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MULTI-CRITERIA ASSESSMENT OF THE SMART GRID EFFICIENCY USING THE FUZZY ANALYTIC HIERARCHY PROCESS

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Abstract: *In this paper, the key performance indicators related to the smart grid efficiency, as the key factor of any energy management system implementation have been analysed. The authors are proposing multi-criteria fuzzy AHP methodology for the determination of overall smart grid efficiency. Four criteria (technology, costs, user satisfaction, and environmental protection) and seven performances (according to EU and US initiatives for analysis of benefits and effects of smart grid systems) for the selection of optimal smart grid project are defined. The analysis shows that the dominant performances of the optimal smart grid project are efficiency, security and quality of supply. The methodology is illustrated on the choice of smart grid development strategy for the medium size power distribution company.*

Key words: *smart grid, multi-criteria analysis, fuzzy analytical hierarchy process*

1. INTRODUCTION

A smart grid is usually defined as an electrical grid that intelligently integrates the actions of all users connected within it – producers, consumers, and those who are both, with the purpose of efficiently producing electricity and delivering it sustainably, economically, and safely [1]. The smart grid promises a variety of efficiency gains for utilities, like the reducing distribution line losses through minimization of reactive power and more precise voltage control [2]. Furthermore, the smart grid should enhance utilities' ability to monitor and measure the effectiveness of end-use energy-efficiency programs, and to better manage energy costs on the customer side, which is confirmed by the numerous projects and organizations that were initiated to facilitate the evolution of the Smart Grid [3], [4].

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In the EU, the concept of smart grids was adopted in 2005, as an official document of the European Commission through the European Technology Platform Smart Grids, and more precisely defined in [5] and [6]. In early April 2010, the European Commission issued a statement reiterating the need to improve the existing grids, listing the following as the main objectives [7]: increased use of renewable electricity sources, grid security, energy conservation and energy efficiency, and deregulated energy market. Therefore, the strategy for sustainable, competitive, and safe energy primarily implies: competitiveness, use of different energy sources, sustainability, innovation, and technological improvement [8]. The result of energy system development is reflected in energy performance, with quantifiable results pertaining to energy (e.g. energy efficiency, energy intensity, or specific energy consumption) and energy performance indicators as quantitative indexes of energy performance.

Energy efficiency is a way of managing and restraining the growth in energy consumption. The key energy performance indicators were defined in 2005 as a result of cooperation between several international organizations – global leaders in energy and environmental statistics and analysis: International Atomic Energy Agency (IAEA), United Nations Department of Economic and Social Affairs (DESA), International Energy Agency (IEA), European Environment Agency (EEA), and the Directorate-General of the European Commission for statistics – Eurostat [9]. The key energy performance indicators include a set of 30 indicators: 4 social indicators, 16 economic indicators, and 10 environmental indicators. The values of the U.S. Energy Security Risk Index were determined based on the data for the period between 1970 and 2010, and predicted for the period between 2011 and 2035 [10]. The indicator values do not merely represent data but the basis for communication between stakeholders regarding sustainable energy use. Each set of indicators (social, economic, or environmental) expresses specific aspects or impacts of energy production and use. The lack of systematic approach in the classification of these indicators is the main reason why the Smart grids were evaluated on individual indicators only. The cyber security indicator has been explored in [11]-[13], while the cost/benefit assessment of a Smart distribution system with intelligent electric vehicle charging has been analysed in [14], [15].

In the Smart Grid context, three main assessment frameworks based on key performance indicators (KPIs) have been introduced. The EC Task Force for Smart grids has introduced the characteristics of the ideal Smart Grids (services) and the outcomes of the implementation of the ideal Smart Grid (benefits) [16], [17]. A measure of the contribution of projects to the ideal Smart Grid is quantified in terms of benefits, via a set of KPIs. The European Electricity Grid Initiative has divided the ideal Smart Grid system into thematic areas (clusters) and is currently mapping Smart Grid projects into clusters [18]. In USA, the ideal characteristics of the Smart Grid and a set of metrics to measure progresses toward the ideal Smart Grids has been defined [19]: build metrics that describe attributes that are built in support of a Smart Grid (e.g. percentage of substations using automation) and value or impact metrics that describe the value that may derive from achieving a Smart Grid (e.g. percentage of energy consumed to generate electricity that is not lost, or quantity of electricity delivered to consumer compared to electricity generated expressed as a percentage).

However, because of proliferation of these energy indicators, it is still very difficult to decision maker to answer to simple questions like:

- Among different smart grid projects, which alternative to choose?
- Which alternative will be the most beneficiary to different stakeholders?
- How to monitor the efficiency of already implemented smart grid project?

The contribution of this paper is the introduction of multi-criteria approach in the smart grid efficiency assessment. Unlike the approach used in [1], the fuzzy AHP method has been proposed, offering much more flexibility in the criteria selection and the evaluation of both criteria and alternatives.

