Benefit-Cost Analyses and Toolkits

Multicriterial decision making:

the smart metering case

Discussion Paper

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ISGAN Annex 3

Task 4.5

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

IEA-ISGAN Annex 3 has started the task 4 with the aim to evaluate existing approaches and develop new approaches as needed for quantitative analysis to 2050 of the benefits and costs, comparing a range of scenarios that vary the rate and depth of smart grids deployment at electrical system level, and also on a regional level.

Smart grid projects are responsible of wide range impacts which span from the electrical power system to the entire society. In general, the investment projects are assessed by a Cost-Benefit Analysis (CBA) which requires to quantify the impacts for converting them in monetary terms. In the smart grid context, not all impacts are quantifiable and/or monetizable; therefore, the CBA lacks in describing completely the smart grid potential.

Since smart grids impacts require new assessment approaches, this report aims at contributing on the debate about the evaluation of costs and benefits of smart grid projects. In particular, the evaluation approach which combines the Multi-Criteria Analysis (MCA) and the Cost-Benefit Analysis (CBA) is employed for evaluating a smart metering infrastructure case study.

Acknowledgments

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Nomenclature or List of Acronyms

AEEGSI	Autorità per l'Energia Elettrica, il Gas ed il Sistema Idrico (Italian Energy Authority)
AHP	Analytic Hierarchy Process
AMI	Advanced Metering Infrastructure
BAU	Business As Usual
CAS	Central Acquisition System
CAPEX	CAPital EXpenditure
CBA	Cost-Benefit Analysis
CBR	Cost Benefit Ratio
DER	Distributed Energy Resource
DM	Decision Maker
DNO	Distribution Network Operator
DSR	Demand Side Response
ELECTRE	ELimination Et Choix Traduisant la Realité
IHD	In Home Device
IIS	Integrated Information System
IRR	Internal Rate of Return
JRC	Joint Research Centre
KPI	Key Performance Indicator
LTE	Long Term Evolution
LV	Low Voltage
MADM	Multi-Attribute Decision-Making
MATLAB	Matrix Laboratory software
MCA	Multi-Criteria Analysis
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
MV	Medium Voltage
NFC	Near Field Communication
NPV	Net Present Value
OA	Outranking Approach
OPEX	OPErational EXpenditures
PLC	Power Line Communication
PM	Performance Matrix
POD	Point Of Delivery
RF	Radio Frequency
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SM	Smart Metering
SG	Smart Grid
THD	Total Harmonic Distortion index
UMTS	Universal Mobile Telecommunications System

Abstract

In this report, an approach that combines the Multi-Criteria Analysis (MCA) and the Cost-Benefit Analysis (CBA) is applied for evaluating a specific smart grid asset.

The impacts generated by the smart metering infrastructure (or Advanced Metering Infrastructure, AMI) are evaluated by means of a tailored MC-CBA approach. In particular, the state of art in Italy of smart metering for low voltage consumers is presented and analysed. The aim of this document is twofold. Firstly, the proposed MC-CBA methodology is applied to a smart grid asset case study. Secondly, the assessment is made by means of a cross-platform which integrates the MCA approach and the ISGAN CBA toolkits. The decision-making problem of identifying the best AMI alternative is modeled as a hierarchical structure of evaluation criteria. Three different area of interest are investigated: economic effects, enhanced smartness of the grid, and externalities. The most suitable criteria are selected to obtain an effective assessment framework and avoid double counting. Firstly, the AMI case study is evaluated by means of the Analytic Hierarchy Process (AHP) technique. The same MCA approach has been applied by using the ELECTRE III technique and the ELECTRE III technique succeeding a fuzzy-scoring method. Finally, the obtained results are compared and the observed peculiarities of the used MCA techniques are described. In particular, the evolutive AMI alternative is always pointed out as the best. On one hand, the AHP appraisal seems to be suitable for preliminary decision-making analysis. On the other hand, the ELECTRE III method appears to be suitable for a deeper analysis of the decision-making problem.

Executive Summary

This report has been developed within the sub-task 4 activities of the ISGAN Annex 3. Since smart grids impacts require new assessment approaches, this report aims at contributing on the debate about the evaluation of costs and benefits of smart grid projects. In particular, the evaluation approach which combines the Multi-Criteria Analysis (MCA) and the Cost-Benefit Analysis (CBA) is employed for evaluating a smart metering infrastructure case study.

The aim of this report is twofold. Firstly, the proposed MC-CBA methodology is applied to a smart grid asset case study. Secondly, the assessment is made by means of the cross-platform toolkit which integrates the MCA approach and the ISGAN (CBA) toolkits. The evaluation is repeated by using different MCA techniques in order to assess the validity of the obtained results. The performances of the alternatives on the evaluation criteria are assessed in qualitative terms on the basis of their described features.

The proposed MC-CBA approach is general purpose since it can be used for assessing different smart grid assets. For each specific smart grid asset, the evaluation criteria have to be carefully chosen in order to obtain an effective assessment and avoid double counting. The overall assessment of a project option is 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). Therefore, the proposed MC-CBA approach formalises the decision-making problem in terms of a hierarchy of criteria made of three independent branches. The overall goal of the hierarchical tree is to identify the best project option according to the decision maker's (DM) perspective.

The economic branch evaluates the monetary impacts of each alternative. The proposed MC-CBA approach involves a CBA of monetary impacts that can be run according to the procedure defined by Joint Research Centre (JRC). Therefore, the monetary costs and benefits can be described by the indices computed by means of the CBA, or explicitly considering the items of monetary cost and benefits in the tree.

The contribution of the alternatives towards the smart grid realization is evaluated by means of the second branch of the hierarchy. The evaluation criteria which belong to this branch are identified among the *Policy Criteria* and the related KPIs defined by the JRC. Since the set of criteria defined by JRC is general purpose in the smart grid context, only significant criteria for assessing the AMI asset have been selected.

The third branch concerns the assessment of the project options in terms of externalities. The single impacts are aggregated in thematic areas related to the effects under analysis. These thematic areas are the second level criteria of the hierarchy, while terminal criteria are related to the single impacts. Also in this branch, only significant criteria for assessing the AMI asset have been identified.

The case study assessed by means of the MC-CBA methodology regards the state of art in Italy of smart metering for low voltage consumers. Two projects of smart metering infrastructure are assessed: one project is based on keeping the current technology

(alternative 1G) even after the substitution for end of life, while the other one is based on the deployment of second generation AMI (alternative 2G) whenever it is necessary to substitute existing meter. Since the 2G alternative is an upgraded 1G AMI, the alternatives under analysis shows some conceptual similarity. The 2G option has enhanced technical features hence greater potential of generating wide impacts on the power system, the electricity market, and the society. Basically, the features of AMI allow the remote monitoring and control of the points of delivery (PODs). Thanks to these basic functionalities, higher level services can be enabled in the power system. Therefore, AMI is a fundamental element for the smart grid deployment.

The MC-CBA methodology uses the Analytic Hierarchy Process (AHP) as MCA technique for evaluating the worthiness of the alternatives under analysis. At the first stage, the AHP has been identified as the most suitable MCA approach to the decision problem at hand:

- AHP is "built-in" technique, the scoring and weighting stages are integrated in its procedure;
- qualitative and quantitative input data can be simultaneously managed;
- its algorithm is transparent and flexible; therefore, it is easy to be employed;
- AHP directly and easy manages large hierarchical structures of criteria.

At the second stage, the assessment of the 1G and 2G AMI alternatives is repeated by using the ELECTRE III method. Among the outranking approach methods, the ELECTRE family is one of the main branches and ELECTRE III is one of the most acknowledged methods. Since ELECTRE III is not a "built-in" technique, the evaluation starts from the flat decision-making problem defined by the terminal criteria of the evaluation tree. The global priorities of terminal criteria obtained in the weighting stage of the AHP assessment are used. To manage qualitative performance as input data, the preferences on the alternatives are converted from verbal judgements to a suitable 7-points interval scale. ELECTRE III requires the DM defines performance thresholds which influence the outranking relationships between the alternatives. In particular, ELECTRE III requires three thresholds: indifference, preference, and veto. Different DM's points of view are investigated by means of several thresholds values used with both weight patterns.

At last stage, the AMI alternatives are evaluated by means of the ELECTRE III method preceded by the use of a fuzzy-scoring technique. Since the verbal terms obtained by means of subjective judgments suffer some degree of vagueness, the related uncertainties may be managed by means of fuzzy sets. Instead of a full-fuzzy MCA technique, a hybrid fuzzy-scoring crisp-MCA technique is employed. The aim is to avoid the increased complexity related to a full-fuzzy MCA evaluation. The hybrid technique involves a fuzzy scoring stage in which the verbal judgements are managed by means of fuzzy sets. Then, the obtained fuzzy scores are converted in crisp scores and provided as input to the classical ELECTRE III technique.

With the aim to analyse two different stakeholders' perspective, the assessments have been repeated by using two different patterns of weights. The first pattern considers the smart grid deployment merit and the externality impacts areas equally relevant, while the economic area is two time more relevant than each of them. Conversely, the second pattern of weights considers an equal relevance for the first level criteria.

In addition, the robustness of the obtained results is investigated by a sensitivity analysis on the economic performance of the 2G alternative.

All tests have shown that the 2G alternative is preferable over the 1G one, if both have the same capital expense (CAPEX).

The AHP evaluation shows that the 2G system is preferable to the 1G one if CAPEX is equal. Both alternatives obtain the same score on the economic criterion. On the smart grid criterion, the 2G alternative achieves a score 2 times higher than the score of the 1G. On the externality criterion, the score of the 2G system is about 3 times higher than the score obtained by the 1G one. Using the first pattern of weights, the overall score is 0.39 for 1G system and 0.61 for the 2G one. The sensitivity analysis highlights that 1G becomes the preferable alternative when the CAPEX of 2G is bigger than 2-3 times the 1G CAPEX. If the second pattern of weights is used, the overall score of the 1G alternative is 0.36, while 0.64 is the overall score of the 2G one. In addition, the sensitivity analysis shows that the 1G is preferable only when the 2G CAPEX is about 9 times 1G CAPEX.

The results obtained by using both ELECTRE III and ELECTRE III with Fuzzy scoring point out that the 2G system is preferable to the 1G one when the amount of CAPEX is the same. The sensitivity analysis on the economic performance shows the considerable influence of threshold values on the robustness of the provided outcome. Considering the first pattern of weights and a high value of thresholds, the alternative 2G is preferable until CAPEX is about 106% of the 1G CAPEX. Conversely, if the thresholds value is low, then the CAPEX level is around 102%. From the results related to the second pattern of weights, one can see that the 2G is preferred for a higher level of CAPEX than the level obtained with the first pattern. When high thresholds values are considered, 2G is preferred until 108% of the 1G CAPEX; whereas by using low thresholds values, then 2G is preferable until 104% of the 1G CAPEX.

Since the 2G alternative is evolutionary with respect to the 1G one, the 2G system is preferable to the 1G one if costs are the same, as pointed out by the overall analysis. Due to the uncertainties on the economic performances of the alternatives under appraisal, a sensitivity analysis is conducted. The differences on the results obtained by using different MCA methods are related to the different assessment approach that they use. The study highlights the positive contribution of the AHP in decomposing the overall decision-making problem. Furthermore, the scoring stage based on qualitative input is eased by the pairwise comparison procedure. However, the use of the ratio scale makes the AHP less flexible for a sensitivity analysis. Accordingly, the AHP appraisal seems to be suitable for preliminary decision-making analysis. Conversely, the ELECTRE III method appears to be suitable for deeper analyses of decision-making problems thanks to the usage of an interval scale.

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1 Introduction

This report presents an application to the smart metering (SM) asset of a formalised Multi-Criteria Analysis (MCA) approach. The best project option is identified by decomposing the whole decision-making problem in a hierarchy of evaluation criteria. In the described case study, the performances of the alternatives are expressed in qualitative terms.

MCA is a useful decision-making tool which help the decision maker (DM) in identifying the best alternative among a given set; the result of the evaluation depends on the DM (or stakeholders) point of view. It is worth to mention that, the MCA can provide an insight to the decision-making problem, but the final decision is up to the DM. Among the MCA approaches, the Multi-Attribute Decision-Making (MADM) methods are suitable for multi-criteria decision problems in which the given set of alternatives is explicitly known. Moreover, MADM methods deal with multiple conflicting criteria and model the DM and stakeholder's point of view by means of the relative importance of the evaluation criteria. Each MADM method can be considered as an algorithm that combines the performances of the alternatives and the relative weights of criteria. Once these two elements are known, different MADM techniques can be applied to the same decision-making problem. Due to the great diversity of real decision problems, a large number of MADM methods have been proposed in Literature. In general, the MADM methods differ in terms of the approach used for combining the performance scores and criteria weights. The multiplicity of approaches allows the DM to find the MADM method that best fit to the decision problem under analysis.

The aim of this document is twofold. Firstly, the previously proposed MC-CBA methodology is applied to a smart grid asset case study. Secondly, the assessment is made by means of a cross-platform toolkit devised by the authors which integrates the MCA approach and the ISGAN cost benefit analysis (CBA) toolkits.

The second section of this document presents the criteria which have been considered for the SM project assessment. In the third section, the set of SM alternatives are described. The fourth section is focused on the project assessment made by means of the MCA approach proposed in the previous document and based on the analytic hierarchy process (AHP) technique. The same MCA approach has been applied by using the ELECTRE III technique in section five. The AHP assessment has been done with the help of the original MC-CBA toolkit devised by authors. This toolkit manages the three-branch hierarchy of evaluation criteria proposed in the previous report and it accepts as input both quantitative and qualitative data. According to ISGAN guidelines (ANNEX 3, Sub-task 4.2), the presented MCA toolkit integrates the MCA approach with the result of the ISGAN CBA toolkits. The ELECTRE III assessment has been made by means of the free tool *MCDA-ULaval* developed by the Faculty of Business Administration of Université Laval - Canada (http://cersvr1.fsa.ulaval.ca/mcda).

