning alternatives identified through the Calliope model, including scenarios with electrification and hydrogen-based heating. The tool supported the evaluation of Pareto-optimal solutions along economic and environmental axes, considering stakeholder perspectives through AHP and regret-based methods.

2 New functionalities NEW !

2.1 Cost benefit analysis integration

A dedicated module for Cost-Benefit Analysis (CBA) has been developed, allowing users to perform CBA calculations either independently or as a foundation for Multi-Criteria Analysis (MCA).

This module offers a flexible input mechanism, enabling users to provide data such as the start year, investment duration, and discount rate through an intuitive interface. The output is presented in a user-friendly format, displaying results such as benefit-cost ratios and net present value directly on-screen. Additionally, users can export these results to Excel for further analysis and documentation.

The Cost-Benefit Analysis (CBA) section of the website is designed to evaluate the economic and societal impacts of smart grid projects through a structured and user-friendly interface. The procedure is organized into the following elements:

1. **Data Inputs:**
   The SmartGridEval platform gathers detailed project-specific data, including capital CAPEX, OPEX, revenues. This information forms the basis for the economic evaluation of the project. The platform applies a user-specified **discount rate** to account for the time value of money. This ensures that future benefits and costs are appropriately discounted to present-day values, enabling accurate comparisons of long-term projects.
2. **Economic Indicators:**
   The tool calculates essential financial metrics to assess the viability and impact of projects. These include:
   - **Net Present Value (NPV):** The present value of cash flows over time, providing insights into the overall profitability of the project.
   - **Benefit-Cost Ratio (BCR):** A ratio that compares the benefits to costs, indicating whether the project generates value for the investment.
   - **Internal Rate of Return (IRR):** The discount rate at which the net present value of the project becomes zero, reflecting the efficiency of the investment.
3. **Outputs:**
   The output is presented in a user-friendly format, displaying results such as benefit-cost ratios and net present value directly on-screen. Additionally, users can export these results to Excel for further analysis and documentation.

Figure 2-1 - CBA-MCA Integration.depicts the integration of Cost-Benefit Analysis (CBA) and Multi-Criteria Analysis (MCA) in a unified decision-making framework.

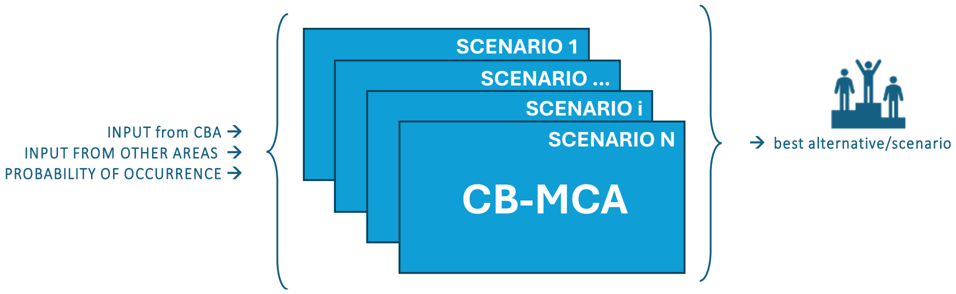


Figure 2-1 - CBA-MCA Integration.

2.1.1 Cost-benefit analysis interface

Figure 2-2 shows the interface of the CBA calculation. shows the main interface of the Cost-Benefit Analysis (CBA) tool. The layout provides a clean and intuitive environment where users can initiate the analysis by clicking the "Calculate CBA" button.

Figure 2-2 – CBA main page

The interface allows the evaluation of up to six investment alternatives by requiring the user to input the following data for each option (**Figure** 2-3):

- **Name**: Identifier for the alternative (default values are A.1 to A.6).
- **CAPEX**: Capital Expenditure (in monetary units).
- **OPEX**: Annual Operational Expenditure (in monetary units).
- **Benefits**: Annual monetary benefits (in monetary units).
- **Years**: Project duration (in years).
- **Discount Rate**: Annual discount rate (as a percentage, e.g., 3 for 3%).

Once the data is entered, the user can start the analysis by clicking the **"Calculate CBA"** button.

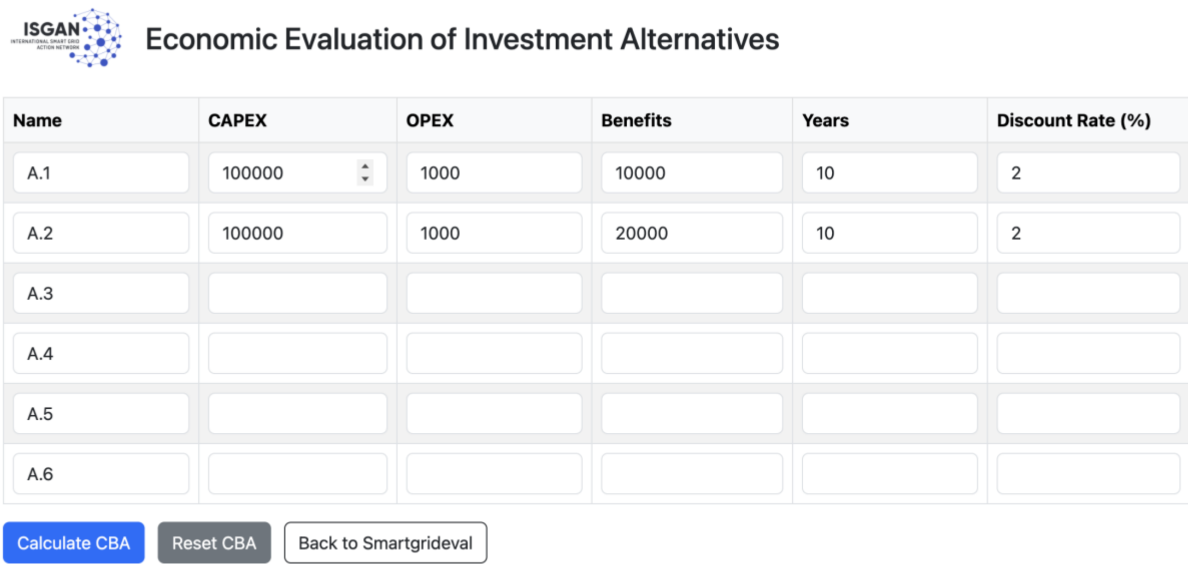


Figure 2-3: CBA Input

The tool computes the following economic indicators:

- **Net Present Value (NPV)**
- **Internal Rate of Return (IRR)**
- **Cost-Benefit Ratio (CBR).**

The results are presented both numerically in a summary table and graphically through three comparative bar charts, one for each indicator (**Figure** 2-4).

Name	CAPEX	OPEX	Benefits	Years	Rate	NPV	IRR	CBR
A.1	100000	1000	10000	10	2	-19156.73	-0.0187	0.8242
A.2	100000	1000	20000	10	2	70669.12	0.1377	1.6484

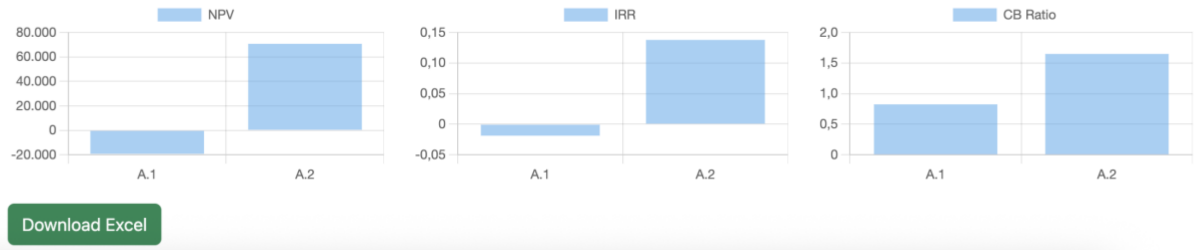


Figure 2-4: CBA Output

Users can export the results by clicking "Download Excel", which generates an .xlsx file containing both input data and computed metrics (Figure 2-5). The "Reset CBA" button allows clearing all input fields and removing any displayed results.

	A	B	C	D	E	F	G	H	I
1	Name	CAPEX	OPEX	Benefits	Years	Rate	NPV	IRR	CBR
2	A.1	100000	100	10000	10	2	-11072.41	-0.0018	0.8903
3	A.2	100000	100	80000	10	2	617708.54	0.7967	7.1221
4	A.3	100000	100	30000	10	2	168579.29	0.272	2.6708
5	A.4	100000	100	90000	10	2	707534.39	0.8975	8.0124
6	A.5	100000	100	85000	10	2	662621.47	0.8472	7.5672
7	A.6	100000	100	95000	10	2	752447.32	0.9478	8.4575
8									

Figure 2-5 Results exported in excel

2.2 Scenario analysis NEW !

During the first year of activity, significant emphasis was placed on incorporating uncertainty into the evaluation tool. Following a comprehensive state-of-the-art analysis, scenario analysis was identified as the most appropriate technique for addressing uncertainty in the context of tool enhancement.

The user can assign probabilities to individual scenarios, enabling the evaluation of different outcomes based on their likelihood of occurrence. By assigning probabilities, users can facilitate robust decision-making, as alternatives are evaluated in terms of their performance across multiple scenarios. Furthermore, the enhanced input mechanism enables users to define input parameters for all the evaluation criteria, including economic factors, smart grid aspects, and externalities, such as Cost-Benefit Analysis (CBA) results and Key Performance Indicators (KPIs), for each specific scenario. This integration ensures a more comprehensive and adaptive decision-making framework.

Figure 2-6 depicts a schematic representation of the new scenario-based CB-MCA (Cost-Benefit and Multi-Criteria Analysis) framework utilized for decision-making under uncertainty.

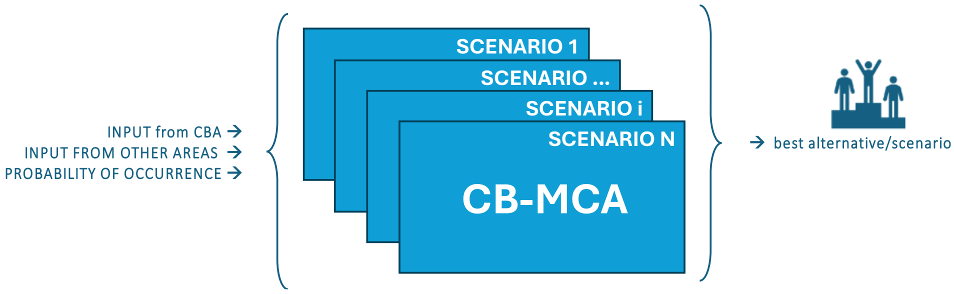


Figure 2-6 - Scenario-Based CB-MCA Framework for Decision-Making.

2.2.1 Updated KPIs NEW !

In the tool, a set of KPIs has been included to capture the main impacts associated with **sector coupling**, which is increasingly recognised at European level as a key enabler for the decarbonisation of the energy system. Sector coupling refers to the integration of the electricity system with other energy vectors (such as thermal energy, transport, gas, and hydrogen) through coordinated planning and operation. This approach supports the efficient use of renewable resources, enhances system flexibility, and enables the electrification of end uses. The selected KPIs (reported in Table 1) reflect these objectives, allowing for a quantitative assessment of cross-sector synergies, energy efficiency improvements, and the deployment of enabling technologies.

Table 1: List of new KPI related to Sector coupling

ID	Description	Mimimise/maximise
DEcons	Variation in energy consumption	Minimise
%RESprod	Percentage of energy produced from renewable sources	Maximise
%REScons	Percentage of energy consumed from renewable sources	Maximise
Eff	Energy efficiency	Maximise
SerSQ	Service security and quality (number and duration of interruptions, etc.)	min
GC	Avoided generation curtailment actions	Maximise

AD	Requested active demand actions	Maximise
DLosses	Losses reduction	Maximise
MaxHC	Increase in hosting capacity	Maximise
UF	Utilization factor	Maximise
Inn	Degree of innovativeness (use of latest-generation technologies, and...)	Maximise
N_EV	Number of electric vehicles	Maximise

2.2.2 Usability and Interface Improvement NEW !

Following user suggestions to enhance the tool's usability, several graphical improvements have been implemented:

- **Accessibility Enhancements:** User manuals and practical examples are now prominently displayed, along with the addition of a “FREE TO USE” badge. This modification highlights the tool’s no-cost accessibility, encouraging its adoption and wider use.
- **Updated Visuals:** Outdated organizational logos have been replaced, and links to relevant institutional resources have been integrated. The previous update, dated 2021, no longer reflected current institutional branding, necessitating these revisions.
- **Interactive Features:** Quick access links to relevant data for KPI computation, such as environmental or employment metrics, have been added. These features are designed to assist users with limited expertise in KPI calculation, enabling them to estimate these indicators more effectively.

3 Model description

3.1 Input and output data

The *SmartGridEval* software provides an assessment based on Multi-Criteria Analysis (MCA) wich integrates quantitative and qualitative inputs. The input data in quantitative terms can be provided by the *ISGAN CBA toolkits* or as input variable by importing the related file. Differently, the input data in qualitative terms can be provided by the Graphical User Interface (GUI).

The input data required are:

- the hierarchical structure of evaluation criteria;
- the performance of the alternatives on the terminal criteria of the hierarchy;
- the preference information about the evaluation criteria relevance.

The principal output data provided are:

- the overall merit score of each alternative;
- the partial merit score of each alternative;

- the global weights of the terminal criteria.

3.2 The hierarchy of the evaluation criteria

The solution of the decision-making problem is based on the overall assessment of the alternatives obtained by combining three independent evaluations:

- the economic evaluation (CBA of monetary impacts);
- the smart grid deployment merit evaluation (MCA of non-monetary impacts);
- the externality evaluation (MCA of non-monetary impacts).

The proposed MCA-CBA approach formalises the decision-making problem in terms of a hierarchy of criteria made of three different branches (Figure 3-1). The first branch is focused on the economic assessment, the second branch evaluates the contribution towards the smart grid realization, the third branch evaluates the effects of the project option in terms of externalities.

The three branches are independent; therefore, an impact can be evaluated through its effects on each area of interest. Conversely within each branch, each impact has to be considered by means of a single effect in order to avoid double counting.

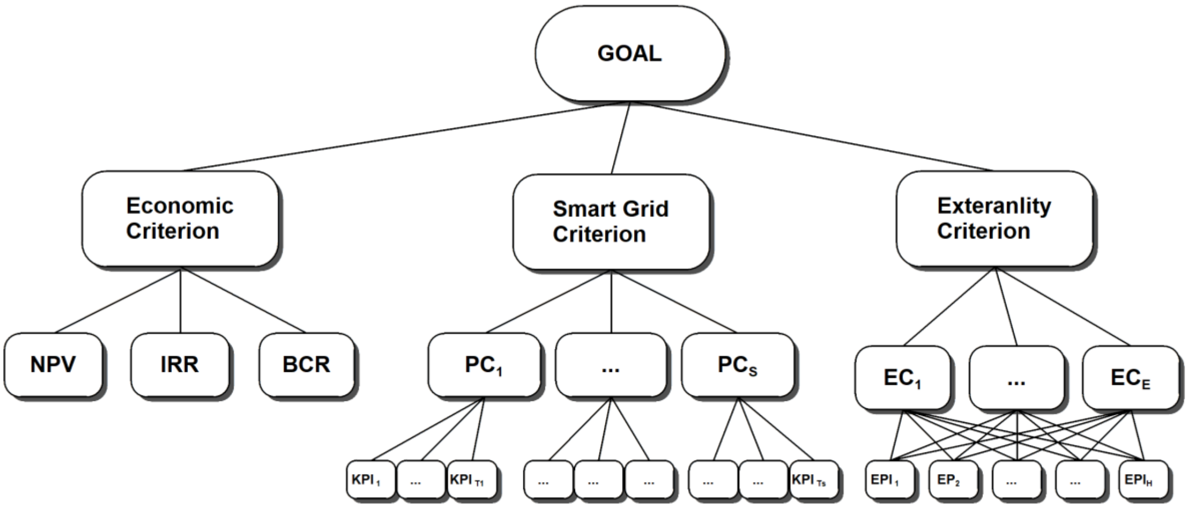


Figure 3-1: General hierarchical structure of criteria of the MC-CBA toolkit

The *SmartGridEval* software appraises the project options by means of the hierarchical structure of the evaluation criteria. The structure is flexible, the number of the criteria for each branch can be chosen by the user.

3.3 The economic assessment NEW !

The economic branch aims at evaluating each alternative in terms of monetary impacts. The proposed MC-CBA approach involves a CBA for monetary impacts that can be carried out by the *ISGAN CBA toolkits*. The monetary costs and benefits can be described by the indices computed by CBA integrated functionalities, or explicitly considering in the tree the monetary cost and benefits. In the first case, the economic branch is formed by three criteria on the second hierarchy level as depicted in Figure 3-2. Each criterion is related to a CBA outcome index.

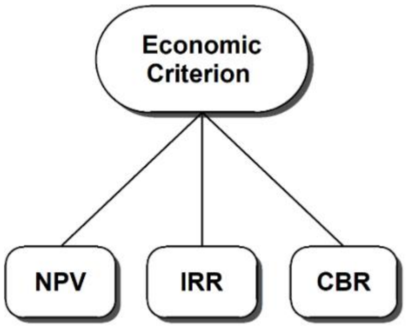


Figure 3-2: Economic tree based on the CBA output indices

The **Net Present Value (NPV) criterion** measures the project profitability in terms of the net benefit. In general, an investment option is economically viable if NPV is positive. The profitability of the investment increases as the related NPV grows. It is a quantitative criterion measured in terms of currency.

The **Internal Rate of Return (IRR) criterion** measures the quality of the investment option. An alternative is positively evaluated if its IRR is higher than the reference social discount rate. It is a quantitative criterion measured in percentage terms.

The **Cost-Benefit Ratio (CBR) criterion** measures the efficiency of the investment option. An alternative is positively evaluated if its CBR is greater than one. It is a quantitative dimensionless criterion.

Those criteria are fulfilled according to the increasing values of the related indices.

In this latest version, the tool allows users to perform the CBA analysis for the alternatives under consideration. If the User decides to use the smartgrideval tool, the CBA results will serve as input for the economic branch of the MCA.

3.4 The smart grid assessment

The second branch of the hierarchy tree evaluates the contribution towards the smart grid realization provided by each project option. In [1] the European Commission (EC) defined a list of benefits for the energetic sector related to the smart grid development. Starting from the EC document, the Joint Research Centre (JRC) devised a list of *Policy Criteria* (PC) with the aim to provide common assessment guidelines for smart grid projects [2]–[4]. Moreover, the fulfillment of the *policy criteria* is appraised by means of *Key Performance Indicators* (KPIs) [2]–[4]. In Table 2 the list of PCs and related KPIs proposed by JRC and included in the *SmartGridEval* software are presented. The formulas useful for computing most of the KPIs have been also proposed by the JRC [4]. Generally, each evaluated KPI is referred to a baseline scenario. It is worth to highlight that the evaluation of the project options through KPIs is outcome oriented. In other words, by means of KPIs are not evaluated the technical features of the infrastructure but the produced effects.

The structure of the “smart grid paradigm branch” reflects the JRC approach; therefore, the second level criteria are the *policy criteria* while the terminal criteria are the related KPIs. The performances of the project options are measured by means of the KPIs. According to the JRC guidelines, *policy criteria* are mutually independent. Furthermore, KPIs related to a same *policy criterion* have the same relevance [2]–[4].

Table 2: List of Policy criteria and related KPIs defined by JRC [2]–[4]

Policy Criterion	KPI
1. Level of sustainability	**a.** Reduction of greenhouse gas emissions (GHG) **b.** Environmental impact of electricity grid infrastructure
2. Capacity of transmission and distribution grids	**a.** Installed capacity of distributed energy resources in distribution networks **b.** Allowable maximum injection of power without congestion risks in transmission networks **c.** Energy not withdrawn from renewable sources due to congestion or security risks
3. Network connectivity	**a.** Methods adopted to calculate charges and tariffs, as well as their structure, for generators, consumers and those that do both **b.** Operational flexibility provided for dynamic balancing of electricity in the network
4. Security and quality of supply	**a.** Ratio of reliably available generation capacity and peak demand **b.** Share of electricity generated from renewable sources **c.** Stability of the electricity system **d.** Duration and frequency of interruptions per customer, including climate related disruptions **e.** Voltage quality performance
5. Efficiency and service quality	**a.** Level of losses in transmission and in distribution networks **b.** Ratio between minimum and maximum electricity demand within a defined time period **c.** Demand side participation in electricity markets and in energy efficiency measures **d.** Percentage utilisation (i.e. average loading) of electricity network components **e.** Availability of network components (related to planned and unplanned maintenance) and its impact on network performances **f.** Actual availability of network capacity with respect to its standard value
6. Contribution to cross-border electricity markets	**a.** Ratio between interconnection capacity of a Member State and its electricity demand **b.** Exploitation of interconnection capacities **c.** Congestion rents across interconnections

3.5 Externality impact assessment

The third branch concerns the assessment of the project options in terms of externalities. With the aim to aggregate single impacts, it is possible to define thematic areas for evaluating the effects under analysis. Single impacts are related to the terminal criteria while the second level criteria are the thematic areas. To illustrate, a thematic area can be the social area, whereas a related terminal criterion can be the consumer satisfaction. Each impact has to be measured by means of a quantitative or qualitative index. Those indices measure the fulfilment of the terminal criteria. Unlike the “smart grid paradigm” branch, it is assumed that the second level criteria are mutually dependent. In fact, an impact related to a thematic area can also influence the other areas.

3.6 The MCA technique

The *SmartGridEval* software analyses the set of the alternatives by means of the Analytic Hierarchy Process (AHP) [5]. The AHP is a Multi-Attribute Decision-Making (MADM) method which belongs to the full aggregation approach (FAA) family [6]. AHP is a fully-structured method which handles simultaneously quantitative and qualitative input data. Key features of AHP are the hierarchical decomposition of the decision problem, the ratio scale used for express preferences, and the pairwise comparison procedure. The scoring and weighing stages are addressed by the pairwise comparison of the objects. In general, the comparison depends on the personal judgments of the decision maker (DM) that has to provide information about the relative importance of one object over another. This information is quantified on a standardized judgment scale (Saaty’s ratio scale) that converts the preference expressed in verbal terms to a numerical value (Table 3). The intermediate integer values (2, 4, 6, 8) and their reciprocal can be used to express a preference between two adjacent judgments

Table 3: Saaty's judgment scale [5]

Verbal judgement	**Saaty’s ratio scale (w_j / w_k)**
Absolute preference for object w_k	1/9
Demonstrated preference for object w_k	1/7
Strong preference for object w_k	1/5
Weak preference for object w_k	1/3
Indifference/equal preference	1
Weak preference for object w_j	3
Strong preference for object w_j	5
Demonstrated preference for object w_j	7
Absolute preference for object w_j	9

The number of required pairwise comparisons for AHP increases as the number of the criteria and/or of the alternatives increases. The DM is assumed coherent in his judgments about each pair of objects. Therefore, the elements of lower triangle of a preference matrix are the reciprocal of the corresponding elements of the upper triangle (i.e., $q_{i,j}^{(k)} = 1/q_{j,i}^{(k)}$). In addition, the entries of the main diagonal are equal to 1. To illustrate, Table 4 depicts an example of a preference matrix.

Table 4: AHP preference matrix example

	A	**B**	**C**
A	1	7	1/9
B	1/7	1	2
C	9	1/2	1

The *SmartGridEval* software uses the pairwise comparison process during the weighting stages. It is also used during the scoring stages based on performances assessed qualitatively. Conversely, the performances expressed in quantitative terms are converted to the Saaty's scale by means of an automatic scoring process [7].

The consistency of the preference matrix is not guaranteed; therefore, it is imperative to check its consistency level. The *SmartGridEval* software implements a consistency check which considers a threshold value $CR^{threshold} = 0.1$ [8]. A warning message is shown if the consistency threshold is exceeded.

For each preference matrix, the corresponding priorities are evaluated. The priorities related to a preference matrix of the scoring stage are the normalized score of each alternative with respect to the criterion under consideration. Conversely, the priorities related to a preference matrix of the weighing stage are the normalized local weights of the criteria involved. The *SmartGridEval* software evaluates the priorities according to the classical approach which establishes that priorities are equal to the normalized eigenvector of the maximum eigenvalue of the preference matrix. If the decision-making problem is not flat (i.e., more than one level of criteria exists), the priorities obtained from a preference matrix of criteria are local priorities. The global priorities are evaluated by means of the hierarchical composition principle.

According to the AHP, the *SmartGridEval* software aggregates scores and weights by means of a linear additive relation, hence an overall worthiness score is assigned to each alternative. Accordingly, the appraised alternatives are ranked; the best alternative of the analysed set is the one that achieves the highest overall score.

4 The web-application

The ISGAN SmartGridEval software is a web-based application developed in HTML5; therefore, it has full compliance with all available browsers for personal computer, tablet, and smartphones.

4.1 Welcome

The welcome page is the page where provide the credential for accessing to the evaluation platform, as shown in Figure 4-1. The main Login menu allows to access to the personal profile (Login) or to request a new one (Signup).