Furthermore, the new hierarchy of four criteria and seven performances has been introduced in order to obtain more consistent evaluation framework. We proved that the method is highly successful in the evaluation of alternatives in the presence of heterogeneous criteria.

Because of the main characteristic of the adopted smart grid evaluation framework and its complex hierarchical structure, we proposed the fuzzy AHP methodology for the project evaluation, structuring a decision into a hierarchy of criteria, sub criteria and alternatives. By means of pair-wise comparisons of two (sub) criteria or alternatives, it generates inconsistency ratios and weighting factors to prioritise the criteria and alternatives.

After the brief overview of key performance indicators for the smart grid evaluation, the fuzzy AHP methodology has been presented. The methodology is illustrated on the choice of smart grid projects deployment for one medium size power distribution company.

2. Smart Grid Assessment Frameworks

The implementation of a Smart Grid is useful to achieve strategic policy goals, such as the smooth integration of renewable energy sources, a more secure and sustainable electricity supply and full inclusion of consumers in the electricity market. Smart Grids help the consumers to better understand their own energy use, which in turn allows them to identify energy saving opportunities. Smart grid and Advanced Metering Infrastructure (AMI) systems could open up opportunities for energy management companies, hired by consumers, to use data from consumers' smart meters to identify opportunities for energy savings or to measure the success of energy savings measures after they are undertaken [20]. For utilities, a better understanding of the electrical grid's status at a second-by-second level allows the grid to be operated at much tighter tolerances, resulting in greater efficiencies and reliability.

Steering the Smart Grid transition is a challenging, long-term task, which requires balancing energy policy goals, environmental constraints and market profitability. In this perspective, a first approach in Smart Grid assessment is to evaluate to what extent Smart Grid projects are contributing to progresses toward the "ideal Smart Grid" and its expected outcomes (e.g. sustainability, efficiency, consumer inclusion), which are directly linked with the policy goals that have triggered the Smart Grid transition. This first approach is conducted via the definition of suitable metrics and key performance. A second complementary approach is to assess the profitability of Smart Grid solutions and investments through an appropriate multi-criteria decision analysis methodology.

2.1. Key performance indicators

The progress of smart grid development can be measured by formulating a set of Key Performance Indicators (KPIs) and applying those to the electricity network. In [17]-[19] the characteristics of the ideal Smart Grids and defined metrics to measure progresses and outcomes resulting from the implementation of Smart Grid projects have been defined. The ideal Smart Grid has been defined in terms of characteristics in the US and in terms of services in the European Union. Built/Value metrics in the USA and Benefits/KPIs in Europe are used to measure progresses toward the ideal Smart Grid.

The EC Smart Grid Task Force has identified a list of benefits deriving from the implementation of a Smart Grid [16]:

- Increased sustainability;
- Adequate capacity of transmission and distribution grids for 'collecting' and bringing electricity to the consumers;
- Adequate grid connection and access for all kinds of grid users;
- Satisfactory levels of security and quality of supply;
- Enhanced efficiency and better service in electricity supply and grid operation;
- Effective support of transnational electricity markets by load flow control to alleviate loop flows and increased interconnection capacities;
- Coordinated grid development through common European, regional and local grid planning to optimise transmission grid infrastructure;
- Enhanced consumer awareness and participation in the market by new players;
- Enable consumers to make informed decisions related to their energy to meet the EU Energy Efficiency targets;
- Create a market mechanism for new energy services such as energy efficiency or energy consulting for customers;
- Consumer bills are either reduced or upward pressure on them is mitigated.

Each benefit is expressed via a set of KPIs including both quantitative and qualitative indicators. For illustration, the first benefit – increased sustainability is valued by the quantified reduction of carbon emissions, environmental impact of electricity grid infrastructure and quantified reduction of accidents and risk associated with generation technologies (this sentence is not clear). The complete list of indicators can be found in [16]. The KPIs can be applied to evaluate project results on smart grids as well. A clearly defined framework can specify where exactly the project contributed to a smart electricity grid. The mixture of quantitative and qualitative indicators is one of the major reasons for introducing the multi-criteria decision analysis techniques. Another reason is the shortcoming of the cost benefit analysis, which will be explained in the sequel.

2.2. Smart grid development assessment model

The implementation of the Smart Grid should be market-driven. Another necessary approach in Smart Grid assessment is therefore to assess the costs, the benefits and the beneficiaries of different Smart Grid solutions. A comprehensive methodology for cost benefit analysis of Smart Grid projects has been defined in [21], while the European Commission has adapted and expanded the DOE/EPRI methodology to fit the European context [22]-[24]. However, the traditional cost benefit analysis approach is not catching all the effects involved in development policies, where intangible aspects are not secondary, but dominating [25]. The main disadvantage of the cost benefit is the translation of all the effects in a common numerical and a single aggregate measure. It is crucially important to ensure that project proposals are evaluated against a common reference system, to integrate the outcome of the KPI and of the economic analysis and come up with an overall project evaluation. Therefore, multiple criteria analysis seems to be better in measuring intangibles and soft impacts than cost benefit; actually, it uses more than one criterion introducing qualitative aspects in the analysis.

