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MULTI–CRITERIA HOME ENERGY MANAGEMENT SYSTEM SELECTION FOR THE SMART GRID SUPPORT

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Abstract. *Home energy management systems (HEMS) are increasingly used as a tool that creates optimal consumption and production schedules for Smart Grids, by considering objectives such as energy costs, environmental concerns, load profiles, and consumer comfort. Multiple criteria selection of optimal HEMS seems to be superior to the traditional cost benefit assessment in measuring intangibles and soft impacts, introducing qualitative aspects in the analysis. This paper proposes an algorithm for the selection of optimal HEMS, using the fuzzy AHP method. This methodological framework provides a multi-criteria approach for estimating the benefits and costs of different HEMS within the Smart Grid uncertain environment. This method allows the decision makers to incorporate unquantifiable, asymmetrical, incomplete, non-obtainable information and partially ignorant facts into a decision model. Four criteria and eleven performances for the optimal solution selection are defined. The method is successful in the evaluation of alternatives in the presence of heterogeneous criteria and uncertain environment. The methodology is illustrated on the choice of HEMS from the power distribution company perspective. It is concluded that the evaluation of weighting factors has a decisive character in the choice of the final one of several alternative variants. Fuzzification of input values can also contribute to a more flexible view of the given problem and analysis of sensitivity to various input parameters.*

Key words: *Home energy management system, Fuzzy AHP, Smart Grid, Multi-criteria decision making*

1. INTRODUCTION

An Energy management system (EMS) is a set of interconnected and interactive elements used to establish energy policy and objectives and to accomplish those objectives. Such a system is established on different hierarchical levels (Home Energy Management System, individual organization, local community, national level). On the level of an individual

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organization, EMS is defined by international standard ISO 50001 [1]. The standard specifies the requirements for establishing, implementing, maintaining, and improving EMS, which allows the organization to continually improve energy performance and energy efficiency. Although the reason for deploying individual EMS/HEMS is the increase of individual object efficiency, from the supply grid perspective, EMS and HEMS indicators are strongly dependent on the efficiency of generation, transmission and distribution companies, integrating those efforts through the concept of a Smart Grid (SG).

A SG refers to an electrical network that intelligently and symmetrically supplies electricity to all connected users through integration of their actions, in sustainable, economical, and safe way [2]. Although the SG increase the utility efficiency (decrease of line losses, minimization of reactive power, more precise voltage control and increased flexibility), the SG should enhance utilities' ability to monitor and measure the effectiveness of end-use energy-energy management programs, and to automatically manage energy costs on the consumer side. In this environment, HEMS can be used as a demand response tools creating optimal consumption and production schedules by considering aspects such as energy costs, environmental protection, load profiles, and consumer comfort [3].

The choice of adequate HEMS within the SG is a complex and difficult task, for several reasons: (1) presence of various technologies, programs and operational practice leading to a great number of alternatives; (2) existence of multiple criteria (economic, technical, environmental, etc.) to be met simultaneously, often incommensurable and incomparable; (3) proliferation of performance indicators with undefined assessment framework; (4) uncertain in assessing the relative importance of attributes and the performance ratings of alternatives with respect to attributes.

So far, there are three main assessment frameworks for defining appropriate SG environment that are based on key performance indicators (KPI). Firstly, the EC Task Force for SG defined benefits of the ideal SG's services introducing a set of the appropriate KPIs [3,4]. Further, in [5], the ideal SG system is divided into thematic areas, while in [6] the SG is defined from the aspect of a metrics for measuring progress for achieving ideal SG, introducing attributes for supporting of SG.

The main disadvantage of adopted KPI systems lays in a rather traditional treatment of costs benefit analysis as a final step in the ranking different SG alternatives. Another disadvantage of traditional cost benefit analysis for promoting any energy efficiency program is that the methods that could lead to reliable data may be difficult or impossible to apply leading to a lack of confidence on a decision based only on benefit – cost ratio [6]. Consequently, multiple criteria analysis appears as a better solution for measuring intangibles and soft impacts compared to cost benefit analysis; actually, it includes more than one criterion introducing qualitative aspects in the analysis.