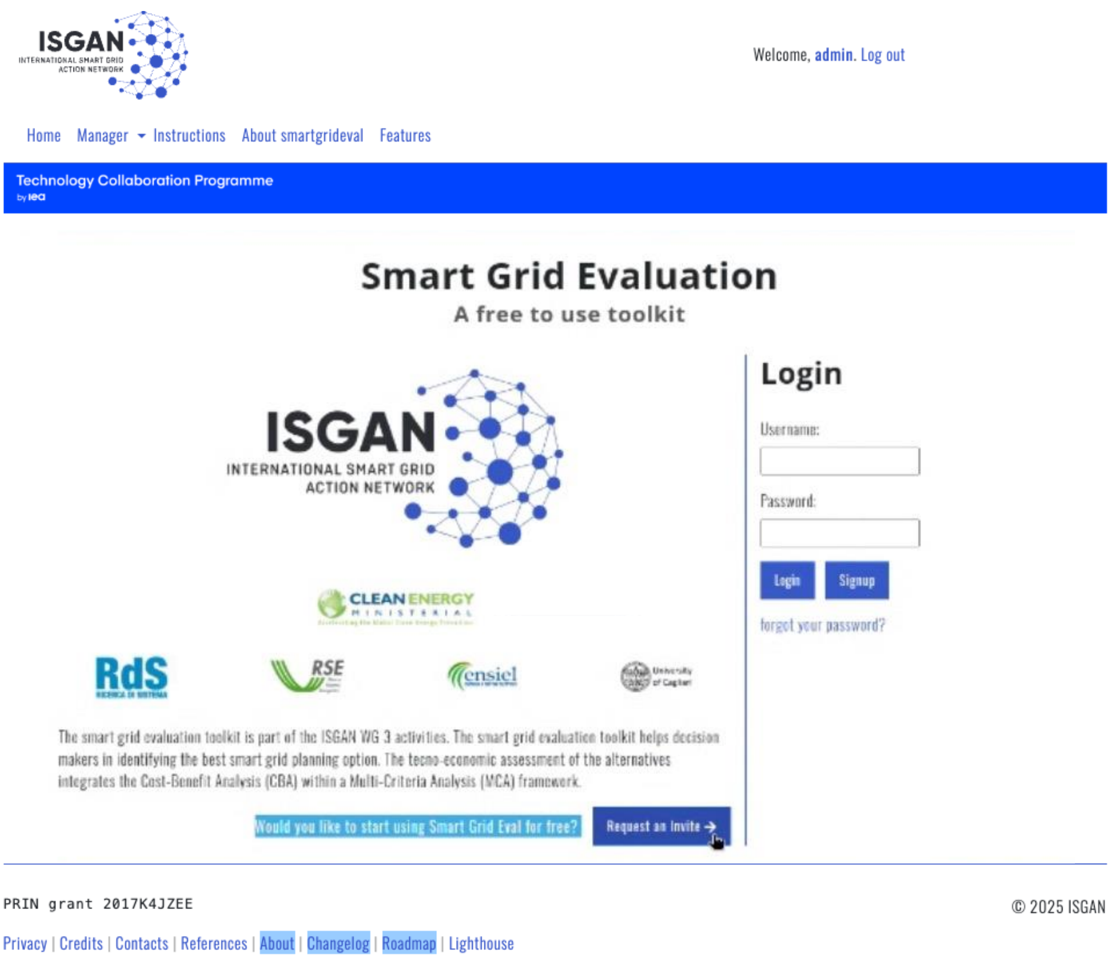


Figure 4-1: Welcome page

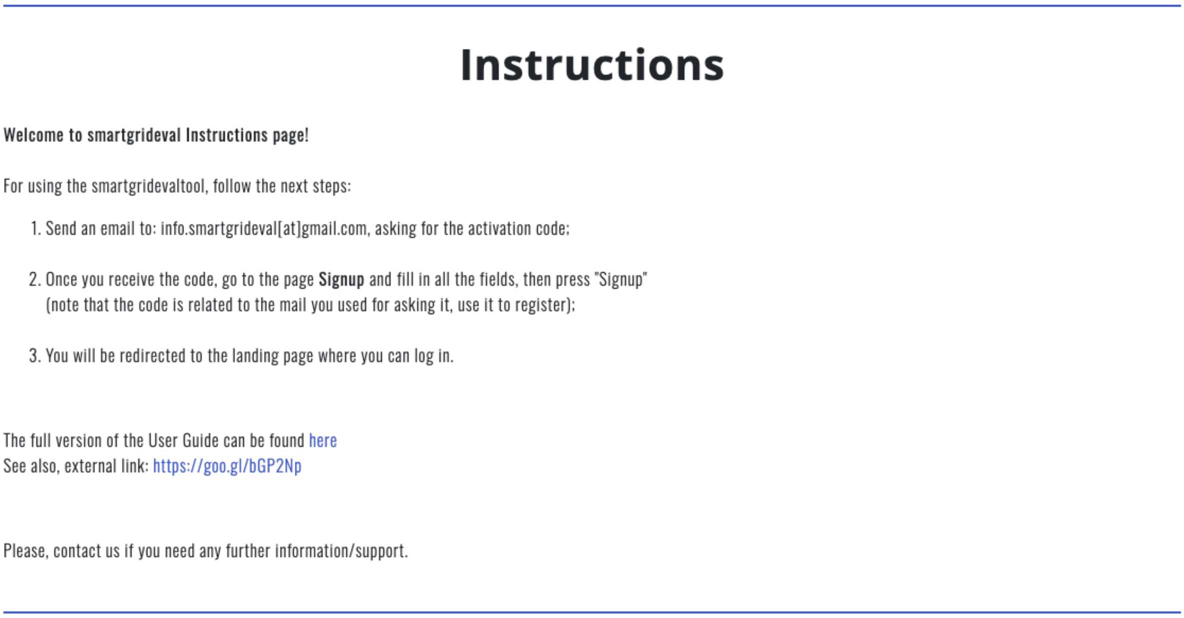
To login, provide your username and password, then press *Login* (see section 5).

To signup, press *Signup,* you will be redirected to the signup page (see section 4.2).

To reset your password, press *forgot your password* (see section 4.5).

4.2 Instruction page NEW!

To facilitate first-time users, an instructions page (Figure 4-2) has been added directly below the SmartGridEval logo within the platform interface. The page provides a clear overview of the steps required to access and use the tool: request the activation code, complete the registration process, and log in to the system securely.


Instructions

Welcome to smartgrideval Instructions page!

For using the smartgridevaltool, follow the next steps:

1. Send an email to: info.smartgrideval[at]gmail.com, asking for the activation code;
2. Once you receive the code, go to the page **Signup** and fill in all the fields, then press "Signup" (note that the code is related to the mail you used for asking it, use it to register);
3. You will be redirected to the landing page where you can log in.

The full version of the User Guide can be found here
See also, external link: https://goo.gl/bGP2Np

Please, contact us if you need any further information/support.

Figure 4-2 Instruction page

4.3 About page NEW !

A new **"About"** page (Figure 4-3) has been added to provide a concise overview of the SmartGridEval tool and to guide users through the key steps of a structured evaluation process.

The aim is to clarify the purpose of the toolkit, and to illustrate the main stages of the decision-making workflow, from the definition of project alternatives to the final analysis of results. This section is intended to support user orientation by emphasizing the integration of CBA and MCA methodologies, as well as the importance of using KPIs aligned with the JRC recommendations.

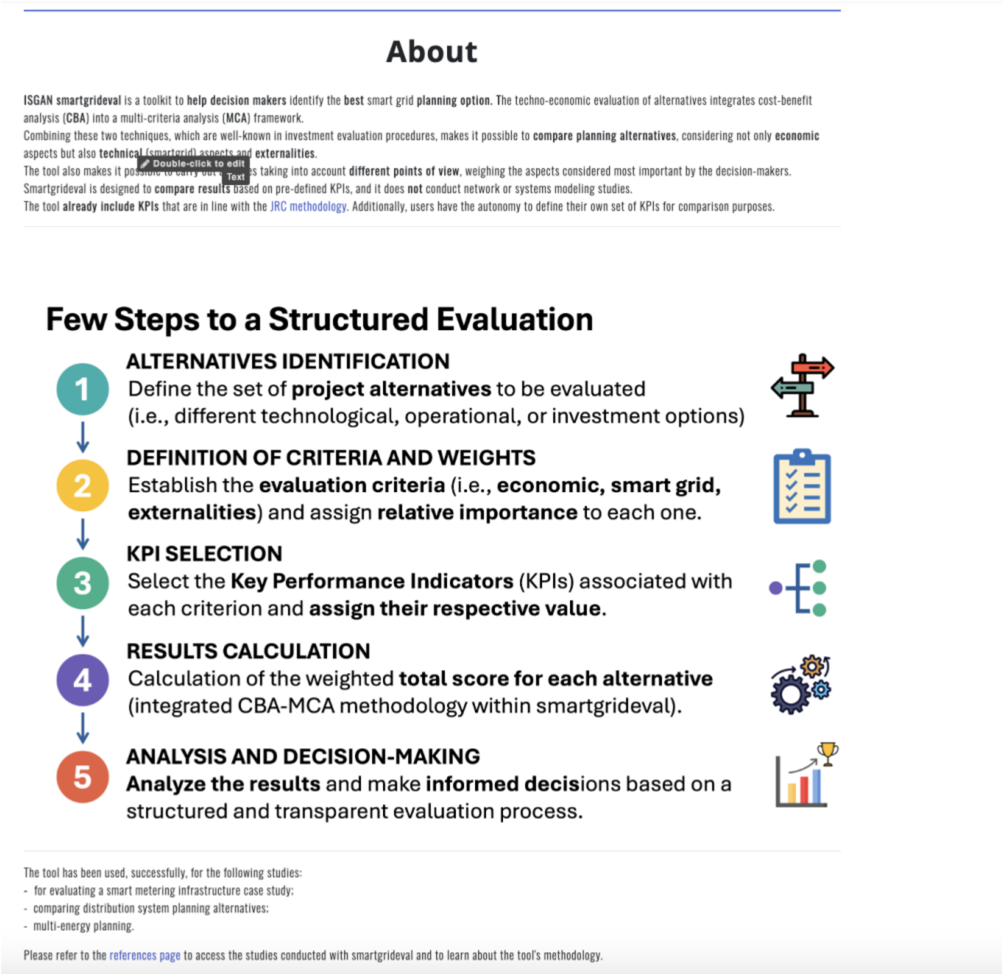


Figure 4-3: Welcome page

4.4 Request a new profile

For requesting a new profile, as depicted in Figure 4-4, provide your:

- Username
- Password
- Email
- First name
- Last name
- Client code

Figure 4-4: Signup page

The client code is your personal invitation token for the SmartGridEval software. You receive the code by the invitation mail, it is a strictly personal code related to the email address which received the invitation email. Once you request for signup, follow the instruction you will receive by email.

Request your client code to: info.smartgrideval@gmail.com

4.5 Reset your password

If you forgot your password, you can set a new password by requesting to reset your login credentials. As depicted in Figure 4-5, provide your registration email address and press *Reset password.* Then, follow the instruction you will receive by email.

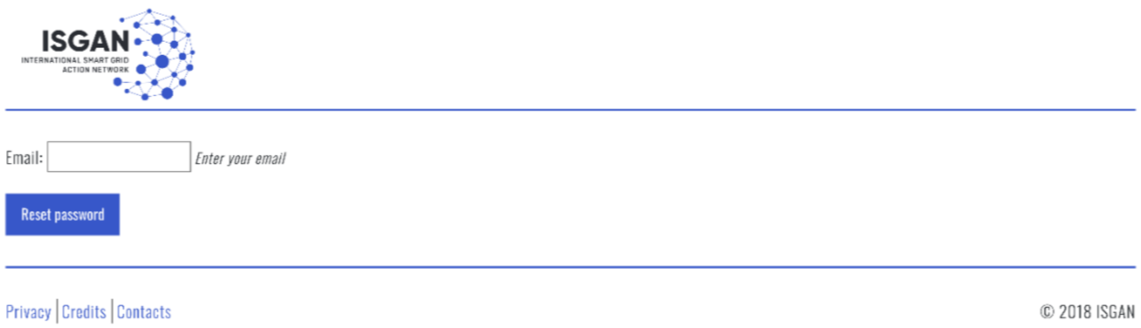


Figure 4-5: Reset password request

4.6 Changelog and roadmap pages NEW!

With the aim of describing the ongoing and future development directions for the SmartGridEval toolkit, two new pages have been created. The changelog page (Figure 4-6) provides a chronological summary of the main updates and milestones in the development of the SmartGridEval toolkit, while the Roadmap page (Figure 4-7) informs users about planned enhancements, such as the integration of hosting capacity analysis, the publication of new case studies, and the release of dedicated training materials.

Changelog

The following summarizes key developments and updates of smartgrideval:

- **Version 1.0 (2019):** Initial release, featuring CBA and MCA integration for smart grid evaluation.
- **Version 2.0 (2021):** Updated release, improvements in information technology security and graphic interface on front-end and back-end sides.
- **Version 2.1 (2024):** Updated release, calculation processes and engines updates.
- **Version 3.0 (2024-2025):** Introduction of CBA functionalities and improved scenario comparison functionalities.

Future versions will continue to expand the toolkit's capabilities based on user feedback and evolving industry needs.

Figure 4-6: New changelog page

Roadmap

Smartgrideval is under continuous development to enhance its capabilities and broaden its applicability. Planned future improvements include:

- Incorporation of hosting capacity analysis.
- New case-studies.
- Development of online training materials and real-world case studies to support users.

User feedback plays a key role in guiding the evolution of the toolkit, ensuring it remains aligned with emerging smart grid challenges and opportunities.

Users are invited to contact the development team to suggest additional application studies, request technical support for specific projects, or contribute to the definition of future features.

Figure 4-7 New roadmap page

4.7 Features page NEW!

A dedicated **"Features"** page (**Figure** 4-8) has been added to highlight the main functionalities of the SmartGridEval tool.

Features

Smartgrideval ensures that complex evaluation processes become accessible, transparent, and decision-oriented.

Smartgrideval provides a range of features that enable efficient and transparent smart grid planning. These can be grouped into two main categories: analytical capabilities and user experience enhancements.

Analytical Capabilities

- **Cost-Benefit Analysis (CBA):** Evaluates the economic performance of different alternatives, highlighting costs, benefits, and net gains.
- **Multi-Criteria Analysis (MCA):** Integrates technical, economic, and externalities criteria into a unified evaluation framework.
- **Scenario Comparison:** Facilitates the comparison of multiple grid development strategies under consistent assumptions.

User Experience and Flexibility

- **User-Friendly Interface:** Simplifies parameter configuration and result visualization, allowing users to focus on analysis and decision-making.
- **Modular and Flexible Architecture:** Supports easy customization and integration of additional indicators or evaluation modules.

Figure 4-8 Features page

5 Main dashboard

Once you login, you access the main dashboard of SmartGridEval, named *Planning activity management* (Figure 5-1). In the main dashboard you can choose one of the following options:

- Create a brand-new planning activity;
- Create a new planning activity starting from a built-in template;
- Load a planning activity from your wallet;
- Clone an existing planning activity.

Each evaluation session is named Planning Activity (PA).

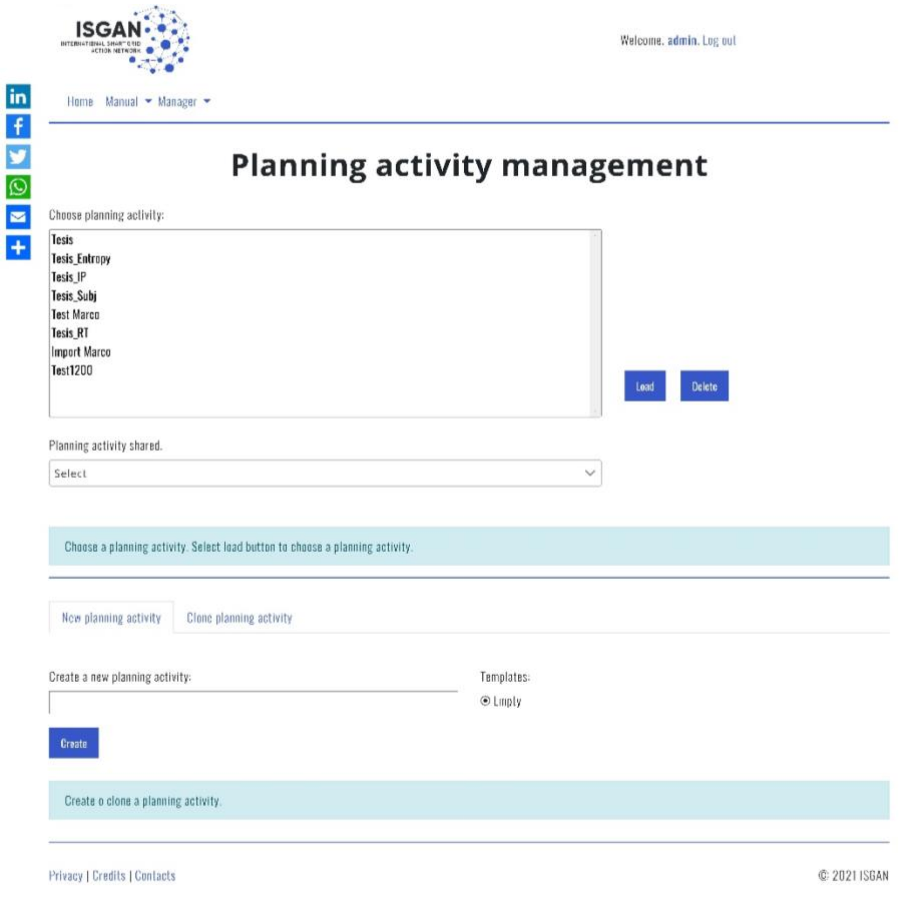


Figure 5-1: Main dashboard, the planning activity management page

In the header of the *Planning activity management* page you can find:

- Your username and the *Log out* button;
- *Current PA*: the link to the page of the ongoing assessment;
- *Change PA*: the link to the main dashboard page.

In the body section of the *Planning activity management* page you can find:

- *Choose planning activity*: the list of the PAs in your wallet;
- The *Load* and *Delete* buttons: for managing the PAs in your wallet
- The dropdown menu of the planning activities that have been shared with the user

In the bottom section of the *Planning activity management* page you can find:

- The *Create a new planning activity* tab: the empty tab where insert the name of your new PA;
- The *Templates* radio button menu: where select if create a new PA from scratch or from an already available template.

- The *Create* button: press *Create* for creating a new PA according to the settings specified in the above fields.

The *Clone planning activity* tab allows the user to create a clone of an existing planning activity, as depicted in Figure 5-2.

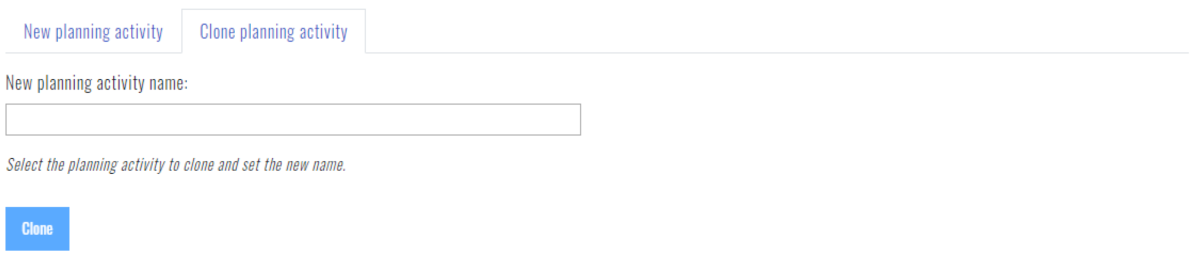


Figure 5-2: Clone planning activity tab

The user has to select in body section which planning activity has to be duplicated, and then specify the name of the planning activity which will be created in the empty gap.

The new planning activity is created by pressing the button "Clone".

In the footer of the *Planning activity management* page you can find the links for the *Privacy*, the *Credits,* and the *Contacts* pages.

5.1 Creating a new PA

For creating a new PA, write down the name of the new PA in the *Create a new planning activity* tab of the bottom section of the *Planning activity management* page (Figure 5-1).

- For creating a new PA from scratch:
  Select the *Empty* option in the radio button list on the right side, then press the *Create.*
- For creating a new PA from an already existing template:
  Select the desired option in the radio button list on the right side, then press the *Create.*

Once you press *Create,* you will be redirected to the PA main page, the *Planning Activity Overview* page (see section 6).

5.2 Loading an existing PA

For loading an existing PA from your wallet, select one PA item in the *Choose planning activity* list of the body section of the *Planning activity management* page (Figure 5-1). The press *Load.*

5.3 Deleting an existing PA

For deleting an existing PA from your wallet, select one PA item in the *Choose planning activity* list of the body section of the *Planning activity management* page (Figure 5-1). The press *Delete.*

Warning: deletions CANNOT be undone.

6 Planning Activity Overview

The *Planning activity overview* page is the dashboard of each PA, it contains the elements for undertake a smart grid initiatives' assessment.

As depicted in Figure 6-1, the *Planning activity overview* page is formed by four sections: the header, the body, the right-side control section, the footer.

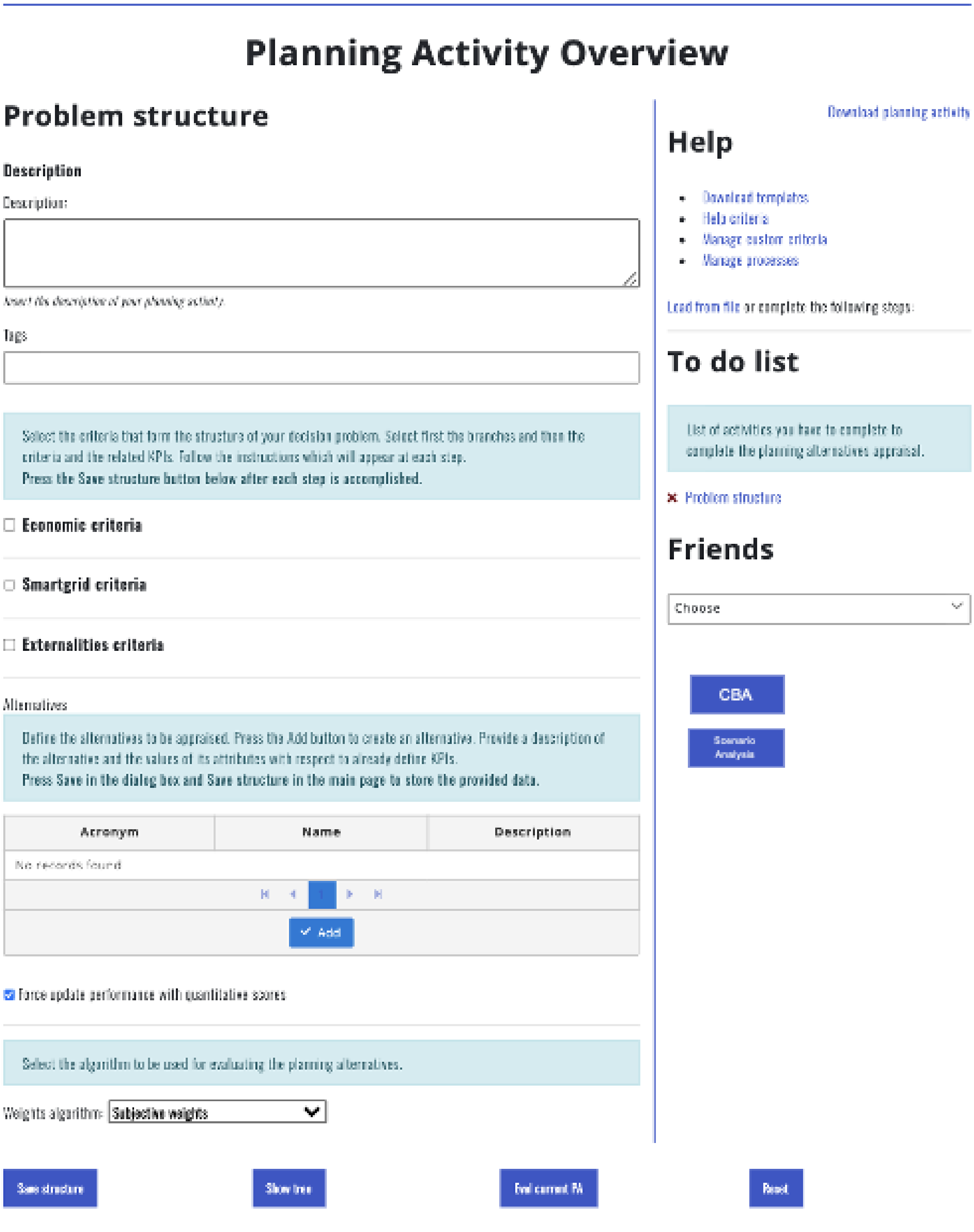


Figure 6-1: The *Planning Activity Overview* page NEW!

6.1 The header: navigation controls

In the header of the *Planning activity management* page you can find:

- Your username and the *Log out* button;
- *Current PA*: the link to the page of the ongoing assessment;
- *Change PA*: the link to the main dashboard page.

In the footer of the *Planning activity management* page you can find the links for the *Privacy*, the *Credits,* and the *Contacts* pages.

6.2 The body: structural parameters

The body section of the *Planning activity overview* page is entitled as *Structural parameters,* it is devoted for defining the structure of the criteria tree of the decision-making problem of the PA.

The elements of the *Structural parameters* section are:

- the *Description* tab;
- the *Tags* tab;
- the checklist for enable the assessment branches (*Economic*, *Smart grid*, *Externalities*);
- the *Number of alternatives* tab;
- the *Weights algorithm* tab;
- the *Save structure*, *Show tree*, *Eval current PA*, *Reset* buttons.

The right-side control section is formed by three parts.

The upper part hosts the links:

- *Download templates;*
- *Help palette;*
- *Manage custom palette.*

The ***Download templates*** link redirects to the page which hosts the default templates for the *SmartGridEval* software and for the *ISGAN CBA* toolkits (see section 6.10).

The ***Help palette*** link redirect to the page where the description of the criteria hosted by the palette is provided (see section 6.11).

The ***Manage custom palette*** link redirects to the page where the user can add and edit the elements of the criteria palette (see section 6.12).

The central part of the right-side control section hosts the links useful for providing to the *SmartGridEval* software the input data about alternatives and criteria relevance (see section 6.5). This subsection provides an explorable ***To-Do*** **checklist** for the PA assessment, once each step is accomplished, the items will be checked (✔); whereas, for missing steps the related item is identified as unchecked (✖). Each item of the checklist is a clickable link which redirects to the related input data page.

The lower part of the interface highlights a recent enhancement of the tool: two dedicated buttons have been added to provide direct access to **CBA** module (see section 6.3.1) and the **Scenario Analysis** functionality (see section 6.3.7), enabling users to deepen the evaluation of planning alternatives.

6.3 Define a new hierarchical structure

For starting the assessment of a brand-new PA, carry out the following steps.

First, provide a short description of your PA in the *Description* tab and define up to three tags related to your PA in the *Tags* tab.

Then, choose the assessment branches you want to consider in your PA. You can choose to carry out the assessment by considering one, just two or all three evaluation branches by checking the related checkbox.

6.3.1 Cost-benefit analysis NEW !

If the user intends to use the tool to perform a cost-benefit analysis, they must first click on the dedicated button, which redirects to the specific CBA interface. Within this section, the user is required to specify the number of alternatives under evaluation. For each alternative, the following data must be entered: CAPEX, OPEX, and the estimated benefits over the project lifetime, start year, reference year, rate of investment (Figure 6-2).

Based on the provided inputs, the tool automatically calculates the selected performance indicators (e.g., NPV) and returns their values directly in the KPI section of the Planning Activities interface.

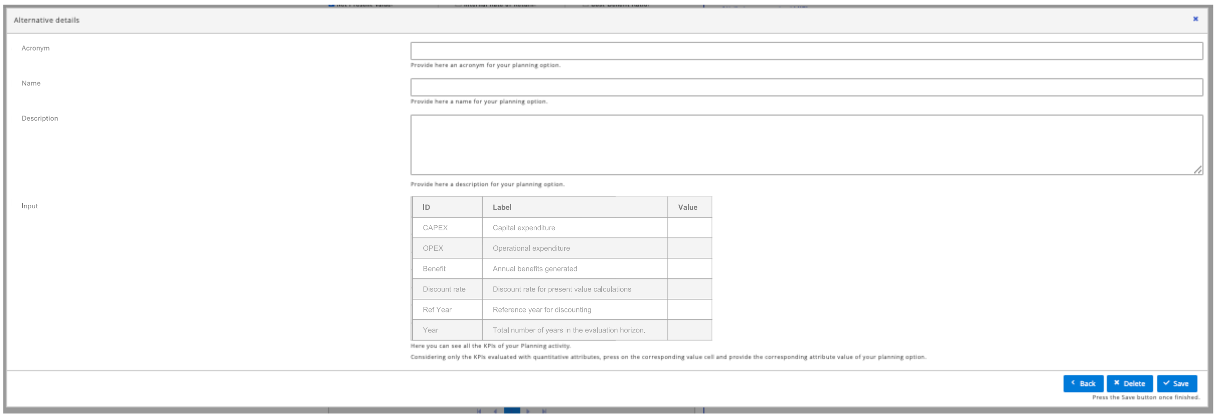


Figure 6-2. CBA input interface

Once the data are defined, press *Done.*

6.3.1.1 Output Visualization – CBA Results Interface NEW !

The figure below illustrates the graphical interface for visualizing the output of a Cost-Benefit Analysis (CBA). The interface is structured into two main sections: a summary table and a KPI Bar Charts.