2 Evaluation Criteria Selection for the SM asset assessment

The evaluation criteria of a MCA have to be carefully chosen in order to obtain an effective assessment and avoid double counting. With the aim to identify the best option, the evaluation criteria have to suit the characteristics of the alternatives so that the respective differences are emphasised. The case study presented involves two different SM systems: the so-called first generation (1G) and the second generation (2G) which has increased functionalities and can enhance the positive impacts of the metering infrastructure to the electrical power systems.

The proposed MC-CBA approach relies on scientific Literature and international guidelines [1]–[3] and the project option assessment is made on three area of interest. The monetary impacts assessment made by means of the CBA is integrated within a MCA framework in which the non-monetary impacts are directly accounted. The overall assessment of a project option is 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);

Therefore, the proposed MC-CBA approach formalises the decision-making problem in terms of a hierarchy of criteria made of three different branches. 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 (Figure 1). The three branches are independent; therefore, an impact can be evaluated through its effects on each area of interest. Conversely, each impact has to be considered by means of a single effect on each branch in order to avoid double counting.

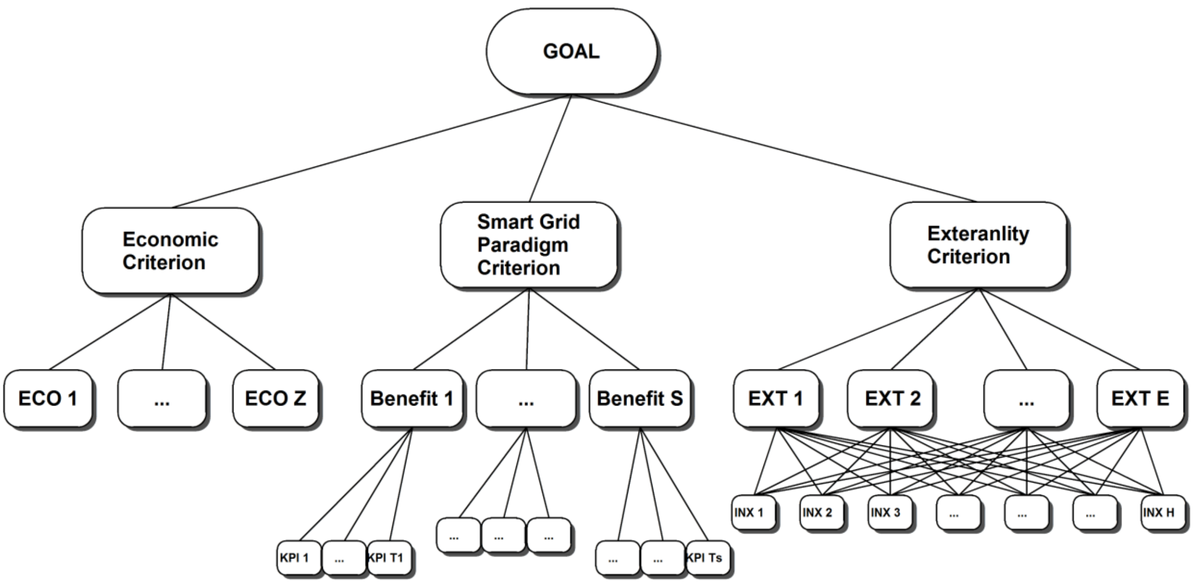


Figure 1. Hierarchical structure of criteria proposed for the MC-CB approach

The hierarchical structure is organised according to the principle of abstraction. The overall goal of the hierarchical tree is to identify the best project option. Consequently, each branch aims at identifying the best project option in the related area of interest.

2.1 The economic branch

The economic branch aims at evaluating the performance of the monetary impacts of each alternative. The proposed MC-CBA approach involves a CBA of monetary impacts that can be run according to the procedure defined by JRC in [1], [2]. Therefore, the monetary costs and benefits can be described by the indices computed by CBA, or explicitly considering the items of monetary cost and benefits in the tree.

In the first case, the economic branch is formed by three criteria on the second hierarchy level (Figure 2).

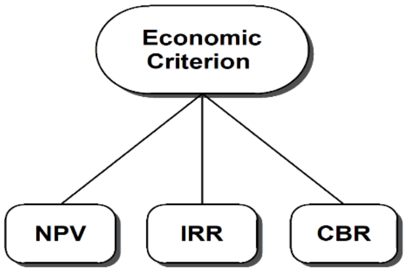


Figure 2. Economic tree based on the CBA output indices

Each criterion is related to a CBA outcome index:

- the **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 **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 **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 the second case, the economic branch shows more than one hierarchical level whose criteria are the cost and benefit items related to the project impacts. Figure 3 depicts a generalised economic branch with elementary cost and benefits explicitly accounted. The criteria on the higher hierarchical levels aggregate the elementary monetary criteria of lower levels.

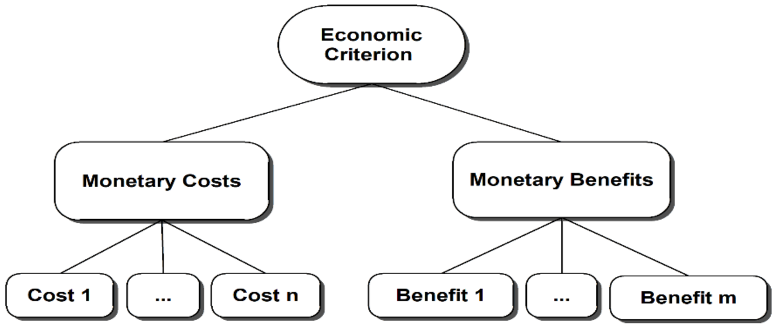
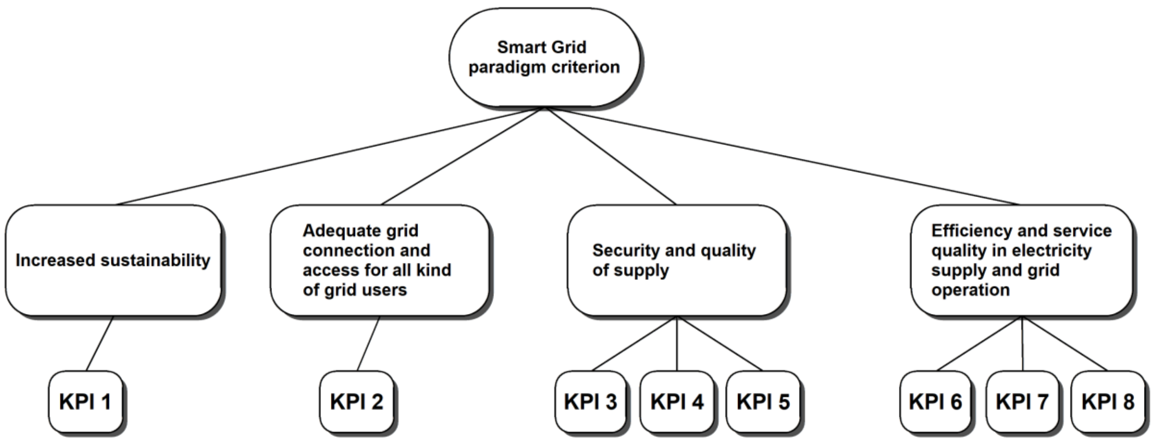


Figure 3. Economic branch with elementary cost and benefits

In general, two sub-branches can be defined: the cost branch and the benefit branch. The performances on all criteria are measured in terms of currency, therefore criteria are fulfilled by performances that minimise costs and maximise monetary benefits.

2.2 The Smart Grid deployment merit branch

The second branch of the hierarchy tree evaluates the contribution towards the smart grid realization given by the project options. The importance of this evaluation arises from the role of the smart grids in the EU policies. The evaluation criteria which belongs to this branch are identified among the *Policy Criteria* and the related *KPIs* defined in [1]–[3]. The set of evaluation criteria defined by JRC is proposed for the evaluation of any smart grid project alternative. Therefore, in order to assess the SM asset, only significant criteria have to be



selected (Figure 4).

Figure 4. Smart Grid deployment merit branch for SM assessment

As depicted in Figure 4, each *Policy Criteria* identifies a sub-branch that is independent of the others and the fulfillment of the *Policy Criteria* is appraised by means of the underlying KPIs [1]–[3].

In Table 1 the criteria which form each sub-branch are presented.

Since the assessment framework has to be tailored to get the assessment of the AMI, from Table 2 to Table 9 the focused description of the terminal criteria of each sub-branch is provided. The index section of the tables describes the feature that can be used for measuring the KPI fulfillment. Due to the flexibility of the MCA approach, each criterion can be assessed by means of the quantitative metrics defined by JRC or in qualitative terms. In the following, the calculation formulas of the KPIs proposed by the JRC are presented [3]. In the formulas, the subscripts BaU and SG respectively represent the value of the indices related to the reference *Business as Usual* (BaU) scenario and to the scenario in which the smart grid (SG) project option is developed.

Table 1. Criteria of the smart grid deployment merit branch for SM asset

Second level criteria		Third level criteria	
$C_1^{(2)}$	Level of sustainability	**KPI_1**	Environmental impact of electricity grid infrastructure
$C_2^{(2)}$	Network connectivity and access to all categories of network users	**KPI_2**	Methods adopted to calculate charges and tariffs, as well as their structure, for generators, consumers, and *prosumers*
$C_3^{(2)}$	Security and quality of supply	**KPI_3**	Stability of the electricity system
		KPI_4	Duration and frequency of interruptions per customer, including climate related disruptions
		KPI_5	Voltage quality performance
$C_4^{(2)}$	Efficiency and service quality in electricity supply and grid operation	**KPI_6**	Demand side participation in electricity markets and in energy efficiency measures
		KPI_7	Availability of network components (related to planned and unplanned maintenance) and its impact on network performances
		KPI_8	Ratio between minimum and maximum electricity demand within a defined time period

Table 2 describes the KPI_1 which is related to the environmental impact of electricity grid infrastructure assessment.

Table 2. KPI_1 description table

KPI_1 - Environmental impact of electricity grid infrastructure	
Description	The SM systems are formed by the metering device and the data communication infrastructure. Thereby, the electromagnetic and the visual impact of a SM project option have to be assessed.
Index	It has to be related to the outcomes of the environmental impact assessment.
Quantitative appraisal **Qualitative appraisal**	The estimation of the KPI_1 can be both quantitative or qualitative; it depends on the particular environmental impact analysis that is undertaken.

Table 3 describes the KPI_2 which evaluates the impact of the project option on charges tariffs and billing processes.

Table 3. KPI_2 description table

KPI_2 - Methods adopted to calculate charges and tariffs, as well as their structure, for generators, consumers and *prosumers*	
Description	This criterion assesses the potential changes on tariffs and billing processes. It is fulfilled by the alternatives that reduce tariffs and better allocate the operative resources of stakeholders. SM systems can enhance the information about the usage of the electrical energy, therefore they have an impact on this topic.
Index	The index can be related to the efficiency of billing processes and to the first-time grid connection tariffs.
Quantitative appraisal	It can be based on the monetary value of the tariffs or quantitative performance efficiency indices.
Qualitative appraisal	It can be related to a subjective analysis of the option characteristics in this area of interest.

Table 4 describes the criterion related to the KPI_3 which appraise the impact of the alternatives on the stability of the electricity system.

Table 4. KPI_3 description table

KPI_3 - Stability of the electricity system	
Description	This criterion assesses the extent to which the project option contributes in removing the cause of possible system frequency and voltage instabilities in the observed portion of the grid. SM systems can enhance the information about the state of the distribution grid.
Index	The index has to measure the contribution of the project option to solving critical stability scenarios.
Quantitative appraisal	A quantitative appraisal is possible by simulating the critical stability scenarios.
Qualitative appraisal	It can be related to a subjective analysis of the option characteristics in this area of interest.

Table 5 describes the KPI_4 which is related to the impact of the alternatives on the quality of the electrical power supply service.

Table 5. KPI_4 description table

KPI_4 - Duration and frequency of interruptions per customer, including climate related disruptions	
Description	This criterion assesses the extent to which the project option contributes in reducing the frequency and the duration of the interruptions. SM systems can improve the fault location and restoration procedures.
Index	System Average Interruption Duration Index [min] (SAIDI) and the System Average Interruption Frequency Index [units of interruptions per customer] (SAIFI)
Quantitative appraisal	The quantitative appraisal of the KPI_4 is possible by comparing the values of the SAIDI and SAIFI before and after the project development (1),(2). $$KPI_4^1 = \frac{SAIDI_{BaU} - SAIDI_{SG}}{SAIDI_{BaU}} * 100 \quad (1)$$ $$KPI_4^2 = \frac{SAIFI_{BaU} - SAIFI_{SG}}{SAIFI_{BaU}} * 100 \quad (2)$$
Qualitative appraisal	A qualitative appraisal can be indirectly made by estimating the level of the monitoring that can be achieved on the basis of the SM system features.

Table 6 presents the terminal criteria KPI_5 which evaluates the effects on voltage quality performances.

Table 6. KPI5 description table

KPI_5 - Voltage quality performance	
Description	This criterion assesses the extent to which the project option contributes in enhancing the voltage quality. SM systems can contribute by improving the voltage quality measurement.
Index	Indices related to voltage variations, voltage events, and Total Harmonic Distortion index (THD).
Quantitative appraisal	The quantitative appraisal is possible by means of (3) and (4). $$KPI_5^1 = \frac{(Voltage\_violations)_{BaU} - (Voltage\_violations)_{SG}}{(Voltage\_violations)_{BaU}} \quad (3)$$ $$KPI_5^2 = \frac{THD_{BaU} - THD_{SG}}{THD_{BaU}} \quad (4)$$
Qualitative appraisal	A qualitative appraisal can be indirectly made by estimating the level of the monitoring that can be achieved on the basis of the SM system features.

Table 7 describes the KPI_6 which assess the contribution of the alternatives on the Demand Side Response (DSR) participation.