A first approach in SG assessment is based on evaluation of the contribution of HEMS strategies in achieving the "ideal SG" and its expected outcomes. This approach is conducted through the definition of suitable metrics and key performances. A second complementary approach is based on an appropriate multi-criteria decision analysis method-ology in order to assess the profitability of SG solutions and investments.

In this paper, due to the above-mentioned constraints of the cost-benefit analysis, two alternative algorithms for the selection of the best HEMS deployment strategy for the SG concept are tested. The two new approaches include the fuzzy Analytic Hierarchy Process (AHP) and multiplicative Best-Worst Method (BWM) for multi-criteria decision making. The proposal of new assessment framework for the evaluation of the HEMS deployment strategy can be considered as the contribution of this paper. Those frameworks are based on the reduced performance indicator set obtained by the proper choice of qualitative and quantitative indicators. The evaluation is based on tree-level hierarchy with four main criteria on top and mix of quantitative and qualitative indicators on the second level, based on 11 adopted performances. The base level is the set of possible alternatives. The integrated assessment approach is realized through the definition of suitable metrics and key performances and multi-criteria decision analysis methodology. Fuzzy Analytic Hierarchy Process (FAHP) and BWM methods for multi-criteria decision making have been tested and compared, considering the uncertainties of indicator evaluation. The paper tests the ability of these methods to evaluate the alternatives in the presence of heterogeneous criteria and uncertain environment.

The remainder of the paper is organized as follows. After the brief overview of related work in this field, SG assessment frameworks and appropriate key performance indicators are presented in Section 2. The multi-criteria decision approach in the SG planning, AHP and BWM methods are introduced in Section 3. In Section 4, the methodology is presented on the example of the choice of HEMS deployment strategy for one medium size power distribution company. Concluding remarks regarding the results acquired by the two alternative methods and their comparisons are given in Section 5.

2. Smart Grid Assessment Frameworks

2.1. Related Work

One of the first attempts of the systematic approach to the definition of key energy performance indicators was in 2005 [7], in which the set of the 30 key energy performance indicators was included: 4 social, 16 economic and 10 environmental indicators. The EC Task Force for SGs [3], included KPIs that represent a type of measure of performance to evaluate progress toward strategic goals. These goals are the progress toward the deployment of SG services and the progress toward the achievement of SG benefits.

The European Commission has defined the characteristics of the ideal SGs through adaption and extension of the DOE/EPRI methodology in order to fit the European context [8,9]. Built/Value metrics and Benefits/KPIs are proposed as to measure progresses toward the ideal SG and outcomes. Table 1 contains a list of benefits deriving from the implementation of a SG, according to [3].

The assessment framework proposed in [3] is based on a merit deployment matrix shown in Table 2 with 11 benefits, corresponding 54 KPIs and 33 functionalities linked to a service.

For each project, the assessment is performed in two main steps: a) Identify links between KPIs, benefits and functionalities; b) Explain how the link between KPIs, benefits and functionalities is achieved in the project, and assign a weight to quantify how strong and relevant the link is. In this way, the impact of the projects in terms of functionalities, and the impact of the project in terms of benefits can be assessed. The impact of different projects to advance the SG concept can be realized using three different sets of KPIs. The set-3 of KPIs is defined directly by individual project coordinators and its purpose is evaluation of the individual projects. Depending on their scope, the individual projects are then linked to the corresponding clusters. The set-2 KPIs measure progresses in each cluster due to related projects. Finally, the set-1 KPIs measure progress in each cluster in turn contribute to the overall impact of the program.

In circumstances, where intangible aspects are dominant [10,11], the traditional cost benefit analysis is not able to account for all the effects involved in development policies. The main disadvantage of the cost benefit approach is the conversion of all the effects in a common numerical and a single aggregate measure. That's the reason why it is important to ensure a common reference for evaluation of the project proposals, in order to integrate the outcome of the KPI and of the economic analysis and come up with an overall project evaluation.

Multi-criteria decision making (MCDM) methods have been used substantially in the energy sector, such as site selection, project and equipment evaluation. The commonly used methods in domain of multi-criteria decision making are AHP, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), ELECTRE, the Analytic Network Process (ANP) and multi-objective programming [12]. Recently, a new method for solving the MCDM problems – the Best-Worst Method (BWM) has been developed, that deals with the inconsistencies of the existing pairwise comparison-based methods, by suggesting a more structured way of deriving the weights based on pairwise comparisons [13].