In order to get a thorough understanding of the status of smart grid development, the main SMART criteria (they have to be Specific, Measurable, Attainable, Relevant and Time-bound) can be defined. Starting from eleven main benefits, presented in previous section, an adapted list of main criteria is defined in our approach, including:

- Technology, covering all aspects of advanced services and new requirements imposed to the distribution and transmission network;
- Costs;
- Customer satisfaction, encompassing different options of customer choice, new energy services and market participation;
- Environmental impact.

Introducing this higher level of four main criteria, after the first set of benefits defined on the base level of efficiency assessment, the higher level of assessment with four criteria explained above can be established. Different levels between relations can be set up in terms of the volume of their inter connectedness.

Multi-criteria methods differ in the way the idea of multiple criteria is treated. Each method shows its own properties with respect to the way of assessing criteria, the application and computation of weights, the mathematical algorithm utilised, the model to describe the system of preferences of the decision maker, and finally, the level of uncertainty embedded in the data set.

Because of the main characteristic of the adopted smart grid evaluation framework and its complex hierarchical structure, we proposed the fuzzy AHP methodology for the project evaluation, structuring a decision into a hierarchy of criteria, sub criteria and alternatives. By means of pair-wise comparisons of two (sub) criteria or alternatives, it generates inconsistency ratios and weighting factors to prioritise the criteria and alternatives. Sensitivity analysis can be applied to test the robustness of the priorities. The main characteristics of this methodology are presented in the sequel.

3. Methodology

Thomas L. Saaty developed the original AHP in the late 1970s [26]. In this method, human's judgments are represented as crisp values. However, in many practical cases the human preference model is uncertain and decision makers cannot to assign crisp values to the comparison judgments. In these cases it is useful implementation of fuzzy AHP method. Fuzzy AHP method is designed to improve decision support for uncertain valuations and priorities. In this method the data and preferences of experts are evaluated under fuzzy set environment [27]. The use of fuzzy set theory allows the decision makers to incorporate unquantifiable information, incomplete information, non-obtainable information and partially ignorant facts into decision model [28]. The basic notions of fuzzy arithmetic are given in the Appendix.

Many authors have used fuzzy AHP method for solving problems in different areas: to solve multi-criteria problems involving qualitative data [29], [30]; water management [31]-[33]; evaluation naval tactical missile systems [34]; hazardous waste management [35]; prioritization of human capital measurement indicators [36]; shipping asset management [37]; occupational safety management [38], [39]. In this paper the fuzzy AHP method is used for smart grid projects ranking and selection, precisely because of many uncertain and non-tangible benefits and criteria involved in the smart grid projects.

The fuzzy AHP method involves the following steps: (1) the overall goal (objective) is identified and clearly defined; (2) the criteria, sub-criteria, and alternatives are identified; (3) the hierarchical structure is formed; (4) pair-wise comparison is made using fuzzified Saaty's evaluation scale; (5) the priority weighting vectors are evaluated; (6) the defuzzification and the final ranking of alternatives are defined.

In this study, the fuzzy AHP method is applied to the ranking of smart grid projects, according to following steps.

1. Goal identification. The goal is to rank different smart grid projects.

2. Identification of criteria, sub-criteria, and alternatives. Criteria for smart grid projects selection are: technology, costs, user's satisfaction and environmental protection. Sub-criteria are project performance: sustainability, capacity of transmission and distribution grids for 'collecting' and bringing electricity to the consumers, possibility of grid connection and access for all kinds of grid users, security and quality of supply, efficiency and good service in electricity supply and grid operation, effective support of transnational projects and electricity markets, transparent information to consumers. Finally, the smart grid projects are identified as alternatives.

3. Hierarchical structure formation. The Fuzzy AHP method presents a problem in the form of hierarchy: the first level represents the goal; the second level considers relevant criteria (four identified criteria); the third level considers relevant sub-criteria (seven identified sub-criteria); and the fourth level defines smart grid projects.

4. Pair-wise comparison. Pairs of elements at each level are compared according to their relative contribution to the elements at the hierarchical level above, using fuzzified Saaty's scale, as shown in Table 1.

Table 1 Crisp and fuzzified Saaty's scale for pairwise comparisons [30].