Table 7. KPI6 description table

KPI_6 - Demand side participation in electricity markets and in energy efficiency measures	
Description	This criterion assesses the extent to which the project option contributes to the demand side participation in electricity markets and in energy efficiency measures. SM system can enable these new services.
Index	Indices related to sharing of loads that are involved in the DSR or in the energy efficiency measures.
Quantitative appraisal	The quantitative appraisal is possible by means of (5). $$KPI_6 = \frac{(P_{DSR})_{SG} - (P_{DSR})_{BaU}}{P_{peak}} * 100 \quad (5)$$ In which P_{DSR} is the load capacity participating in DSR and P_{peak} represents the maximum electricity demand.
Qualitative appraisal	A qualitative appraisal can be indirectly made by establishing if the SM system can enable the DSR and then estimating the share of power loads involved.

Table 8 presents the KPI_7 which is related to the assessment of the impacts on the availability of the network components.

Table 8. KPI_7 description table

KPI_7 - Availability of network components (related to planned and unplanned maintenance) and its impact on network performances	
Description	This criterion assesses the extent to which the project option contributes to the enhance the availability of network components. SM system can directly influence component reliability by substituting the existing infrastructure. Moreover, an indirect impact is possible if the SM system contributes to reducing the operating stress of grid components.
Index	Indices related to the reliability of the network components or the expected duration of their operating life.
Quantitative appraisal	The qualitative assessment of the KPI_7 proposed by JRC is based on the evaluation of the availability of the network components (6). $$Availability = \frac{MTBF}{MTBF - MTTR} \quad (6)$$ In which MTBF is the mean time between failures, while MTTR is the mean time to repair of each component under analysis.
Qualitative appraisal	A qualitative appraisal can be indirectly made on the basis of the amount of component that are substituted during the deployment plan.

Table 9 describes the KPI_8 which assess the contribution of the alternatives to the load levelling.

Table 9. KPI_8 description table

KPI_8 - Ratio between minimum and maximum electricity demand within a defined time period	
Description	This criterion assesses the extent to which the project option contributes to reducing the peaks of power load demand.
Index	Maximum peak power value and minimum power value.
Quantitative appraisal	The quantitative evaluation formula of KPI_8 proposed by JRC is (7). $$KPI_8 = \frac{(\frac{P_{min}}{P_{max}})_{SG} - (\frac{P_{min}}{P_{max}})_{BaU}}{(\frac{P_{min}}{P_{max}})_{BaU}} * 100 \quad (7)$$ In which P_{min} and P_{max} respectively are the minimum and maximum electricity demand within a defined time period.
Qualitative appraisal	A qualitative appraisal can be indirectly made on the basis of the number of the daily pricing periods available for the time of use tariffs.

2.3 The Externality assessment branch

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 in which evaluating the effects under analysis. Single impacts are related to the terminal criteria while the second level criteria are the thematic areas. In Figure 5 the tree of the selected criteria for the assessment of the SM impacts is depicted.

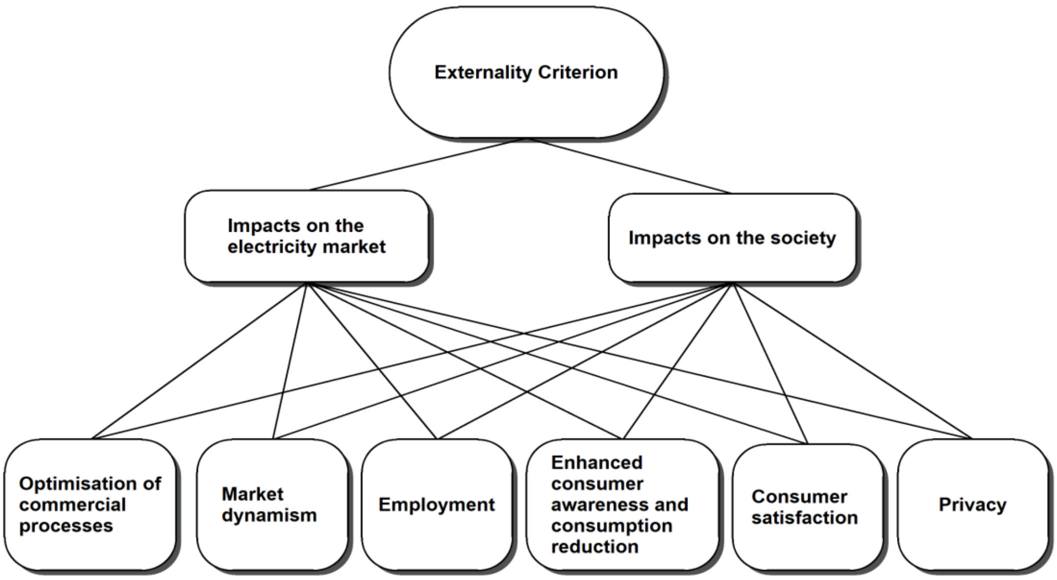


Figure 5. The externality branch for the SM assessment

In the tables Table 10 - Table 15 the description of the terminal criteria of the externality assessment branch is provided from the SM asset appraisal point of view.

Table 10 describes the terminal criteria that assess the impact of the SM alternatives in terms of the optimisation of the commercial process.

Table 10. $C_1^{(3)}$ description table

$C_1^{(3)}$ – Optimisation of the commercial processes	
Description	The accuracy of the acquired data about the energy consumption influences the effectiveness of the commercial processes. A faster and more detailed consumption reporting can optimise the billing processes.
Index	The index of this criteria can be related to the level of effectiveness of the billing process.
Quantitative appraisal	Delay rate, number of complaining procedures, amount of bills of balance.
Qualitative appraisal	The qualitative appraisal can be made on the basis of the features of the SM system related to the measurement rate, the data communication speed, and the remote control of the point of delivery.

Table 11 describes the market dynamism terminal criteria.

Table 11. $C_2^{(3)}$ description table

$C_1^{(3)}$ – Market Dynamism	
Description	The basic features of a SM system can potentially enable new tariff schemes and services. Thereby, the retail electricity market can enhance its dynamism.
Index	The index of this criteria can be related to the level of competition, the ease of switching from an energy supply company to another.
Quantitative appraisal	Number of time slots available for the time of use tariffs, new services enabled (e.g., DSR, energy saving service), time consumed by company supplier switching processes.
Qualitative appraisal	The qualitative appraisal can be made on the basis of the features of the SM system.

The Table 12 presents the terminal criterion related to the impacts on jobs.

Table 12. $C_3^{(3)}$ description table

$C_3^{(3)}$ – Employment	
Description	The SM deployment and the enabled new services can have impacts on jobs.
Index	Job rate.
Quantitative appraisal	Jobs may be lost by automatizing some metering activities. Conversely, new functionalities and services enabled may increase the job rate.
Qualitative appraisal	The qualitative appraisal can be made on the basis of the features of the SM system.

Table 13 describes the terminal criterion which evaluates the enhanced consumer awareness and the consumption reduction due to the SM alternative.

Table 13. $C_4^{(3)}$ description table

$C_4^{(3)}$ – Enhanced consumer awareness and consumption reduction	
Description	The SM provides information to the consumer about his electricity usage. Therefore, SM systems determine the consumer awareness and influence the amount of energy consumption.
Index	The avoided share of energy consumption due to the SM option.
Quantitative appraisal	Energy saving rate related to direct and indirect feedbacks. Adoption rate of energy efficiency services.
Qualitative appraisal	The qualitative appraisal can be made on the basis of the features of the SM system.

In Table 14 the consumer satisfaction criterion is described.

Table 14. $C_5^{(3)}$ description table

$C_5^{(3)}$ – Consumer satisfaction	
Description	The SM systems are responsible for wide range impacts which influence the consumer daily life. The social acceptance of the SM project option depends on the consumer satisfaction with respect to the changes that it leads.
Index	The consumer satisfaction index can be related to the customer care activities.
Quantitative appraisal	Number of complaining procedures, time consumed by company supplier switching processes, changes in the tariffs.
Qualitative appraisal	The qualitative appraisal can be made on the basis of the features of the SM system.

Finally, Table 15 describes the terminal criterion which assesses the level of data privacy and cyber security related to the SM alternatives.

Table 15. $C_6^{(3)}$ description table

$C_6^{(3)}$ – Privacy	
Description	The level of data privacy and cyber security influences the social acceptance of the SM alternative since it collects sensible data about the consumer habits.
Index	
Quantitative appraisal	Security of communication protocols, data property, level of data diffusion.
Qualitative appraisal	The qualitative appraisal can be made on the basis of the features of the SM system.

3 The 1G and 2G Smart Metering Systems

3.1 Introduction

In the present section, the state of art in Italy of smart metering for low voltage consumers is presented. For the sake of brevity, only the main aspects are presented in this document.

A SM system is an advanced metering infrastructure (AMI) which enables a remote monitoring and management of the low voltage points of delivery (PODs). According to [4], an AMI is "a system of technologies that measure, collect, communicate, aggregate and analyse energy usage data from metering devices". Thanks to the monitoring and communication capabilities of AMI, functionalities and higher-level services can be enabled [4].

In Italy, the first generation of smart metering is also known as *Telegestore*®. This project has been developed by *ENEL* since 2000, its full deployment has been achieved in 2006 [5]. In 2016, the minimum features of the second generation of SM systems have been defined by the Italian energy regulator although an upgrade of the metering infrastructure is not yet compulsory [6]. Nevertheless, in 2016, the *e-distribuzione* utility (formerly named as *ENEL distribuzione*) devised a development plan for a full upgrade of its SM infrastructure. This 2G SM infrastructure project is called *Open meter*® [5].

3.2 The 1G SM system features

According to [5], the Italian 1G SM infrastructure has 31797758 active measurement devices (revealed at 31 October 2016). In the first year of the 1G deployment (2000) 1084 measurement devices have been installed. At the moment of speaking, the 77% of the single-phase meters are older than 10 years, among three-phase meters this share is the 45%. The expected lifetime of a 1G meter is 15 years. *ENEL* voluntary developed the 1G SM infrastructure while in the 2007 the SM roll out became compulsory in Italy [7]. The unitary cost of the 1G deployment has been estimated in 97€/POD [8].

Main positive impacts of the 1G SM system are:

- Automatic monthly readings of the actual energy consumption;
- Remote on/off control of the PODs;
- Remote management of rated power of the PODs;
- Reduction of non-technical losses.

Main technical features of the 1G SM infrastructure developed by *ENEL* are [5], [9]:

- **Two-layers architecture:** the data communication architecture is made of two layers. The lower level concerns an A-band PLC channel between meter devices and data concentrators. In the higher level, the data concentrators are connected to the central acquisition system (CAS) of the utility by means of the GSM infrastructure.

- **Remote readings:** energy and power peaks data are measured by the meter. First, these data are stored in the meter memory. By means of a monthly procedure, data are acquired and aggregated according to the time of use tariffs. Only for PODs which have a rated power greater than 55kW the hourly pricing is enabled. Moreover, the well-functioning of the meter device is remotely monitored.
- **Remote control:** remote on/off control and remote rated power management of the PODs.

3.3 The 2G SM system features

According to [5], in the first year of deployment (2017) 1,8 millions of 2G smart meters are expected to be activated. In the last year of the deployment plan (2031), the 2G smart metering infrastructure is expected to have 41,8 millions of active metering devices. The massive deployment phase of the upgrading plan will last 8 years and the 80% of the old 1G meters will be replaced in the first six years.

The two layers architecture structure is preserved, each data concentrator is able to manage 80 smart meters. The novelty with respect to the 1G architecture relies on the double chain for data communication.

Chain 1 – The communication channel called chain 1 is used for billing purpose; validated consumption data is collected from the PODs by means of this chain. The data flow from the smart meter to the CAS of the utility through the data concentrator. The measured data are validated by the distribution network operator (DNO) and sent to the Integrated Information System (IIS) operated by the authority. Through the IIS, the data about the energy consumption are submitted to the energy suppliers. With respect to the 1G, this communication chain is enhanced for improving commercial and billing processes.

Chain 2 – The aim of the communication channel defined as chain 2 is to provide the data about the energy consumption directly to the users by means of an in-home device (IHD). These non-validated data can be used for defining the *energy footprint* of the customers. Consequently, new services and tailored tariffs can be provided to each customer. In particular, the retail market of energy efficiency services can be enabled [9].

Table 16 resumes the goals which led the Italian authority in defining the required minimum features of 2G SM systems. Table 16 also describes the functionality proposed for achieving the related goal. In Table 17 the main enhancement of the 2G SM system with respect to the 1G technology is shown.

Table 16. Objectives and functionalities of the 2G SM system deployment [9]

Objective	Related Functionality
Enhance the remote reading and control efficiency	The use of two alternative channels (PLC/radio) for chain 1
Increase the temporal granularity of remote readings	The daily energy consumption is acquired every 15 minutes (96 energy samples per day).
Submit the measurement data to energy suppliers within 24 hours.	By means of the chain 1, the daily profile of energy consumption is collected daily from the meter memory.
Real time feedback to the customer	Chain 2
Event monitoring on PODs (e.g., outages)	The smart meter is capable to send push messages to the CAS.

According to the authority point of view, the 2G SM system will enable new services thanks to a faster submission to energy suppliers of the data about the energy consumption, and a real time direct feedback to the customer.

Table 17. Main upgrading features of 2G SM system vs. 1G

Functionality 1
C-band PLC channel for the chain 2   Thanks to the chain 2, services related to energy management and home automation can be enabled. The residential load flexibility can be enhanced, a better integration of distributed energy resources (DERs) on the power system can be achieved.
Functionality 2
Increased memory of the metering device   The increased memory of the metering devices allows storing a bigger share of historical data about the consumption. Moreover, other electricity parameters can be stored locally. The feedback to the customer is enhanced. Therefore, the integration of the prosumers is encouraged.
Functionality 3
Enhanced flexibility of the smart meter firmware   Specific tariffs schemes can be tailored to each customer. In particular, the 2G smart meter system has to provide at least 10 time-slots for defining 6 tariffs (the 1G smart meters enabled 4 tariffs).
Functionality 4
The new functionalities have to enable the active demand services
Functionality 5
Enhanced computational speed of meters and data concentrator devices   A decreased communication failure rate is expected. Moreover, the enhanced computational and communication speeds reduce the data acquisition time and the time taken for firmware upgrading.