A summary table (Figure 6-3) is used to report the main financial indicators for each evaluated alternative:

- **NPV** representing the total net benefit over the project lifetime, discounted to present value.
- **IRR (Internal Rate of Return)**: expressed as a percentage, indicating the return rate that equalizes discounted revenues and costs.
- **CBR (Cost-Benefit Ratio)**: dimensionless index obtained as the ratio of discounted benefits to discounted costs.

Each row corresponds to a different alternative under evaluation.

Beneath the table, a bar chart presents a visual comparison of the alternatives with respect to the three KPIs:

- The **NPV chart** highlights the net economic advantage of each option. Negative NPVs are shown in red to indicate unprofitable alternatives.
- The **IRR chart** compares the internal return rates. Values above a pre-defined threshold (e.g., MARR) are favorable.

- The **CBR chart** shows investment efficiency. Values below 1.0 are displayed in red to signal that costs exceed benefits.

Figure 6-4 shows the table chart related to the NPV.

CBA results ranking

This is the overall ranking of the alternatives evaluated according to the economic criteria.

Table Chart

	Alternatives	NPV	IRR	CBR
1	A_5	500.000	15,0 %	0,90
2	A_4	400.000	2,0 %	0,95
3	A_3	200.000	12,0 %	1,05
4	A_2	100.000	2,0 %	1,15
5	A_1	10.000	8,0 %	2,00

Figure 6-3. Alternatives summary table

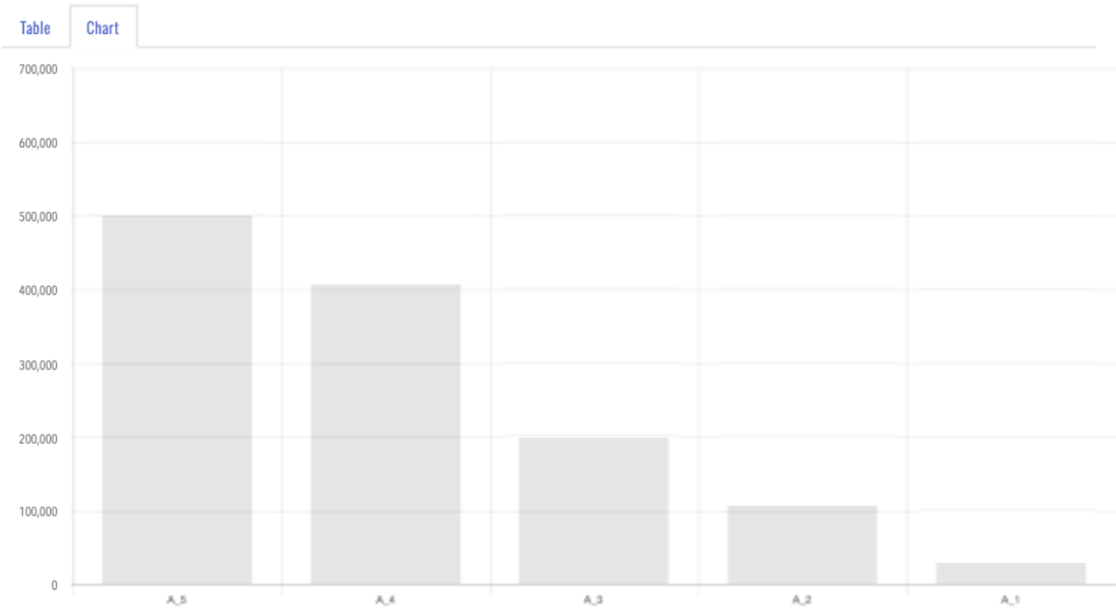


Figure 6-4: NPV bar chart

6.3.2 Economic criteria

For considering the *Economic criteria*, check the *Economic criteria* check box; then, select the which metrics you want to assess by checking the related checkbox. For example, Figure 6-5 depicts the *Economic branch* checkboxes, only the *Net Present Value* metric is selected.

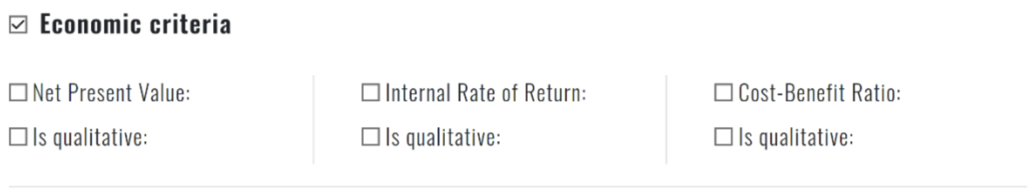


Figure 6-5: Economic branch checkboxes

If the options' attributes corresponding to the economic KPIs are quantitative, the checkboxes have to be unchecked. Conversely, if the economic attributes are assessed qualitatively, the checkbox corresponding to the economic KPIs has to be checked.

6.3.3 Smart grid criteria

For considering the *Smart grid criteria*, check the *Smart grid criteria* check box; then, select the which metrics you want to assess by selecting the items in the dropdown menu which appears.

First select a *Policy Criterion* in the dropdown menu which appears on the left, as depicted in Figure 6-6.

Then, select one of the related KPI in the dropdown menu that appears on the right, as depicted in Figure 6-7.

Once you selected the KPI, press *Add* to confirm.

To build the smart grid evaluation branch of your PA, repeat the steps described in this section. The built-in palette encompasses the criteria and related KPI described in Table 2. The list of *Policy Criteria* and KPIs is fully customizable, see section 6.12.

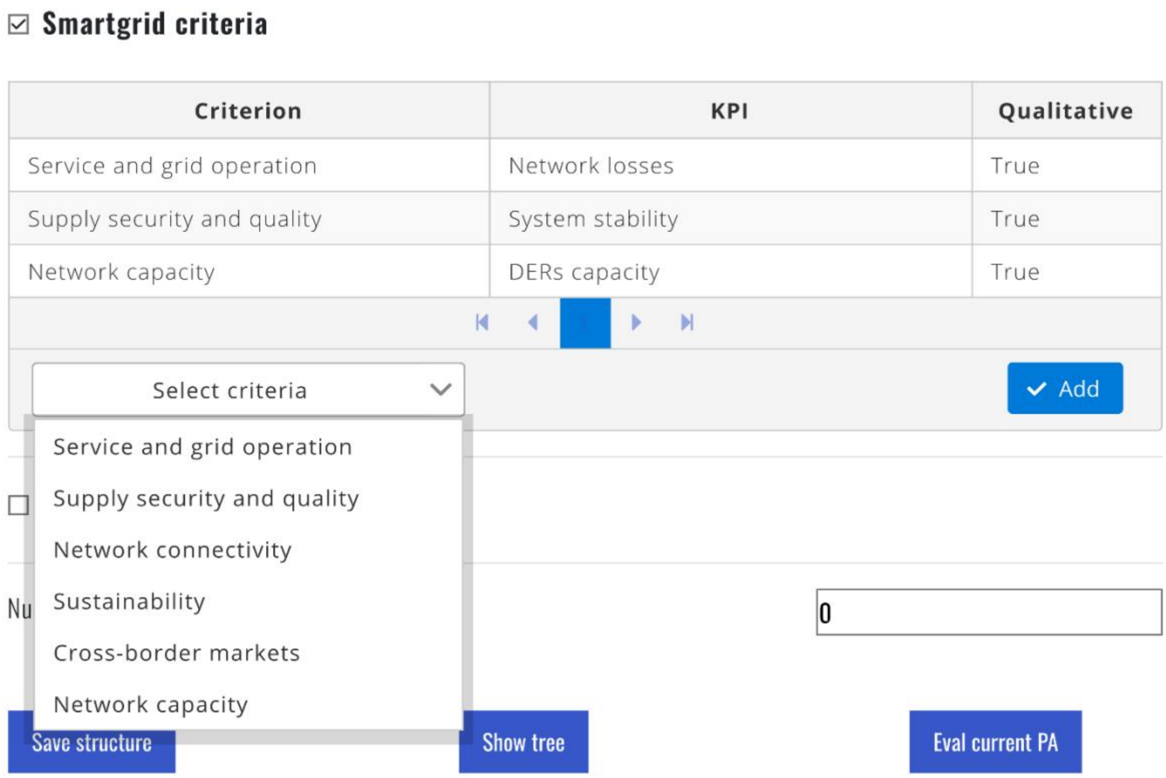


Figure 6-6: Policy Criterion selection for smart grid branch

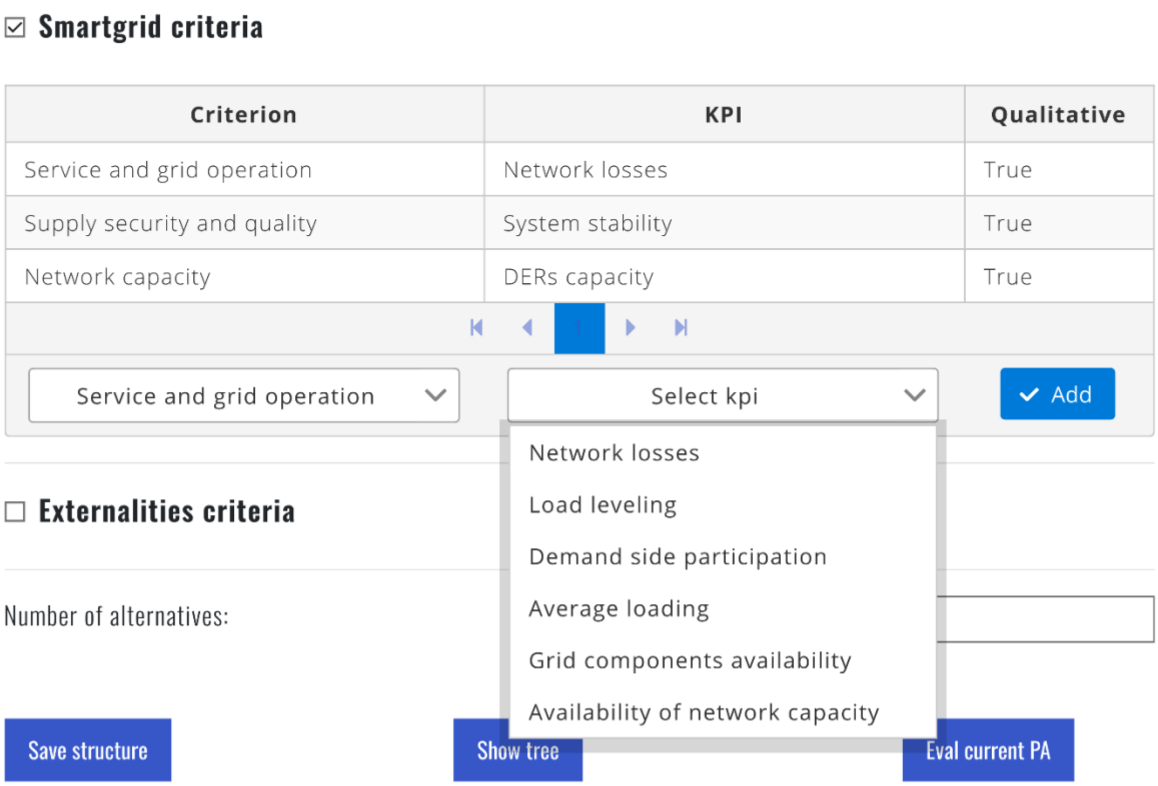


Figure 6-7: KPI selection for smart grid branch

When the KPI is included in the decision-problem structure, the user has to specify if the KPI is evaluated according to a quantitative or qualitative assessment of the options attributes, as depicted in Figure 6-8. If the options' attributes corresponding to the economic KPIs are quantitative, the checkboxes have to be unchecked. Conversely, if the economic attributes are assessed qualitatively, the checkbox corresponding to the economic KPIs has to be checked.

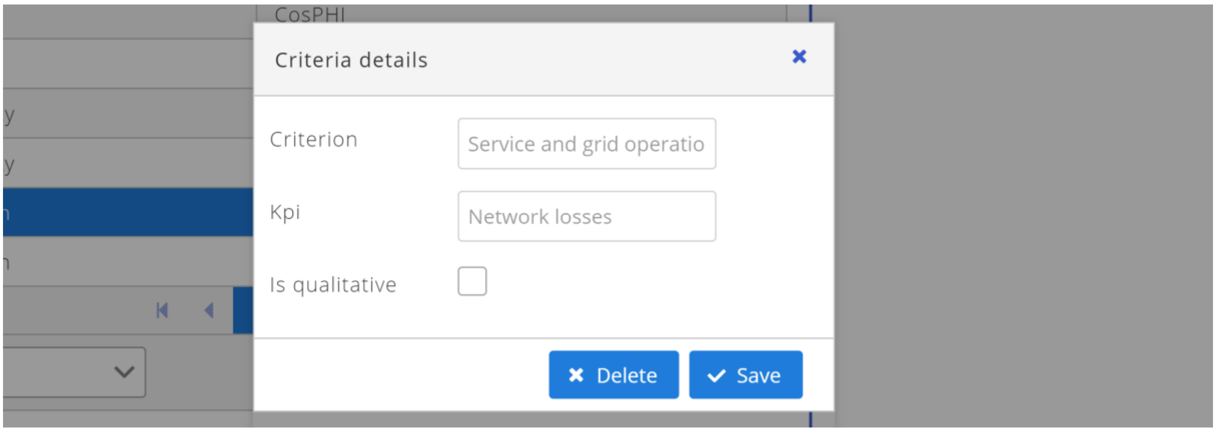


Figure 6-8: Smart grid KPI details

6.3.4 The Externality criteria

For considering the *Externality criteria*, check the *Externality criteria* check box; then, select the which metrics you want to assess by selecting the items in the dropdown menu which appears.

First select an *Externality Criterion* in the dropdown menu which appears on the left, as depicted in Figure 6-9.

Then, select one of the externalities KPIs in the dropdown menu that appears on the right, as depicted in Figure 6-10.

Once you have selected the externality KPI, press *Add* to confirm.

To build the externality evaluation branch of your PA, repeat the steps described in this section. The built-in palette encompasses the criteria and related KPI in Table 5 and Table 6.
The list of *Externality Criteria* and Externality KPIs is fully customizable, see section 6.12.

Table 5: Externality criteria palette

Item n.	Externality Criterion
1	Impacts on society
2	Impacts on environment
3	Impacts on electricity actors

Table 6: Externality KPI palette

Item n.	Externality KPI
1	Job creation
2	Safety
3	Environmental impact
4	Privacy and security
5	Ageing workforce
6	Social acceptance
7	Time saved by consumer
8	Enhanced market dynamism
9	Enhanced service offer
10	Enhanced network user inclusion

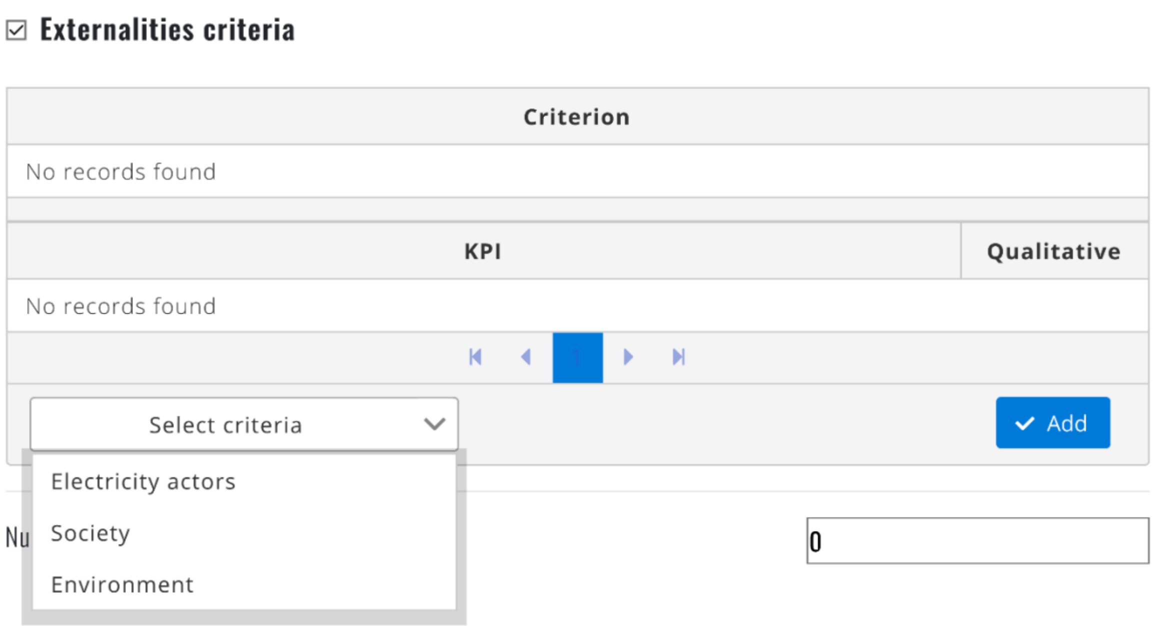


Figure 6-9: Externality criterion selection for externality branch

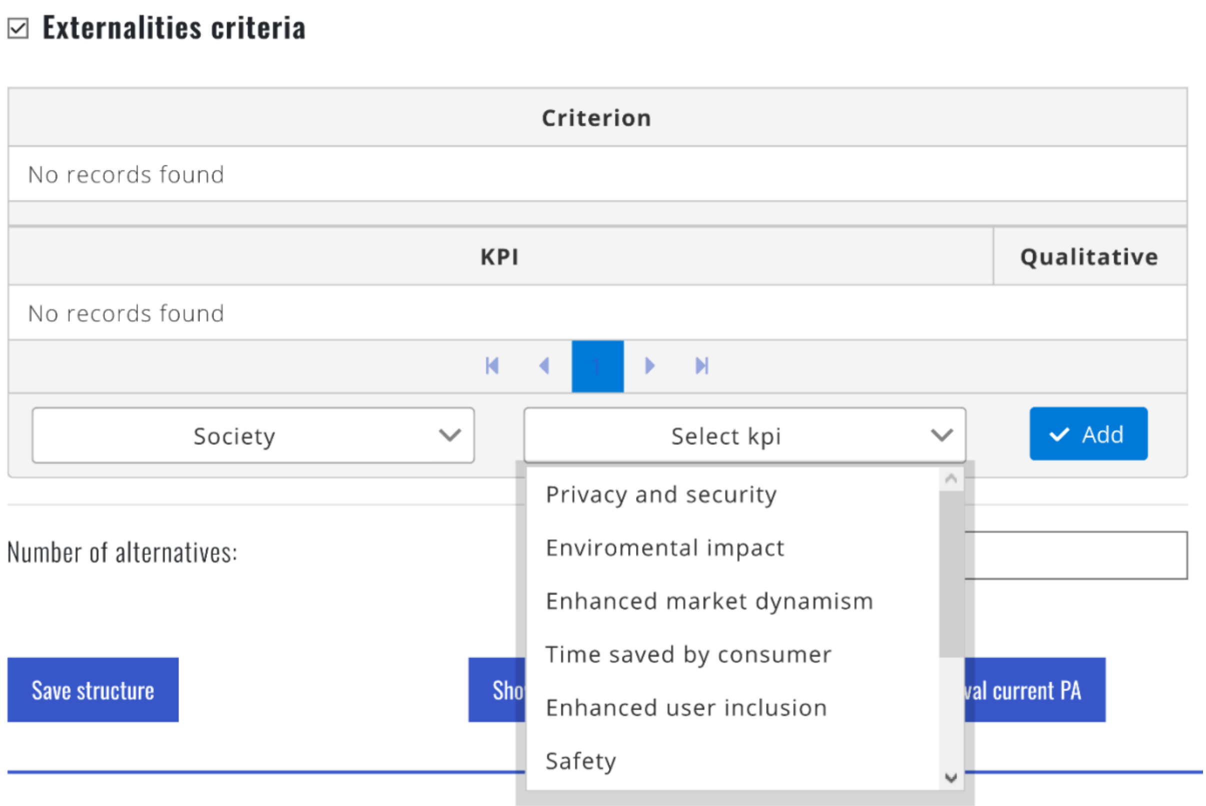


Figure 6-10: KPI selection for externality branch

When the KPI is included in the decision-problem structure, the user has to specify if the KPI is evaluated according to a quantitative or qualitative assessment of the options attributes, as depicted in Figure 6-11. If the options' attributes corresponding to the economic KPIs are quantitative, the checkboxes have to be unchecked. Conversely, if the economic attributes are assessed qualitatively, the checkbox corresponding to the economic KPIs has to be checked.

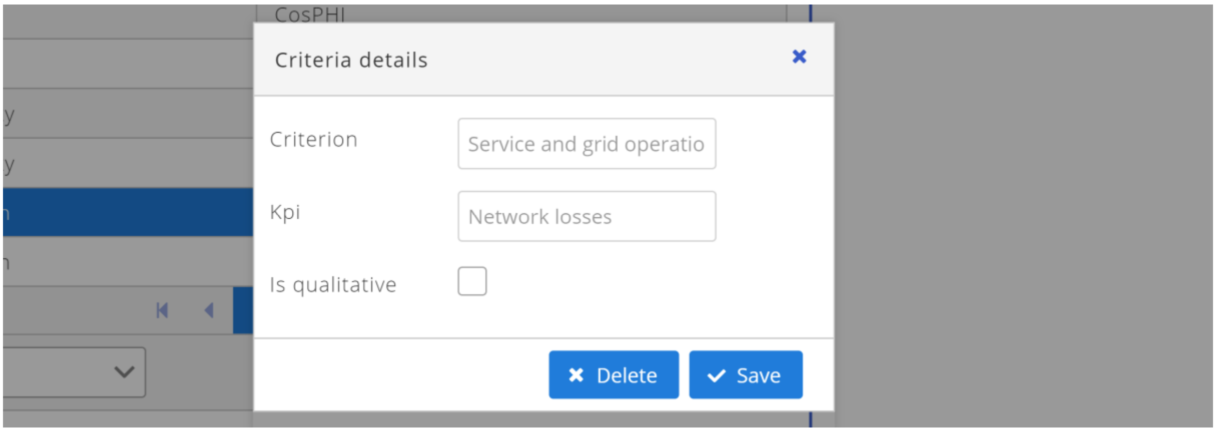


Figure 6-11: Externality KPI details

6.3.5 Definition of the alternatives

Once the hierarchical structure of the decision-making problem is defined according to the steps described in section 6.3.2, 6.3.3 and 6.3.4, the alternatives that form the decision making problem have has to be specified.

A dedicated section is devised for defining the input data of the options under appraisal, as depicted in Figure 6-12.

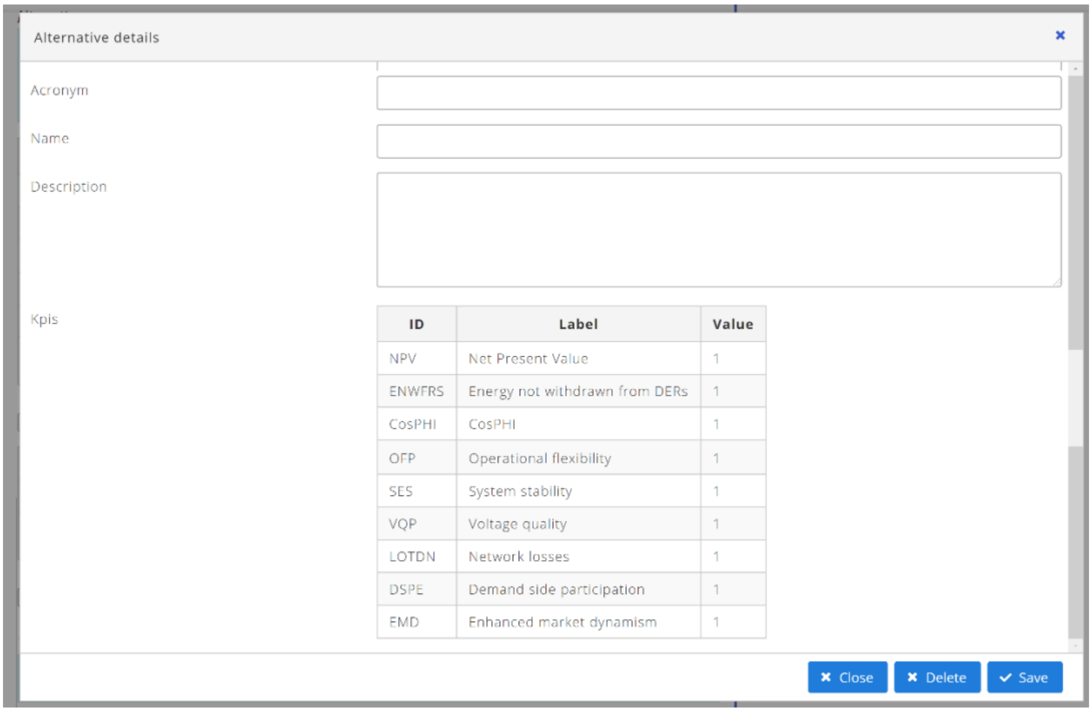


Figure 6-12: Provide the number of the alternatives

For each option of the decision-making problem has to be specified:

- Acronym
- Name
- Description
- Quantitative attribute values for each KPI.

The definition of the quantitative attribute values for each KPI is possible by means of the interactive table that lists all the KPIs of the decision-making problem.

The attributes' information corresponding to KPIs that are qualitatively evaluated has to be provided according to the procedure described in sections 6.5.4.2, 6.5.5.2, and 6.5.6.2.

6.3.6 Select the algorithm to solve the decision making problem

The *Weights algorithm* tab allows the user to selecting the weighting method to be used define the weights of criteria for the evaluation of the planning activity. Six methodologies are implemented:

- Subjective weights,
- Synthetic entropy weights,
- Synthetic ideal point weights,
- Synthetic standard deviation weights,
- Hybrid entropy weights,
- Hybrid ideal point weights,
- Hybrid standard deviation weights.
- Regret Theory algorithm

A detailed description of the algorithms of the implemented weighting methods is provided in the Appendix.

The manual weights algorithm requires the user to express its preference about the relevance of the evaluation criteria, as described in sections 6.5.1, 6.5.2, and 6.5.3.

The entropy weights algorithm calculates the weight of criteria according to the Shannon's Entropy method on the basis of the information available on the performances of the alternatives.

The standard weights algorithm calculates the weight of criteria on the basis of the standard deviation of the data available on the performances of the alternatives.

The Synthetic ideal point weights are calculated on the basis of the data available from the performance matrix of the alternatives by exploiting the Ideal point algorithm.

The hybrid methods evaluate the weights of the criteria by combining the subjective weights obtained by means of the Manual weights algorithm and one of the synthetic weighting algorithms. Therefore, the procedure for defining the Manual weights have to be undertaken also in the case of evaluation based on a hybrid algorithm.

The exploitation of hybrid methods requires to define the algorithm that has to be used for combining the manual and the synthetic weights. The aggregation algorithms that can be selected are:

- Aggregation by product;
- Aggregation by linear combination;
- Aggregation by power.

A detailed description of each algorithm is provided in Appendix 11.2.