Each of these methods have its own properties with respect to the way of assessing criteria, the mathematical algorithm utilized, the application and computation of weights, the model to describe the system of preferences of the decision maker, and finally, the level of uncertainty embedded in the data set. The comprehensive review of different methods, their advantages and disadvantages of these methods is given in [14]. The fuzzy set theory is introduced into MCDM method in order to reflect the subjective preferences of experts more precisely, like the usage of fuzzy AHP to evaluate the renewable energy dissemination program [15-17]. On the other hand, owing to its superior performance regarding the consistency of the comparisons as well as lower requirements of comparison data, the BMW is taken into account as a MCDM method that produces rather reliable results. It has already been applied in solving environmental management issues as well as technological innovation analysis [18]. There are a few cases where BWM has been used in the field of energy efficiency [19], as well as water and sewage systems [20,21].

Unlike classical AHP, the fuzzy AHP method is introduced to improve multiple criteria decision making for uncertain valuations and priorities. In this method, the data and preferences of experts are evaluated under fuzzy set environment [22].

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 [23,24]. The problem of evaluation index system and weights and application of adjustable weight fuzzy evaluation in the distribution network is elaborated in [25]. In [26] both qualitative and quantitative variables in the design of a decision support system for solar plant site selection using fuzzy AHP are combined.

The BWM method has been recently developed by Rezaei [13], offering an improved technique for structuring pairwise comparisons. Drawing on the problems of low consistency and the complexity of pairwise comparisons in AHP method, the BWM method overcomes these problems by introducing the best and the worst criterion, that serve as a reference for all the rest of the criteria to be compared with. In this sense, the experts only need to predefine the best and the worst criterion, CB and CW respectively, so the pairwise comparisons are only performed in reference to these two criteria. Since the reference comparisons include only the comparisons of CB/CW with other criteria, the number of pairwise comparisons is significantly reduced compared to AHP, where each criterion is compared to all other criteria. This way, the comparisons that add up to the complexity and the inconsistency of comparison are eliminated.

Table 1 Smart Grid benefits for stakeholder

Stakeholder	Benefits
Grid operator	▪ Increased distribution network stability and performance ▪ Optimized facility utilization and enhanced efficiency ▪ Predictive maintenance and "self-healing" responses to system disturbances ▪ Automated maintenance and operation ▪ New opportunities to improve grid security ▪ Improved resilience to disruption ▪ Increased lifespan of existing infrastructure ▪ Reduction of technical losses
Grid user	▪ Expanded deployment of feed-in tariffs by renewable energy sources ▪ More efficient peak energy demand with less detriment to the environment ▪ Increased sustainability ▪ Effective support of transnational electricity markets by load-flow control to alleviate loop-flows and increased interconnection capacities ▪ New services
End customer	▪ Option to plug-in electric vehicles and new energy storage options ▪ Increasing reliability of power supply ▪ Decentralized energy ▪ Bills reduction ▪ Decentralized Renewable Energy
Sources	▪ Balancing energy consumption and production
Municipalities	▪ Decentralized Renewable Energy Sources ▪ Positive image as an innovative community ▪ Cost reduction through energy conservation and efficiency ▪ Sustainability
Politics/society	▪ Increased market competition ▪ New jobs ▪ Achievement of climate targets ▪ Securing the business location ▪ More efficient peak energy demand with less detriment to the environment
Industries	▪ New product opportunities ▪ New Business areas

Table 2 Merit deployment matrix

		Functionality 1	...	Functionality 33
Benefit 1	KPI 1	0–1	...	0–1
...	...	...	...	...
...	...	...	...	...
...	...	...	...	...
Benefit 11	KPI 54	...	...	...

Because of the main characteristic of the adopted SG evaluation framework and its complex hierarchical structure, the fuzzy AHP methodology for the project evaluation, structuring a decision into a hierarchy of criteria, sub-criteria and alternatives, as well as the alternative, the BWM methodology, is the basis of the methodology presented in this paper. The modified set of SG indicators, as the required input in MCDM Fuzzy AHP methodology is presented in the next section.