Functionality 6
The customer load profile and the peaks of absorbed power are collected daily This functionality can enable dynamic prices.
Functionality 7
The smart meter measures the main electrical parameters on the POD Smart meters as distribution grid probes. Therefore, the power system monitoring is enhanced (the 1G meters are not capable for voltage measuring). The MV/LV substations will be also equipped with 2G metering devices in order to assess technical and non-technical losses. A reduction of operating expenditures (OPEX) can be achieved.
Functionality 8
Enhanced tamper security
Functionality 9
Chain 1 communication channel backup (RF 169 MHz) for push message between meters and data concentrators. ***Push messages between data concentrators and CAS enabled by the UMTS/LTE network infrastructure*** The DNO will receive real-time warnings about critical events (e.g., outages). These warnings can be used by the distribution automation infrastructure in order to improve the network reliability.
Functionality 10
Near Field Communication (NFC) interface The entire life-cycle of 2G metering devices will be managed in an automated fashion.

3.4 Comparison between the 1G and 2G SM systems

The 1G and 2G SM systems show some similarities in terms of the infrastructure architecture, the 2G SM system is an upgrade of the existing infrastructure aimed at achieving higher reliability and better performances. The SM infrastructure is a fundamental requirement for enabling new smart grid services, the increased smartness of the metering infrastructure is necessary for transforming the distribution network into a smart grid. To illustrate, an enhanced flexibility of the distribution network can be achieved through dynamic prices in the electricity retail market. To enable this tariff scheme, the energy consumption has to be measured with a 15 minutes sample time and daily acquired by the utility [9]. The 1G SM system ensures a monthly acquisition of the measured energy consumption, therefore, a dynamic tariff scheme has not been developable. Conversely, the 2G SM system can enable dynamic hourly based tariffs. The main benefits that the 2G SM system can provide to the electricity market processes are [9]:

- reduction of the estimated and balance bills;
- a decreased amount of deposit required from end-users;
- decreased imbalances in the wholesale electricity market (more accurate knowledge of the retail users power demand, enhanced scheduling of the loads);
- hourly based tariffs, dynamic pricing, prepaid tariffs;
- decreased the economic losses related to bad payers.

The increased feedbacks to end-users enhance the consumer awareness and can lead to a more sustainable use of the electric energy and active demand services.

In Table 18, the 1G and 2G SM systems are compared on the basis of their main features. The comparison is focused on the benefits which these features can provide.

Table 18. Synthetic comparison between the 1G and 2G SM system

1	**Retail billing process [9]**
1G	Energy suppliers receive monthly the data about the energy consumed by the end-users in the previous month. Typically, the information is submitted to suppliers within the firsts 20 days of the following month. Therefore, the computation of the bills is delayed with respect to the real consumption period.
2G	By means of the chain 1, the energy suppliers receive daily the data about the energy consumed by the end-users in previous day. The information gathered by the supplier is the actual daily load profile. Therefore, the bills can be computed closer to the actual consumption period (6 days after the last day of that period). Moreover, the accuracy of the bills enhances.
The positive impacts on the retail billing process are related to the increased performances of the billing process. Consequently, a reduction of complains is expected.	
2	**Flexibility of the energy tariffs [9]**
1G	The tariffs are not customisable. A unique tariff scheme based on 4 different time-based prices is defined for all end-users.
2G	The tariffs can be tailored to the end-user *energy footprint.* Utmost 6 different time-based prices are defined for all end-users. The tariff scheme can be easily modified by means of the remote management.
The 2G system may increase the retail market dynamism. The customer is more involved into market mechanisms.	
3	**Supplier switching process [9]**
1G	The switching of the supplier is possible only at the first day of the month. Consequently, the switching procedure can experience utmost 50 days of delay.
2G	The switching of the supplier can be accomplished in every day of the month. The data on the actual energy consumption is promptly gathered by the suppliers.
The supplier switching procedure is simplified and shorten. Therefore, an enhanced customer satisfaction can be also achieved. The accuracy of the last bill of the former supplier is improved, a reduction of complains is expected.	
4	**Prepaid offers [9]**
1G	Theoretically possible.
2G	Fully enabled.
The positive impacts are related to the enhanced market dynamism and consumer awareness.	

5	**Energy footprint e reporting [9]**
1G	A direct channel for feedbacks to the end user is theoretically disposable. Actually, its use is strongly limited for avoiding communication failures. Third part devices are not supported.
2G	Thanks to the chain 2, direct and indirect feedbacks are enabled. The *energy footprint* of each customer can be defined.
	The consumer may achieve an enhanced awareness of its energy habits; therefore, a reduced energy consumption and better use of the electricity is expected. Energy efficiency services may be enabled. Furthermore, third part devices, DERs, and home automation solutions can benefit from the data measured by the meter.
6	**Demand Side Response (DSR) [9]**
1G	Not enabled.
2G	The upgraded metering performances can enable the DSR in the future.
	The DSR can simplify the wholesale market processes, therefore the implied costs transferred to the end-user bills may be reduced. Enhanced flexibility of the distribution network.
7	**Size of the data storage on the metering device [5]**
1G	Energy data and maximum power peak value of the ongoing billing period are stored.
2G	Energy data and maximum power peak value of the ongoing billing period are stored. Furthermore, these information about the previous 6 billing periods are stored in the meter.
	Enhanced consumer awareness. Improved integration of prosumers.
8	**Monitoring of network parameters [5]**
1G	Utmost 10 outage events can be stored on the meter (time resolution 1s). Synthetic information about voltage are measured and stored (EN 50160).
2G	Enhanced monitoring of the PODs. The metering devices can be considered as a distribution network probe.
	Enhanced distribution network monitoring, improved knowledge of the state of the grid.
9	**Backup channel of the chain 1 [5]**
1G	No backup communication channel.
2G	Chain 1 has a backup communication channel (RF 169MHz). Moreover, this allows spontaneous push messages from the meter device to the data concentrator.
	Reduced data acquisition failure rate.
10	**Spontaneous push messages from the meter [5]**
1G	Not enabled. Data from the meters is acquired by the data concentrator only by means of polling procedures.
2G	Enabled. The RF channel allows real-time push messages from the SM to the data concentrator. These messages are then submitted to the CAS through the UMTS/LTE infrastructure.
	The DNO has a real-time snapshot of its low voltage network. The network reliability may be improved if distribution automation solutions are able to receive these push messages.

11	**Tamper and data privacy security [5]**
1G	Absolute data not disposable.
2G	Enhanced tamper security. An advanced encryption standard (128/256 bit) is used for protecting the exchanged data.
	A reduction of non-technical losses is expected. The cyber-security is enhanced even if an increased amount of data is collected from users.

4 The MC-CBA approach used to analyse the SM systems

The proposed MC-CBA approach is used for analysing the 1G and 2G systems described in the previous sections. Although the 2G deployment is already on-going in Italy, the following analysis aims at proving the effectiveness of the MC-CBA approach on a real case of smart grid asset development. The MC-CBA has been conducted by means of an original cross-platform toolkit which integrates the ISGAN CBA toolkits within the MCA framework devised on MATLAB. In particular, the MADM technique that is used for identifying the best alternative is the Analytic Hierarchy Process (AHP).

At the first stage, the AHP has been identified as the most suitable MCA approach to the decision problem at hand:

- AHP is “built-in” technique, the scoring and weighting stages are integrated in its procedure;
- qualitative and quantitative input data can be simultaneously managed;
- its algorithm is transparent and flexible; therefore, it is easy to be employed;
- AHP directly and easy manages large hierarchical structures of criteria.

4.1 Tailoring the hierarchical structure on the decision problem

4.1.1 General hypothesis

According to the MCA theoretical pillars, the structure of criteria has to be tailored on the decision-making problem under analysis [10]. In fact, to obtain an effective outcome of the MCA, evaluation criteria and related performance indices have to emphasise the differences among the alternatives in the appraisal set. Moreover, if the number of the evaluation criteria is high, the risk of inconsistent DM’s judgments increases. Therefore, the number of the criteria has to be minimised.

In general, to avoid inconsistency in judgements and minimise the subjectivity of the DM some preliminary activity can be accomplished prior to the pairwise comparison process [10]:

- The objects have to be sorted according to their relative importance;
- The pairwise comparison has to start from the most relevant objects;
- The weighting stage has to follow the scoring phase;
- The weighting stage of hierarchical structures has to follow a bottom-up approach.

In absence of detailed quantitative data on the alternatives under analysis, the MC-CBA on the SM systems has been conducted on performances expressed in qualitative terms. The qualitative performances are based on the information acquired and briefly resumed in the previous sections. Subjectivity may be introduced in the analysis by the qualitative appraisal of the performances. Nevertheless, if the analysis is conducted following proper practises, the reliability of the outcome provided by the MCA is not jeopardised [10]. MCA aims at supporting the DM in complex decision-making process, thanks to its flexibility qualitative and quantitative appraisals may be user together. Impacts appraised with uncertainties may be included in the MCA, hence the resources for conducting the overall analysis are reduced because the efforts for an accurate quantitative estimation of all impacts may be avoided.

The MC-CBA approach is flexible; once quantitative information about the SM alternatives are gathered, the analysis can be repeated by following the described framework. However, some criteria may be adjusted to better fit to the related quantitative performance index.

4.1.2 The reduced hierarchical structure

As highlighted in previous sections, a reduced hierarchical structure has been defined in order to tailor the general structure on the SM alternatives under appraisal.

The Economic branch

According to the proposed MC-CBA approach, a preliminary CBA has to be conducted for each alternative. The outcome of the CBA represents the economic performance of each alternatives which is the input of the economic branch.

At the time of the analysis, detailed information on monetary costs and benefits of both the 1G and 2G scenarios were not of public domain. On the basis of the partial information disposable, the analysis has been conducted by considering an economic branch defined as in Figure 3. This branch has been particularised by considering in the second level only the criterion *"Costs",* and in the third level only a criterion *"Expenditures"* (Table 19). As a consequence, the economic performances are based on the discounted total capital expenditures which occurs in the whole lifetime plan of the investment.

The Smart grid merit and externality branches

Starting from the general branches defined in sections 2.2 and 2.3, a subset of evaluation criteria has been defined on the basis of the available information about the 1G and 2G SM alternatives.

In the smart grid deployment merit branch, the third level criterion KPI_3 has been neglected. The KPI_3 aims at evaluating the contribution of the alternatives on power system stability [3]. Not enough detailed information were available even for a qualitative appraisal of the performances on this criterion.

In the externality assessment branch, the third level criterion $C_5^{(3)}$ has been neglected. This criterion aims at evaluating the customer satisfaction originated by the deployment of each alternative. Also in this case, not enough detailed information were available even for a qualitative appraisal of the performances on this criterion.

Table 19 schematically resumes the evaluation tree that is used in the MC-CBA analysis of the 1G and 2G SM systems.

Table 19. Scheme of the hierarchy tree of the selected evaluation criteria

First Level Criteria	Second Level Criteria		Third Level Criteria	
Economic Branch	**COSTS**	Expected monetary costs	**Expenditure**	Discounted total capital expenditures which occurs in the whole lifetime plan of the investment
Smart grid deployment merit branch	**SMART_1**	Level of sustainability	**KPI_1**	Environmental impact of electricity grid infrastructure
	SMART_2	Network connectivity and access to all categories of network users	**KPI_2**	Methods for calculating charges and tariffs, as well as their structure, for generators, consumers and prosumers
	SMART_3	Security and quality of supply	**KPI_4**	Duration and frequency of interruptions per customer, including climate related disruptions
			KPI_5	Voltage quality performance
	SMART_4	Efficiency and service quality in electricity supply and grid operation	**KPI_6**	Demand side participation in electricity markets and in energy efficiency measures
			KPI_7	Availability of network components (related to planned and unplanned maintenance) and its impact on network performances
			KPI_8	Ratio between minimum and maximum electricity demand within a defined time period
Externality assessment branch	**EXT_1**	Impacts on the electricity markets	$C_1^{(3)}$	Optimisation of the commercial processes
			$C_2^{(3)}$	Market Dynamism
	EXT_2	Impacts on the society	$C_3^{(3)}$	Employment
			$C_4^{(3)}$	Enhanced consumer awareness and consumption reduction
			$C_5^{(3)}$	Privacy and data security

4.2 AHP technique applied on the MC-CBA approach

4.2.1 Pairwise comparison by means of the Saaty's ratio scale

The scoring and the weighting stages on the AHP are addressed by means of a pairwise comparison procedure. This process involves a fundamental scale of judgement also known as Saaty's scale (Table 20).

To illustrate, the weighting stage involves the pairwise comparison of the criteria which belongs on a same hierarchical level of a branch. In order to collect the DM's preferences, he has to answer to question such as "*How important is criterion 'j' relative to criterion 'k'?*" [10]. The answers are collected through the verbal scale described in Table 20 which directly corresponds to the Saaty's ratio scale.

Table 20. Saaty's judgment scale [11]

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 intermediate integer values (2, 4, 6, 8) can be used to express a preference between two adjacent judgments. The number of required pairwise comparisons for AHP increases as the number of the criteria and/or of the alternatives increase. Each pairwise comparison process aims at building a preference matrix which collects the preferences among the compared objects. In the scoring stage, a preference matrix of the alternatives is obtained for each terminal criterion. In the weighting stage, a preference matrix of the criteria is computed for every criterion of the upper level. 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 21 depicts an example of a preference matrix.

Table 21. AHP preference matrix example

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

The priorities related to a preference matrix of the scoring stage represent the normalized score of each alternative with respect to the considered criterion. Conversely, the priorities related to a preference matrix of the weighing stage are the normalized local weights of the criteria involved. Priorities from preference matrices can be evaluated by using different approaches; the classical one establishes that the priorities are equal to the normalized eigenvector of the maximum eigenvalue of the preference matrix. The output provided by the AHP is a complete ranking of the alternatives that is obtained by the linear combination of the alternative's priorities with global priorities of terminal criteria of the hierarchy. The alternative that achieves the highest overall score is the one that the AHP indicates as the best alternative of the analysed set.