Each combination algorithm requires to define a combination parameter (α) which models the relevance of the manual weights over the synthetic weights in defining the final value of the hybrid weights. To illustrate, α equals to one means that the hybrid weights will coincide with the manual weights; on the contrary, α equals to one means that the hybrid weights will coincide with the synthetic weights.

6.3.7 Scenario analysis NEW !

If the user intends to use the tool to perform a weighted scenario analysis, they must first click on the dedicated button, which redirects to the specific Scenario weights interface.

This section allows the user to assign relative importance to each scenario considered in the evaluation. The weights, entered manually or adjusted via sliders (see), determine the contribution of each scenario to the overall analysis. By default, weights are uniformly distributed. The system ensures that the total weight sums to one, maintaining consistency across the comparative assessment of alternatives.

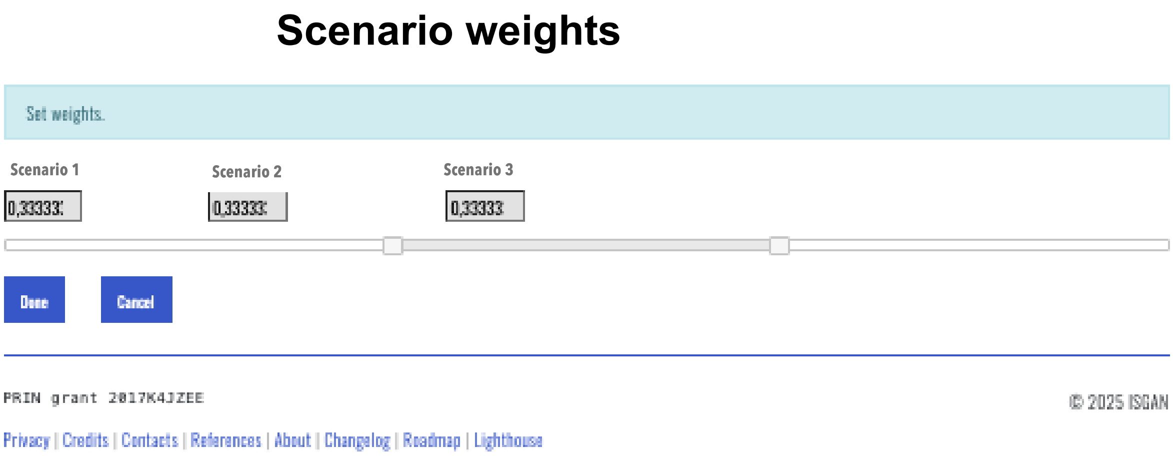


Figure 6-13 Scenario weights page

Once the main criteria weights are defined, press *Done.*

6.3.8 Save the hierarchical structure

To save the hierarchical structure of the PA provided according to steps described in section 6.3, press the *Save structure* button on the bottom-left of the *Planning activity overview* page.

6.4 Show tree

The hierarchical structure of the PA provided according to steps described in section 6.3 can be depicted in terms of a tree of criteria.

To show the graphical representation of the hierarchical structure of the PA press *Show tree.* Figure 6-14 represents an example of the tree of criteria of a PA. The horizontal tree is interactive and full explorable. To explode a subbranch, press the icon "+" of the item. To reduce a subbranch, press the icon "-" of the item.

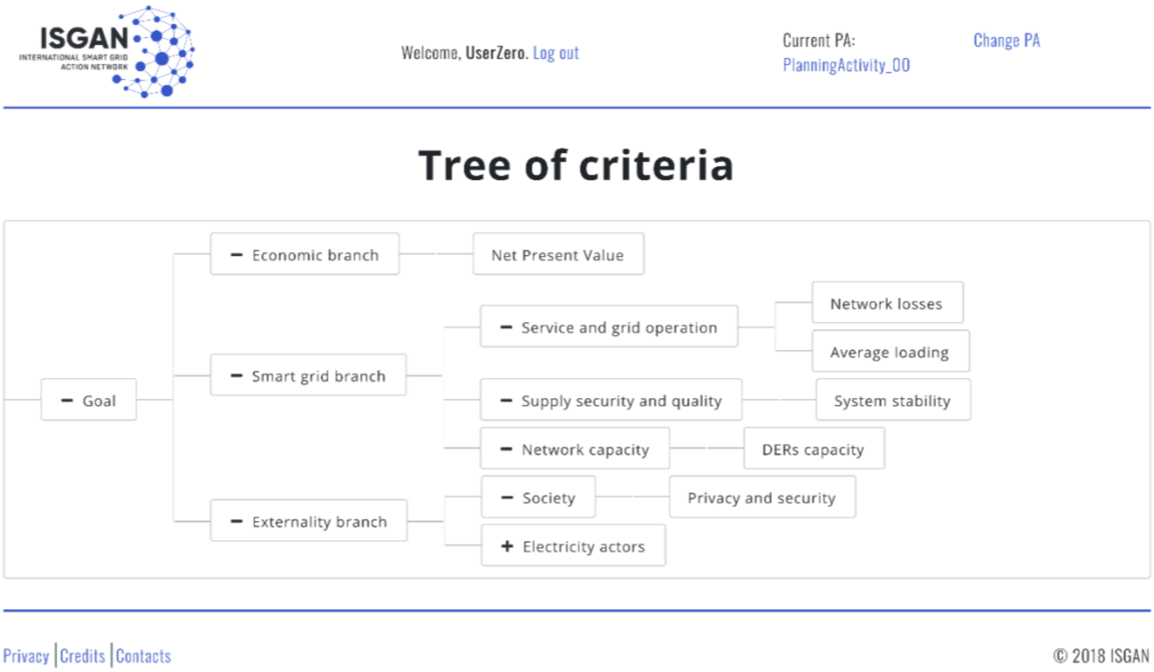


Figure 6-14: Example of tree of criteria

6.5 To-Do checklist

The *To-Do checklist* subsection provides an explorable to-do checklist for the PA assessment, once each step is accomplished, the items will be checked (✓); whereas, for missing steps the related item is identified as unchecked (✗). Each item of the checklist is a clickable link which redirects to the related input data page.

Once the hierarchical structure is specified and saved, if it results congruent, the structural parameters item is positively checked: ✓ Structural parameters;

6.5.1 Branch weights

The overall PA assessment requires to specify the relevance of the evaluation branches.

To specify the branch weights, click on the ✗ Branch weights item on the *To-Do checklist*.

The *Main criteria weights* page is depicted in Figure 6-15, to define the numerical value of the weights of the three branches, move the position of the points in the slider.

By default, an equal relevance is provided to each branch.

If the PA encompasses all three evaluation branches, the first sector is related to the economic branch relevance, the second to the smart grid merit relevance, and the third branch to the externality criteria relevance.

If the PA encompasses two evaluation branches, the sector order of the slider follows the order of the checked elements in the *Structural parameters* section.

If the PA encompasses only one evaluation branch, the branch weight is equal to 1, therefore it is not necessary to specify a weight by means of the slider.

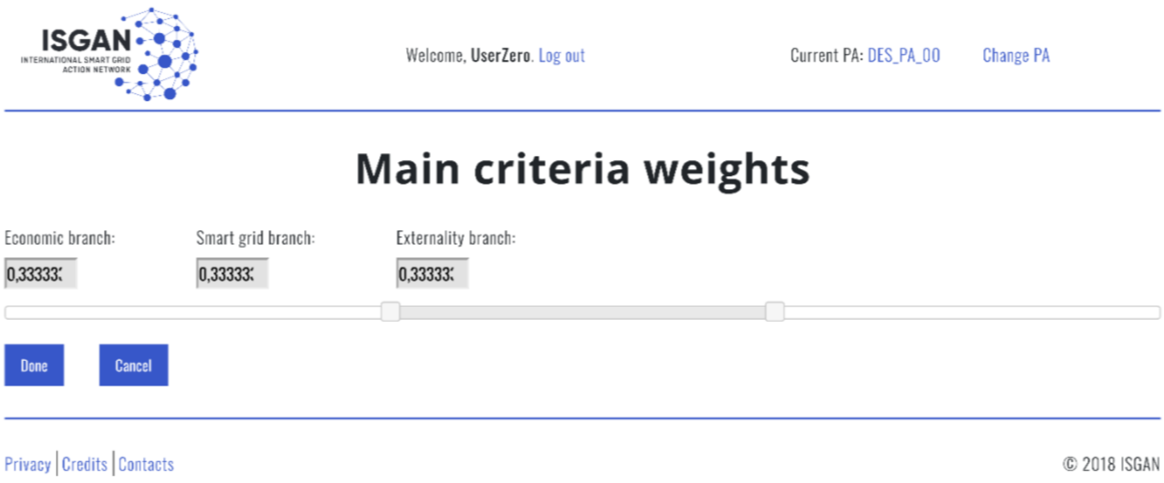


Figure 6-15: Main criteria weights page

Once the main criteria weights are defined, press *Done.*

The item on the *To-Do checklist* becomes positively checked: ✓ Branch weights.

6.5.2 Economic criteria weights

The economic PA assessment requires to specify the relevance of the evaluation criteria in the bottom level.

To specify the weights of economic terminal criteria, click on the ✗ Economic criteria weights item on the *To-Do checklist*.

The *Economic criteria weights* page is depicted in Figure 6-16, to define the numerical value of the weights of the three criteria, move the position of the points in the slider.

By default, an equal relevance is provided to each criterion.

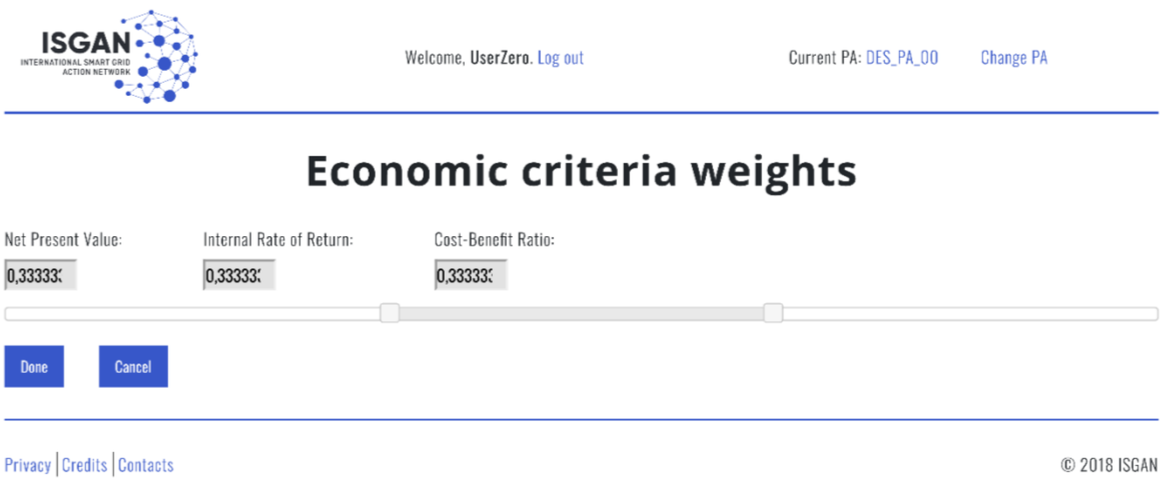


Figure 6-16: Economic criteria weights page

The order of the sectors in the slider follows the position of the terminal criteria in the economic branch.

Therefore:

- If the PA encompasses all three economic terminal criteria, the first sector is related to the NPV relevance, the second to the IRR relevance, and the third branch to the BCR relevance.
- If the PA encompasses two economic terminal criteria, the sector order of the slider follows the order of the checked elements in the *Economic criteria* section.
- If the PA encompasses only one economic terminal criterion, the criterion weight is equal to 1, therefore it is not necessary to specify a weight by means of the slider.

Once the economic terminal criteria weights are defined, press *Done.*

The item on the *To-Do checklist* becomes positively checked: ✓ Economic criteria weights.

6.5.3 Externality criteria weights

The externality PA assessment requires to specify the relevance of the evaluation criteria in the branch.

To specify the weights of the criteria in the externality branch, click on the
✗ Externality criteria weights item on the *To-Do checklist*.

An example of the *Externality criteria weights* page is depicted in Figure 6-17, to define the numerical value of the weights of the criteria, choose one of the following options:

- Local weights (see section 6.5.3.1)
- Matrix weights (see section 6.5.3.2).

By default, the equal relevance is assigned to all criteria on a same level; to keep this value, click on *Submit* button.

6.5.3.1 Local weights on externality branch

To specify the local weights of the criteria of externality branch, upload the .xlsx file which contains the local priority vectors in a sheet named EXTW. The local priority vectors in the EXTW sheet have to following the structure described in Table 7.

Table 7: Local priority vector for the externality branch

Cells	A	B	C		n	m
1		**EC₁**	**EC₂**	**…**	**ECₙ**	
2	**Externality criteria layer**	v_1	v_2	v_j	v_n	
3	**KPIs vs. EC₁**	$w_{1,1}$	$w_{2,1}$	$w_{i,1}$	$\dots$	$w_{m,1}$
4	**KPIs vs. EC₂**	$w_{1,2}$	$w_{2,2}$	$w_{i,2}$	$\dots$	$w_{m,2}$
	…	$\dots$	..		$w_{i,j}$	
n+1	**KPIs vs. ECₙ**	$w_{1,n}$	$w_{2,n}$	$w_{i,n}$	$\dots$	$w_{m,n}$

Where *n* is the number of Externality Criteria while *m* is the number of externality KPIs in the terminal level of the branch. The first row of the local priority matrix hosts the local priority vector of the Externality Criteria (from cell B2), v_j is the local priority of the j-th Externality Criterion. The following *n* rows of the local priority matrix host the local priority vectors of the KPIs with respect to each Externality Criterion. To illustrate, the row that starts from cell B3 is the local priority vectors of KPIs with respect to the Externality Criterion EC_1. $w_{i,j}$ is the local priority of the i-th externality KPI with respect to the j-th Externality Criterion. Note that the priority vectors have to satisfy the condition defined by the relation (1) and (2).

$$\sum_{j=1}^{n} \boldsymbol{v_j} = \mathbf{1} \tag{1}$$

$$\sum_{i=1}^{m} w_{i,j} = 1 \tag{2}$$

To upload the .xlsx file press on *Choose file.* Select the .xlsx file from the dialog box which appears. Once the .xlsx file is selected press *Done.*

If the upload is successful a green colored message appears, press on the name of your PA in the header to come back to the *Planning activity overview* page.

If the upload is not successful a red colored message appears, repeat the steps for achieving a successful upload.

6.5.3.2 Matrix weights on externality branch

To specify the weights of the criteria of externality branch in terms of matrix weights, edit the pairwise comparison matrices of the first level and second level criteria, as shown in Figure 6-17. The pairwise comparison follows the procedure define by Saaty in AHP described in section 3.5 [5]. First define the preferences on the Externality Criteria by editing the *First level* matrix. Then, for each Externality Criterion, express the preferences on externality KPIs by editing the related *Second level* matrix. Each second level matrix appears by clicking on the name of the related Externality Criterion.

The *Generate consistent matrix* button allows to complete the preference matrix according to the information provided in the first row. It simplifies the weighing procedure by defining a consistent set of preferences.

Once the pairwise comparison procedure is completed, click on *Submit* to submit the provided data.

Press on the name of your PA in the header to come back to the *Planning activity overview* page.

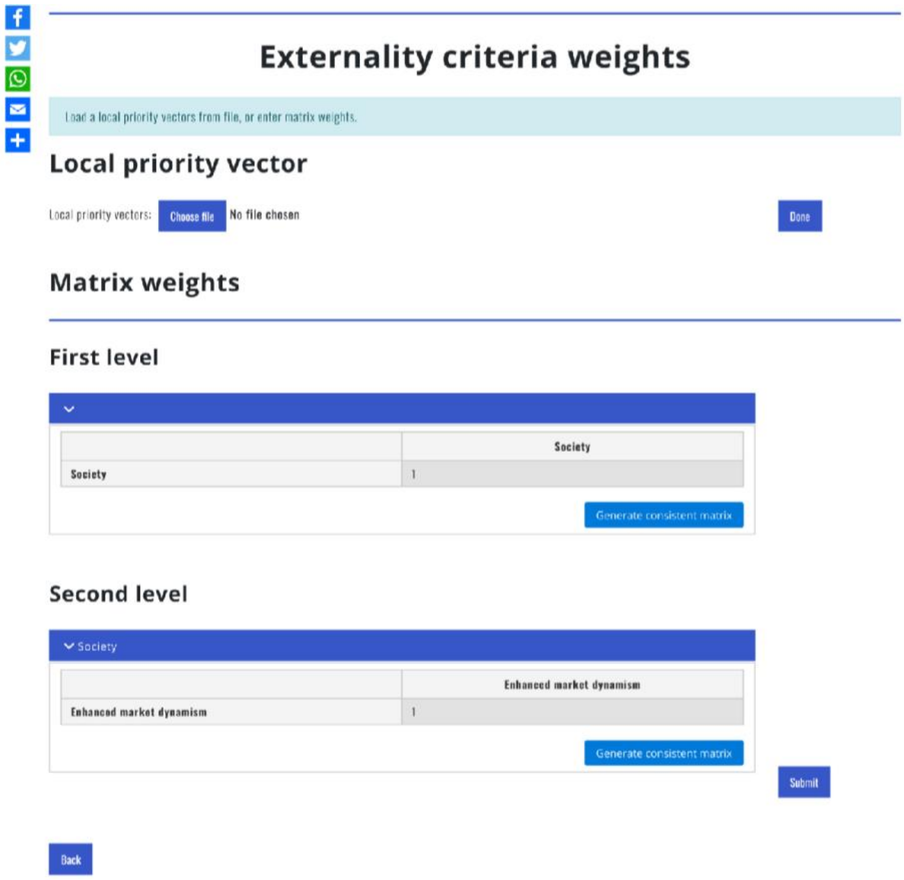


Figure 6-17: Externality criteria weights page

6.5.4 Attributes on economic criteria

The economic PA assessment requires to specify the economic performances of the alternatives.

To specify the economic performances of the alternatives on the economic terminal criteria, click on the ✕ Performances on economic criteria item on the *To-Do checklist*.

An example of the *Performances on economic criteria* page is depicted in Figure 6-18, to define the performances of the alternatives with respect to the economic terminal criteria, choose one of the following options:

- Quantitative scoring (see section 6.5.4.1)
- Qualitative scoring (see section 6.5.4.2).

By default, the equal level of performances is assigned to the alternatives on all criteria.

The *Generate consistent matrix* button allows to complete the preference matrix according to the information provided in the first row. It simplifies the weighing procedure by defining a consistent set of preferences.

Once the information is provided, click on *Submit* button.

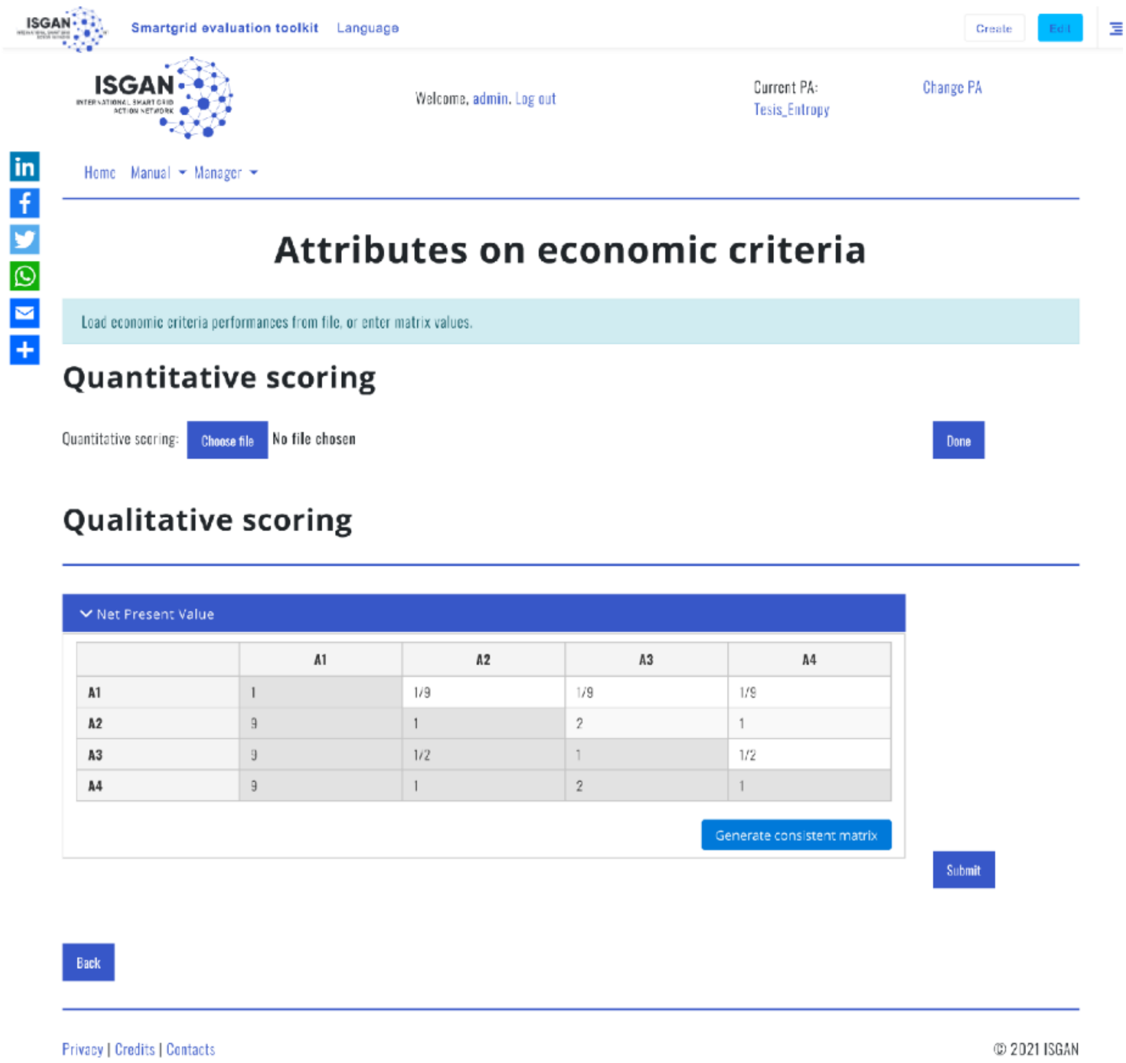


Figure 6-18: Performances on economic criteria page

6.5.4.1 Quantitative scoring on economic branch

To submit a quantitative scoring of the alternatives, upload the .xlsx file which contains the Performance Matrix of the alternatives on the economic criteria in a sheet named ECO. The Performance Matrix in the ECO sheet has to following the structure described in Table 8.

Table 8: Local priority vector for the externality branch

Cells	A	B	C	D
1		NPV	IRR	BCR
2	Alternative 1	$a_{1,1}$	$a_{1,2}$	$a_{1,3}$
3	Alternative 2	$a_{2,1}$	$a_{2,2}$	$a_{2,3}$
i-th	Alternative i	$a_{i,1}$	$a_{i,2}$	$a_{i,3}$
Q	Alternative q	$a_{q,1}$	$a_{q,2}$	$a_{q,3}$

Where

- q is the number of the alternatives of the PA, has defined in section 6.3.5;
- $a_{i,1}$ is the attribute of the i-th alternative in terms of NPV;
- $a_{i,2}$ is the attribute of the i-th alternative in terms of IRR;
- $a_{i,3}$ is the attribute of the i-th alternative in terms of BCR.

If one or two economic terminal criteria are neglected from the PA, the column of the remaining are moved to the left according to the position in the checklist of the *Planning activity overview* (see Figure 6-5).

Since the aim is to identify the best smart grid option, the three terminal criteria, NPV, IRR, and BCR are satisfied with increasing values of the attributes. However, an assessment that favor the alternatives which minimize the attribute values on these criteria is possible by uploading an .xlsx file with the sign of the entries changed.

To upload the .xlsx file press on *Choose file.* Select the .xlsx file from the dialog box which appears. Once the .xlsx file is selected press *Done.*

If the upload is successful a green colored message appears, press on the name of your PA in the header to come back to the *Planning activity overview* page.

If the upload is not successful a red colored message appears, repeat the steps for achieving a successful upload.

6.5.4.2 Qualitative scoring on economic branch

To submit a qualitative scoring of the alternatives, edit the pairwise comparison matrices of the alternatives on the economic terminal criteria, as shown in Figure 6-18. The pairwise comparison follows the procedure define by Saaty in AHP described in section 3.5 [5].

For each economic terminal criterion, express the preferences on the alternatives by editing the related matrix. Each matrix appears by clicking on the name of the related economic terminal criterion.

Once the pairwise comparison procedure is completed, click on *Submit* to submit the provided data.

Press on the name of your PA in the header to come back to the *Planning activity overview* page.

6.5.5 Attributes on smart grid KPIs

The smart grid merit PA assessment requires to specify the smart grid performances of the alternatives.

To specify the performances of the alternatives on the smart grid terminal criteria, click on the ✖ Performances on smart grid KPIs item on the *To-Do checklist*.

An example of the *Performances on smart grid KPIs* page is depicted in Figure 6-19, to define the performances of the alternatives with respect to the smart grid KPIs, choose one of the following options:

- Quantitative scoring (see section 6.5.5.1)
- Qualitative scoring (see section 6.5.5.2).

By default, the equal level of performances is assigned to the alternatives on all criteria; to keep this value, click on *Submit* button.

6.5.5.1 Quantitative scoring on smart grid branch

To submit a quantitative scoring of the alternatives, upload the .xlsx file which contains the Performance Matrix of the alternatives on the smart grid KPIs in a sheet named SG. The Performance Matrix in the SG sheet has to following the structure described in Table 9.

Table 9: Performance Matrix for the smart grid branch

Cells	A	B	C	D
1		**KPI_1**	**KPI_j**	**KPI_m**
2	**Alternative 1**	$a_{1,1}$	$a_{1,j}$	$a_{1,m}$
3	**Alternative 2**	$a_{2,1}$	$a_{2,j}$	$a_{2,m}$
i-th	**Alternative i**	$a_{i,1}$	$a_{i,j}$	$a_{i,m}$
q	**Alternative q**	$a_{q,1}$	$a_{q,j}$	$a_{q,m}$

Where

- q is the number of the alternatives of the PA, has defined in section 6.3.5;
- m is the number of the smart grid KPI of the PA, has defined in section 6.3.3;
- $a_{i,j}$ is the attribute of the i-th alternative in terms of j-th smart grid KPI;

If one or more smart grid KPIs are evaluated according to qualitative attributes, the column of the corresponding KPI in the SG sheet has to be filled by zeros. To illustrate, if the j-th smart grid KPI is evaluated qualitatively, all the $a_{i,j}$ elements with i=1,2, ..., q as to be equal to zero.

The attributes of the alternatives have to be provided by means of the pairwise comparison process as described in section 6.5.5.2.

Since the aim is to identify the best smart grid option, the KPIs are satisfied with increasing values of the attributes. However, an assessment that favor the alternatives which minimize the attribute values on a KPI is possible by uploading an .xlsx file with the sign of the entries in the related column changed.

To upload the .xlsx file press on *Choose file.* Select the .xlsx file from the dialog box which appears. Once the .xlsx file is selected press *Done.*

If the upload is successful a green colored message appears, press on the name of your PA in the header to come back to the *Planning activity overview* page.