Crisp values (x)	Judgment description	Fuzzy values
1	Equal importance	(1, 1, 1+δ)
3	Week dominance	(3-δ, 3, 3+δ)
5	Strong dominance	(5-δ, 5, 5+δ)
7	Demonstrated dominance	(7-δ, 7, 7+δ)
9	Absolute dominance	(9-δ, 9, 9)
2, 4, 6, 8	Intermediate values	(x-1, x, x+1)

In this paper fuzzification is implemented by triangular fuzzy numbers, and the value of fuzzy distance of 2 is used; on boundaries, (1,1,3) is used for 1, and (7,9,9) is used for 9. It is used a fuzzy distance of 2 for odds (3, 5, 7), and a fuzzy distance of 1 for pairs (2, 4, 6, 8), as recommended in [33], because the most consistent results can be expected.

Pair-wise comparisons at each level, starting from the top of the hierarchy, are presented in the square matrix form $A=\left[\tilde{a}_{ij}\right]_{i,j=\overline{1,n}}$, where $\tilde{a}_{ij}$ is the fuzzy value about the relative importance of criteria/cub-criteria/alternative i over criteria/cub-criteria/alternative j, $\tilde{a}_{ij}=1$ for $i = j$ and $\tilde{a}_{ij}=1/\tilde{a}_{ji}$ for $i \neq j$.

5. Priority weights vectors evaluation. The ranking procedure starts with the determination of criteria weighting vector:

$$W_c=(w_{c1},w_{c2},w_{c3},w_{c4})^T\ . \tag{1}$$

Elements of criteria weighting vector, with respect to Equation (A.7), are determined as:

$$w_{ci} = \sum_{j=1}^{4} \tilde{a}_{ij} \otimes [\sum_{i=1}^{4}\sum_{j=1}^{4} \tilde{a}_{ij}]^{-1},\ i = 1,2,3,4\,. \tag{2}$$

Performance weighting vectors are defined by pair wise comparison of performance according to every single criterion. Appropriate elements of this vector, according to Equation (A.7), are calculated as follows:

$$x_{ij} = \sum_{j=1}^{4} \tilde{a}_{ij} \otimes \left[\sum_{l=1}^{7}\sum_{j=1}^{4} \tilde{a}_{lj}\right]^{-1}, \tag{3}$$

where x_{ij} represents the fuzzy weights of the i-th performance with respect to the j-th criterion. Final performance weights are derived through the aggregation of the weights at two consecutive levels, i.e. multiplying performance weights by criteria weights:

$$W_{sc} = X \otimes W_c = (w_{sc1}, w_{sc2}, w_{sc3}, w_{sc4}, w_{sc5}, w_{sc6}, w_{sc7})^T\,. \tag{4}$$

Finally, the smart grid projects are compared according to the relevant performance. Proper weights of projects for individual performance are determined according to Equation (A.7), as follows:

$$y_{ij} = \sum_{j=1}^{7} \tilde{a}_{ij} \otimes \left[\sum_{l=1}^{3}\sum_{j=1}^{7} \tilde{a}_{lj}\right]^{-1}, \tag{5}$$

where y_{ij} represents the fuzzy weights of the i-th project with respect to the j-th performance. Final smart grid projects weights are obtained by multiplying the weights of the projects and the final performance weights:

$$W_a = Y \otimes W_{sc} = (w_{a1}, w_{a2}, w_{a3})^T\,. \tag{6}$$

6. Defuzzification and the final ranking of alternatives. In this paper triangular fuzzy numbers are ranked by applying the total integral value method. This method is used for ranking of smart grid projects according to moderate and optimistic attitude toward risk.

4. RESULTS AND DISCUSSION

The proposed methodology is illustrated on the choice of the smart grid deployment strategy in a hypothetical power distribution company of medium size. The company is supposed to supply 50 000 consumers, and the list of alternatives with the description of proposed actions and appropriate indicators is given in Table 2.

Table 2 Different development alternatives.

No	Description of the proposed action	Performance indicator	Alternative 1	Alternative 2	Alternative 3
1	Advanced meter installation	Number of advanced meter installed	20 000	10 000	5 000
2	Substation automation	Percentage of substations applying automation technologies	20%	30%	40%
3	Introduction of dynamic line rating technology	Number of lines operated under dynamic line ratings	2	3	4
		Percentage of kilometres of transmission circuits operated under dynamic line ratings	15%	20%	15%
4	Solar power plant connection	Total installed power (MW)	3	5	7

Three alternatives are evaluated, encompassing four activities introducing new technologies in the distribution network: replacement of old meters with the remotely read meters; the remote control and introduction of substation in the SCADA system; dynamic line rating of transmission lines; construction of new photovoltaic plant embedded in the distribution network. All activities are planned inside the same approximate budget of 5 000 000 € and the planners proposed three different development strategies.

Using the presented methodology, experts (in the field of smart grid technologies and multi-criteria decision-making) ranked three smart grid projects whose characteristics are presented in Table 3.