4.2.2 AHP scoring stage

The scoring stage that here is described is based on the information which have been briefly resumed in section 3. According to the classic procedure of the AHP, the fulfilment of each criteria is assessed in qualitative terms [12]. During the AHP scoring stage the alternatives are pairwise compared on the basis of their performance levels. The scoring stage of the alternatives can be based on absolute performances or on relative performance. In the first case, the impacts related to each alternative have to be evaluated with respect to a common reference scenario. In the second case, the performances are expressed in relative terms with respect to the other alternatives of the appraisal set under analysis.

4.2.2.1 Scoring of the economic performances

The economic performances of the 2G alternatives can be inferred from the deployment plan proposed in [5] in which the capital expenditure (CAPEX) for each year of the plan (2017-2031) is accounted. In order to compare this economic performance with the one of the 1G SM system, a similar 2017-2031 scenario for the 1G SM system has to be devised.

Considering that:

- at the moment, neither the 2G deployment and the 1G devices replacement is compulsory in Italy.
- The well-functioning of smart meter devices installed since 2007 have to be verified every 15 years (compulsory in Italy).

Therefore, two fictitious scenarios can be devised for the 1G system.:

- (1G.a) *do-nothing* scenario. The 1G meter devices are replaced only when malfunctioning.
- (1G.b) massive replacement of the older 1G meters with new 1G meters (AEEGSI baseline).

The information required in order to build the 1G.a scenario are:

a. The current DNO expenditure for the 1G infrastructure;

b. The failure rate of the 1G smart meters;

c. The cost related to the periodic test of the meters installed after 2007. This test concerns the 28% of the 1G meters installed by *e-distribuzione* in the 2001-2016 period [5].

d. The yearly growth rate of new PODs.

Although the information *d.* may be inferred from the 2G deployment plan [5], the information described by the points *a., b.,* and *c.* is missing. Furthermore, an estimated value of these parameters based on the available information would lead to an unreliable value of cost.

The 1G.b scenario represents a fictitious scenario devised by the Italian regulator for assessing the 2G SM system deployment plans [13]. The purposed 2G SM deployment plan receives subsidies if it passes the economical comparison with respect to the related fictitious 1G scenario. This fictitious scenario exactly follows deadlines and volumes of installation of the proposed 2G plan. The CAPEX related to the 1G.b scenario is obtained by multiplying the maximum unitary expenditure in the t-1 year and the number of the 1G metering devices. The unitary expenditure is obtained by the sum of:

- the 125% of the supplying expenditure for smart meters in 2015;
- the cost related to the replacement of the data concentrators (estimated in 51€ for each 1G metering device);

The number of 1G metering devices descend from the amount of 2G meters that have to be installed. The number of meters has to be adjusted taking into account an estimated failure rate for 1G meters (1%) and the expected failure rate for the 2G devices for the time horizon of the plan.

At the moment of the analysis, the supplying expenditure for smart meters in 2015 is unknown; therefore, the 1G.b scenario would have been obtainable only by means of an estimated expenditure value.

The 1G.b is a conventional scenario because the replacement of the installed 1G smart meters is not yet compulsory. Therefore, a massive 1G to 1G replacement may be supposed only as systematic maintenance plan. The aim of the Italian Authority is to identify the 2G SM plans which do not increase the cost of the measurement service. From the Authority point of view, if the costs of a 2G plan are similar to the cost of the related 1G plan, then the former will not lead to an increased measurement service cost.

In the following, the 2G SM system is compared to its related fictitious 1G plan. Since the missing information about the expenditure of the 1G.b scenario, a qualitative appraisal is made also for the economic branch. The hypothesis made relies on the Authority point of view which encourages 2G plans only if their cost is similar to their 1G dual scenario. Taking into account that the plan proposed by *e-distribuzione* has passed the comparison with respect to the related 1G fictitious scenario [14], then an equal score on the economic criterion is assigned to both alternatives under analysis (Table 22).

Table 22. Scoring stage of the economic branch

Third level criteria	1G System (M€)	2G System (M€)	1G System Qualitative estimation	2G System Qualitative estimation	Notes
Expenditure	n.d.	4398,3	1	1	According to [14], it is assumed that the alternatives have a similar economic performance

The second level criteria "*COSTS*" and the third level criteria "*Expenditure*" have to be minimised. Therefore, the alternative that shows less expenditures better fulfils the related criterion.

4.2.2.2 Scoring of the performances in the Smart Grid deployment merit branch

The performances of the alternatives in terms of their smart grid deployment merit depend on the technical features of the SM systems. These performances have been evaluated taking into account a full developed infrastructure. The qualitative scores have been assigned by means of a pairwise comparison procedure. The Saaty's ratio scale (Table 20) has been used for converting the verbal judgement. In Table 23 the scoring stage of the smart grid deployment merit branch is resumed.

Table 23. Scoring stage of the smart grid deployment merit branch

KPI_1 - Environmental impact of electricity grid infrastructure				
	1G	**2G**		
Score:	1	1	**Notes:**	The analysed SM infrastructure have a similar infrastructure, therefore the environmental impact of them is **comparable**. An **equal preference** is assigned to the alternatives.
KPI_2 - Methods adopted to calculate charges and tariffs, as well as their structure, for generators, consumers and prosumers				
	1G	**2G**		
Score:	1/3	3	**Notes:**	The 2G system allows the energy supplier to receive the daily consumption data of all consumers. Therefore, an enhanced load profiling is achievable. As a result, the grid tariffs for end-user may be reduced. A **weak preference for the 2G** alternative is assigned.
KPI_4 - Duration and frequency of interruptions per customer, including climate related disruptions				
	1G	**2G**		
Score:	1/2	2	**Notes:**	The 2G system allows an enhanced monitoring and real-time events detection. However, the reduction of SAIDI and SAIFI indices depends on the 2G integration in the distribution automation framework. If this integration is not on place, it is assumed that the 2G SM system slightly improves the 1G system scenario. A **slightly preference for the 2G** alternative is assigned.

KPI_5 - Voltage quality performance				
Score:	**1G** 1/2	**2G** 2	**Notes:**	The 2G system allows an enhanced monitoring of the POD voltage parameters. The 2G system cannot directly improve the voltage quality if it is not integrated with the distribution automation framework. A **slightly preference for the 2G** alternative is assigned.
KPI_6 - Demand side participation in electricity markets and in energy efficiency measures				
Score:	**1G** 1/7	**2G** 7	**Notes:**	The 2G system enables future services based on the active participation of the end-user in the electricity market. **A demonstrated preference for the 2G** alternative is assigned.
KPI_7 - Availability of network components (related to planned and unplanned maintenance) and its impact on network performances				
Score:	**1G** 1	**2G** 1	**Notes:**	It is assumed that the alternatives under analysis have the same failure rate. An **equal preference** is assigned to the alternatives.
KPI_8 - Ratio between minimum and maximum electricity demand within a defined time period				
Score:	**1G** 1/5	**2G** 5	**Notes:**	The 2G system increases the segmentation of the time of use tariffs. The tariffs may be more flexible during the day. An increased load levelling may be achieved. A **strong preference for the 2G** alternative is assigned.

4.2.2.3 Scoring of the Externality branch

As for the Smart Grid deployment merit branch, the performances of the alternatives in terms of their externality impacts depend on the technical features of the SM systems. These performances have been evaluated taking into account a full developed infrastructure. The qualitative scores have been assigned by means of a pairwise comparison procedure. The Saaty's ratio scale (Table 20) has been used for converting the verbal judgement. In Table 24 the scoring stage of the externality impacts assessment branch is resumed.

Table 24. Scoring stage of the externality impacts assessment branch

$C_1^{(3)}$ - Optimisation of the commercial processes				
Score:	**1G** 1/7	**2G** 7	**Notes:**	The 2G system allows the energy supplier to receive the daily consumption data of all consumers. Therefore, the 2G SM system can strongly improve the efficiency of commercial processes. A **demonstrated preference for the 2G** alternative is assigned.
$C_2^{(3)}$ - Market Dynamism				
Score:	**1G** 1/5	**2G** 5	**Notes:**	A huge variety of tariff schemes are enabled by the 2G features. Moreover, the switching between different energy suppliers is simplified. A **strong preference for the 2G** alternative is assigned.

$C_3^{(3)}$ – Employment				
	1G	**2G**		
Score:	1/2	2	**Notes:**	Nevertheless the enhanced market dynamism, the positive impacts of the 2G system on jobs may be limited only to the new energy services enabled. A **slightly preference for the 2G** alternative is assigned.

$C_4^{(3)}$ – Enhanced consumer awareness and consumption reduction				
	1G	**2G**		
Score:	1/2	2	**Notes:**	Although the 2G system increased the feedbacks to the end-users, the consumption reduction contributes are not fully cumulative [9]. Furthermore, the enhanced level of feedbacks is reachable only by using IHDs which are not provided together with the meter. A **slightly preference for the 2G** alternative is assigned.

$C_5^{(3)}$ – Privacy and data security				
	1G	**2G**		
Score:	2	1/2	**Notes:**	The cyber-security is enhanced even if an increased amount of data is collected from users by means of the 2G SM system. A **slightly preference for the 1G** alternative is assigned.

4.2.3 The weighting stage

During the weighting stage, the pairwise comparison of the evaluation criteria belonging to a same hierarchical level of a branch is conducted. According to their relevance for the DM, a relative weight is assigned to each criterion.

As previously stated, in order to reject inconsistencies and reduce subjectivity, a bottom-up approach has been exploited. Moreover, prior to the pairwise comparison procedure, the criteria have been ranked according to their relevance. Then, the pairwise comparison began from the most relevant pair of criteria. In the next sections, the results of the weighting stages of all branches are described.

4.2.3.1 Weighting of the smart grid deployment merit branch

The relevance of the *Policy Criteria* and the related *KPIs* is inherited from the JRC guidelines [1], [2]. JRC suggests assigning an equal relevance to all *Policy Criteria.* Similarly, all the *KPI* related to a same *Policy Criterion* have to be the same relevance. Consequently, all the elements of the preference matrices of the smart grid deployment merit branch are unitary. Therefore, the local priorities are equal to the reciprocal of the number of criteria of each preference matrix. In Table 25 and Table 26 the local priorities of the *Policy Criteria* and of *KPI* are respectively shown.

Table 25. Local weights of the Policy Criteria (the second level criteria)

Criterion	SMART_1	SMART_2	SMART_3	SMART_4
Local Priority	0.25	0.25	0.25	0.25

As highlighted in Table 26, the KPI_1 and KPI_2 local weights have both a unitary value because these KPIs are the only third level criterion related to their parent *Policy Criterion*.

Table 26. Local weights of the KPIs (third level criteria)

Criterion	**KPI_1**		
Local Priority	1		
Criterion	**KPI_2**		
Local Priority	1		
Criterion	**KPI_4**	**KPI_5**	
Local Priority	0.5	0.5	
Criterion	**KPI_6**	**KPI_7**	**KPI_8**
Local Priority	0.3333	0.3333	0.3333

4.2.3.2 Weighting of the externality impacts assessment branch

In the weighting stage of the criteria belonging to the externality impacts assessment branch the point of view of the stakeholder has been introduced. Table 27 represents the preference matrix of the second level criteria of the externality branch. This matrix resumes the pairwise comparison procedure of the two second level criteria in the externality branch.

Table 27. Preference matrix of the second level criteria - Externality branch

	EXT_1	**EXT_2**	**Local weight**
EXT_1	1	3	0.75
EXT_2		1	0.25

Inconsistency index: 0,0

In order to collect the DM's preferences, he has to answer to question such as "In order to fulfil the externality criterion, how important is criterion 'EXT_1' relative to criterion 'EXT_2'?". In this analysis, a weak preference on the "EXT_1" has been given. The electricity market has been considered weakly more relevant than the social area because the main target of the SM system is to measure properly the energy consumption in order to compute the energy bills.

Table 28 represents the preference matrix of the third level criteria of the externality branch evaluated with respect to the EXT_1 criterion of the second level.

Table 28. First preference matrix of third level criteria - Externality branch

EXT_1	**C_1**	**C_2**	**C_3**	**C_4**	**C_5**	**Local weight**
C_1	1	1	7	9	9	0,41313
C_2		1	7	9	9	0,41313
C_3			1	3	5	0.09532
C_4				1	3	0,04900
C_5					1	0,02942

Inconsistency index: 0,072

The pairwise comparison process among the third level criteria has been conducted according to the previous described procedure. The criteria related to the optimisation of the commercial processes and market dynamism have been considered strongly more important with respect to the others for improving the electricity market.

Table 29 represents the preference matrix of the third level criteria of the externality branch evaluated with respect to the EXT_2 criterion of the second level.

Table 29. Second preference matrix of third level criteria - Externality branch

EXT_2	C_1	C_2	C_3	C_4	C_5	Local weight
C_1	1	3	1/5	1/5	1/3	0,07609
C_2		1	1/5	1/5	1/5	0,04577
C_3			1	3	3	0,43888
C_4				1	3	0,28053
C_5					1	0,15872

Inconsistency index: 0,0873

The pairwise comparison process among the third level criteria has been conducted according to the previous described procedure. The criteria related to the employment impacts and the enhanced awareness of the end-users have been considered strongly more important with respect to the others for fulfilling the social criterion.

4.2.3.3 Weighting of the economic branch

Two criteria form the economic branch: one criterion in the second level and one criterion in the third level. Therefore, their local weight is unitary.

4.2.3.4 Weighting of the first level criteria

By means of the pairwise comparison procedure, the local weights of the first level criteria have been evaluated. The aim of this procedure is to define the relevance of the 3 branches with respect to the main goal of the analysis.

Table 30 represents the preference matrix of the first level criteria. The main goal at the top of the hierarchy aims at identifying the best SM alternative.

Table 30. Preference matrix of the first level criteria

	ECO	SMART	EXT	Local weight
ECO	1	2	2	0.5
SMART		1	1	0.25
EXT			1	0.25

Inconsistency index: 0,0

The pairwise comparison process among the first level criteria has been conducted according to the previous described procedure. The economic branch evaluates only costs, while in the other two branches only benefits are assessed. Therefore, the given preference models a pattern of weights in which costs and benefits have the same relevance.