If the upload is not successful a red colored message appears, repeat the steps for achieving a successful upload.

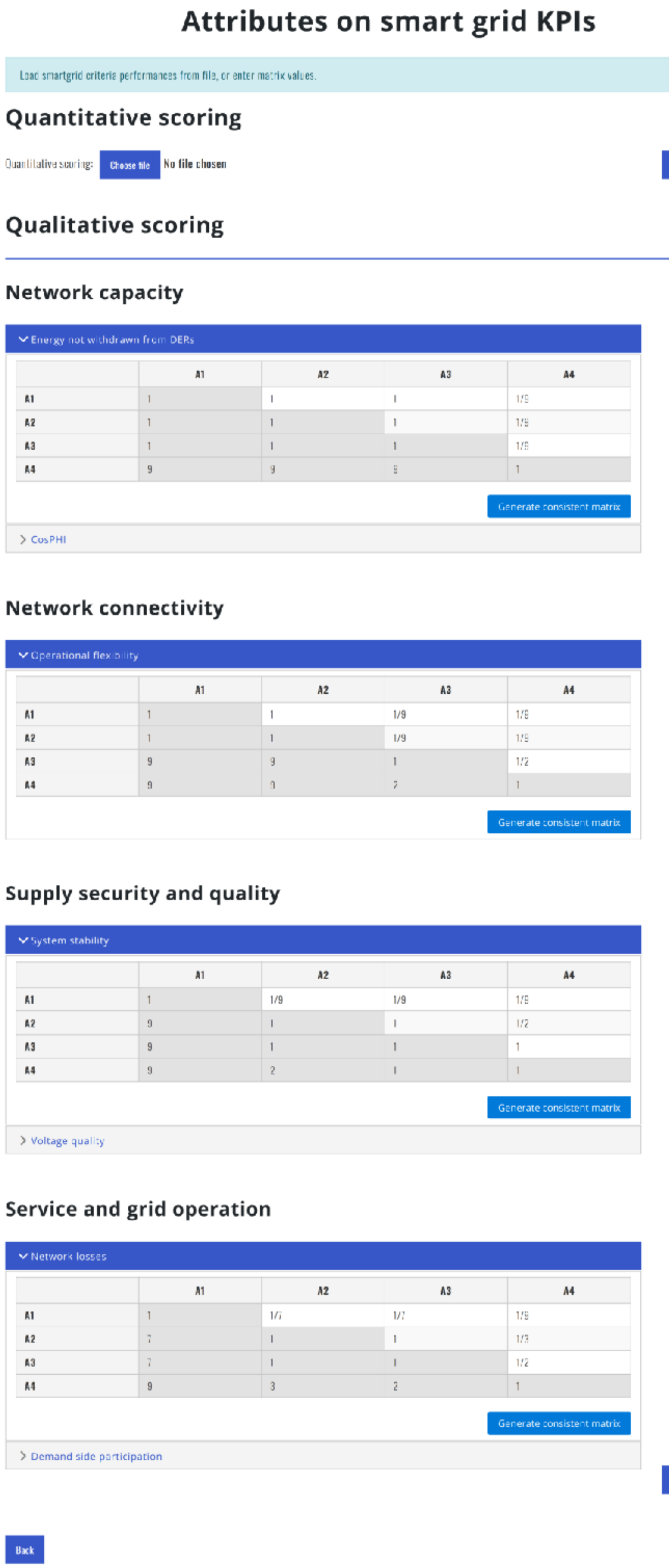


Figure 6-19: Performances on smart grid KPIs page

The *Generate consistent matrix* button allows to complete the preference matrix according to the information provided in the first row. It simplifies the weighing procedure by defining a consistent set of preferences.

6.5.5.2 Qualitative scoring on smart grid branch

To submit a qualitative scoring of the alternatives, edit the pairwise comparison matrices of the alternatives on the KPIs, as shown in Figure 6-19. The pairwise comparison follows the procedure define by Saaty in AHP described in section 3.5 [5].

For each KPI, express the preferences on the alternatives by editing the related matrix. Each matrix appears by clicking on the name of the related KPI.

Once the pairwise comparison procedure is completed, click on *Submit* to submit the provided data.

Press on the name of your PA in the header to come back to the *Planning activity overview* page.

6.5.6 Attributes on externality KPIs

The externality PA assessment requires to specify the impacts in terms of externalities of the alternatives.

To specify the performances of the alternatives on the externality terminal criteria, click on the ✕ Performances on externality KPIs item on the *To-Do checklist*.

An example of the *Performances on externality KPIs* page is depicted in Figure 6-20, to define the performances of the alternatives with respect to the externality KPIs, choose one of the following options:

- Quantitative scoring (see section 6.5.6.1)
- Qualitative scoring (see section 6.5.6.2).

By default, the equal level of performances is assigned to the alternatives on all criteria; to keep this value, click on *Submit* button.

6.5.6.1 Quantitative scoring on smart grid branch

To submit a quantitative scoring of the alternatives, upload the .xlsx file which contains the Performance Matrix of the alternatives on the externality KPIs in a sheet named EXT. The Performance Matrix in the EXT sheet has to following the structure described in Table 10.

Table 10: Performance Matrix for the externality branch

Cells	A	B	C	D
1		**EPI1**	**EPIj**	**EPIm**
2	**Alternative 1**	$a_{1,1}$	$a_{1,j}$	$a_{1,m}$
3	**Alternative 2**	$a_{2,1}$	$a_{2,j}$	$a_{2,m}$
i-th	**Alternative i**	$a_{i,1}$	$a_{i,j}$	$a_{i,m}$
q	**Alternative q**	$a_{q,1}$	$a_{q,j}$	$a_{q,m}$

Where

- q is the number of the alternatives of the PA, has defined in section 6.3.5;
- m is the number of the externality KPI (EPI) of the PA, has defined in section 6.3.3;
- $a_{i,j}$ is the attribute of the i-th alternative in terms of j-th externality KPI;

If one or more externality KPIs are evaluated according to qualitative attributes, the column of the corresponding KPI in the EXT sheet has to be filled by zeros. To illustrate, if the j-th externality KPI is evaluated qualitatively, all the $a_{i,j}$ elements with i=1,2, ..., q as to be equal to zero. The attributes of the alternatives have to be provided by means of the pairwise comparison process as described in section 6.5.6.2.

Since the aim is to identify the best smart grid option, the EPIs are satisfied with increasing values of the attributes. However, an assessment that favor the alternatives which minimize the attribute values on an EPI is possible by uploading an .xlsx file with the sign of the entries in the related column changed.

To upload the .xlsx file press on *Choose file.* Select the .xlsx file from the dialog box which appears. Once the .xlsx file is selected press *Done.*

If the upload is successful a green colored message appears, press on the name of your PA in the header to come back to the *Planning activity overview* page.

If the upload is not successful a red colored message appears, repeat the steps for achieving a successful upload.

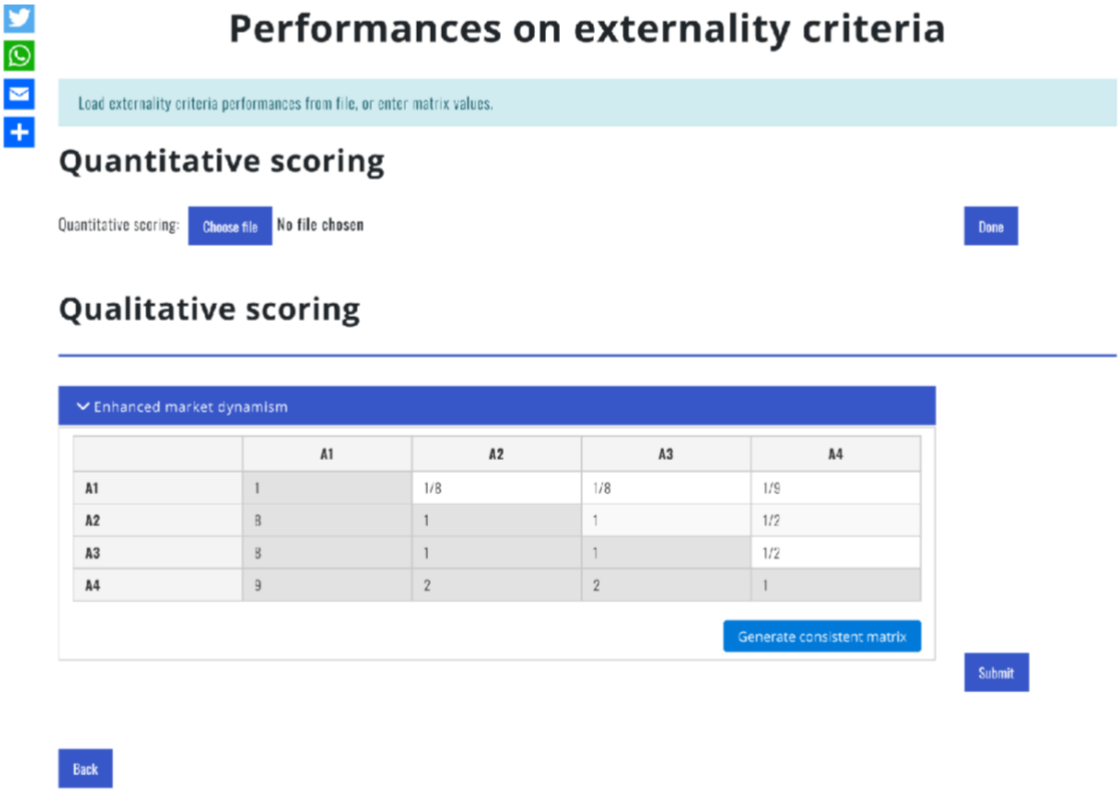


Figure 6-20: Performances on externality KPIs page

6.5.6.2 Qualitative scoring on externality branch

To submit a qualitative scoring of the alternatives, edit the pairwise comparison matrices of the alternatives on the KPIs, as shown in Figure 6-20. The pairwise comparison follows the procedure define by Saaty in AHP described in section 3.5 [5].

For each KPI, express the preferences on the alternatives by editing the related matrix. Each matrix appears by clicking on the name of the related KPI.

The *Generate consistent matrix* button allows to complete the preference matrix according to the information provided in the first row. It simplifies the weighing procedure by defining a consistent set of preferences.

Once the pairwise comparison procedure is completed, click on *Submit* to submit the provided data.

Press on the name of your PA in the header to come back to the *Planning activity overview* page.

6.5.7 Load from file

For expert users.

The process described from section 6.5.3 to 6.5.6 can be accomplished in one step by uploading an unique .xlsx file which contains all the information about the PA. The .xlsx file has to contain a sheet named STRUCT which contains the information for building the hierarchy of criteria.

6.6 Boundaries for weights (Regret Theory algorithm)

The Regret Theory algorithm does not require to specify weights for the evaluation criteria. This algorithm is based on an optimization process that finds the best option of the decision-making problem by searching in a region of the weight space. The region of the weight space is delimited by boundaries for weights defined by the user, as depicted in Figure 6-21.

In the *Boundaries for weights* page the user have to specify the minimum and the maximum value allowed for the weight of each KPI. The set of minimum and maximum values defines the boundaries of the weight space within which the decision problem is solved.

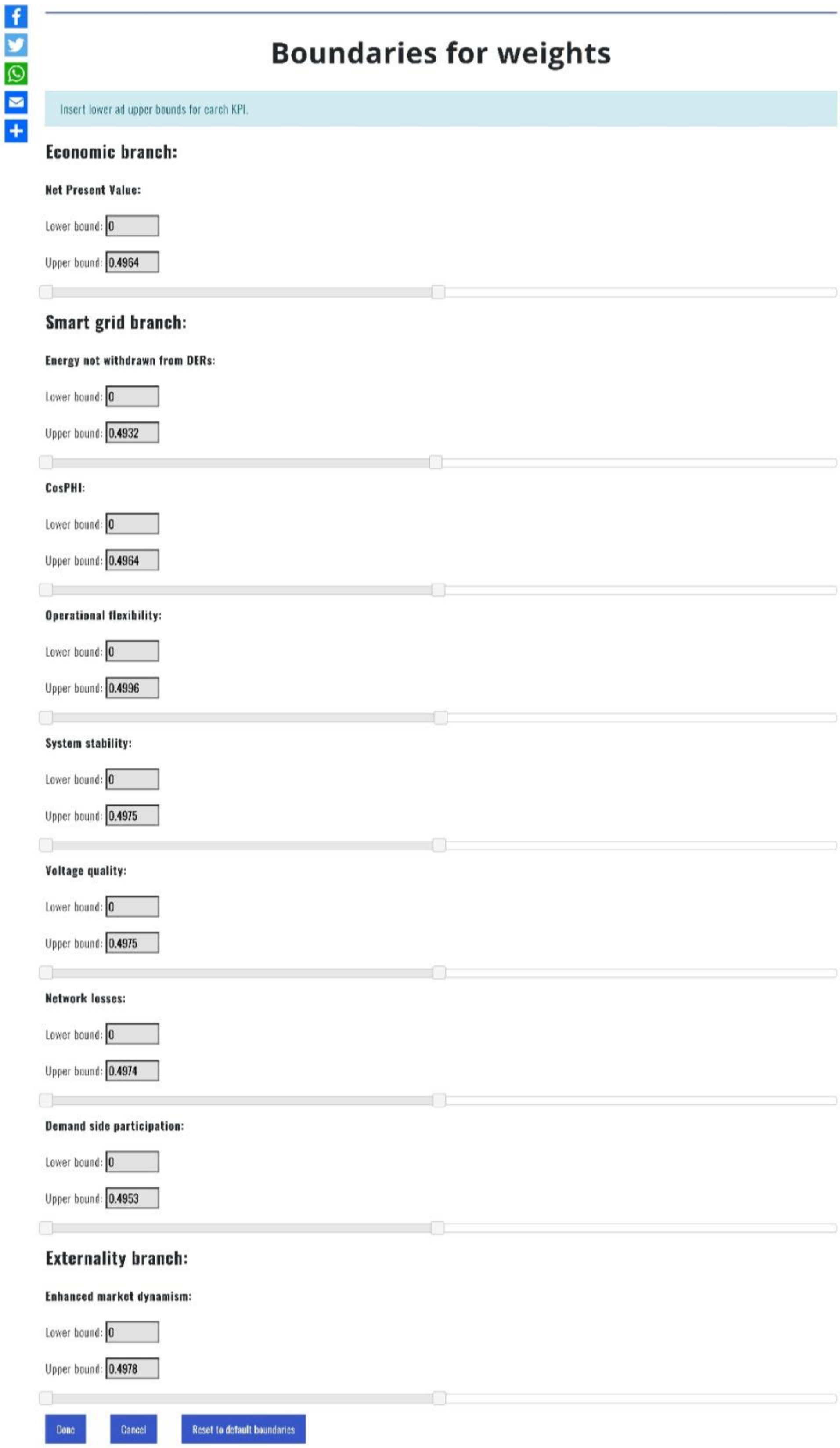


Figure 6-21: Boundaries for weight page

6.7 Evaluate the current PA

Once all the items on the checklist described in section 6.5 are completed, it is possible to obtain the overall assessment of the PA.

To evaluate the current PA, press the *Eval current PA* button in the bottom of the *Planning activity overview* page, you will be redirected to the *Result* page.

6.8 Management of process

The user can monitor the calculation processes based on the Regret Theory algorithm in the *Manage processes* page, as depicted in Figure 6-22.

In the *Manage processes* page the use can monitor the progress of the calculation task. Each calculation task is identified by a unique name, status, and creation and modification date-time strings. Furthermore, in case unexpected behavior, the user can stop and delete the calculation tasks.

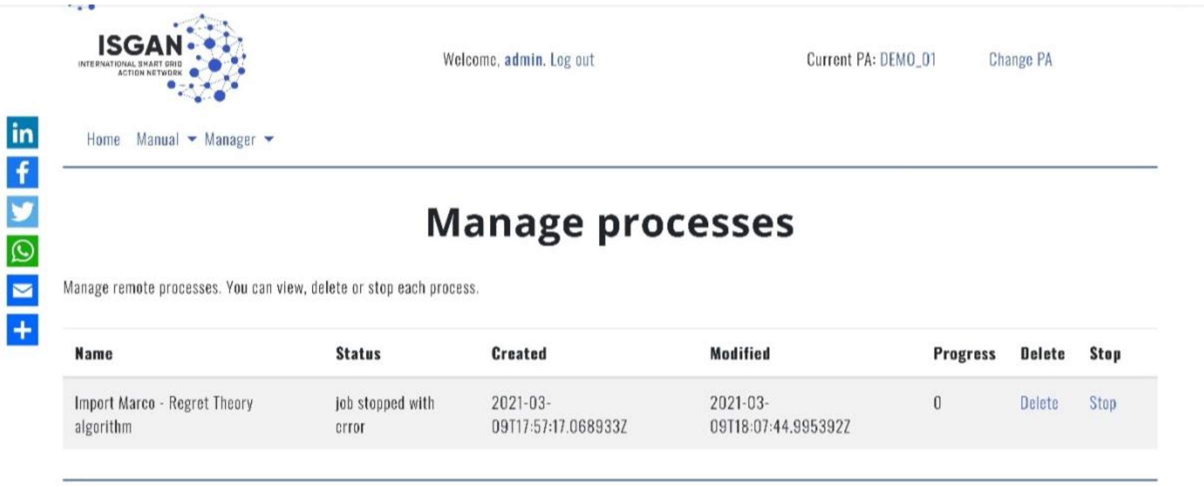


Figure 6-22: Manage processes page

6.9 Page of results

As depicted in Figure 6-23, the results of the PA assessment are showed in terms of table. The first table shows the overall ranking of the alternatives. The alternatives which achieves the highest overall score is the best alternative according to the *SmatGridEval* assessment. The second table resumes the relevance assigned to each evaluation branch. The third table shows the global weights evaluated for the terminal criteria of the hierarchy.

If one of the synthetic or hybrid algorithm is selected, the tables reporting the information about overall ranking for synthetic weights and the flat weights obtained by means of the synthetic algorithm are displayed.

To show the results in term of charts, click on the *Chart* tab on the top of each table, as shown in Figure 6-24.

At the bottom of the page, in the Others parameter table, the value of the Indicator of ranking stability is reported. This parameter provides the information about the stability of the obtained solution. The higher is the value of the Indicator, the more stable is the indication of the best alternative with respect to variations of weights values. A detailed explanation of the Indicator of ranking stability is provided in Appendix 11.3.

To export the results in a .xlsx file, click on the Download output file link on the top right of the *Result* page (Figure 6-23, Figure 6-24).

To back to the *Planning activity overview* page, click on the *Current PA* link in the header.

ISGAN INTERNATIONAL SMART GRID ACTION NETWORK

Welcome, **UserZero**. Log out

Current PA: PlanningActivity_00

Change PA

Results

Overall Ranking

Download output file

Table Chart

	Alternatives	Scores
1	alt1	0.22661615324189693
2	alt5	0.2261159562249626
3	alt3	0.2224469771967258
4	alt4	0.16416304121206116
5	alt2	0.16065787212335364

Branch weights

Table Chart

	Branch	Weight
1	Economic branch	0.333333333333
2	Smart grid branch	0.333333333333
3	Externality branch	0.333333333333

Flat weights

Table Chart

	KPI	Weight
1	Net Present Value	0.125
2	Network losses	0.125
3	Average loading	0.125
4	Privacy and security	0.125
5	System stability	0.125
6	Privacy and security	0.125
7	DERs capacity	0.125
8	Privacy and security	0.125

Privacy | Credits | Contacts

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Figure 6-23: *Result* page, with tables

Figure 6-24: *Result* page, with charts

6.10 Download template

The download template page hosts the template of the .xlsx files that are useful for uploading the performances of the alternatives in the SmartGridEval software. As shown in Figure 6-25, also the .xlsx file of the ISGAN CBA toolkit are provided. The ISGAN CBA toolkits provide a simplified CBA of a specific smart asset. The result of the CBA obtained by means of the ISGAN CBA toolkit can be exploited as input data for the economic criteria of the SmartGridEval assessment.

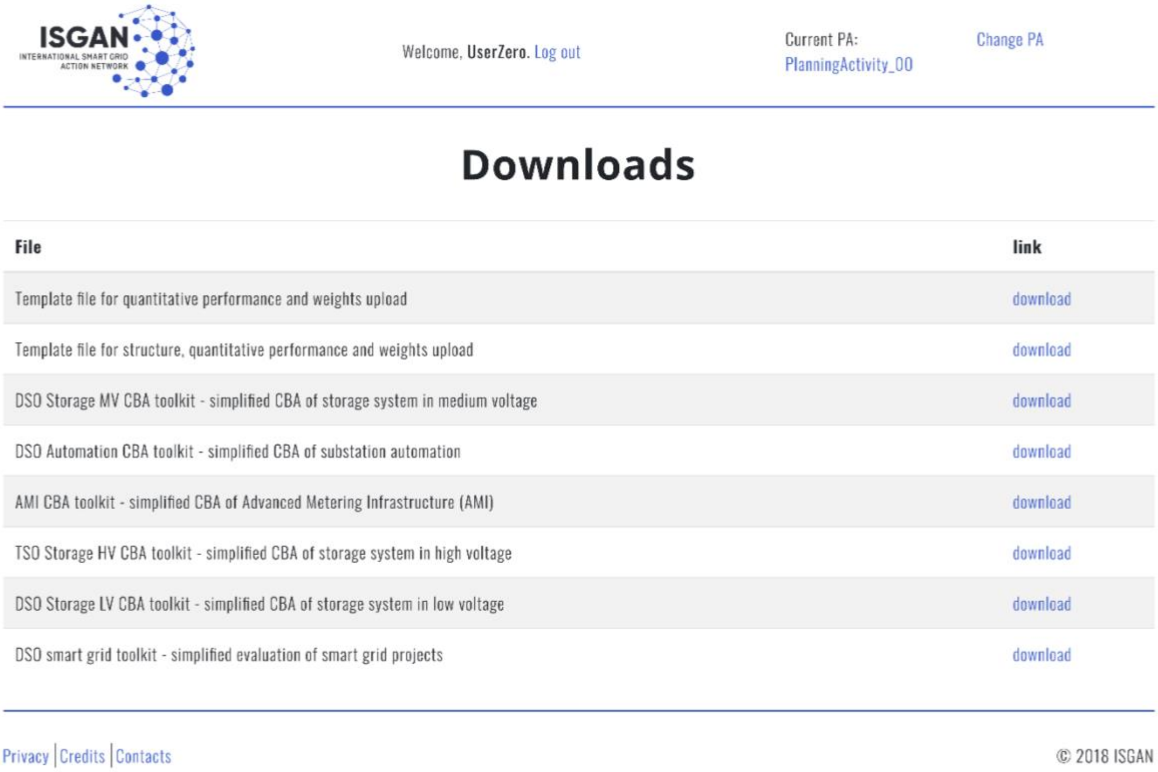

Figure 6-25: *Downloads* page

6.11 Help palette

The *Help Palette* page provides information about the criteria that belong to the palette. The built-in criteria are explained along with the custom criteria.

6.12 Customize your palette

To customize your evaluation criteria set click on the *Manage custom palette* page. As depicted in Figure 6-26, the *Manage custom palette* page is composed by two subsections: the upper part for creating new criteria, the lower part for creating new KPIs.

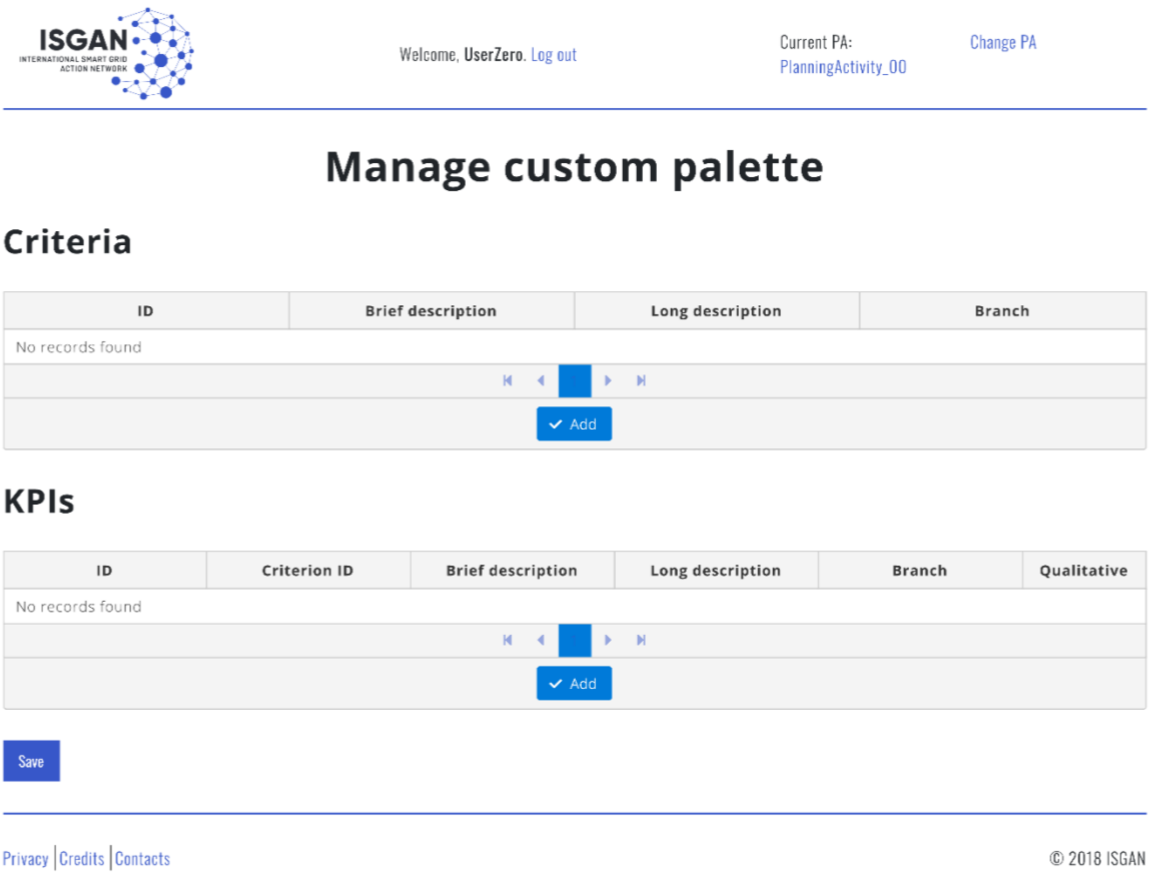

Figure 6-26: The *Manage custom palette* page

6.12.1 Create a new criterion

To create a new criterion, click on add in the criteria subsection. A new item will be created in the corresponding table. To customize the new item, click on it in the table, a dialog box appears, as depicted in Figure 6-27.

To enable the custom item:

- Edit the *ID* field;
- Edit the *Brief description* field;
- Edit the *Long description* field;
- Select the branch which the custom item belongs;
- Click on *Save.*

Once you click on *Save,* the customized information appears in the related row of the table.

To save the new element in and customize the criteria palette, click on *Save* in the *Manage custom palette* page.