2.2. Smart Grid Indicators

In order to evaluate SG solutions, total costs, benefits and the beneficiaries should be assessed, including both tangible and intangible criteria. Risk and uncertainties are also present in the process of decision making, whether it is in presupposed data (consumption increase rate, prices, preferences) whether it is in decision factors of business environment that affect the process of decision making.

The identification of SG beneficiaries is crucial, besides recognized benefits. Most important beneficiaries are certainly consumers themselves, in terms of higher service quality, reduced businesses losses, energy savings and lower transport costs using electric vehicles. Form the social perspective, SG, together with Advanced Metering Infrastructure (AMI) enables energy management companies to create opportunities for energy savings based on data from consumers' smart meters. It is possible to measure the amount of saved energy and encourage more renewable energy resources. SG also benefits the utilities, since better understanding of the electrical grid's status in the real time environment results in greater efficiency and reliability.

Some questions in this approach deserve further discussion including: the treatment of immeasurable impacts (social and environmental effects); the measurement of social impact; collection and analysis of performance feedback from all stakeholders of electric power (providers, commercial and industrial consumers, vendors, regulators and re-search organizations); the combination of cost/benefit with KPI analysis. Furthermore, a benefit to any one of mentioned stakeholders can in turn benefit the others. For example, those benefits that reduce costs for a distribution system opera-tor could lower prices, or prevent price increases, for customers. Uncertainty with respect to the magnitude of benefits is present as well. See [27] for more detailed report on the requirements of the SG assessment framework.

Based on the above-mentioned reasons, the multi-layer hierarchical structure has been adopted in this paper. Adopted layers include: the top layer of main criteria, performance layer consisting of 11 performances presented in Table 3, a set of quantitative and qualitative indicators and the layer of possible alternatives that are combination of different actions on the field.

Each benefit is described by a set of quantitative and qualitative KPIs. For example, increased sustainability is evaluated by the reduction of carbon emissions. This indicator measures the CO_2 emission per kWh of produced energy.

2.2.1. Quantitative Indicators

The evaluation of the project is based on the analysis of project performance considering each KPI. One part of the analysis concerns a quantitative evaluation of KPIs. The measurable indicators include reducing carbon emissions, voltage quality performance of electricity grids (e.g. voltage dips, voltage and frequency deviations and the level of losses in distribution networks (absolute or relative), or the net present value of the investment. The choice of quantitative indicators should not be constrained to the mentioned set of indicators, and it should reflect the real process

Table 3 SG required performances

No	Performance
1	Increased sustainability
2	Adequate capacity of transmission and distribution grids for “collecting” and bringing electricity to the consumers
3	Adequate grid connection and access for all kinds of grid users
4	Satisfactory levels of security and quality of supply
5	Enhanced efficiency and better service in electricity supply and grid operation
6	Effective support of transnational electricity markets by load flow control to alleviate loop-flows and increased interconnection capacities
7	Coordinated grid development through common European, regional and local grid planning to optimize transmission grid infrastructure
8	Enhanced consumer awareness and participation in the market by new players
9	Ability of consumers to make informed decisions related to their energy to meet the EU Energy Efficiency targets
10	Creation of a market mechanism for new energy services such as energy efficiency or energy consulting for customers
11	Consumer bills are either reduced or upward pressure on them is mitigated

2.2.2. Qualitative Indicators

A number of indicators that cannot be quantified, such as social and environmental impacts and benefits are usually evaluated by the means of ordinal comparison. For the purpose of evaluating such indicators, in our assessment methodology, we use five-grade verbal scale, derived from opinion polls, expert opinions or integrated approach. For the sake of illustration, the environmental and social indicators and the quantitative five grade verbal scales are reported below:

a) Environmental impact;
   - Minor grade, with no substantial environmental impact.
   - Low grade, with no visual and noise problems.
   - Moderate grade, with certain visual or noise problems, creating disruption to the environment but not affecting the wildlife.
   - High grade, with increased pollution, impact to the wildlife and landscape.
   - Very high grade, with large emission pollutants and life-cycle steps contributing significantly to the total environmental impact.

b) Social benefits;
   - Minor grade, with local economy unaffected or without enhancement in market services.
   - Low grade, creating new jobs, but retaining risk of new renewable energy sources.
   - Moderate grade, with new market mechanism for energy services (energy efficiency or energy consulting).
   - High grade, with improvement of market mechanisms and customer service, creating and retaining jobs.
   - Very high grade, involving consumers in energy usage and management, new jobs created and retained.