In general, different patterns of weights can be defined in order to model different stakeholder's point of view. In this analysis, the defined weighs strive for modelling the point of view of the Italian authority which is focused on the invariance of the cost for the metering service [13], [14]. In section 4.2.5, the analysis has been repeated considering a different pattern of weight for the first level criteria.

4.2.4 Results

The outcome of the AHP evaluation is presented in Table 31. The AHP evaluation indicates the 2G SM system as the best alternative.

Table 31. Outcome of the AHP assessment

Alternative	Overall score
1G	0.39216
2G	0.60784

Both the 1G and 2G alternatives shows an equal economic performance, while the 2G alternative achieve a better score on the smart grid merit criterion and the externality criterion (Table 32). Due to the fact that the 2G system is the upgrade of the alternative 1G, its performances are higher than the performances of the 1G system in the majority of the evaluation criteria, as highlighted in Table 23 and Table 24.

Table 32. Partial scores of the alternatives under analysis

	1G Partial score	2G Partial score
Economic branch	0,5	0,5
Smart grid branch	0,33680	0,66320
Externality branch	0,23185	0,76815

The sensitivity analysis made by varying the weights of the first level criteria highlights that the 2G alternative is always preferred. Only if the economic criterion has absolute relevance (local weight equal to 1), the two alternatives becomes equally preferred by the AHP method. The described behaviour is caused by the prevalence of the 2G alternative in the other two criteria of the first level.

In addition, a sensitivity analysis by varying the economic performance of the 2G alternative is made. The preference on the '*Expenditure'* criterion has been considered as the ratio of the costs related to the two alternatives under analysis. In this context, the alternative 1G becomes the best alternative indicated by the AHP if the costs related to the 2G system are at least three times greater than the costs related to the 1G scenario.

In Table 33 the global weights of the terminal criteria of the hierarchy are presented.

Table 33. Global weight of terminal criteria

Criterion	Global Weight
C_1	0,08222
C_2	0,08032
C_3	0,04530
C_4	0,02672
C_5	0,01544
Expenditure	0,5
KPI_1	0,0625
KPI_2	0,0625
KPI_4	0,03125
KPI_5	0,03125
KPI_6	0,02083
KPI_7	0,02083
KPI_8	0,02083

4.2.5 AHP for a different first level criteria relative relevance

In this section, the AHP evaluation repeated by considering an equal relevance for the first level criteria is described. The outcomes of the weighting stages of low levels criteria are maintained. However, the global priorities of the terminal criteria changes because of the different value of first level criteria weights.

Table 34 represents the preference matrix of the first level criteria according to the new preference scheme.

Table 34. Preference matrix of the first level criteria

	ECO	SMART	EXT	Local weight
ECO	1	1	1	0.3333
SMART		1	1	0.3333
EXT			1	0.3333

Inconsistency index: 0,0

In Table 35 the new global weights of the terminal criteria of the hierarchy are presented.

Table 35. Global weight of terminal criteria in the second pattern of first level criteria weights

Criterion	Global Weight
C_1	0.10962
C_2	0.10710
C_3	0.06040
C_4	0.03563
C_5	0.02058
Expenditure	0,33333
KPI_1	0.08333
KPI_2	0.08333
KPI_4	0.04167
KPI_5	0.04167
KPI_6	0.02778
KPI_7	0.02778
KPI_8	0.02778

The partial score of the alternatives with respect to each branch does not changes because the lower level local weights are maintained. In this new analysis, the relevance of all three branches is equal. The outcome of the AHP evaluation is presented in Table 36.

Table 36. Outcome of the AHP assessment

Alternative	Overall score
1G	0.35622
2G	0.64378

According to AHP, also in this case the best alternative is the 2G SM system. Its overall score is increased because of the enhanced relevance of the smart grid deployment and externality merit evaluations.

Also in this case the sensitivity analysis made by varying the economic performance of the 2G alternative has been made. Due to decreased relevance of the economic criterion, the alternative 1G is indicated as the best only if the cost related to the 2G system becomes 9 times higher than the 1G expenditure.

5 Outranking approach methods used for analysing the SM systems

In this section, the analysis of the SM infrastructure previously described is addressed by means of an Outranking Approach (OA) method. With this aim, most of the outcomes previously achieved can be used as a starting point.

5.1 The ELECRE III Method

The OA methods are based on the outranking concept: "Option A outranks Option B if, given what is understood of the decision maker's preferences, the quality of the evaluation of the options and the context of the problem, there are enough arguments to decide that A is at least as good as B, while there is no overwhelming reason to refute that statement" [10], [15]. In OA methods, the alternatives are pairwise compared in terms of their performances in order to define the outranking binary relation. Weights of criteria influence the dominance relationship within each pair. The OA methods are not compensative i.e., in the overall assessment of an alternative, good performances on some criteria cannot counterbalance poor performances on other criteria. Thanks to this feature, OA methods capture the real DMs' behaviour related to the rejection of the alternatives that show an intolerable level of performances on some criteria.

Among the OAs, the family of ELECTRE methods is one of the main branches and ELECTRE III is one of the most acknowledged methods. Its algorithm is divided into two stages [16]:

1. The computation of the outranking relationships;
2. The exploiting of the obtained outranking relationships.

In the first stage, the DM has to define weights of criteria and preference, indifference, and veto thresholds; then, the outranking relationship of each pair of alternative can be built. In the second stage, the outranking relationships are analysed for identifying the dominant set of alternatives.

In general, the operators used to describe the binary relationship between each pair of alternatives are:

- *S:* outranking operator (i.e., *aSb: a* is at least as good as *b*);
- *P:* strictly preference operator (i.e., *aPb: a* is strictly preferred to *b*);
- *I:* indifference operator (i.e., *aIb: a* is indifferent to *b*);
- *R:* incomparability operator (i.e., *aRb: a* is incomparable to *b*).

The possible binary relations among each pair of alternatives are four [16]:

1. *aSb* and *not bSa* (hence *aPb*): *a* outranks *b*;
2. *bSa* and *not aSb* (hence b*Pa*): *b* outranks *a*;
3. *aSb* and *bSa* (hence *aIb*);
4. *not aSb* and *not bSa* (hence *aRb*).

The outranking relationship (*aSb*) between each pair of alternatives is not transitive, it can be crisp, fuzzy or embedded, and it is built on the concepts of *Concordance* and *Discordance* of the criteria on the *aSb* statement. *Concordance* exists if a sufficient majority of criteria agree with the dominance relationships while none of the *discordant* criteria strongly disagree on *aSb*.

5.2 The ELECTRE III method for the SM analysis

The analysis of the SM infrastructure by means of the ELECTRE III method starts from the flat decision-making problem defined by the terminal criteria of the evaluation tree. ELECTRE III is not a 'built-in' technique, therefore a specific weighting stage has to be previously addressed. For this reason, the global priorities of terminal criteria obtained in the weighting stage of the AHP assessment are used.

Since the performances are handled by means of an interval scale, the scoring stage is not strictly required on ELECTRE methods. In order to manage qualitative performance as input data, the preferences on the alternatives have to be converted from verbal judgements to a suitable interval scale. Furthermore, the DM has to define the indifference, preference, and veto threshold for each criterion [17]:

- *The indifference threshold* q_i: it is the greatest difference on performances on a criterion that makes two options indifferent for the DM's point of view.
- *The preference threshold* p_i: it is the smallest difference on performances on a criterion that makes an option preferred to the other for the DM's point of view.
- *The veto threshold* v_i: it is the smallest difference on performances on a criterion which leads to the rejection of the proposed outranking relationship, albeit the other criteria agrees with it.

5.2.1 Qualitative scoring of performances

The scores which are assigned in this step relies on the same concepts that have been used for the scoring stage of the AHP assessment. For the ELECTRE III analysis, a 7 points qualitative judgment scale has been employed (Table 37). The 7-point interval scale is assumed as linear, ie., the 7 points are equidistant. A similar qualitative interval scale has been proposed in [18]. Due to the use of an interval scale, the qualitative assessment has to focus on the differences between the performance of the alternatives on each criterion. Considering the actual characteristics of the alternatives under analysis, in order to reduce the subjectivity of the qualitative scoring stage, the 1G alternative is considered as a reference and as a *status quo scenario*. Therefore, the impacts related to the 2G alternative are relatively estimated.

The ELECTRE III flexibility allows to simultaneously consider quantitative and qualitative impacts. In this analysis, all the criteria are assessed in qualitative terms except the '*Expenditure*' criterion.

The 'Expenditure' and the 'KPI1' criteria are fulfilled by decreasing performances. Conversely, the remaining criteria have to be maximised.

Table 37. 7-points qualitative judgement scale for the ELECTRE III analysis

Verbal description of the performance	Numerical Value
Strongly negative impact	1
Negative impact	2
Weak negative impact	3
No impact	4
Weak positive impact	5
Positive impact	6
Strongly positive impact	7

Table 38 represents the performance matrix (PM) of the alternatives with respect to the economic criterion '*Expenditure*'.

Table 38. Performance Matrix of the 'Expenditure' criterion

Expenditure				
	1G	**2G**		
Value [M€]:	4398,3 (*supposed*)	4398,3 (*known*)	**Notes:**	According to [14], it is assumed that the alternatives have a similar economic performance. Therefore, the economic performance of the 1G alternative has been supposed equal to the performance of the 2G.

Table 39 represents the PM of the alternatives with respect to the *KPIs,* and resumes the reasoning behind the preferences.

Table 39. Performance Matrix of the alternatives with respect to the KPIs

KPI_1 - Environmental impact of electricity grid infrastructure				
	1G	**2G**		
Score:	4	4	**Notes:**	The analysed SM alternatives have a similar infrastructure, therefore their environmental impact is **comparable**. **No difference between the impacts** is expected**.**
KPI_2 - Methods adopted to calculate charges and tariffs, as well as their structure, for generators, consumers and prosumers				
	1G	**2G**		
Score:	4	5	**Notes:**	The 2G system allows the energy supplier to receive the daily consumption data of all consumers. Therefore, an enhanced load profiling and settlement is achievable. As a result, the grid tariffs for end-user may be reduced. The 2G leads to a **weak positive impact** in reference to the 1G.

KPI$_4$ - Duration and frequency of interruptions per customer, including climate related disruptions					
	1G	**2G**			
Score:	4	5	**Notes:**	The 2G system allows an enhanced monitoring and real-time events detection. However, the reduction of SAIDI and SAIFI indices depends on the 2G integration in the distribution automation framework. If this integration is not on place, it is assumed that the 2G SM system slightly improves the 1G system scenario. The 2G leads to a **weak positive impact** in reference to the 1G.	
KPI$_5$ - Voltage quality performance					
	1G	**2G**			
Score:	4	5	**Notes:**	The 2G system allows an enhanced monitoring of the POD voltage parameters. The 2G system cannot directly improve the voltage quality if it is not integrated with the distribution automation framework. The 2G leads to a **weak positive impact** in reference to the 1G.	
KPI$_6$ - Demand side participation in electricity markets and in energy efficiency measures					
	1G	**2G**			
Score:	4	7	**Notes:**	The 2G system enables future services based on the active participation of the end-user in the electricity market. The 2G leads to a **strongly positive impact** in reference to the 1G.	
KPI$_7$ - Availability of network components (related to planned and unplanned maintenance) and its impact on network performances					
	1G	**2G**			
Score:	4	4	**Notes:**	It is assumed that the alternatives under analysis have the same failure rate. **No difference between the impacts** is expected**.**	
KPI$_8$ - Ratio between minimum and maximum electricity demand within a defined time period					
	1G	**2G**			
Score:	4	6	**Notes:**	The 2G system increases the segmentation of the on peak and off-peak tariffs. The tariffs may be more flexible during the day. An increased load levelling may be achieved. The 2G leads to a **positive impact** in reference to the 1G.	

Table 40 represents the PM of the alternatives with respect to the terminal criteria of the Externality merit branch. It also resumes the reasoning behind the preferences.

Table 40. Scoring stage of the externality impacts assessment branch

$C_1^{(3)}$ - Optimisation of the commercial processes				
	1G	**2G**		
Score:	4	7	**Notes:**	The 2G system allows the energy supplier to receive the daily consumption data of all consumers. Therefore, the 2G SM system can strongly improve the efficiency of commercial processes. The 2G leads to a **strongly positive impact** in reference to the 1G.
$C_2^{(3)}$ - Market Dynamism				
	1G	**2G**		
Score:	4	6	**Notes:**	A huge variety of tariff schemes are enabled by the 2G features. Moreover, the switching between different energy suppliers is simplified. The 2G leads to a **positive impact** in reference to the 1G.
$C_3^{(3)}$ – Employment				
	1G	**2G**		
Score:	4	5	**Notes:**	The positive impacts of the 2G system on jobs may be limited only to the new energy services enabled. The 2G leads to a **weak positive impact** in reference to the 1G.
$C_4^{(3)}$ – Enhanced consumer awareness and consumption reduction				
	1G	**2G**		
Score:	4	5	**Notes:**	Although the 2G system increased the feedbacks to the end-users, the consumption reduction contributes are not fully cumulative [9]. Furthermore, the enhanced level of feedbacks is reachable only by using IHDs which are not provided with the meter. The 2G leads to a **weak positive impact** in reference to the 1G.
$C_5^{(3)}$ – Privacy and data security				
	1G	**2G**		
Score:	4	3	**Notes:**	The cyber-security is enhanced even if an increased amount of data is collected from users by means of the 2G SM system. The 2G leads to a **weak negative impact** in reference to the 1G.

5.2.2 Weighting stage and threshold levels definition

The value of the indifference, preference, and veto thresholds influence the extent to which the performance on each criterion contribute to the concordance and the discordance on the outranking relationship. Therefore, the value of the thresholds on each criterion have to be related on the DM's sensitivity on differences between performances.

The thresholds on the '*Expenditure'* criterion are related to the difference between the CAPEX of the alternatives. As previously described, the Italian authority aims at promoting the 2G alternative which has a value of expenditure similar to the value of the related 1G fictitious scenario. In order to model this point of view, an indifference threshold of 5% and a preference threshold of 10% are initially chosen. To illustrate, in constructing the "*Expenditure"* outranking relationship between the alternatives, the preferred option of the pair is the one which achieves a CAPEX 10% less than the value of the other option.