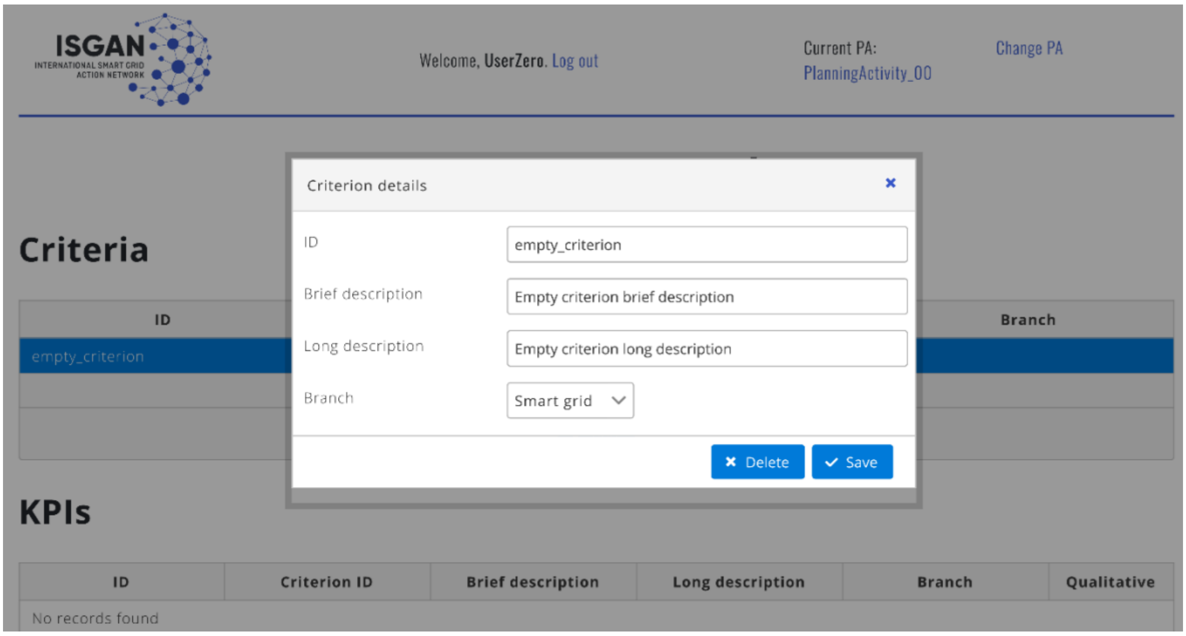

Figure 6-27: Customization criteria dialog box

6.12.2 Create a new KPI

To create a new KPI, click on add in the KPI subsection. A new item will be created in the corresponding table. To customize the new item, click on it in the table, a dialog box appears, as depicted in Figure 6-28.

To enable the custom item:

- Edit the *ID* field;
- Edit the *Brief description* field;
- Edit the *Long description* field;
- Select the branch which the custom item belongs;
- Click on *Save.*

Once you click on *Save,* the customized information appears in the related row of the table. To save the new element in and customize the criteria palette, click on *Save* in the *Manage custom palette* page.

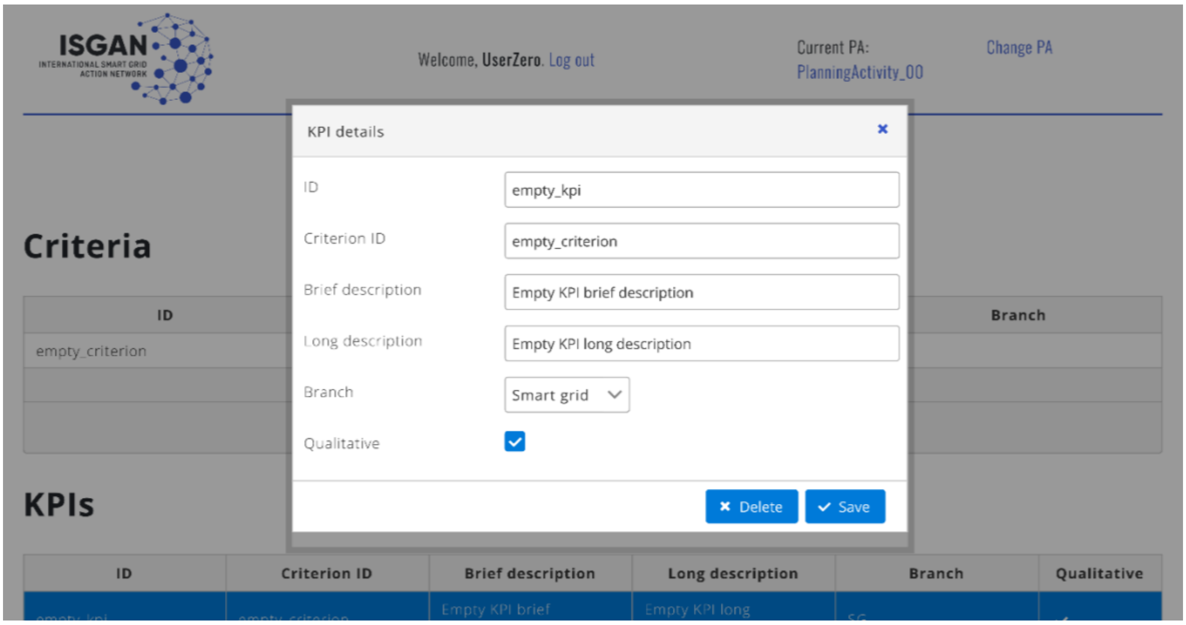

Figure 6-28: Customization KPI dialog box

6.13 Reset your PA

To delete all the information in your PA, click on the *Reset* button.

Warning: deletions CANNOT be undone.

6.14 Change PA

To change the current PA, click on *Change PA* on the header. You will be redirected to the *Planning activity management* page.

7 Your Account

In the smartgrideval platform you can create your personal account by pressing on your username, as depicted in Figure 7-1 in which the username is **admin**.

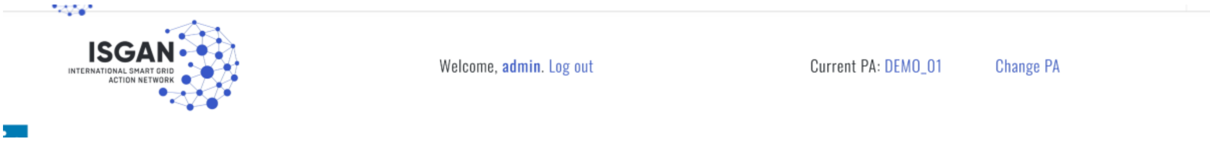

Figure 7-1: Top dashboard

Figure 7-2 depicts the page dedicate to your personal profile. In this page is possible to customize your account by providing personal details such as name or nickname, descriptions, areas of interest, nationality, picture. The personal profile can be customized by clicking on the *Edit your personal information* link on the right section of the page. It will open the page depicted in Figure 7-3. In this page can be also enabled the platform tour that guides the user in the platforms' functionalities.

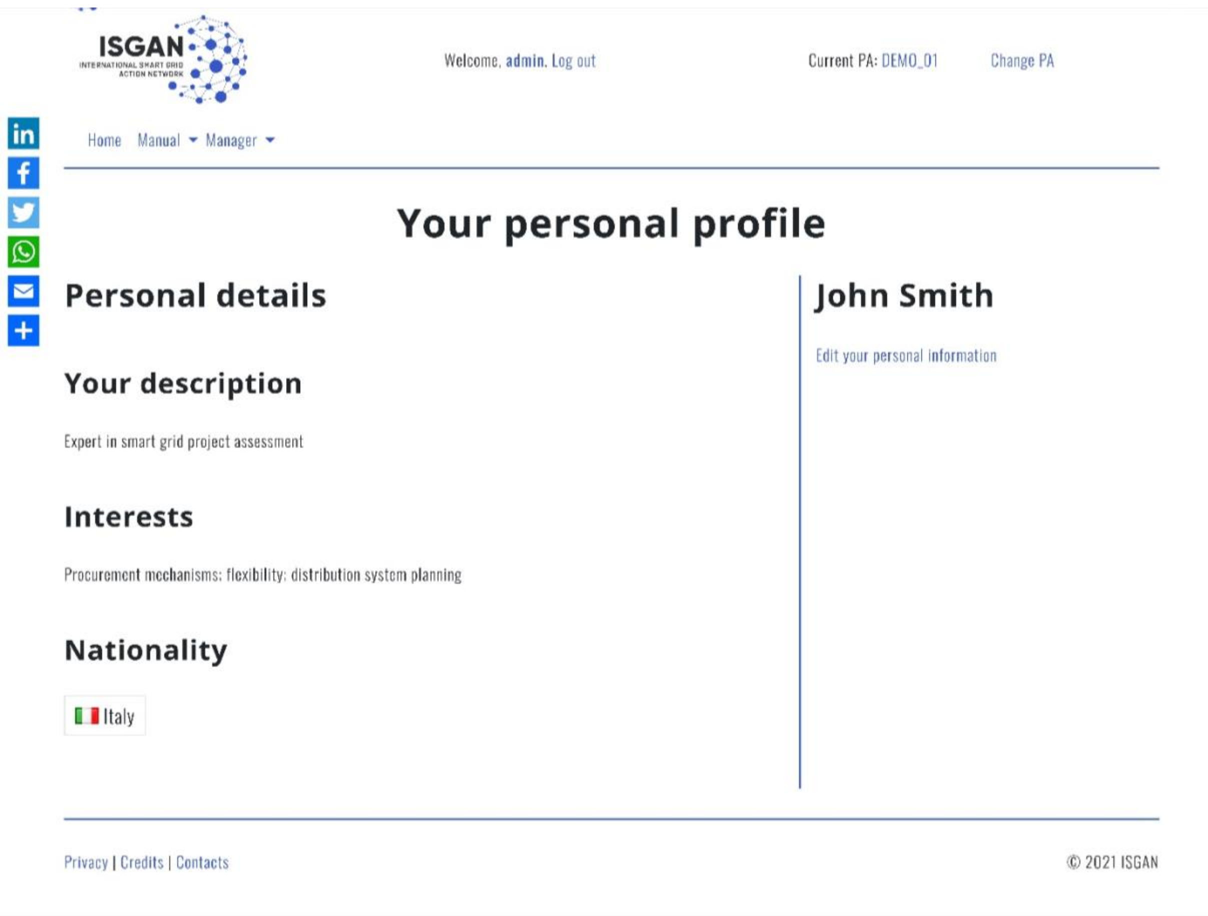

Figure 7-2: Your personal profile page

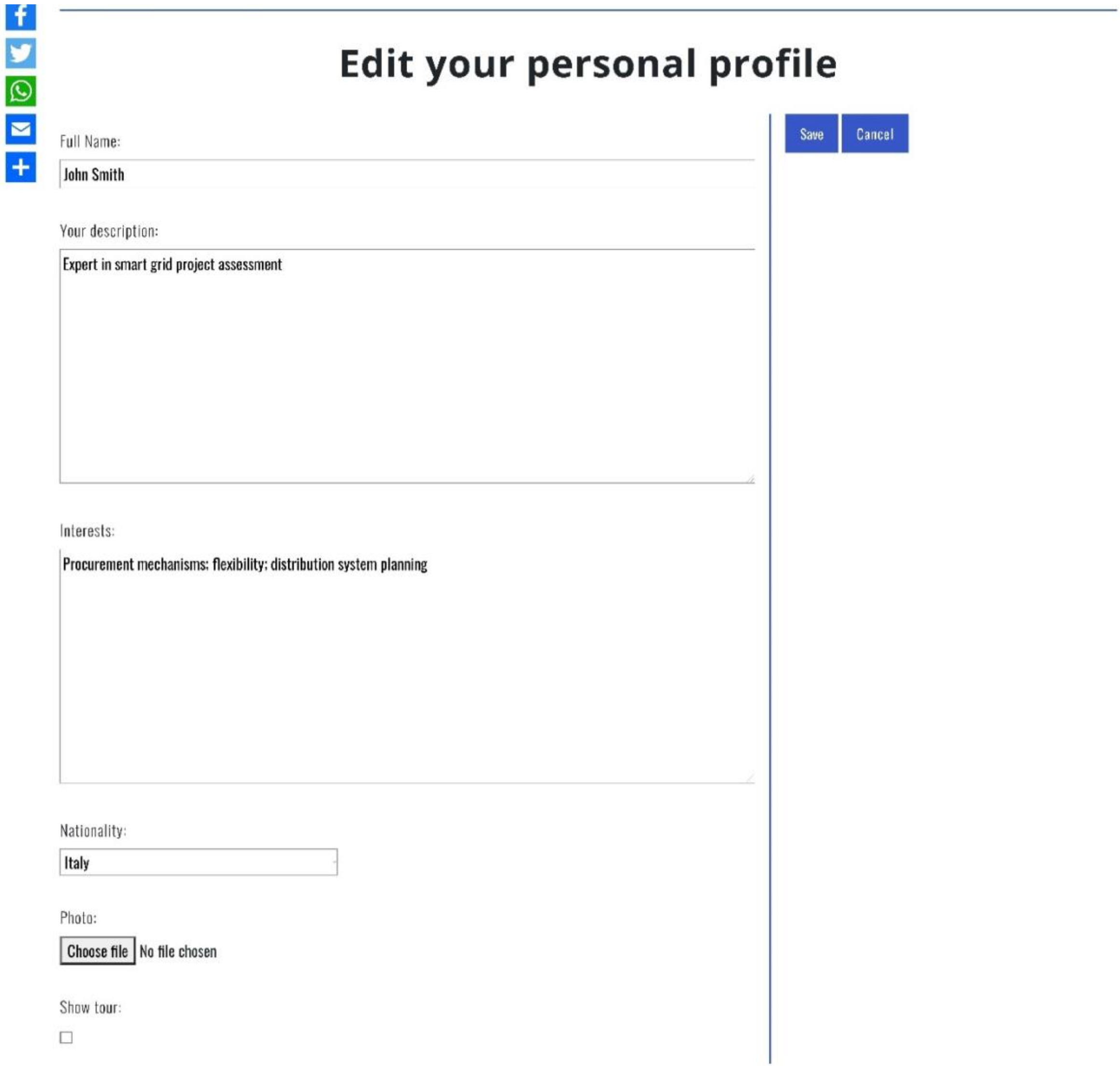

Figure 7-3: Edit your profile page

8 Sharing the planning activities

The *smartgrideval* platform allow to share the planning activities among users. The planning activities can be shared within and outside the platform.

8.1 Sharing the planning activities in the platform

Each planning activity can be shared in the platform by enabling the sharing option in the *Friends* dropdown menu on the right section of the *Planning activity overview* page, as depicted in Figure 8-1. In the *Friends* dropdown menu, the user can select using the checkbox the users that are able to collaborate in the planning activity.

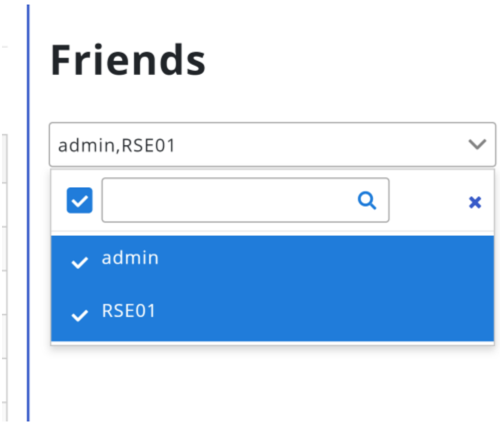

Figure 8-1: Friends dropdown menu

The users that receive the invitation will see the shared planning activity in the *Planning activity management* page in the *Planning activity shared* dropdown menu, as depicted in Figure 8-2.

Figure 8-2: Shared planning activities

8.2 Sharing the planning activities outside the platform

The planning activities can be shared outside the *smartgrideval* platform by using the left-sided panel, as depicted in Figure 8-3. By clicking on the icons, the planning activity can be shared by email and trough the most common social media platforms.

Figure 8-3: Panel for sharing the planning activities outside the platform

9 Contacts

The smart grid evaluation toolkit is part of the ISGAN WG 3 activities.
http://www.iea-isgan.org/our-work/annex-3/

The full version of the User Guide can be found at: **https://goo.gl/f2WpVp**

For any information or for support on the SmartGridEval software, write to:

info.smartgrideval@gmail.com

10 References

[1] European Commission, 'Smart Grids: From Innovation to Deployment'. Apr. 2011, Accessed: Aug. 09, 2017. [Online]. Available: https://www.smartgrid.gov/document/smart_grids_innovation_deployment.

[2] V. Giordano, I. Onyeji, G. Fulli, M. S. Jiménez, and C. Filiou, 'Cost-benefit analysis of Smart Grid projects', 2012.

[3] V. Giordano, I. Onyeji, G. Fulli, M. Jiménez, and C. Filiou, 'Guidelines for cost benefit analysis of smart metering deployment', *Jt. Res. Cent. Ed JRC Sci. Tech. Res.*, p. 88, 2012.

[4] V. Giordano, S. Vitiello, and J. Vasiljevska, 'Definition of an assessment framework for projects of common interest in the field of smart grids', *JRC Sci. Policy Rep.*, 2014.

[5] T. L. Saaty, 'Decision making with the analytic hierarchy process', *Int. J. Serv. Sci.*, vol. 1, no. 1, pp. 83–98, Jan. 2008, doi: 10.1504/IJSSci.2008.01759.

[6] A. Ishizaka and P. Nemery, *Multi-criteria Decision Analysis: Methods and Software*. John Wiley & Sons, 2013.

[7] G. Celli, N. Chowdhury, F. Pilo, G. G. Soma, M. Troncia, and I. M. Gianinoni, 'Multi-Criteria Analysis for decision making applied to active distribution network planning', *Electr. Power Syst. Res.*, vol. 164, pp. 103–111, Nov. 2018, doi: 10.1016/j.epsr.2018.07.017.

[8] J. A. Alonso and M. T. Lamata, 'Consistency in the analytic hierarchy process: a new approach', *Int. J. Uncertain. Fuzziness Knowl.-Based Syst.*, vol. 14, no. 04, pp. 445–459, Aug. 2006, doi: 10.1142/S0218488506004114.

[9] C. E. Shannon, 'A Mathematical Theory of Communication', Bell Syst. Tech. J., vol. 27, no. 3, pp. 379–423, Jul. 1948, doi: 10.1002/j.1538-7305.1948.tb01338.x.

[10] T.-C. Wang and H.-D. Lee, 'Developing a fuzzy TOPSIS approach based on subjective weights and objective weights', *Expert Syst. Appl.*, vol. 36, no. 5, pp. 8980–8985, Jul. 2009, doi: 10.1016/j.eswa.2008.11.035.

[11] D. Diakoulaki, G. Mavrotas, and L. Papayannakis, 'Determining objective weights in multiple criteria problems: The critic method', *Comput. Oper. Res.*, vol. 22, no. 7, pp. 763–770, Aug. 1995, doi: 10.1016/0305-0548(94)00059-H.

[12] J. Ma, Z.-P. Fan, and L.-H. Huang, 'A subjective and objective integrated approach to determine attribute weights', *Eur. J. Oper. Res.*, vol. 112, no. 2, pp. 397–404, Jan. 1999, doi: 10.1016/S0377-2217(98)00141-6.

[13] Z. Zou, Y. Yun, and J. Sun, 'Entropy method for determination of weight of evaluating indicators in fuzzy synthetic evaluation for water quality assessment', *J. Environ. Sci.*, vol. 18, no. 5, pp. 1020–1023, Sep. 2006, doi: 10.1016/S1001-0742(06)60032-6.

[14] D.-L. Mon, C.-H. Cheng, and J.-C. Lin, 'Evaluating weapon system using fuzzy analytic hierarchy process based on entropy weight', p. 8.

[15] Y.-M. Wang and Y. Luo, 'Integration of correlations with standard deviations for determining attribute weights in multiple attribute decision making', *Math. Comput. Model.*, vol. 51, no. 1–2, pp. 1–12, Jan. 2010, doi: 10.1016/j.mcm.2009.07.016.

[16] R. V. Rao and B. K. Patel, 'A subjective and objective integrated multiple attribute decision making method for material selection', *Mater. Des.*, vol. 31, no. 10, pp. 4738–4747, Dec. 2010, doi: 10.1016/j.matdes.2010.05.014.

[17] A. A. Salo and R. P. Hämäläinen, 'Preference Assessment by Imprecise Ratio Statements', *Oper. Res.*, vol. 40, no. 6, pp. 1053–1061, 1992.

[18] Guangdong Wu, K. Duan, J. Zuo, X. Zhao, and D. Tang, 'Integrated Sustainability Assessment of Public Rental Housing Community Based on a Hybrid Method of AHP-Entropy Weight and Cloud Model', *Sustainability*, vol. 9, no. 4, p. 603, Apr. 2017, doi: 10.3390/su9040603.

[19] X. Chuansheng, D. Dapeng, H. Shengping, X. Xin, and C. Yingjie, 'Safety Evaluation of Smart Grid based on AHP-Entropy Method', *Syst. Eng. Procedia*, vol. 4, pp. 203–209, Jan. 2012, doi: 10.1016/j.sepro.2011.11.067.

[20] D.-H. Jee and K.-J. Kang, 'A method for optimal material selection aided with decision making theory', *Mater. Des.*, vol. 21, no. 3, pp. 199–206, Jun. 2000, doi: 10.1016/S0261-3069(99)00066-7.

[21] J. Freeman and T. Chen, 'Green supplier selection using an AHP-Entropy-TOPSIS framework', *Supply Chain Manag. Int. J.*, vol. 20, no. 3, pp. 327–340, May 2015, doi: 10.1108/SCM-04-2014-0142.
[22] B. Mareschal, 'Weight stability intervals in multicriteria decision aid', *Eur. J. Oper. Res.*, vol. 33, no. 1, pp. 54–64, Jan. 1988, doi: 10.1016/0377-2217(88)90254-8.
[23] V. Miranda and L. M. Proenca, 'Probabilistic choice vs. risk analysis-conflicts and synthesis in power system planning', in *Proceedings of the 20th International Conference on Power Industry Computer Applications*, May 1997, pp. 16–21, doi: 10.1109/PICA.1997.599368.
[24] V. Miranda and L. M. Proenca, 'Why risk analysis outperforms probabilistic choice as the effective decision support paradigm for power system planning', *IEEE Trans. Power Syst.*, vol. 13, no. 2, pp. 643–648, May 1998, doi: 10.1109/59.667394.
[25] G. Celli and F. Pilo, 'MV network planning under uncertainties on distributed generation penetration', in *2001 Power Engineering Society Summer Meeting. Conference Proceedings (Cat. No.01CH37262)*, Jul. 2001, vol. 1, pp. 485–490 vol.1, doi: 10.1109/PESS.2001.970074.
[26] Terna S.p.A., 'Schema di rapporto di identificazione delle capacità obiettivo'. Sep. 2018, Accessed: Dec. 04, 2018. [Online]. Available: http://download.terna.it/terna/0000/1111/01.PDF.

[1] M. Troncia, S. Ruggeri, G. G. Soma, F. Pilo, I. M. Gianinoni e et al., «Strategic decision-making support for distribution system planning with flexibility alternatives,» *Sustainable Energy, Grids and Networks,* vol. 35, 2023.
[2] E. Commission, «Guide to Cost-Benefit Analysis of Investment Projects: Economic Appraisal Tool for Cohesion Policy 2014–2020,» Dec. 2014.
[3] F. Alpizar, M. Bernedo del Carpio e . R. Cremades, «High discount rates by private actors undermine climate change adaptation policies,» *Climate Risk Management,* vol. 40, 2023.

11 Appendix

11.1 Objective methods for weighting the criteria

In multi-criteria decision-making problems, the relevance of the evaluation criteria is modeled by a numerical value (the weight). The objective methodologies for determining the weight of criteria do not consider the preferences expressed by the stakeholders but only exploit the information on the alternatives available in the DM.

Objective methods for determining the criteria weights analyze the distribution of attribute values among the alternatives and define the relevance of the criteria by quantifying the level of discrimination of the alternatives that each of them achieves. This concept is in line with the principle of multi-criteria analysis which establishes that it is not of interest a criterion with respect to which all the alternatives show the same performance.

This section describes some of the most used objective methods for calculating the weights of the evaluation criteria: the Shannon entropy-based method [9], [10], the standard deviation method [11], and the Ideal point method [12].

11.1.1 Normalization of the decision matrix

The objective methodologies for calculating the weights of the criteria are based on the value of the attributes of the alternatives in the DM. In general, the metrics for measuring attributes are heterogeneous, the performances of the alternatives are therefore incommensurable. In order to be able to compare different evaluation criteria, it is necessary to normalize the numerical values of the attributes.

In general, the normalization of the DM converts all the entries of the matrix to the interval [0, 1]. In order to obtain a generalized normalization procedure it is possible to exploit (11.1) and (11.2) [13]. If a KPI is related to a criterion which has to be maximized, (11.1) has to be used for normalization, otherwise (11.2).

$$z_{i,j} = \frac{x_{i,j} - min\{x_{1,j}, \dots, x_{n,j}\}}{max\{x_{1,j}, \dots, x_{n,j}\} - min\{x_{1,j}, \dots, x_{n,j}\}} \tag{11.1}$$

$$z_{i,j} = \frac{max\{x_{1,j}, \dots, x_{n,j}\} - x_{i,j}}{max\{x_{1,j}, \dots, x_{n,j}\} - min\{x_{1,j}, \dots, x_{n,j}\}} \tag{11.2}$$

Where $z_{i,j}$ is the normalized value of the attribute $x_{i,j}$ related to the i-th alternative and the j-th criterion.

The exploitation of (11.1) and (11.2) allows to obtain a normalized DM in which all criteria have to be maximized by considering the normalized value of the attributes.

11.1.2 Shannon's entropy weighting method

Among objective methods for determining the criteria weights, the method based on the Shannon's entropy [9] focuses on entropy of the information contained in the attributes' value distribution. This method captures the share of information contained in the attribute values of evaluation criteria [10]. The entropy concept has been introduced in the information theory by Shannon [9], in this context, entropy measures the amount of useful information contained in the analyzed data. Then, the concept of Shannon's entropy has been extended for defining a weighting method for MCA [13]. The entropy weight is the parameter that describes the extent to which the alternatives are different from each other considering an evaluation criterion. The entropy value and the related entropy weight are inversely proportional; therefore, the higher the entropy value, the lower the entropy weight. It occurs in cases in which the set of alternatives has small differences in the attribute value of the criterion considered. Consequently, the analyzed attribute has a low value of information, then it has little relevance for the decision-making problem [10].