The proposed set of actions is bringing some qualitative and quantitative benefits. For instance, the increased number of advanced meters installed in the first alternatives will strongly affect both the adequate grid connection because of the enhanced low voltage network management and transparent information to consumers. The quantitative aggregated performance indicators for different alternatives are calculated and represented in Table 3.

Table 3.Quantitative aggregated performance indicators for different alternatives.

No	Performance indicator	Alternative 1	Alternative 2	Alternative 3
1	Energy losses reduction [MWh/year]	3000	8000	11000
2	Quantified reduction of carbon emissions (t)	5 400	14 000	19 000
3	Probability of injures reduction (in percentage)	10	15	20

Although the calculation of these parameters is outside the scope of this paper, the relation between the proposed actions and the expected results is obvious. Energy loss reduction is caused by the dynamic line rating enabling the more economic line loading and the connection of the photovoltaic plant (row 1). This renewable source is reducing the carbon emission according to the installed plant power (row 2). Finally, the automation of substations reduces the probability of injures during the equipment manipulation (row 3).

Experts first performed pair wise comparison of the following criteria: technology (C_1), costs (C_2), customer satisfaction (C_3) and environmental (C_4). The results of the comparison, fuzzy weights, final weights (FWs) and ranks of criteria are shown in Table 4.

Table 4 The pairwise comparison, fuzzy weights, final weights and ranks of criteria.

	C_1	C_2	C_3	C_4	Fuzzy weights w_{ci}	λ=0.5		λ=1.0	
						FWs	Rank	FWs	Rank
C_1	$\tilde{1}$	$\tilde{3}$	$\tilde{5}$	$\tilde{5}$	(0.1967,0.5303, 1.3141)	0.5096	1	0.5023	1
C_2	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	(0.0787, 0.2778, 0.7885)	0.2819	2	0.2904	2
C_3	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{1}$	(0.0576, 0.0960, 0.3504)	0.1189	3	0.1216	3
C_4	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$	$\tilde{1}$	(0.0412, 0.0960,0.2190)	0.0896	4	0.0858	4

Then the experts compared the following performance indicators in relation to every criterion: sustainability (SC_1), capacity of transmission and distribution grids for ‘collecting’ and bringing electricity to the consumers (SC_2), possibility of grid connection and access for all kinds of grid users (SC_3), security and quality of supply (SC_4), efficiency and good service in electricity supply and grid operation (SC_5), effective support of transnational projects and electricity markets (SC_6), transparent information to consumers (SC_7). This step is necessary because of different economical, social and political conditions for different distribution companies. As stated above, the pairwise comparison made by experts is performed both by qualitative and quantitative indicators. For instance, security criteria (SC_4) can be supported by the reduction of injuries (Table 3), while the market development criteria (SC_6) is much more susceptible to subjective experts judgments. The results are presented in Tables 5 to 8.

Table 5 The pairwise comparison matrix of sub-criteria in relation to the technology.

	SC_1	SC_2	SC_3	SC_4	SC_5	SC_6	SC_7	Fuzzy weights x_{i1}
SC_1	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{3}$	$\tilde{7}^{-1}$	$\tilde{7}^{-1}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	(0.0179, 0.0489, 0.1307)
SC_2	$\tilde{3}$	$\tilde{1}$	$\tilde{5}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	(0.0376, 0.0981, 0.2539)
SC_3	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	$\tilde{1}$	$\tilde{7}^{-1}$	$\tilde{7}^{-1}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	(0.0122, 0.0216, 0.0551)
SC_4	$\tilde{7}$	$\tilde{5}$	$\tilde{7}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	(0.1125, 0.2631, 0.6320)
SC_5	$\tilde{7}$	$\tilde{5}$	$\tilde{7}$	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	(0.1081, 0.2631, 0.5996)
SC_6	$\tilde{5}$	$\tilde{3}$	$\tilde{5}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{1}$	(0.0622, 0.1526, 0.4051)
SC_7	$\tilde{5}$	$\tilde{3}$	$\tilde{5}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$	$\tilde{1}$	(0.0578, 0.1526, 0.3727)

Table 6 The pairwise comparison matrix of sub-criteria in relation to the costs.