On the other criteria, a null indifference threshold is chosen. Conversely, the preference threshold is defined at value 2. These values have been chosen considering the small value of the difference between the performances of the alternatives under analysis. On each criterion, an alternative is identified as preferred only if its performances are definitively higher.

At first, the veto condition has been disabled by setting the threshold to a proper high value on each criterion.

Table 41 resumes the values of the decision thresholds which have been defined.

Table 41. Threshold values for the evaluation criteria

	Indifference threshold	Preference threshold	Veto threshold
Expenditure criterion	219.9 M€	439.8 M€	4500 M€
Qualitative criteria	0	2	7

Table 42 resumes the weights of criteria which are used in the first ELECTRE III assessment. These values are the global weights obtained in the first evaluation made by means of the AHP.

Table 42 - Global weight of terminal criteria

Criterion	Global Weight
C_1	0,08222
C_2	0,08032
C_3	0,04530
C_4	0,02672
C_5	0,01544
Expenditure	0,5
KPI_1	0,0625
KPI_2	0,0625
KPI_4	0,03125
KPI_5	0,03125
KPI_6	0,02083
KPI_7	0,02083
KPI_8	0,02083

5.2.3 Results

The result provided by the ELECTRE III method by combining the performances of the alternatives (Table 38, Table 39, and Table 40), criteria weights (Table 42), and performance threshold (Table 41) are presented in Table 43. The outcome of the ELECTRE III method points out that the 2G alternative outranks the 1G.

Table 43. Result of the ELECTRE III evaluation

	1G	2G
1G	~	P-
2G	P+	~

The symbols used in Table 43 mean: the alternative 1G is outranked (P-) by the alternative 2G, while the alternative 2G outranks (P+) the 1G alternative. The obtained outranking relationship between the alternative can be also graphically depicted (Figure 6).

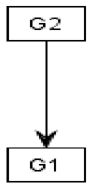


Figure 6 - Graph of the ELECTRE III

This obtained result is related to the performances of the alternative on the evaluation criteria. The 2G alternative has higher performances on the majority of the criteria, while only on three criteria the alternatives achieve the same level of performances. Among the 13 evaluation criteria, the 2G alternative outclasses the preference threshold on four criteria. The alternative 1G has a greater performance than the 2G only on one criterion, but the preference threshold is not outclassed.

A sensitivity analysis by varying the economic performance of the 2G alternative has been made. The ELECTRE III method evaluates the alternatives according the value of the difference between the performances on each criterion. Therefore, the sensitivity analysis is made in relative terms. The economic performance of the 1G alternative is considered as a reference (value 100), then the relative value of the expenditure of the alternative 2G has been varied within the 100-110 range. Furthermore, different DM's point of view are investigated by considering several thresholds on the '*Expenditure*' criterion (Table 44).

Table 44. DM's settings for the *Expenditure criterion*

	DM_1	DM_2	DM_3	DM_4	DM_5	DM_6	DM_7
Indifference threshold	5	0	0	3	2	1	3
Preference threshold	10	10	5	5	5	5	5
Veto threshold	1000	1000	1000	1000	1000	1000	50

The outcome provided by the ELECTRE III method is analysed, Table 45 resumes the obtained results. The symbols that are used in Table 45 mean:

- $A \succ B$: the alternative A outranks the alternative B;
- $A \sim B$: the alternatives are indifferent from the DM's point of view.

Table 45. Results of the ELECTRE III sensitivity test

Case	$\Delta p_{Expenditure}$	DM_1	DM_2	DM_3	DM_4	DM_5	DM_6
Case 0	0	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$
Case 1	1	-	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$
Case 2	2	-	$2G \succ 1G$	$2G \sim 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$
Case 3	3	-	$2G \sim 1G$	$2G \sim 1G$	$2G \succ 1G$	$2G \sim 1G$	$2G \sim 1G$
Case 4	4	-	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
Case 5	5	$2G \succ 1G$	$2G \sim 1G$	$1G \succ 2G$	$1G \succ 2G$	$1G \succ 2G$	$1G \succ 2G$
Case 6	6	$2G \succ 1G$	$2G \sim 1G$	-	-	-	-
Case 7	7	$2G \sim 1G$	$2G \sim 1G$	-	-	-	-
Case 8	8	$2G \sim 1G$	$2G \sim 1G$	-	-	-	-
Case 9	9	$2G \sim 1G$	$2G \sim 1G$	-	-	-	-
Case 10	10	$1G \succ 2G$	$1G \succ 2G$	-	-	-	-

By observing Table 45, according to the DM_1 setting, the two alternatives are indifferent only if the cost related to the 2G lies in the 107-109% range of the cost related to the 1G. Therefore, if the cost of the 2G system is less than the 107% of the 1G cost, the 2G is globally preferred. Moreover, if the expenditure of the 2G is equal or greater than the 110% of the cost related to the 1G, then the latter alternatives outranks the 2G one.

Table 45 also highlights that the absence of an indifference thresholds enlarges the range of indifference between the alternatives. Furthermore, from Table 45 one can see the extent to which the "*Expenditure*" criterion leads the overall result. In fact, the *non-dictatorship* condition [17] is not strictly satisfied by the used pattern of weights (i.e., the weight of the "*Expenditure*" criterion is equal to the sum of the remaining criteria, as defined in Table 42).

In the following, the pattern of weights defined in section 4.2.5 is used for the ELECTRE III assessment. These weights for terminal criteria have been obtained by imposing a same relevance on the three first level criteria of the evaluation tree. The weights of the terminal criteria are reported in Table 46.

Table 46. Global weight of terminal criteria (second pattern of weights)

Criterion	Global Weight
C_1	0.10962
C_2	0.10710
C_3	0.06040
C_4	0.03563
C_5	0.02058
Expenditure	0,33333
KPI_1	0.08333
KPI_2	0.08333
KPI_4	0.04167
KPI_5	0.04167
KPI_6	0.02778
KPI_7	0.02778
KPI_8	0.02778

By using the criteria weights defined in Table 46, the ELECTRE III analysis of the 1G and 2G SM system is repeated. Some of the DM's settings defined in Table 44 are used. The results of the assessment are presented in Table 47.

Table 47. Outcomes of ELECTRE III by using the second pattern of weights

Case	$\Delta p_{Expenditure}$	DM_1	DM_3	DM_4	DM_7
Case 0	0	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$
Case 3	3	-	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$
Case 4	4	-	$2G \sim 1G$	$2G \succ 1G$	-
Case 5	5	$2G \succ 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
Case 6	6	$2G \succ 1G$	-	-	-
Case 7	7	$2G \succ 1G$	-	-	-
Case 8	8	$2G \succ 1G$	-	-	-
Case 9	9	$2G \sim 1G$	-	-	-
Case 10	10	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
Case 20	20	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
Case 40	40	-	-	-	$2G \sim 1G$
Case 41	41	-	-	-	$1G \succ 2G$
Case 50	50	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$1G \succ 2G$
Case 100	100	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$1G \succ 2G$

Table 47 highlights that, if the thresholds are defined as in the DM_1, DM_3, and DM_4 settings, the indifference among the alternative persists even if the expenditure related to the 2G alternative becomes equal to the 200% of the 1G expenditure. Conversely, due to the veto threshold set as in the DM_7 setting, if the 2G expenditure is higher than the 140% of the 1G costs, the ELECTRE III method indicates the 1G alternative as preferred.

5.3 The OA approach based on fuzzy scoring

5.3.1 Introduction

In MCA, the uncertainties related to subjective judgments on the criteria relevance and on qualitative assessed performances may be addressed by means of fuzzy sets. Fuzzy sets represent qualitative data and preferences by means of membership functions with the aim to model the natural language imprecision [10]. Therefore, the attractiveness of an option can be quantified by means of a fuzzy number between [0, 1]. In MCA methods based on fuzzy sets, performances and weights are expressed and managed in terms of fuzzy numbers, but the methodological framework is inherited from the corresponding MCA technique devised for crisp numbers. Due to the higher complexity, fuzzy-MCA methods are not widely employed in practice, their use is limited to the academic studies [10].

Real decision-making problems face simultaneously with crisp and fuzzy data. Fuzzy data can be used in order to include data with uncertainties in the overall assessment. Sometimes, resolving the uncertainty may involve an unsustainable use of the resources devoted to the overall analysis; therefore, an analysis made on uncertain or qualitative data is preferable. By means of fuzzy sets, unquantifiable and uncomplete data can be considered in the MCA.

The fuzzy approach used in the presented analysis is based on the methodology defined in [19]. Instead of a full-fuzzy MCA technique, a hybrid fuzzy-scoring crisp-MCA technique is employed. The aim is to avoid the increased complexity related to the evaluation made by means of full-fuzzy MCA technique. Due to the availability of the input data expressed in qualitative terms, the hybrid technique has been elected for conducting the analysis.

The hybrid technique involves a fuzzy scoring stage in which the verbal judgements are managed by means of fuzzy sets. Then, the obtained fuzzy scores are converted in crisp scores and provided as input to a classical crisp MCA technique. Therefore, the procedure involves three main steps:

1. The verbal judgment on the performances of the alternative are converted to a fuzzy number by means of standardised fuzzy scales.
2. The fuzzy scores are then converted to an equivalent crisp score.
3. The PM obtained by aggregating the crisp score of the alternatives is managed by means of a MCA technique.

5.3.2 Key features of the fuzzy-scoring method

5.3.2.1 Semantic modelling of language terms

The verbal terms obtained by means of subjective judgments suffer from some level of vagueness which depends on the number and the peculiarities of the objects under analysis [19]. Those verbal terms are not directly manageable mathematically; therefore, a conversion towards an equivalent fuzzy set can be suitable.

The approach devised in [19] propose 8 different verbal scales for converting the natural language judgements in terms of fuzzy numbers (Figure 7). On each criterion, the performances of all the alternatives have to been considered for identifying the verbal scale which encompasses all the used verbal terms. The verbal scale that encompasses the less number of points has to be chosen. Therefore, on a same MCA, the verbal scale related to each criterion can differ. At the end of the fuzzy-scoring procedure, a PM which contains the fuzzy scores related to the verbal judgements is obtained.

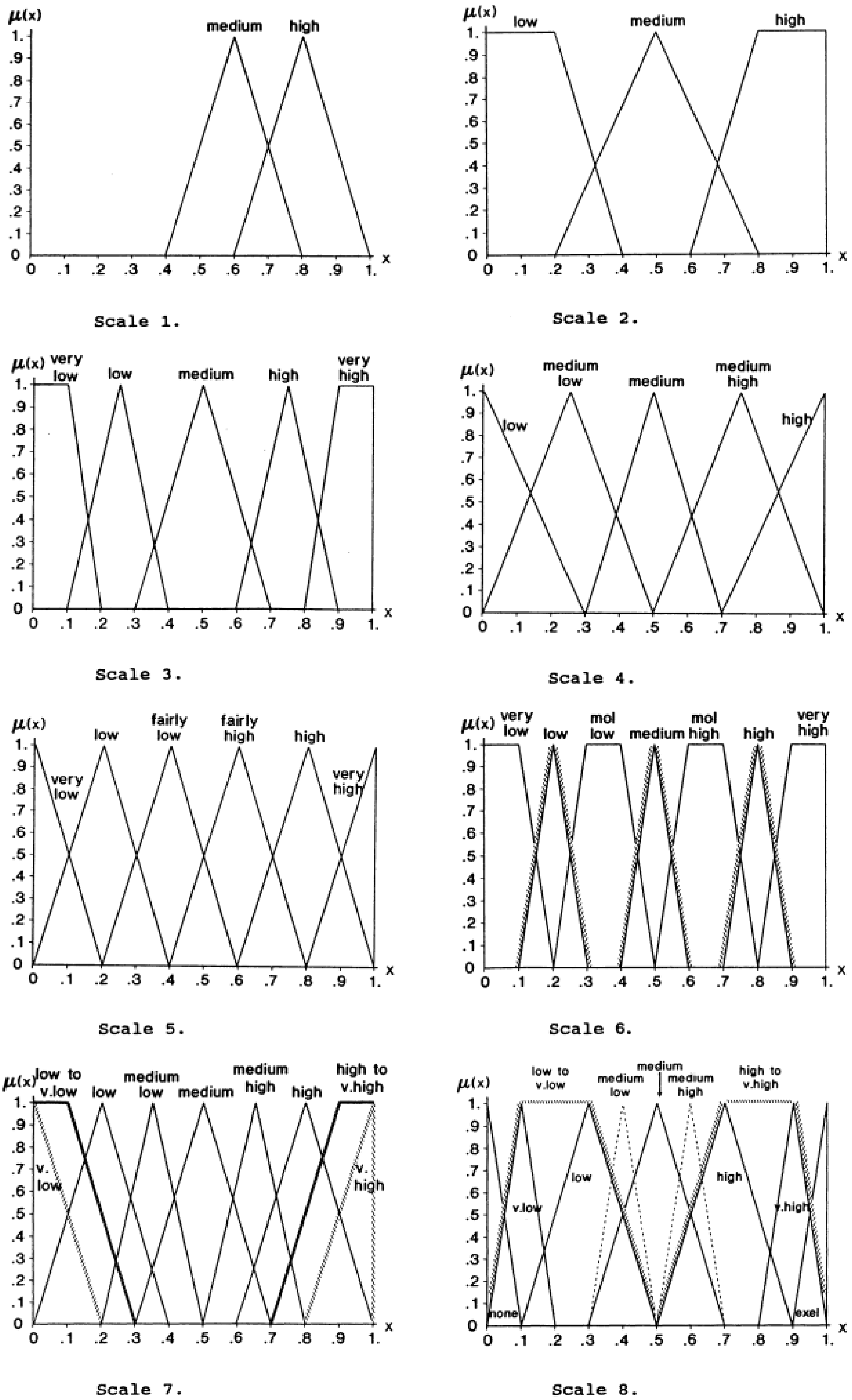


Figure 7. Fuzzy scale for converting the verbal judgements [19]

5.3.2.2 *Crisp conversion of the fuzzy scores*

The second step of the fuzzy-scoring procedure aims at converting the previously obtained fuzzy scores to equivalent crisp scores.