A clearly defined framework can concretize where exactly the project contributed to a smart electricity grid. The presence of both quantitative and qualitative indicators is the rationale for introducing the multi-criteria decision making (MCDM) methods explained in the next section.

3. Multi-criteria Assessment Model

Multi-criteria decision-making deals with decisions involving the choice of a best alternative from several potential candidates in a decision, subject to several criteria or attributes that may be tangible or intangible. SG planning is a difficult process of decision making, because the asset management in power utilities relates the balancing of costs, performance and risk.

The number and structure of these categories is changing, depending of particular conditions (legislative, regulatory requirements etc.) but four main criteria defined in the previous section are the basic attributes. Their simultaneous treatment is a difficult task, solved mainly in two ways:

- The contribution of each project component is analysed and evaluated regarding criteria defined above. Then, introducing weighting factors, influence of each criterion is reduced to one measuring unit (e.g. monetary) [28];
- For each project, the aggregation of individual criteria is made, resulting in one general index. This index is formed based on estimated benefits and condition of asset regarding required criteria, and their weighting factors [29,30].

The disadvantage of these methods is non-realistic approach of reducing all criteria to just one value, and great sensibility to weighting of criteria. These disadvantages are surpassed by multi-criteria optimization. For that reasons, techniques of Multi Criteria Decision Analysis (MCDA) become more and more needed in the power system sustainable development planning. MCDA is a scientific discipline that deals with methods and procedures for solving problems with several, often conflict criteria.

The mathematical model has following structure:

$$Max\{f_1(x), f_2(x), \ldots, f_n(x), n \geq 2\} \tag{1}$$

under condition $x \in A = [a_1, a_2, \ldots, a_3]$, where:

f_j - criteria function, $j = 1, 2, ..., n$,

a_i - alternatives, $i = 1, 2, ..., m$,

A - feasible set of actions.

A multi-criteria decision problem is most often represented through the matrix, with the elements representing the out-comes scores that can be quantitatively or qualitatively expressed. The analysis is based on a set of values and preferences of the decision maker, with different weights for comparison of criteria. The choice of particular method depends on available information of preferences and attributes. In cases of certainty about the outcomes, alternatives and consequences are directly corresponding in terms of the criteria. Moreover, these outcomes are deterministic. In situations of uncertainty the outcomes can be assigned many possible values that are difficult to express. The description of the out-comes under uncertainty can be quantitative (using probabilistic quantities), fuzzy, or qualitatively (through verbal descriptions) – in situations when outcomes are not fully known or understood.

Considering the specifics and the hierarchical structure of the adopted SG evaluation framework, we evaluate two MCDM methods: the fuzzy AHP, that structures a decision into a hierarchy of criteria, sub-criteria and alternatives as well as the BWM that offers a different structure of the comparisons. Using pairwise comparisons of two (sub) criteria or alternatives, both models generate inconsistency ratios and assign weights to the criteria and alternatives. For testing the robustness of the priorities, sensitivity analysis can be applied.

Several factors can cause imprecisions in assessing the relative importance of attributes and the performance ratings of alternatives with respect to attributes.

All indicators (quantitative and qualitative) affect four main criteria in the extent determined by the decision maker. For instance, reduced voltage deviation and stable voltage profile in the network can induce the usage of advanced technologies and services; this will decrease the costs of low power quality and increase the customer satisfaction. The complete algorithm for the ranking of HEMS strategies is explained below:

- Goal of the analysis. The goal is ranking various HEMS strategies;
- Identification of stakeholders, performances criteria, sub-criteria, and alternatives. Criteria for HEMS strategies selection are technology, costs, users' satisfaction and environmental protection. Sub-criteria are chosen from the list of benefits.
- Hierarchical structure formation. The method is structuring a problem in the hierarchical form: the first level considers relevant criteria (four main identified criteria); the second level considers relevant performances (chosen from eleven identified sub-criteria); and the third level defines HEMS alternative strategies.
- Pairwise comparison. The fuzzified Saaty's scale, as shown in Table 4 has been used for the pair wise comparison of elements at each level. The fuzzification is implemented by triangular fuzzy numbers with the value of fuzzy distance of 2 (for instance, fuzzy number (1,1,3) is used for 1, etc.).