11.1.2.1 Shannon's entropy for MCA

In the context of probability theory, the Shannon's entropy measures the information contained in the available information. The concept of entropy derives from thermodynamics in which it describes the irreversibility of phenomena. The entropy of a set of observations can be expressed mathematically by (11.3), in which p_i represent the relative frequency of the i-th element [14].

$$H(p_1, p_2, \dots, p_n) = -\sum_{i=1}^{n} p_i \ln p_i \tag{11.3}$$

The entropy function is unique and (11.3) is valid if (11.4), (11.5) and (11.6) are satisfied.

$$H(p_1, p_2, \dots, p_n) \leq H(1/n, 1/n, \dots, 1/n) \tag{11.4}$$

$$H(p_1, p_2, \dots, p_n) = H(p_1, p_2, \dots, p_n, 0) \tag{11.5}$$

$$H(AB) = H(A) + H(A|B) \tag{11.6}$$

The Shannon's entropy can be used in the context of multi-criteria analysis for the defining the weights of the evaluation criteria [14]: given a DM $\underline{X}$ characterized by *m* rows (number of alternatives) and *n* columns (number of evaluation criteria), as represented by (11.7).

$$\underline{X} = \begin{bmatrix} x_{1,1} & \cdots & x_{1,n} \\ \vdots & \ddots & \vdots \\ x_{m,1} & \cdots & x_{m,n} \end{bmatrix} \tag{11.7}$$

Then, calculating S_j (j=1, 2, …, m) as the sum of the entries in the j-th column, the relative frequency $f_{i,j}$ of the entry in the i-th row and j-th column is calculated as (11.8).

$$f_{i,j} = \frac{x_{i,j}}{S_j} \tag{11.8}$$

The DM in terms of relative frequencies of the attributes represents the normalized matrix to be used for calculating the entropy related to the evaluation criteria, the (11.9) is exploited.

$$H_j = -\sum_{i=1}^{m} f_{i,j} \ln f_{i,j} \tag{11.9}$$

Where H_j is the entropy of the information contained in the j-th column of the matrix $\underline{X}$; $f_{i,j}$ is the relative frequency of the element in the i-th row and j-th column.

The entropy weights for the decision-making problem are obtained by normalizing the values calculated through (11.9).

11.1.2.2 Algorithm for calculating the Shannon's entropy weights

Given a decision-making problem characterized by *m* alternatives, described as A_i in which *i=1, 2, ..., m,* and *n* evaluation criteria, described as C_j in which *j=1, 2, ..., n.* Then, the DM of the decision-making problem is formed by *n* rows and *m* columns. The entry $x_{i,j}$ represents the attribute of the i-th alternative with respect to the j-th criterion. The entropy weights of the *n* evaluation criteria are based on the values of the attributes described in the DM $\underline{X}$.

Step 1 - Normalization of the $\underline{X}$ matrix

The method for calculating the criteria weights according to Shannon's entropy requires the DM to be in terms of relative frequency. Normalization is addressed criterion by criterion according to the relationships (11.10) and (11.11).

$$p_{i,j} = \frac{x_{i,j}}{\sum_{i=1}^{m} x_{i,j}} \tag{11.10}$$

$$p_{i,j} = \frac{(x_{i,j})^{-1}}{\sum_{i=1}^{m} (x_{i,j})^{-1}} \; ; i = 1,2, \dots, n \tag{11.11}$$

Where $x_{i,j}$ is the attribute of the i-th alternative with respect to the j-th criterion, $p_{i,j}$ is the related normalized attribute in terms of relative frequency.

If a criterion has to be maximized, (11.10) is exploited; (11.11) otherwise. As a result, the normalized DM $\underline{P}$ is obtained. However, this methodology for normalizing is not directly applicable in the cases in which a given criterion shows values of the attributes of the alternatives have values of different sign. In order to generalize the entropy weighting method it is possible to exploit (11.10) and (11.11) on the previously normalized $\underline{Z}$ matrix obtained from $\underline{X}$ through the use of (11.1) and (11.2). Consequently, the normalizing relationship useful for the evaluating the entropy weights is (11.12) [15].

$$p_{i,j} = \frac{z_{i,j}}{\sum_{i=1}^{m} z_{i,j}} \; ; i = 1,2, \dots , n \; , j = 1,2, \dots , m \tag{11.12}$$

Step 2 – Evaluating the values of entropy

The entropy related to with each criterion are calculated on the elements of the matrix $\underline{P}$ according to (11.13).

$$e_j = -\frac{1}{\ln m} \sum_{j=1}^{n} p_{i,j} \ln p_{i,j} \tag{11.13}$$

Where e_j is the entropy of the j-th crierion, $p_{i,j}$ is the relative value of the attribute of the alternative i-th with respect to the j-th criterion.

Step 3 – Evaluating the degree of divergence

The third step involves calculating the degree of divergence related to each criterion. The degree of divergence of a criterion measures the dispersion of the values that the alternatives show in terms of attributes. Therefore, as the degree of divergence increases, also increases the relevance of the related criterion. The degree of divergence d_j of the j-th criterion is calculated according to (11.14).

$$d_j = 1 - e_j \tag{11.14}$$

Step 4 – Calculating the entropy weight

The entropy weight of a criterion depends on the value of the degree of divergence assumed by the set of criteria. The entropy weight w_j of the j-th criterion of the set formed by n criteria can be obtained by exploiting (11.15).

$$w_j = \frac{d_j}{\sum_{k=1}^{n} d_k} \tag{11.15}$$

11.1.3 The standard deviation method

The method for calculating the weights of the evaluation criteria based on statistical variance exploits the dispersion of the attributes' numerical values of the alternatives [16]. Statistical variance measures the dispersion that the values of a set of observations show with respect to the average value. The statistical variance takes into account all the points of the set and quantifies the distribution, this aspect gives to the variance a great relevance in practical and statistical applications [16]. On the basis of the concept of statistical variance it is possible to define the objective weights for the evaluation criteria of a decision-making problem. The greater the variance of a given attribute, the greater the relevance that the related criterion has for discriminating the alternatives.

The statistical variance method has a lower computational burden than the method based on the Shannon entropy [16]. Similarly to the Shannon's entropy weights method, the variance method also requires the normalization of the DM in terms of relative frequency of attributes, as described in Appendix 0.

The objective method for weighting the evaluation criteria which exploits the standard deviation (SD) determines the weight of each criterion on the basis of the value of the standard deviation that the various alternatives show on each attribute [11]. Considering the j-th evaluation criteria, the objective weight according to the standard deviation method is obtained by (11.16).

$$w_j = \frac{\sigma_j}{\sum_{k=1}^{m} \sigma_k} \; ; j = 1,2, \dots , m \tag{11.16}$$

Where w_j is the weight of the j-th criterion, σ_j is the standard deviation of the alternatives' attributes with respect to the j-th criterion obtained as the squared statistical variance.

11.1.4 The Ideal point method Integrated weighting methods based on optimization models

The Ideal point method is an integrated weighting method based on an optimization model. The integrated methods for determining the weight of the evaluation criteria are based on optimization models whose solution offers the optimal value of the criteria weights for the studied decision-making problem. These methodologies can be defined as integrated as they allow to include preference information in their model which constrains the values that can be assumed by criteria weights. In the case in which the subjective constraints on the criteria weight criteria are not included in the model, the method leads back to an objective approach. The use of optimization methods to define the weights of evaluation criteria allows solving the decision-making problem even when only partial or incomplete information on the decision-making problem is available. Complete information on criteria relevance represents all the information that allows us to univocally determine the numerical value of the weight of each criterion. Partial or incomplete information is represented by the set of information expressed in verbal, sorting or numerical form that allow to deduce the relevance of the criteria and to determine the numerical value given a share of uncertainty [17]. In general, it is not guaranteed that the final ranking of alternatives remains unchanged within this uncertainty range.

When partial information on criteria relevance is available, regardless of the collection procedure, the partial information can be modeled in terms of linear inequalities, as shown in Table 11-1, where $0 \leq \alpha_i \leq \alpha_i + \varepsilon_i \leq 1$.

Table 11-1: Inequalities for ranking criteria according to relevance

Type	Relationship	Model
Form 1	Weak ranking	$w_i \geq w_j$
Form 2	Strict ranking	$w_i - w_j \geq \alpha_i$
Form 3	Ranking on differences	$w_i - w_j \geq w_k - w_l \; per \; j \neq k \neq l$
Form 4	Product ranking	$w_i \geq \alpha_i w_j$
Form 5	Value interval	$\alpha_i \leq w_i \leq \alpha_i + \varepsilon_i$

In particular, the Ideal Point method for evaluating criteria weights is based on an optimization model which builds a virtual alternative, weights are obtained by optimizing the distance between each alternative and the virtual one [12].

Given the matrix <u>*B*</u> which dimension is (*n, m*) as the weighted DM of the decision-making problem characterized by *n* alternatives and *m* criteria. Each entry of the matrix <u>*B*</u> is obtained according to $b_{i,j}=z_{ij}w_j$ where $i=1,2,\dots,n$ e $j=1,2,\dots,m$; w_j is the weight of the j-th criterion. The virtual alternative S^* is built by considering the maximum value of each attribute of the set of alternatives in the evaluation set, as described in (11.17).

$$S^* = \{b_1^*, \dots , b_m^*\}$$
$$\text{where } \; b_j^* = max\{b_{1,j,} \dots , b_{n,j}\} = z_j^* w_j \tag{11.17}$$

and $z_j^* = max\{z_{1,j}, \dots, z_{n,j}\}$

$j = 1,2, \dots, m$

The distance g_i between the i-th alternative and the virtual one can be quantified according to (11.18).

$$g_i = \sum_{j=1}^{m} \left(b_j^* - b_{i,j}\right)^2 = \sum_{j=1}^{m} \left(z_j^* - z_{i,j}\right)^2 w_j^2 \ ; i = 1,2, \dots, n \tag{11.18}$$

By minimizing the objective function formed by the sum of the distances g_i it is possible to obtain the weights for the evaluation criteria. The optimization model is described by (11.19).

$$\min(J) = \min\left\{\sum_{j=1}^{n} g_i\right\} = \min\left\{\sum_{i=1}^{n}\sum_{j=1}^{m} \left(z_j^* - z_{i,j}\right)^2 w_j^2\right\}$$
$$s.t. \begin{cases} \sum_{j=1}^{m} w_j = 1 \\ w_j \geq 0 \ ; \ j = 1,2, \dots, m \end{cases} \tag{11.19}$$

The optimization model defined in (11.19) leads to a finite form if no constraints on criteria weights value are available, as shown is (11.20).

$$w_j^* = \frac{\left(\sum_{i=1}^{n}\left(z_j^* - z_{i,j}\right)^2\right)^{-1}}{\sum_{k=1}^{m}\left(\sum_{i=1}^{n}\left(z_k^* - z_{i,k}\right)^2\right)^{-1}} \ ; \ j,k = 1,2, \dots, m \tag{11.20}$$

Whereas, if the set of constraints Ω is not empty, a finite form for the optimization model expressed by (11.21) does not exist.

$$\min(J) = \min\left\{\sum_{j=1}^{n} g_i\right\} = \min\left\{\sum_{i=1}^{n}\sum_{j=1}^{m} \left(z_j^* - z_{i,j}\right)^2 w_j^2\right\}$$
$$s.t. \begin{cases} w_j \in \Omega \\ \sum_{j=1}^{m} w_j = 1 \\ w_j \geq 0 \ ; \ j = 1,2, \dots, m \end{cases} \tag{11.21}$$

The main disadvantage of the Ideal Point method is represented by the fact that a weight value equal to one may be assigned to a single criterion.

11.2 Aggregation strategies

The relevance assigned to the evaluation criteria influences the decision-making processes, therefore the approach used for defining criteria weights plays a key role. In the context of the weighting methods, useful relationships have been proposed for aggregating the numerical value obtained independently through an objective and a subjective evaluation approach. In [18], subjective weights obtained through the AHP comparison process are combined with the objective weights determined by the Shannon entropy method. In [19], a similar procedure is used to assess the security offered by a set of smart grid initiatives. The combined use of objective and subjective methodologies for the calculation of the criteria weights can effectively contribute to reduce the influence of the subjectivity on the analysis.

11.2.1 Aggregation by product

The weights of evaluation criteria can be obtained by combining the weights determined by objective methodologies and subjective methodologies. A possible combination approach is represented by (11.22) [20].

$$w_j^{(h)} = \frac{w_j^{(s)} w_j^{(o)}}{\sum_{k=1}^{n} w_k^{(s)} w_k^{(o)}} \tag{11.22}$$

Where

- $w_j^{(h)}$ is the aggregated weight of the j-th criterion;
- $w_j^{(s)}$ is the subjective weight of the j-th criterion;
- $w_j^{(o)}$ is the objective weight of the j-th criterion.

If the subjective weight $w_j^{(s)}$ is not assigned, the value of the aggregated weight coincides with the objective weight.

11.2.2 Aggregation by linear combination

The aggregation of the criteria weights obtained with a subjective method and with an objective method is possible through a linear combination [16], as described in (11.23).

$$w_j^{(h)} = \alpha^{(s)} w_j^{(s)} + \alpha^{(o)} w_j^{(o)} \tag{11.23}$$

Where

- $w_j^{(h)}$ is the aggregated weight of the j-th criterion;
- $w_j^{(s)}$ is the subjective weight of the j-th criterion;
- $w_j^{(o)}$ is the objective weight of the j-th criterion;
- $\alpha^{(s)}$ is the relevance of the subjective approach over the objective;
- $\alpha^{(o)}$ is the relevance of the objective approach over the subjective.

$\alpha^{(o)}$ and $\alpha^{(s)}$ have to comply with (11.24).

$$\begin{cases} \alpha^{(s)}, \alpha^{(o)} \in [0,1] \\ \alpha^{(s)} + \alpha^{(o)} = 1 \end{cases} \tag{11.24}$$

In each decision-making problem, the decision maker can set the relevance of the subjective evaluation over the subjective one by defining the value of the parameters $\alpha^{(o)}$ and $\alpha^{(s)}$.

11.2.3 Aggregation by power

The combination of the objective and subjective weights of the criteria can be obtained considering in exponential terms the mutual relevance of the two evaluation approaches [21]. The weight of the j-th criterion can be calculated according to (11.25).

$$w_j^{(h)} = \frac{\left(w_j^{(s)}\right)^{\alpha} \left(w_j^{(o)}\right)^{1-\alpha}}{\sum_{j=1}^{n} \left(\left(w_j^{(s)}\right)^{\alpha} \left(w_j^{(o)}\right)^{1-\alpha}\right)} \; ; j = 1,2, \dots, n \tag{11.25}$$

Where

- $w_j^{(h)}$ is the aggregated weight of the j-th criterion;
- $w_j^{(s)}$ is the subjective weight of the j-th criterion;
- $w_j^{(o)}$ is the objective weight of the j-th criterion;
- $\alpha \in [0, 1]$ is the coefficient which models the relevance assigned to the subjective weights over the objective weights.

11.3 Global ranking stability

If the MADM methodology used for solving the decision problem is based on an additive linear model for combining attributes and criteria weights, then the incomplete information regarding the relevance of the criteria can be mathematically expressed in terms of ranges of values in the weight-space. This information defines the constraints which determines a subspace in the weight-space in which the best solution of the set is to be sought, this subspace represents the feasible region for criteria weights [15]. Within the feasible region, a subspace within which the indication of the best alternative does not change can be considered as a criteria weight interval in which the solution of the method is stable. The global sensitivity analysis of the criteria weights is useful for analyzing the stability of the result obtained from the multi-attribute analysis. The stability of the result can be understood in terms of invariance of the best alternative indication or in terms of invariance of the entire final ordering. The identification of the range of values within which the weights can vary without involving a change in the final result allows to estimate the stability and robustness of the solution suggested by a MADM method.

Given a ranking of alternatives $Q_i^* = \left(A_{i,1}^* \succ A_{i,2}^* \succ \dots \succ A_{i,n}^*\right)$ which has been obtained by means of a MCA; and considering the weight vector $W^* = (w_1^*, w_2^*, \dots, w_m^*)$ related to the evaluation criteria. The goal of the global stability analysis is to identify the range of variation of criteria weights within which the ranking of alternatives is invariant. This range of variation ensures that the best alternative, or the entire ordering, is robust and stable with respect to the weight of the criteria [15]. This range of variation cannot be determined arbitrarily; therefore, the method of global stability analysis assumes that the weights of all criteria vary according to the same proportionality coefficient [15], [22]. Accordingly, the range of variation of the weight of the j-th criterion is defined by (11-26).

$$w_j = w_j^*(1 \pm \eta) \in \left[w_j^* - \eta w_j^*, w_j^* + \eta w_j^*\right] ; j = 1,2, \dots, m \tag{11-26}$$

Where w_j^* is the weight of the j-th criterion; η is the proportionality constant.

For determining η, is possible to consider the ranking of alternatives $Q_i^* = \left(A_{i,1}^* \succ A_{i,2}^* \succ \dots \succ A_{i,n}^*\right)$ obtained by evaluating the values of the overall score received by each alternative: $d_{i,1}^* \geq d_{i,2}^* \geq \dots \geq d_{i,n}^*$.

Two adjacent alternatives have an overall non-negative score difference, that is, for the generic s-th alternative, (11.27) holds.

$$d_{i,s}^* - d_{i,s+1}^* \geq 0 ; s = 1,2, \dots, n-1 \tag{11.27}$$

Therefore, also (11.28) holds.

$$D_{k.l} = d_k - d_l = \sum_{j=1}^{m} \left(z_{k,j} - z_{l,j}\right) w_j \geq 0 \qquad k = i_s , l = i_s + 1, s = 1,2, \dots, n-1 \tag{11.28}$$

Where $D_{k.l}$ is the difference between the overall score of the k-th and l-th adjacent alternatives evaluated by considering the initial values of criteria weights.

To guarantee the compliance with (11.28) when w_j varies within the range $\left[w_j^* - \eta w_j^*, w_j^* + \eta w_j^*\right]$, then w_j has to comply with (11.29).

$$w_j = \begin{cases} w_j^* - \eta w_j^* ; & if \left(z_{k,j} - z_{l,j}\right) \geq 0 \\ w_j^* + \eta w_j^* ; & if \left(z_{k,j} - z_{l,j}\right) < 0 \end{cases} \qquad j = 1,2, \dots, m \tag{11.29}$$

By substituting (11.29) in (11.28), (11.30) is obtained.

$$D_{k.l} = \sum_{j=1}^{m} \left(z_{k,j} - z_{l,j}\right) w_j^* - \eta \sum_{j=1}^{m} \left|z_{k,j} - z_{l,j}\right| w_j^* \geq 0 \qquad k = i_s , l = i_s + 1, s = 1,2, \dots, n-1 \tag{11.30}$$

From (11.30), the calculation of the proportionality constant η is obtained by (11.31).

$$\eta \leq \frac{\sum_{j=1}^{m}\left(z_{k,j}-z_{l,j}\right) w_j^*}{\sum_{j=1}^{m}\left|z_{k,j}-z_{l,j}\right| w_j^*} \tag{11.31}$$

$$k=i_s\,, l=i_s+1, s=1,2,\dots,n-1$$

The maximum value of η which does not produce a change in the ranking of alternatives is defined by (11.32).

$$\eta^*=min\left\{\frac{\sum_{j=1}^{m}\left(z_{k,j}-z_{l,j}\right) w_j^*}{\sum_{j=1}^{m}\left|z_{k,j}-z_{l,j}\right| w_j^*}; k=i_s\,, l=i_s+1, s=1,2,\dots,n-1\right\} \tag{11.32}$$

Once the value of η^* is obtained, the admissible range of variation for criteria weights is defined by (11.33).

$$w_j \in \left[w_j^*-\eta^* w_j^*\,,\ w_j^*+\eta^* w_j^*\right]; j=1,2,\dots,m \tag{11.33}$$

By considering the weight vector $W=(w_1, w_2, \dots, w_1)$ where $w_j \in \left[w_j^L\,,\ w_j^U\right]$ and $0 \leq w_j^L \leq\ w_j^U$ for $j=1,2,\dots,m$. If the vector *W* satisfies (11.34) and (11.35), then it is normalized.

$$\sum_{j=1}^{m} w_j^L + max\left(w_i^U - w_i^L\right) \leq 1 \tag{11.34}$$

$$\sum_{j=1}^{m} w_j^U + max\left(w_i^U - w_i^L\right) \geq 1 \tag{11.35}$$

The weighs obtained by means of (11.33) are normalized if (11.36) is true.

$$max\left\{w_j^* \mid j=1,2,\dots,m\right\}\ \leq 0.5 \tag{11.36}$$

If (11.36) is not satisfied, the vector *W* can be normalized by solving for each *m* entry the linear programming problem defined by (11.37).

$$\begin{gathered} min\left(\widehat{w}_j\right); max\left(\widehat{w}_j\right) \\ s.t.\begin{cases} w_j^L \leq \widehat{w}_j \leq w_j^U\ j=1,2,\dots,m \\ \sum_{j=1}^{m}\widehat{w}_j = 1 \end{cases} \end{gathered} \tag{11.37}$$

The linear programming problem defined by (11.37) leads to (11.38) and (11.39).

$$\widehat{w}_j^L = max\left\{w_j^L\,, 1-\sum_{i \neq j} w_j^U\right\}; j=1,2,\dots,m \tag{11.38}$$

$$\widehat{w}_j^U = min\left\{w_i^U\,, 1-\sum_{i \neq j} w_j^L\right\}; j=1,2,\dots,m \tag{11.39}$$

The range of weights for the stability of the best alternative of the set can be obtained by particularizing the expressions presented in this section. Assuming that the best alternative of the set is A_{i_1} to which the rank index i_1 is related, the maximum value of η can be calculated by means of (11.32) considering *k*=i_1 and *l*=1, 2, …, *n* with *l*≠ i_1.

$$\eta^*=min\left\{\frac{\sum_{j=1}^{m}\left(z_{i_1,j}-z_{l,j}\right) w_j^*}{\sum_{j=1}^{m}\left|z_{i_1,j}-z_{l,j}\right| w_j^*};\ l=1,2,\dots,n\,; l \neq\ i1\right\} \tag{11.40}$$

Once the parameter η^* has been obtained, the admissible range for criteria weights can be obtained by means of (11.33).

11.4 Optimization method based on decision theory

In planning activities, the goal of the decision-making problem is the selection of the alternative which leads to the optimal allocation of available resources. Typically, this choice is made under risk or uncertainty; therefore, it is of interest the selection of the option able to ensure the highest utility considering all possible scenarios. The identification of the alternative to be implemented have to be based on a process that ensures a rational choice.

In this document, the selection problem of the best planning alternative for smart grids is addressed through a decision support tool that includes economic analysis within a multi-criteria approach. This evaluation framework considers the performances achieved by each alternative according to various criteria and produces an overall assessment. On the basis of the overall score obtained by the alternatives, the best alternative of the set is selected. This approach requires the definition of the relevance of evaluation criteria, the result obtained is influenced by the weighting scheme used. As highlighted in the previous sections, the decision-making problems are not under certainty, nor in terms of performance of the alternatives, nor in terms of relevance assigned to evaluation criteria. Therefore, the methodologies used to calculate the numerical value of the criteria weights have a key role. Subjective methods directly involve stakeholders but are affected by the vagueness of the language; furthermore, the methodology used influences the obtained result. Objective methodologies calculate the weight of the criteria on the basis of the attributes of the alternatives. These methodologies reject the subjectivity on criteria weights, consequently the result obtained may be far from the expectations of the stakeholders. In the context of decision-making problems, no general law appears to ensure the absolute validity of the result obtained by exploiting objective methodologies. Given the large number of methods available in the literature, the choice to use a technique over the others represents an arbitrary choice. The integrated methodologies are a compromise with respect to the use of a subjective and an objective methodology. By exploiting an optimization model, these methods combine objective information on attributes with partial information on the relevance of the criteria. The result offered represents a compromising weight scheme which, however, depends on the optimization model used and the features of the decision-making problem under analysis. The methods analyzed in this document aim at defining a specific weighting scheme that leads to the identification of the dominant alternative. The stability of the solution obtained can be assessed ex-post.

When a decision-making problem under uncertainty is addressed, the decision maker may be interested in identifying an alternative that achieves satisfactory performances in all possible scenarios. Unlike an approach that suggests the best alternative under particular conditions, a strategy that identifies a valid compromising alternative even in the worst scenario can be effective. However, choosing the best alternative in the worst possible scenario can be excessively cautious. In order to avoid sub-optimal choices, the approach of minimizing the maximum regret (MinMax Regret - MMR) allows to identify the alternative that leads to the least maximum regret for the stakeholders considering the worst possible scenario [23]–[25]. Over time, this approach has been widely applied in industrial decision-making processes. Recently, an approach based on the assessment of the least regret has been exploited to identify the target capacity value for the Italian transmission system [26].

In decision-making problems, regret occurs when, given a scenario, the selected action leads to fewer benefits than those that would have been produced by an alternative action. The regret between two alternatives can be quantified in terms of the difference of their utilities. The MinMaxRegret approach consists in selecting the alternative that has the minimum maximum regret value; the maximum regret is calculated with respect to the best alternative for each possible scenario.

Considering the multi-criteria framework for evaluating the alternatives in the smart grid sector, it is of interest to identify alternatives that bring an adequate degree of satisfaction for the all categories of stakeholders. The impacts produced by smart grids affect various sectors of society; therefore, synthetizing the point of view of the various categories of stakeholders assumes relevance for the success of the initiatives. In this context, the MinMaxRegret approach is presented to identify the alternative that is able to bring the least disappointment to all possible categories of stakeholders. Instead of synthetizing the various points of view of stakeholders in terms of a unique scheme of weights, this section proposes an optimization model based on the MinMaxRegret approach which identifies the best compromising alternative based on the analysis of all possible points of view available for the decision-making problem. This approach allows for a conservative but not pessimistic choice to be made.

Given the decision-making problem characterized by the set of alternatives $A=(A_1, A_2, \ldots, A_n)$ and by the set of criteria $C=(C_1, C_2, \ldots, C_m)$. Each alternative A_i is described by a vector X_i in which each entry x_{ij} is the attribute of the i-th alternative with respect to the j-th criterion. The DM $\underline{X}$ is then normalized by means of the procedure described in section 11.1.1 by means of (11.1) and (11.2). Therefore, the decision-making problem is described by the normalized decision-matrix $\underline{Z}$ in which the entry z_{ij} is the normalized attribute of the i-th alternative with respect to the j-th criterion and the vector W_k of criteria weights. W_k models the k-th scenario in terms of the evaluation criteria relevance. The entries of the vector W_k are in terms of $w_{j,k}$ which represent the weight of the j-th criterion in the k-th scenario. In each scenario the weight vector has to comply with (11.41) and (11.42).

$$\sum_{j=1}^{m} w_{k,j} = 1 \tag{11.41}$$

$$w_{k,j} \in [0, 1]\ ;\ j = 1, \ldots, m \tag{11.42}$$

The utility $U_{i,k}$ of the i-th alternative evaluated in the k-th scenario represents the overall score obtained by the linear combination of weights and normalized attributes (11.43).

$$U_{i,k} = \sum_{j=1}^{m} w_{k,j} z_{i,j} \tag{11.43}$$

The maximum regret related to the i-th alternative in the k-th scenario is evaluated by means of (11.44).

$$R_{i,k} = \left[\max_{t}\left(U_{t,k}\right) - U_{i,k}\right]\ ;\ t = 1, \ldots, n \tag{11.44}$$

Where $R_{i,k}$ is the maximum regret of the i-th alternative in the k-th scenario calculated as the difference of the maximum utility value among the alternatives in the k-th scenario and the utility value achieved by the i-th alternative.

By considering the set Q of the scenarios defined by (11.41) and (11.42), the optimization model for identifying the alternative which shows the minimum value of the maximum regret is defined by (11.45).