Given fuzzy number *M*, its crisp conversion begins by defining its maximising (8) and its minimising (9) sets.

$$\mu_{max}(x) = \begin{cases} x, & 0 \le x \le 1 \\ 0, & otherwise \end{cases} \tag{8}$$

$$\mu_{min}(x) = \begin{cases} 1 - x, & 0 \le x \le 1 \\ 0, & otherwise \end{cases} \tag{9}$$

Where x is the membership variable, and $\mu_{max}(x)$ and $\mu_{min}(x)$ are the maximising and the minimising sets, respectively.

Once the maximising and the minimising sets are obtained, the right and the left score related to the fuzzy number *M* are evaluated by means of (10) and (11). Figure 8 depicts a graphical scheme of the right and left score evaluation.

$$\mu_R(M) = sup_x[\mu_M(x) \cap \mu_{max}(x)] \tag{10}$$

$$\mu_L(M) = sup_x[\mu_M(x) \cap \mu_{max}(x)] \tag{11}$$

where $\mu_R(M)$ and $\mu_L(M)$ are the right and the left score of M, respectively.

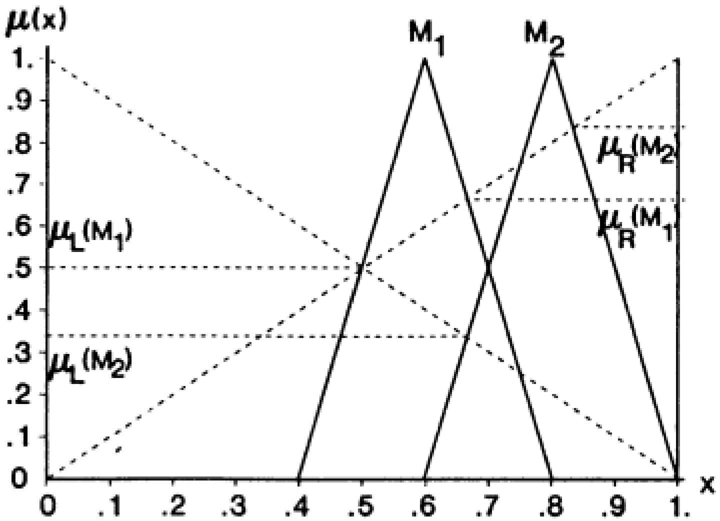


Figure 8. Graphic scheme of the left and right score evaluation [19]

Once the right and left score of *M* are obtained, the total score $\mu_T(M)$ is evaluated by means of (12).

$$\mu_T(M) = \frac{[\mu_R(M) + 1 - \mu_L(M)]}{2} \tag{12}$$

The total score $\mu_T(M)$ is the crisp score that represents the fuzzy score M. By converting all the fuzzy elements of the PM, an equivalent crisp PM is obtained.

5.3.3 The fuzzy scoring approach for the SM system analysis

The fuzzy scoring approach proposed in [19] is employed for the analysis of the 1G and 2G SM infrastructures. The performances, in terms of equivalent crisp scores, are then managed by means of the ELECTRE III method. The analysis of the SM infrastructure starts from the flat decision-making problem defined by the terminal criteria of the evaluation tree. The global priorities of terminal criteria obtained in the weighting stages of the AHP assessment are used.

5.3.3.1 Scoring stage

The scores which are assigned in this step relies on the same concepts used for the scoring stage of the AHP assessment. The problem under analysis is characterised by 1 criteria quantitatively assessed (the '*Expenditure*' criterion), whereas the fulfilment of the remaining criteria is assessed by means performance expressed in qualitative terms. Those qualitative performances are collected by means of the linguistic terms reported in Table 48.

Table 48. Linguistic terms

Linguist terms of verbal description of the performance on a criterion
Strongly negative impact
Negative impact
Weak negative impact
No impact
Weak positive impact
Positive impact
Strongly positive impact

According to the linguistic terms defined in Table 48, the performances of the 1G and the 2G SM alternatives are collected on each criterion. These verbal judgements are based on the reasoning already presented in Table 38, Table 39, and Table 40; therefore, the PM in Table 49 only resumes the related linguist terms.

Table 49. PM of the fuzzy scoring procedure

Third level criteria	Criterion Description	1G	2G
Expenditures	Discounted total capital expenditures which occurs in the whole lifetime plan of the investment	4398,3 (*supposed*)	4398,3 (*known*)
KPI_1	Environmental impact of electricity grid infrastructure	No impact	No impact
KPI_2	Methods adopted to calculate charges and tariffs, as well as their structure, for generators, consumers, and *prosumers*	No impact	Weak positive impact
KPI_4	Duration and frequency of interruptions per customer, including climate related disruptions	No impact	Weak positive impact
KPI_5	Voltage quality performance	No impact	Weak positive impact
KPI_6	Demand side participation in electricity markets and in energy efficiency measures	No impact	Strongly positive impact
KPI_7	Availability of network components (related to planned and unplanned maintenance) and its impact on network performances	No impact	No impact
KPI_8	Ratio between minimum and maximum electricity demand within a defined time period	No impact	Positive impact
$\boldsymbol{C}_1^{(3)}$	Optimisation of the commercial processes	No impact	Strongly positive impact
$\boldsymbol{C}_2^{(3)}$	Market Dynamism	No impact	Positive impact
$\boldsymbol{C}_3^{(3)}$	Employment	No impact	Weak positive impact
$\boldsymbol{C}_4^{(3)}$	Enhanced consumer awareness and consumption reduction	No impact	Weak positive impact
$\boldsymbol{C}_5^{(3)}$	Privacy and data security	No impact	Weak negative impact

In the first step of the fuzzy-scoring approach, the verbal scales for converting the natural language judgements in terms of fuzzy numbers has to be identified for each criterion. Among those defined in Figure 7, the scale which involves the less number of terms has to be chosen. Once the suitable verbal scale is identified, the fuzzy numbers related to the verbal terms are obtained. The last step involves the conversion of the fuzzy score in terms of the equivalent crisp score. Table 50 resumes the results obtained by using the fuzzy-scoring procedure in the SM system analysis.

Table 50. Results of the fuzzy-scoring procedure

Third level criteria	Scale n.	Fuzzy score for 1G (M_{1G})				Fuzzy score for 2G (M_{2G})				Equivalent crisp score 1G $\mu_{1G}(M_{1G})$	Equivalent crisp score 2G $\mu_{2G}(M_{2G})$
		X_l	X_{c1}	X_{c2}	X_r	X_l	X_{c1}	X_{c1}	X_r		
KPI_1	1	0.4	0.6	0.6	0.8	0.4	0.6	0.6	0.8	4.3	4.3
KPI_2	7	0.4	0.5	0.5	0.6	0.5	0.6	0.7	0.8	4.2	5.6
KPI_4	7	0.4	0.5	0.5	0.6	0.5	0.6	0.7	0.8	4.2	5.6
KPI_5	7	0.4	0.5	0.5	0.6	0.5	0.6	0.7	0.8	4.2	5.6
KPI_6	3	0.3	0.5	0.5	0.7	0.8	0.9	1	1	3.9	8.5
KPI_7	1	0.4	0.6	0.6	0.8	0.4	0.6	0.6	0.8	4.3	4.3
KPI_8	1	0.4	0.6	0.6	0.8	0.6	0.8	0.8	1	4.3	6.7
$C_1^{(3)}$	3	0.3	0.5	0.5	0.7	0.8	0.9	1	1	3.9	8.5
$C_2^{(3)}$	1	0.4	0.6	0.6	0.8	0.6	0.8	0.8	1	4.3	6.7
$C_3^{(3)}$	7	0.4	0.5	0.5	0.6	0.5	0.6	0.7	0.8	4.2	5.6
$C_4^{(3)}$	7	0.4	0.5	0.5	0.6	0.5	0.6	0.7	0.8	4.2	5.6
$C_5^{(3)}$	7	0.4	0.5	0.5	0.6	0.2	0.3	0.4	0.5	4.2	2.8

Where X_l, X_r are respectively the left and the right values of the membership function which defines the fuzzy score. X_{c1}, X_{c2} are the membership values in which the membership function achieves the unitary value. If the fuzzy score is a triangular fuzzy number, then $X_{c1} = X_{c2}$; conversely if the fuzzy number is trapezoidal, then $X_{c1} \neq X_{c2}$. The crisp scores $\mu_{1G}(M_{1G})$ and $\mu_{2G}(M_{2G})$ are obtained by means of the procedure described in section 5.3.2.2; then, the obtained value has been multiplied by 10.

5.3.3.2 The ELECTRE III evaluation

Once the equivalent crisp scores are obtained, the ELECTRE III method is used to identify which alternative is the preferred one. For conducting the analysis described in this section, the same approach defined in section 5.2.2 is used. In particular, the weights defined in Table 51 are employed for the evaluation criteria.

Table 51. Global weight of terminal criteria

Criterion	Global Weight
C_1	0,08222
C_2	0,08032
C_3	0,04530
C_4	0,02672
C_5	0,01544
Expenditure	0,5
KPI_1	0,0625
KPI_2	0,0625
KPI_4	0,03125
KPI_5	0,03125
KPI_6	0,02083
KPI_7	0,02083
KPI_8	0,02083

Furthermore, several DM's points of view are investigated (Table 52).

Table 52. DM's settings for the *Expenditure criterion*

	DM_1	DM_2	DM_3	DM_4	DM_5	DM_6	DM_7
Indifference threshold on the *Expenditure* criterion	5	0	0	3	2	1	3
Preference threshold on the *Expenditure* criterion	10	10	5	5	5	5	5
Veto threshold on the *Expenditure* criterion	1000	1000	1000	1000	1000	1000	50
Indifference threshold on the qualitative criteria	0	0	0	0	0	0	0
Preference threshold on the qualitative criteria	2	2	2	2	2	2	2
Veto threshold on the qualitative criteria	7	7	7	7	7	7	7

5.3.4 Results

The ELECTRE III evaluation has been repeated several times by considering different values of the economic performance of the 2G alternative. The ELECTRE III method evaluates the alternatives according the value of the difference between the performances on each criterion. Therefore, the analysis is made in relative terms. The economic performance of the 1G alternative is considered as a reference (value 100), then the relative value of the expenditure of the alternative 2G has been varied within the 100-150 range.

The outcome provided by the ELECTRE III method is analysed, Table 53 resumes the obtained results. The symbols that are used in Table 53 mean:

- $A \succ B$: the alternative A outranks the alternative B;
- $A \sim B$: the alternatives are indifferent from the DM's point of view.

Table 53. Results of the ELECTRE III method applied on the crisp scores

Case	Δp Expenditures	DM_1	DM_2	DM_3	DM_4	DM_5	DM_6	DM_7
0	0	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$
1	1	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$
2	2	$2G \succ 1G$	$2G \succ 1G$	$2G \sim 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$	$2G \succ 1G$
3	3	$2G \succ 1G$	$2G \succ 1G$	$2G \sim 1G$	$2G \succ 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \succ 1G$
4	4	$2G \succ 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
5	5	$2G \succ 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
6	6	$2G \succ 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
7	7	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
8	8	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
9	9	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
10	10	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
11	11	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
15	15	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$	$2G \sim 1G$
30	11	/	/	/	/	/	/	$1G \succ 2G$
50	50	/	/	/	/	/	/	$1G \succ 2G$

The 2G alternative achieves higher performances on the majority of the criteria; therefore, if both the alternatives have a similar cost, the 2G outranks the 1G alternative.

The fuzzy scoring approach increased the extent of the difference between the performance of the alternatives with respect to the qualitative score obtained in the analysis described in section 5.2.1. This effect advantages the 2G alternative due to its dominance in the majority of the qualitative criteria. By comparing the outcome of the ELECTRE III method reported in Table 45 and Table 53, one can see that in the latter case even if the cost related to 2G highly increases, the method still produces an indifference outcome. In order to obtain a preference output, a proper veto threshold needs to be set (e.g., DM_7). With regard to the small difference interval (G2 cost equal to 101-104% of the 1G cost), the outputs produced in the latter analysis are similar to the results previously obtained.

6 Conclusions

The features of SM systems allow a remote monitoring and control of the PODs. An enhancement of these features can originate wide impacts on the power system, the electricity market, and the society. Therefore, an effective assessment of the SM infrastructure has to consider the new functionalities and services which can be enabled. An assessment of the impacts related only to the basic features and monetary impacts may be incomplete.

In this context, a MC-CBA method allows:

- to simultaneously consider impacts on heterogenous areas;
- to simultaneously consider monetary and non-monetary impacts;
- to include the stakeholders' point of view in the analysis;
- to manage input data with uncertainties.

These aspects are crucial in the public sector, the strategic policies strongly influence the citizen's life.

In general, the robustness of the outcome provided by a MCA can be tested by applying different techniques on the same decision-making problem. For this reason, three different MADM approach applied on the same case study are presented in this report. Two of the most acknowledged MCA techniques are used (AHP and ELECTRE III); moreover, a fuzzy-based scoring method is introduced in order to proper manage the vagueness of the performances expressed in qualitative terms.

The 2G alternative considered in this report is an upgraded 1G SM infrastructure. As a consequence, if the economic performance of the 1G and 2G alternatives is similar, the result of the analysis states that the 2G SM system is preferred. Due to the uncertainties on the economic performances of the alternatives under appraisal, a sensitivity analysis has been conducted.

The study presented in this report highlight the positive contribution of the AHP in decomposing the overall decision-making problem. Furthermore, the scoring stage based on qualitative input is eased thanks to the pairwise comparison process between the alternatives. However, the use of the ratio scale makes the AHP less flexible for a sensitivity analysis. Accordingly, the AHP appraisal seems to be suitable for preliminary decision-making analysis. Conversely, the ELECTRE III method appear to be suitable for a deeper analysis of the decision problem thanks to the usage of an interval scale.

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