Table 4 Crisp and fuzzified Saaty's scale [31]

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)

The comparison results are presented in the form of the square matrix $A=[\tilde{a}_{i_j}]_{i,j=\overline{1,n}} \cdot \tilde{a}_{i_j}$ is the fuzzy value about the relative importance of criteria *i* over criteria *j*, where $\tilde{a}_{i_j}=1$ for $i=j$ and $\tilde{a}_{i_j}=1/\tilde{a}_{i_j}$ for $i \neq j$.

Pairwise comparisons at each level, starting from the top of the hierarchy, are presented in:

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

$$W_c=(w_{c_1}, w_{c_2}, w_{c_3}, w_{c_4})^T . \tag{2}$$

Elements of criteria weighting vector are determined as:

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

Performance weighting vectors are defined by pairwise comparison of performance according to every single criterion. Appropriate elements of this vector, according to Equation (2), are calculated as follows:

$$x_{i_j} = \sum_{j=1}^{4} \tilde{a}_{i_j} \otimes \left[\sum_{i=1}^{5} \sum_{j=1}^{4} \tilde{a}_{i_j} \right]^{-1}, \quad (4)$$

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:

$$W_{sc} = X \otimes W_c = (w_{sc_1}, w_{sc_2}, w_{sc_3}, w_{sc_4}, w_{sc_5})^T. \quad (5)$$

Finally, the HEMS strategies are compared according to the relevant performance. Proper weights of projects for individual performance are determined according to Equation (6), as follows:

$$y_{i_j} = \sum_{j=1}^{5} \tilde{a}_{i_j} \otimes \left[\sum_{i=1}^{3} \sum_{j=1}^{5} \tilde{a}_{i_j} \right]^{-1}, \quad (6)$$

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

$$W_a = Y \otimes W_{sc} = (w_{a_1}, w_{a_2}, w_{a_3})^T. \quad (7)$$

- *Defuzzification and the final ranking of alternatives*.

In this paper triangular fuzzy numbers are ranked by applying the total integral value method. Alternatively, determining the weights of the defined criteria can be performed by the BWM, following the next five steps:

Step 1. Determining the decision criteria, $\{c_1, c_2, \ldots, c_n\}$..

Step 2. Choosing the best, CB, and the worst, CW criterion.

Step 3. Performing the comparisons in reference to the best criterion CB

The resulting Best-to-Others (BO) vector would be: $A_B = (a_{B_1}, a_{B_2}, \ldots, a_{B_n})$, where a_{Bj} indicates the preference of the best criterion B over criterion j.

Step 4. Performing the comparisons in reference to the worst criterion CW. The resulting Others-to-Worst (OW) vector would be: $A_W = (a_{1_W}, a_{2_W}, \ldots, a_{n_W})^T$, where a_{j_W} indicates the preference of the criterion j over the worst criterion W.

Step 5. Using the optimization models to calculate the weights.

The optimal weights for the criteria is the one where, for each pair of w_B / w_j and w_j / w_W, we have $w_B / w_j = a_{Bj}$ and $w_j / w_W = a_{jW}$. To satisfy these conditions for all j, we should find a solution where the maximum absolute differences $| w_B / w_j = a_{Bj} |$ and $| w_j / w_W = a_{j_W} |$ for all j is minimized.

The proposed methodologies are applied on the choice of the optimal home energy management program within a SG deployment of the medium size power distribution company.

4. CASE STUDY

Utilities recognize the need to provide better information to customers about the cost of supply and the time-specific us-age levels. Customers are becoming aware of new technologies that make modifying usage easier to accomplish, reducing electricity costs. Planners proposed three different development alternatives with the description of proposed actions, the number of installed device and their unit installation prices given in Table 5.

Table 5 Different development alternatives

No	Description of the proposed action	Per unit costs ($)	Alt. 1	Alt. 2	Alt. 3
1	In home displays	187	10.000	5.000	3.000
2	Direct load control devices	2.242	1.000	2.000	4.000
3	Programmable communicating thermostats	549	3.000	2.000	1.000
4	Smart appliances	2.767	200	500	200

The proposed development alternatives provide both qualitative and quantitative benefits. With the additional in-formation that the in-home display (IHD) provides the consumer, customers would use the real-time metering data available on the IHD to better understand their total energy consumption patterns and those of individual appliances.