The optimization model represented by (11.45) identifies the alternative of the set which achieves the minimum value of the maximum regret by considering all possible weight schemes.

$$\min_{\substack{i \\ i=1,\ldots,n}} \max_{\substack{k \\ k=1,\ldots,m}} \left\{\left[\max_{\substack{t \\ t=1,\ldots,n}}\left(\sum_{j=1}^{m} w_{k,j} z_{t,j}\right) - \sum_{j=1}^{m} w_{k,j} z_{i,j}\right]\right\} \tag{11.45}$$

$$s.t. \begin{cases} w_j \in \Omega_0 \\ \sum_{j=1}^{m} w_{k,j} = 1 \\ w_j \in [0, 1] \end{cases}$$

Where Ω_0 is the set of constraints of the value of the weights expressed in terms of the relationships described in Table 11-1. In addition, the non-dominance condition is considered (11.46). It avoids that a single criterion assumes a weight greater than the sum of the weights of the remaining *n*-1 criteria.

$$w_{k,s} < \sum_{\substack{j=1 \\ j \neq s}}^{m} w_{k,j} \tag{11.46}$$

The model described by (11.45) allows to identify the alternative which achieves the highest consensus among the stakeholders by considering all possible point of views. The best alternatives represent the option that leads to the least regret to the most skeptical stakeholder.

The objective function of the model (11.45) is nonlinear because of the term $\underset{\substack{t \\ t=1,\dots,n}}{max}\left(\sum_{j=1}^{m} w_{k,j} z_{t,j}\right)$. When the weights vary within the feasible region, also varies the value of utility related to the best alternative. Therefore, a discontinuity exists for all weight values in which the alternative which achieves the highest utility changes. However, the objective function is continuous in the weight intervals in which the alternative which achieves the highest utility score does not change. Within these subspaces, the objective function is linear if ε is equal to zero; otherwise non-linear due to the quadratic term of the probability function. The constraints of the optimization model are linear.

With the aim to solve the optimization model described by (11.45), an analytic algorithm is exploited. The non-linearity of the objective function is addressed by an initialization procedure which restricts the search region in the weight-space. The algorithm is formed by three steps:

- Initialization, the starting point for the maximization process is identified;
- For each alternative of the set, the objective function $\{R_{i,k}\}$ is maximized;
- The alternative which achieves the minimum value of the maximized objective function in the solution point of the maximization process is selected as the best alternative.

The initialization process identifies the region in the weight-space which contains the solution point for the objective function. The initial point is identified by means of a brute force solution approach characterized by a large evaluation step. Then, for each alternative the optimization model is solved for identifying the point in the weight-space in which the maximum regret is achieved. In practice, the maximization problem is converted to a minimization problem by changing the sign of the objective function. The independent variables of the optimization problem are the entries of the weight vector. By considering the objective function in the neighborhood of the initial point, the Interior Point method has been selected for solving the minimization problem. The solution of the problem is the weight vector with respect to which the maximum value of regret is achieved. The value of the objective function in this solution point represent the maximum regret achieved by the considered alternative. Once the maximizing problem is solved for each alternative, the alternative which achieved the minimum value of the maximum regret is selected as the suggested solution for the decision-making problem.

The computational burden of the model described by (11.45) increases as increases the size of the decision-making problem defined by the number of alternatives and of criteria. As the computational burden increases, the convergence of the model on the solution point is not guaranteed in a reasonable amount of time. Therefore, for improving the efficiency of the solution algorithm in view of including in the model also the evaluation of uncertainties, the development of an analytical and / or heuristic resolution approach will be addressed in future studies.

11.5 Cost-benefit analysis NEW !

CBA serves as a rigorous tool for evaluating the economic feasibility of projects by systematically comparing the costs associated with implementation against the benefits they are expected to generate. This systematic approach ensures that resources are directed toward initiatives that offer the most substantial net contribution to societal and economic welfare. In the energy sector, this methodology is particularly critical, as projects often require substantial capital investments and long-term operational commitments.

Costs, within the context of CBA, encompass all expenditures necessary for project realization. For example, in an oil refinery modernization project, costs would include capital expenses such as the procurement of advanced processing units, installation costs, and the temporary reduction in production capacity during the upgrade. Operating costs, including maintenance, energy consumption, and workforce training, represent the ongoing expenditures required to sustain the upgraded systems. These costs are expressed in monetary terms to enable precise accounting and comparison.

In projects related to smart grids, costs similarly involve the procurement and deployment of advanced technologies. These may include smart meters, grid automation systems, and communication infrastructure. For instance, the rollout of smart meters across a distribution network incurs significant capital costs for hardware and installation, along with operational expenditures for maintaining and updating the technology over its lifecycle. Additionally, costs may arise from logistical challenges or interruptions to existing services during the installation phase. Benefits, on the other hand, represent the quantifiable outcomes of a project, framed within the same monetary units as the costs. Continuing with the oil refinery example, benefits might include a reduction in operational costs due to improved energy efficiency and enhanced production capabilities. For instance, the adoption of advanced catalytic processes could reduce fuel consumption and allow the refinery to produce higher-value outputs, directly increasing profitability.

In the case of smart grid projects, benefits are similarly quantifiable and directly tied to the operational enhancements introduced by the new systems. For example, the deployment of smart meters facilitates accurate billing and reduces non-technical losses, such as unmetered electricity consumption. Automated fault detection systems improve the reliability of electricity delivery, minimizing downtime and associated costs. These benefits are evaluated over the project's lifespan and discounted to their present value to ensure comparability with upfront and operational costs.

11.5.1.1 CBA Key elements NEW !

Key elements influencing the cash flows and long-term sustainability of a project include revenues, operating and investment costs, discount rates, and project lifetime. A definition of each element, along with the role in the cost-benefit analysis, is provided below (Vinod & Namrata, 2023).

- **Capital Expenditures (CAPEX)**

  Capital expenditures represent the initial investment required to establish the project. These include the costs of infrastructure, equipment, and other resources necessary for implementation. CAPEX is typically incurred during the initial stages of a project and is critical for defining the financial outlays that must be recovered over time. For instance, in a smart grid project, CAPEX may encompass the installation of advanced metering infrastructure, automation systems, and communication networks. CAPEX is modeled as an upfront cash outflow as showed in equation (1):

$$CAPEX_t = \sum_{i=1}^{n} I_{i,t} \tag{1}$$

  Where $I_{i,t}$ represents the cost of the i-th investment component at time t.

- **Operating Expenditures (OPEX)**
  Operating expenditures are the recurring costs incurred during the operational phase of the project, as formulated in equation (2). These include expenses such as maintenance ($C_{m,t}$), energy consumption ($C_{e,t}$), labor ($C_{l,t}$), and system upgrades. OPEX typically continues throughout the project's operational life and reflects the cost of maintaining functionality. For example, in a smart grid project, OPEX would include maintenance of communication systems and software updates:

$$OPEX_t = \sum_{i=1}^{n} C_{i,t} = C_{m,t} + C_{l,t} + C_{e,t} + \cdots \qquad (2)$$

- **Annual Revenues**
  Revenues are the cash inflows generated by the project during its operational phase. These inflows are determined by the quantity of electricity or related services delivered and their associated prices. In the context of a smart grid project, revenues might stem from reduced energy losses, increased grid reliability leading to higher service fees, or income from integrating distributed energy resources (DERs), such as rooftop solar, into the grid. For instance, utilities may charge a premium for providing enhanced grid stability or for managing energy flows efficiently between prosumers and the grid.

  Annual revenues are expressed as (equation (3)):

$$Revenue_t = p_t \cdot Q_t \qquad (3)$$

  Where:
  - p_t: Price of the good or service provided at time,
  - Q_t: Quantity of the good or service delivered at time t.

  For example, in a project incorporating time-of-use (TOU) tariffs, p_t may vary based on demand peaks, while Q_t: reflects the electricity consumed or supplied during those periods. This model enables utilities to optimize revenues by encouraging off-peak usage and better utilizing grid resources.

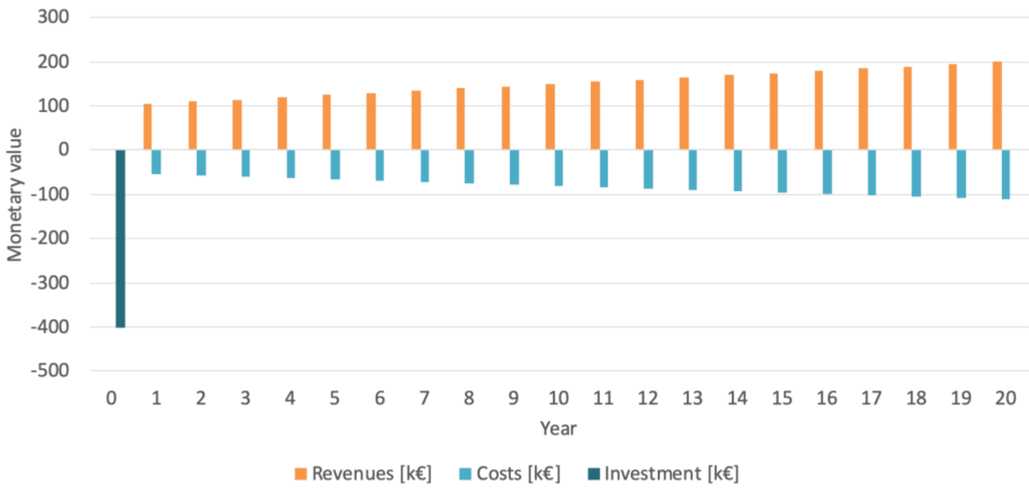

Figure 11-1 Revenues, Costs and Investmet for a 20-Year Project considering (IR=4%)

Figure 11-1 illustrates the initial investment or CAPEX (dark blue bar at year 0), Operating Expenditures (light blue bars), and Annual Revenues (orange bars) across the time horizon of a project.

- **Annual Cash Flow**

  The annual cash flow (equation (4)) represents the net financial outcome of the project for each year, calculated as the difference between revenues and costs (CAPEX and OPEX). It is a critical input for evaluating the project's financial performance over its life cycle:

$$Cash\ Flow_t = Revenue_t - (CAPEX_t + OPEX_t) \qquad (4)$$

  Cash flow does not account for the time value of money, meaning it treats cash received today as having the same value as cash received in the future.

- **Discount Rate or Interest Rate**

  The interest rate reflects the cost of capital for financing the project. It is a key parameter in financial analysis, influencing the discounting of cash flows to present value. For economic analysis, the Social Discount Rate (SDR) is used instead, emphasizing societal opportunity costs. The discounted cash flow (DCF) formula incorporates the interest rate or SDR.

  Figure 11-2 represents a financial analysis of a project over a 20-year time horizon, showing CAPEX (dark blue bar at year 0), Revenues (orange bars), Costs (light blue bars), Cash Flow (purple line), and Discounted Cash Flow (green line), calculated considering an IR equal to 4%.

  From the figure, it emerges that the distinction between cash flow and discounted cash flow lies in their treatment of time: cash flow illustrates the net financial inflows and outflows in nominal terms for each period, while discounted cash flow adjusts these values to account for the time value of money, reflecting their worth in present terms.

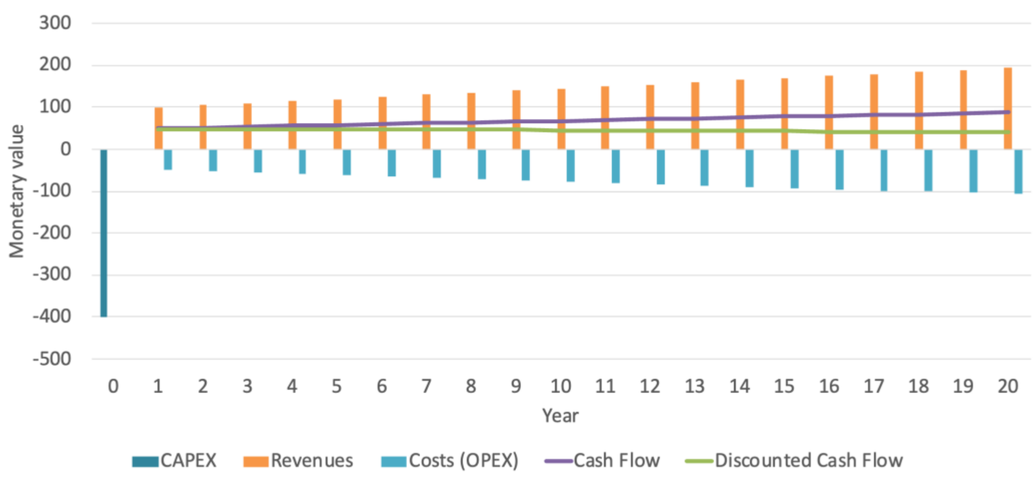

Figure 11-2. Cash Flow and Discounted Cash Flow Analysis for a 20-Year Project considering (IR=4%)

- **Project Life Time**

The project lifetime defines the period over which costs and benefits are analyzed. It typically includes the construction phase and the operational phase, reflecting the economic lifespan of the project. For smart grid projects, this might range from 20 to 30 years, depending on the expected durability of the infrastructure. A longer project lifetime increases the significance of future cash flows, which are discounted accordingly.

It is important to distinguish the project lifetime from the project time horizon (or reference period), which refers to the specific timeframe chosen for the analytical evaluation in a cost-benefit analysis. While the project lifetime encompasses the full operational lifespan of the assets, the project time horizon is often shorter and reflects a practical period for forecasting costs and benefits, such as 15–25 years for energy-related projects, as recommended by EU guidelines (Commission, Dec. 2014).

This distinction ensures that evaluations remain manageable and realistic, particularly when future uncertainties make long-term projections less reliable. For assets with lifetimes exceeding the chosen time horizon, the analysis incorporates their remaining economic value through a residual value, calculated as the present value of cash flows beyond the reference period or as the depreciated value of the assets.

Table 11-2European Commission's reference periods by sector (Commission, Dec. 2014)

Sector	Reference period (years)
Railways	30
Roads	25-30
Ports and airports	25
Urban transport	25-30
Water supply/sanitatian	30
Waste management	25-30
Energy	**15-25**
Broadband	15-20
Research and Innovation	15-25
Business infrastructure	10-15
Other sectors	10-15

In 2014, the agency for the Cooperation for Energy Regulators (ACER) highlights the importance of a standardized 25-year lifecycle evaluation for energy infrastructure, promoting comparability and transparency in project assessments.

11.5.1.2 CBA Performance Indicators NEW !

CBA employs specific performance indicators to quantify the outcomes of projects in monetary terms and collectively provide a framework for evaluating a project's economic desirability, offering clear benchmarks for decision-making: the Net Present Value, the Economic Net Present Value, the Internal Rate of Return and the Benefit Cost Ratio.

1. **Net Present Value (NPV):** is a core metric in CBA, representing the difference between the present value of benefits and costs over a project's lifespan (equation (5)):

$$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+r)^t} \qquad (5)$$

Where:

- B_t: Benefits in year t,
- C_t: Costs in year t,
- r: Discount rate,
- T: Time horizon of the project.

A project is financially viable if NPV > 0 when using market prices. A project is economically desirable if NPV > 0 when using shadow prices to account for externalities.

Table 11-3 presents the calculation of the Net Present Value (NPV) under varying discount rates. For simplicity, it is assumed that initial investments and costs are zero.

Table 11-3Calculation of NPV's for alternative scenarios

Year	Annual Net Benefit [€]	Discount rate		
		5%	7%	3%
1	100	95.2	93.5	97.1
2	100	90.7	87.3	94.3
3	100	86.4	81.6	91.5
4	100	82.3	76.3	88.8
5	100	78.4	71.3	86.3
6	100	74.6	66.6	83.7
7	100	71.1	62.3	81.3
8	100	67.7	58.2	78.9
9	100	64.5	54.4	76.6
10	100	61.4	50.8	74.4
Net present values		**772.2 €**	**702.36 €**	**853.02 €**

2. **Economic Net Present Value (ENPV)**: for societal analysis, the **ENPV** adjusts costs and benefits to reflect their true economic value, accounting for market distortions and externalities. ENPV is calculated as the difference between the discounted present value of a project's benefits and costs over its lifecycle (equation (6)).

$$ENPV = \sum_{t=0}^{T} \frac{EB_t - EC_t}{(1+SDR)^t} \tag{6}$$

Where:

- EB_t: Benefits in year t,
- EC_t: Costs in year t,
- SDR: Social Discount Rate, reflecting societal time preferences.

A positive ENPV indicates that the project contributes a net benefit to society. For example, an ENPV of €15 million for a smart grid project suggests that its societal benefits—such as reduced energy losses and enhanced system reliability—exceed its costs.

3. **Internal Rate of Return (IRR)**: The IRR represents the discount rate at which the net present value of a project equals zero (equation (7)).

$$IRR = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+r^*)^t} \tag{7}$$

In economic analysis, the Economic IRR (EIRR) measures the efficiency of a project in generating returns that exceed the societal cost of capital. For instance, a smart grid project with an EIRR of 10% compared to a Social Discount Rate (SDR) of 4% would be deemed highly favorable.

4. **Benefit-Cost Ratio (BCR)**: The BCR is a dimensionless metric defined as the ratio of the present value of benefits to the present value of costs (equation (8)).

$$BCR = \frac{\sum_{t=0}^{T} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}} \tag{8}$$

A BCR greater than 1 indicates that a project's benefits outweigh its costs. In the case of a smart grid initiative, a BCR of 1.4 means that every euro invested yields €1.40 in societal benefits.

11.6 Uncertainty integration in smartgrideval NEW !

Despite their effectiveness, both Multi-Criteria Analysis (MCA) and Cost-Benefit Analysis (CBA) present significant limitations when addressing uncertainty in the parameters or aspects underlying benefit estimations and criteria evaluations. While costs are often observable and easily quantifiable, input data—such as local and global climate data or energy consumption patterns—and the expected benefits are typically affected by considerable uncertainty. In particular, benefit estimation involves planning and forecasting how systems might respond to specific choices (e.g., technological maturity, social acceptance, CO_2 emission reductions), which inherently introduces uncertainty.

The literature proposes various methodologies to handle uncertainty; however, no universally optimal approach has emerged. Instead, specific techniques demonstrate greater suitability for particular types of uncertainty. Consequently, decision-making procedures under uncertainty must first identify the sources of uncertainty to select the most appropriate methodological approach. Practical considerations, such as computational burden and the accessibility of the methodology for non-expert users (e.g., decision-makers unfamiliar with mathematical modeling), are also crucial.

Scenario-based analysis, which involves evaluating multiple scenarios characterized by simultaneous variations in one or more parameters, provides a particularly effective compromise. It delivers robust results while maintaining usability even for decision-makers with limited technical skills or computational resources. Other techniques, such as fuzzy logic (appropriate mainly for qualitative assessments), Robust Decision Making (RDM, computationally intensive and requiring iterative expert involvement), and Monte Carlo simulations (dependent on the availability of reliable probability distributions, often lacking), do not achieve the same balance between rigor and practical applicability.

Moreover, scenario analysis enables the consideration of uncertainty related to future developments by associating each scenario with a probability of occurrence and applying the min-max regret criterion to assess alternative performances. The review of the literature also highlights that, given the diversity of uncertainty sources, the combined application of different approaches may be necessary. Sensitivity analysis can assess the influence of input parameter variations, whereas fuzzy logic can support the evaluation of uncertainties stemming from expert opinions.

Figure 12 provides a guide for selecting the most appropriate uncertainty management technique. Once the uncertain aspect is identified (e.g., values of selected criteria, input data, criteria weights, expert qualitative judgments, system modeling, future scenarios), the diagram directs the user to the most suitable approach. For each technique, a brief methodological description (yellow band), main strengths (green band), and main limitations (red band) are provided.

Specifically, for enhancing the Smartgrideval tool, scenario analysis appears to be the most appropriate choice. It offers a favorable balance between robustness and ease of use, making it particularly suitable for decision-makers with limited computational resources and expertise, for whom more sophisticated techniques, such as robust approaches, would impose an unsustainable technical burden.

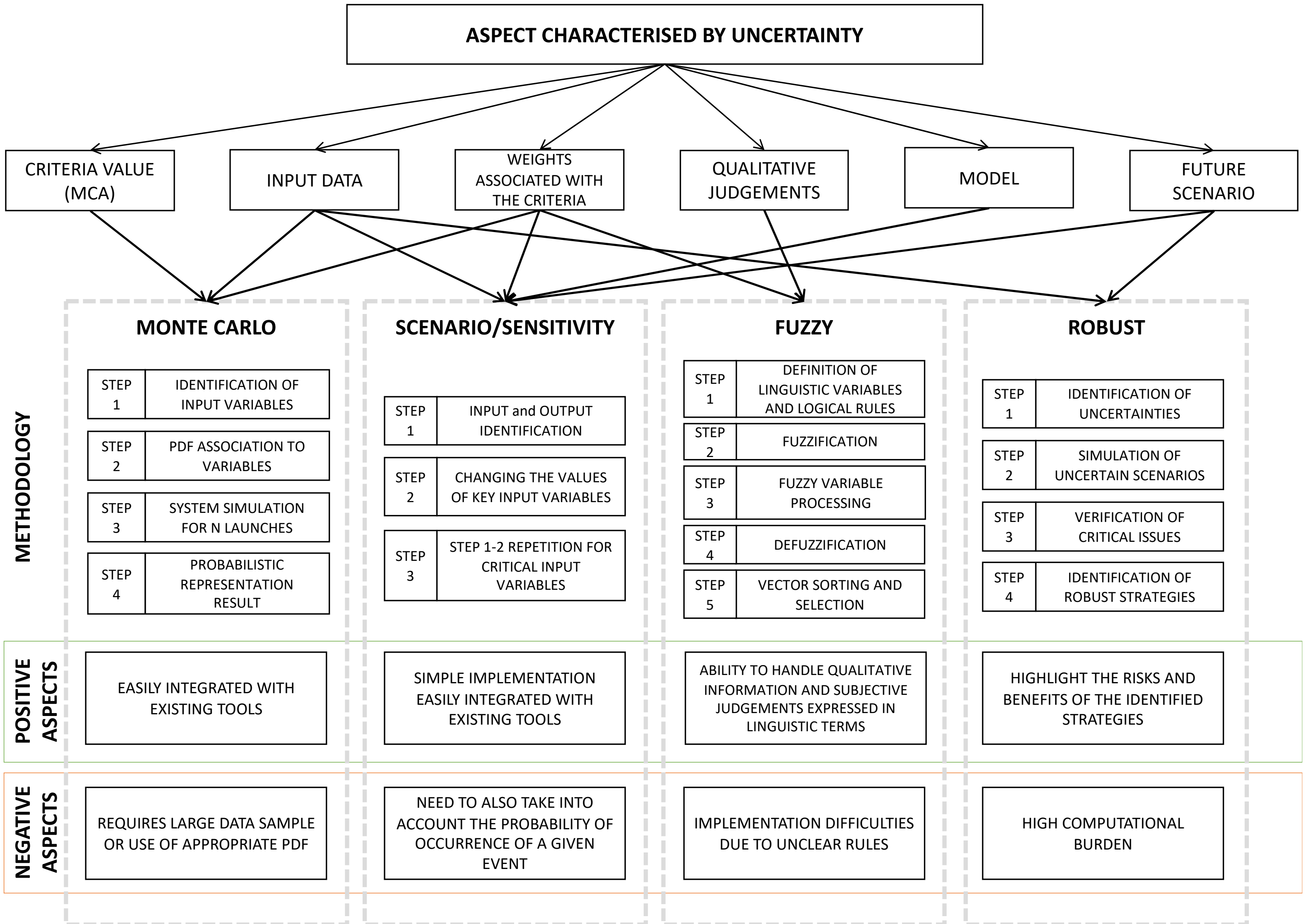
ASPECT CHARACTERISED BY UNCERTAINTY
CRITERIA VALUE (MCA)
INPUT DATA
WEIGHTS ASSOCIATED WITH THE CRITERIA
QUALITATIVE JUDGEMENTS
MODEL
FUTURE SCENARIO
MONTE CARLO
SCENARIO/SENSITIVITY
FUZZY
ROBUST
METHODOLOGY
STEP 1 IDENTIFICATION OF INPUT VARIABLES
STEP 2 PDF ASSOCIATION TO VARIABLES
STEP 3 SYSTEM SIMULATION FOR N LAUNCHES
STEP 4 PROBABILISTIC REPRESENTATION RESULT
STEP 1 INPUT and OUTPUT IDENTIFICATION
STEP 2 CHANGING THE VALUES OF KEY INPUT VARIABLES
STEP 3 STEP 1-2 REPETITION FOR CRITICAL INPUT VARIABLES
STEP 1 DEFINITION OF LINGUISTIC VARIABLES AND LOGICAL RULES
STEP 2 FUZZIFICATION
STEP 3 FUZZY VARIABLE PROCESSING
STEP 4 DEFUZZIFICATION
STEP 5 VECTOR SORTING AND SELECTION
STEP 1 IDENTIFICATION OF UNCERTAINTIES
STEP 2 SIMULATION OF UNCERTAIN SCENARIOS
STEP 3 VERIFICATION OF CRITICAL ISSUES
STEP 4 IDENTIFICATION OF ROBUST STRATEGIES
POSITIVE ASPECTS
EASILY INTEGRATED WITH EXISTING TOOLS
SIMPLE IMPLEMENTATION EASILY INTEGRATED WITH EXISTING TOOLS
ABILITY TO HANDLE QUALITATIVE INFORMATION AND SUBJECTIVE JUDGEMENTS EXPRESSED IN LINGUISTIC TERMS
HIGHLIGHT THE RISKS AND BENEFITS OF THE IDENTIFIED STRATEGIES
NEGATIVE ASPECTS
REQUIRES LARGE DATA SAMPLE OR USE OF APPROPRIATE PDF
NEED TO ALSO TAKE INTO ACCOUNT THE PROBABILITY OF OCCURRENCE OF A GIVEN EVENT
IMPLEMENTATION DIFFICULTIES DUE TO UNCLEAR RULES
HIGH COMPUTATIONAL BURDEN

Figure 11-3

11.6.1 Weighted Scenario Analysis in Multi-Criteria Evaluation

This section provides a formal description of the methodology used in SmartGridEval to combine multi-criteria analysis (MCA) with scenario-based evaluation. The method is designed to support structured decision-making under uncertainty, where multiple planning alternatives are assessed across diverse future scenarios and evaluation criteria.

- **Problem Structure**

Let us consider:

- A finite set of planning **alternatives** $A = \{A_1, A_2, ..., A_m\}$
- A finite set of possible **scenarios** $S = \{S_1, S_2, ..., S_n\}$, each representing a distinct vision of the future (e.g., levels of electric vehicle penetration)
- A fixed set of **evaluation criteria** $C = \{C_1, C_2, ..., C_k\}$, typically grouped in branches such as economic, smart grid, and externalities

Each criterion C_k is assigned a normalized weight $w_k \in [0,1]$, with $\sum w_k = 1$.

Each scenario S_j is assigned a plausibility weight $p_j \in [0,1]$, with $\sum p_j = 1$.

- **Multi-Criteria Aggregation per Scenario**

For each alternative A_i and each scenario S_j, a performance score is defined for every criterion C_k:

v_{ijk} =score of alternative A_i under scenario S_j on criterion C_k.

An aggregated performance score f_{ij} is computed for each alternative-scenario pair using a weighted sum over the criteria: $f_{ij} = \sum w_k \cdot v_{ijk}$

- **Scenario-Weighted Aggregation**

The overall score F_i of each alternative A_i is then computed as the expected value of its performance across all scenarios, weighted by their plausibility: $F_i = \sum p_j \cdot f_{ij}$

This yields a single global score F_i for each alternative that accounts for both the relative importance of criteria and the likelihood of each scenario.