	SC_1	SC_2	SC_3	SC_4	SC_5	SC_6	SC_7	Fuzzy weights x_{i2}
SC_1	$\tilde{1}$	$\tilde{5}^{-1}$	$\tilde{3}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{5}$	(0.0364, 0.0939, 0.2361)
SC_2	$\tilde{5}$	$\tilde{1}$	$\tilde{7}$	$\tilde{3}$	$\tilde{3}$	$\tilde{5}$	$\tilde{7}$	(0.1230, 0.2929, 0.6769)
SC_3	$\tilde{3}^{-1}$	$\tilde{7}^{-1}$	$\tilde{1}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}$	(0.0181, 0.0492, 0.1396)
SC_4	$\tilde{5}$	$\tilde{3}^{-1}$	$\tilde{5}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{7}$	(0.0919, 0.2110, 0.5195)
SC_5	$\tilde{5}$	$\tilde{3}^{-1}$	$\tilde{5}$	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{7}$	(0.0876, 0.2110, 0.4880)
SC_6	$\tilde{3}$	$\tilde{5}^{-1}$	$\tilde{3}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{5}$	(0.0424, 0.1216, 0.3201)
SC_7	$\tilde{5}^{-1}$	$\tilde{7}^{-1}$	$\tilde{3}^{-1}$	$\tilde{7}^{-1}$	$\tilde{7}^{-1}$	$\tilde{5}^{-1}$	$\tilde{1}$	(0.0118, 0.0204, 0.0514)

Table 7 The pairwise comparison matrix of sub-criteria in relation to the customer satisfaction.

	SC_1	SC_2	SC_3	SC_4	SC_5	SC_6	SC_7	Fuzzy weights x_{i3}
SC_1	$\tilde{1}$	$\tilde{1}$	$\tilde{7}^{-1}$	$\tilde{7}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	(0.0186, 0.0319, 0.1164)
SC_2	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{7}^{-1}$	$\tilde{7}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	(0.0141, 0.0319, 0.0819)
SC_3	$\tilde{7}$	$\tilde{7}$	$\tilde{1}$	$\tilde{1}$	$\tilde{5}$	$\tilde{3}$	$\tilde{3}$	(0.1145, 0.2730, 0.6744)
SC_4	$\tilde{7}$	$\tilde{7}$	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{5}$	$\tilde{3}$	$\tilde{3}$	(0.1100, 0.2730, 0.6399)
SC_5	$\tilde{3}$	$\tilde{3}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	(0.0244, 0.0802, 0.2248)
SC_6	$\tilde{3}$	$\tilde{3}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}$	$\tilde{1}$	$\tilde{3}^{-1}$	(0.0310, 0.1112, 0.3286)
SC_7	$\tilde{5}$	$\tilde{5}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{5}$	$\tilde{3}$	$\tilde{1}$	(0.0768, 0.1988, 0.5015)

Table 8 The pairwise comparison matrix of sub-criteria in relation to the environmental protection.

	SC_1	SC_2	SC_3	SC_4	SC_5	SC_6	SC_7	Fuzzy weights xi4
SC_1	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	$\tilde{5}$	$\tilde{5}$	$\tilde{3}$	$\tilde{7}$	(0.1101, 0.3115,0.8074)
SC_2	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$	$\tilde{5}$	(0.0602, 0.1654, 0.5176)
SC_3	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$	$\tilde{5}$	(0.0553, 0.1654, 0.4762)
SC_4	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	(0.0422, 0.0946, 0.2967)
SC_5	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{3}$	(0.0226, 0.0715, 0.2139)
SC_6	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$	$\tilde{1}^{-1}$	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$	$\tilde{5}$	(0.0504, 0.1654, 0.4348)
SC_7	$\tilde{7}^{-1}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	$\tilde{5}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	$\tilde{1}$	(0.0138, 0.0263, 0.0732)

The final vector of fuzzy weights of the performance of the projects, according to Equation (4) and Tables 4-8, is:

$$W_{sc} = X \otimes W_c = \left[x_{ij}\right]_{7x4} \otimes \left[w_{ci}\right]_{4x1} = \left[w_{sci}\right]_{7x1} = \begin{bmatrix} (0.0120, 0.0850, 0.5756) \\ (0.0204, 0.1523, 1.0094) \\ (0.0127, 0.0672, 0.5231) \\ (0.0374, 0.2334, 1.5294) \\ (0.0305, 0.2127, 1.2984) \\ (0.0194, 0.4113, 0.9951) \\ (0.0173, 0.1082, 0.7221) \end{bmatrix} \quad (7)$$

At the end, three smart grid projects (Project 1 [A_1], Project 2 [A_2], and Project 3 [A_3]) are compared in relation to performance presented in Tables 3 and 4 as presented in Table 9.