Customers would find the estimated bill information provided on the IHD useful in managing the energy usage costs. Studies have shown that IHD users may reduce their overall energy consumption by as much as 2-7%. The increased number of smart appliances determines the grid connection (owing to the enhanced low voltage network management) and transparent information to consumers. Direct load control can significantly delay or avoid network investments and reduce the need for peaking generators. The technologies underpinning demand management may also produce other benefits, such as those associated with remote metering and the provision of information on energy consumption to consumers.

The performance indicators for different alternatives are presented in Table 6.

Table 6 Quantitative aggregated performance indicators for different alternatives

No	Performance indicator	Project 1	Project 2	Project 3
1	Energy losses reduction [MWh/year]	3.000	8.000	11.000
2	Quantified reduction of carbon emissions (*t*)	5.400	14.000	19.000
3	Installation costs (Mio. $)	6.300	7.900	10.600

The paper does not aim to provide the detailed calculation of these parameters. Energy loss reduction is caused by the direct load control and peak power shaving enabling the economic line loading. Decrease in energy losses is reducing the carbon emission. Final quantitative value is related to the installation costs based on per unit costs. Concerning the qualitative indicators, all of these actions are evaluated with moderate grade of social benefit, including market mechanisms for innovative energy services such as energy efficiency or energy consulting for customers. The hierarchy of adopted criteria, performances and indicators is given in Figure 1. Some of performances listed in Table 3 are not applicable for this particular case study (performance concerning the transmission level) resulting in reduced number of performances.