Table 9 The pair wise comparison of alternatives in relation to performance

SC		A_1	A_2	A_3	Fuzzy weights y_{ij}
SC_1	A_1	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	(0.0601,0.1031,0.2731)
	A_2	$\tilde{3}$	$\tilde{1}$	$\tilde{3}^{-1}$	(0.0985,0.2915,0.8194)
	A_3	$\tilde{5}$	$\tilde{3}$	$\tilde{1}$	(0.2239,0.6054,1.5217)
SC_2	A_1	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	(0.2000,0.3333,1.0000)
	A_2	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{1}$	(0.1556,0.3333,0.7143)
	A_3	$\tilde{1}^{-1}$	$\tilde{1}^{-1}$	$\tilde{1}$	(0.1111,0.3333,0.4286)
SC_3	A_1	$\tilde{1}$	$\tilde{3}$	$\tilde{5}$	(0.2239,0.6054,1.5217)
	A_2	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{3}$	(0.0985,0.2915,0.8194)
	A_3	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}$	(0.0601,0.1031,0.2731)
SC_4	A_1	$\tilde{1}$	$\tilde{1}$	$\tilde{3}^{-1}$	(0.1158,0.2000,0.7426)
	A_2	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	(0.0807,0.2000,0.4455)
	A_3	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$	(0.1579,0.6000,1.6337)
SC_5	A_1	$\tilde{1}$	$\tilde{1}$	$\tilde{3}^{-1}$	(0.1158,0.2000,0.7426)
	A_2	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	(0.0807,0.2000,0.4455)
	A_3	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$	(0.1579,0.6000,1.6337)
SC_6	A_1	$\tilde{1}$	$\tilde{1}$	$\tilde{3}^{-1}$	(0.0667,0.1282,0.4545)
	A_2	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	(0.1048,0.3333,1.0606)
	A_3	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$	(0.1429,0.5385,1.6667)
SC_7	A_1	$\tilde{1}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	(0.0593,0.0909,0.1570)
	A_2	$\tilde{5}$	$\tilde{1}$	$\tilde{1}$	(0.2308,0.4545,1.0359)
	A_3	$\tilde{5}$	$\tilde{1}^{-1}$	$\tilde{1}$	(0.2000,0.4545,0.8475)

The final vector of fuzzy weights for smart grid projects, according to Equation (16) is:

$$W_a = Y \otimes W_{sc} = \left[y_{ij}\right]_{3x7} \otimes \left[w_{sci}\right]_{7x1} = \begin{bmatrix} (0.0168, 0.2079, 4.5137) \\ (0.0136, 0.2445, 4.1205) \\ (0.0190, 0.4394, 7.4556) \end{bmatrix} \quad (8)$$

After the defuzzification of final weights vectors of performance and projects, according to Equation (11), performance and smart grid projects are ranked. Ranking results are shown in Table 10 (FWs are final weights).

Table 10 Ranking of project performance and smart grid projects.

	λ=0.5		λ=1.0	
	FWs	Rank	FWs	Rank
Project performance				
Sustainability (SC_1)	0.0861	6	0.0863	6
Capacity of transmission and distribution Grids for 'collecting' and bringing electricity to the consumers (SC_2)	0.1516	3	0.1518	3
Possibility of grid connection and access for all kinds of grid users (SC_3)	0.0761	7	0.0771	7
Security and quality of supply (SC_4)	0.2310	1	0.2303	1
Efficiency and good service in electricity supply and grid operation (SC_5)	0.1993	2	0.1974	2
Effective support of transnational projects and electricity markets (SC_6)	0.1473	4	0.1485	4
Transparent information to consumers (SC_7)	0.1086	5	0.1085	5
Smart grid projects				
Project 1 (A_1)	0.2669	2	0.2781	2
Project 2 (A_2)	0.2580	3	0.2570	3
Project 3 (A_3)	0.4661	1	0.4647	1

Based on the previous results, we can conclude the following:

1. The most important criterion for the selection of smart grid (for this particular distribution company) is the selected technology, followed by the costs, the customer satisfaction and the environmental protection (Table 5). Advanced technology increases the efficiency and security of energy supply of high performance, thus increases user satisfaction and protects the environment.

2. In relation to the technology, the best ranked performance is security and quality of supply; in relation to the costs - grids for 'collecting' and bringing electricity to the consumers; in relation to the user satisfaction - possibility of grid connection and access for all kinds of grid users; and in relation to the environmental protection - sustainability.

3. The final ranking of the project performance, based on all criteria, is:

- security and quality of supply
- efficiency and good service in electricity supply and grid operation
- capacity of transmission and distribution grids for 'collecting' and bringing electricity to the consumers
- effective support of transnational projects and electricity markets
- transparent information to consumers
- sustainability
- possibility of grid connection and access for all kinds of grid users.

The best-ranked performance (security and quality of supply, and efficiency and good service in electricity supply and grid operation) are supported by the advanced technology.

4. The final rank of the alternatives indicates that the highest rank has the A_3 project, followed by the A_2 project; the lowest priority has the A_1 project. This means that for the implementation of the smart grid Project 3 should be selected.

5. CONCLUSION

In this paper, starting from a general set of smart grid performance indicators, a new assessment framework for the evaluation of the smart grid efficiency has been established, as one of the main conditions for the successful implementation of any energy management program. Using the fuzzy AHP methodology with four main criteria and seven sub criteria derived from the adopted set of smart grid benefits, we proved that the method is highly successful in the evaluation of alternatives in the presence of heterogeneous criteria. This method allows the decision makers to incorporate unquantifiable information, incomplete information, non-obtainable information and partially ignorant facts into decision model.

The proposed methodology is illustrated on the choice of the right smart grid deployment strategy in the medium size power distribution company. The analysis shows that the dominant performances of the optimal smart grid project are the selected technology, followed by the costs, the customer satisfaction and the environmental protection. This methodology is applied to the general assessment of smart grid efficiency, while the further research will be focused on particular aspects of the project implementation.

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APPENDIX

A.1. Fuzzy set, triangular fuzzy number and fuzzy arithmetic

Mathematical basis for fuzzy AHP method is based on fuzzy sets and fuzzy arithmetic. In [40] it is defined a fuzzy set A by degree of membership $\mu_A(x)$ over a universe of discourse X as:

$$\mu_A(x): X \to [0,1] \tag{A.1}$$

A fuzzy number is a convex and normalized fuzzy set $A = \{(x, \mu_A(x)), x \in R\}$. A triangular fuzzy number can be denoted as $M = (a,b,c)$, and the membership function is:

$$\mu_A(x) = \begin{cases} \dfrac{x-a}{b-a}, x \in [a,b] \\ \dfrac{c-x}{c-b}, x \in [b,c] \\ 0, \quad \quad otherwise \end{cases} \tag{A.2}$$

where $a \le b \le c$, a and c stand for the lower and upper value of the support of *M*, respectively, and b is the modal value. When $a = b = c$, it is a “normal”, crisp number.

Fuzzy arithmetic is based on Zadeh’s extension principle. If $f: X \to Y$ is a function, and A is a fuzzy set in X, then $f(A)$ is defined as:

$$\mu_{f(A)}(y) = \sup \mu_A(x)_{x\in X, f(x)=y} , \quad \text{(A.3)}$$

where $y \in Y$.

The main laws for operations for two triangular fuzzy numbers $M_1(a_1,b_1,c_1)$ and $M_2(a_2,b_2,c_2)$ are:

$$M_1 \oplus M_2 = (a_1,b_1,c_1) \oplus (a_2,b_2,c_2) = (a_1+a_2, b_1+b_2, c_1+c_2) , \quad \text{(A.4)}$$

$$M_1 \otimes M_2 = (a_1,b_1,c_1) \otimes (a_2,b_2,c_2) = (a_1 \cdot a_2, b_1 \cdot b_2, c_1 \cdot c_2),\ a_1,a_2 > 0 , \quad \text{(A.5)}$$

$$M_1^{-1} = (a_1,b_1,c_1)^{-1} = (\frac{1}{c_1}, \frac{1}{b_1}, \frac{1}{a_1}) . \quad \text{(A.6)}$$

A.2. Fuzzy synthetic extent

The value of fuzzy synthetic extent, according to Chang's extent analysis method, is defined as [41]:

$$S_i = \sum_{j=1}^{m} M_{g_i}^j \otimes [\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j]^{-1},\ i = 1,2,...,n , \quad \text{(A.7)}$$

where $M_{g_i}^j$ is a triangular fuzzy number representing the extent analysis value for decision element i with respect to goal j and $\otimes$ is fuzzy multiplication operator.

Sum in Equation (A.7) are determined using Equations (A.4) and (A.6):

$$\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{j=1}^{m} a_j, \sum_{j=1}^{m} b_j, \sum_{j=1}^{m} c_j \right) = (a_i, b_i, c_i) , \quad \text{(A.8)}$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{i=1}^{n} a_i, \sum_{i=1}^{n} b_i, \sum_{i=1}^{n} c_i \right), \quad \text{(A.9)}$$

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} c_i}, \frac{1}{\sum_{i=1}^{n} b_i}, \frac{1}{\sum_{i=1}^{n} a_i} \right) . \quad \text{(A.10)}$$

A.3. Total integral value method for defuzzification

For the given triangular fuzzy number $M = (a,b,c)$ the total integral value is defined as follows [38]:

$$I_T^{\lambda}(M) = 0.5(\lambda c + b + (1-\lambda)a), \lambda \in [0,1] , \quad \text{(A.11)}$$

where λ represents an optimism index. It describes the decision maker's attitude toward risk. Values 0, 0.5 and 1 are used respectively to represent the pessimistic, moderate and optimistic views of the decision maker. If $I_T^{\lambda}(M_1) < I_T^{\lambda}(M_2)$, then $M_1 \prec M_2$; if $I_T^{\lambda}(M_1) = I_T^{\lambda}(M_2)$, then $M_1 \approx M_2$; if $I_T^{\lambda}(M_1) > I_T^{\lambda}(M_2)$, then $M_1 \succ M_2$.

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