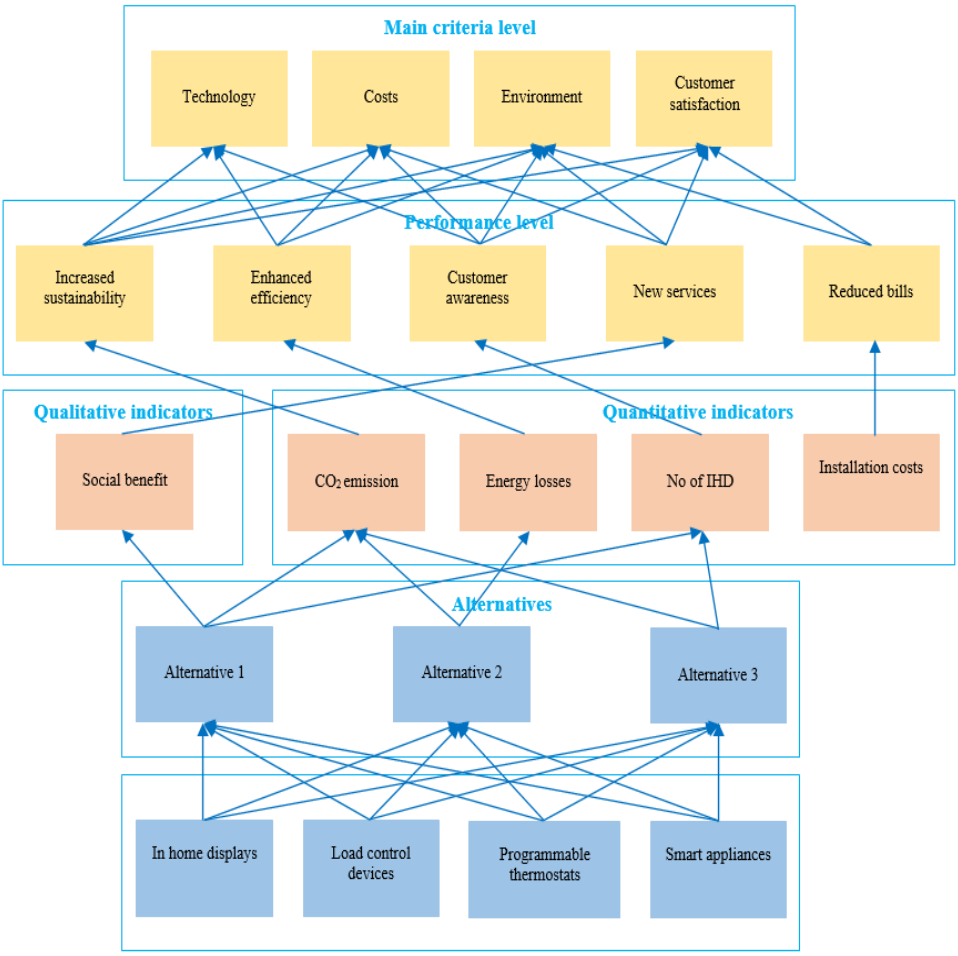

Fig. 1 Hierarchical scheme of criteria, selected performances and indicators

The multi criteria algorithm begins with expert's pairwise comparison of the criteria: technology improvement (C_1), costs (C_2), customer satisfaction (C_3) and environmental protection (C_4). The results are shown in Table 7.

In the second step, experts choose adequate benefits from the list of benefits and appropriate indicators. In this particular case, 5 performances are recognized: (SC_1) Enhanced efficiency and better service in electricity supply and grid operation; (SC_2) Enhanced consumer awareness and participation in the market by new players; (SC_3) Ability of consumers to make informed decisions related to Energy Efficiency targets; (SC_4) Creation of a market mechanism for new energy services such as energy efficiency or energy consulting for customers; (SC_5) Consumer bills are either reduced or upward pressure on them is mitigated. The selection of appropriate sub-criteria and associated KPI is given in Table 8.

Table 7 The pairwise comparison, fuzzy weights, final weights and ranks of criteria

	C_1	C_2	C_3	C_4	Fuzzy weights w_{c_i}
C_1	$\tilde{1}$	$\tilde{3}$	$\tilde{5}$	$\tilde{5}$	(0.1967, 0.5303, 1.3141)
C_2	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	(0.0787, 0.2778, 0.7885)
C_3	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{1}$	(0.0576, 0.0960, 0.3504)
C_4	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$	$\tilde{1}$	(0.0412, 0.0960,0.2190)

λ=0.5		λ=1.0	
FWs	Rank	FWs	Rank
0.5096	1	0.5023	1
0.2819	2	0.2904	2
0.1189	3	0.1216	3
0.0896	4	0.0858	4

Table 8 Sub-criteria and KPI selection

	Sub-criteria KPI	KPI type	Performance description
SC_1	CO_2 reduction	Quantitative	Increased sustainability
SC_2	Energy losses	Quantitative	Enhanced efficiency and better service in electricity supply and grid operation
SC_3	Social benefit	Qualitative	Creation of a market mechanism for new energy services such as energy efficiency or energy consulting for customers
SC_4	Number of IHD installed	Quantitative	Enhanced consumer awareness and participation in the market by new players
SC_5	Installation costs	Quantitative	Consumer bills are either reduced or upward pressure on them is miti-gated

Both qualitative and quantitative indicators are included in the pairwise comparison made by experts, as presented in Tables 9 to 12.

Table 9 The pairwise comparison matrix of sub-criteria in relation to technology

	SC_1	SC_2	SC_3	SC_4	SC_5	Fuzzy weights x_{i_1}
SC_1	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{3}$	$\tilde{7}^{-1}$	$\tilde{7}^{-1}$	(0.0304, 0.0799, 0.1917)
SC_2	$\tilde{3}$	$\tilde{1}$	$\tilde{5}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	(0.0662, 0.1625, 0.3540)
SC_3	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	$\tilde{1}$	$\tilde{7}^{-1}$	$\tilde{7}^{-1}$	(0.0196, 0.0315, 0.0708)
SC_4	$\tilde{7}$	$\tilde{5}$	$\tilde{7}$	$\tilde{1}$	$\tilde{1}$	(0.1880, 0.3631, 0.7512)
SC_5	$\tilde{7}$	$\tilde{5}$	$\tilde{7}$	$\tilde{1}^{-1}$	$\tilde{1}$	(0.1796, 0.3631, 0.6994)

Table 10 The pairwise comparison matrix of sub-criteria in relation to costs

	SC_1	SC_2	SC_3	SC_4	SC_5	Fuzzy weights x_{i_2}
SC_1	$\tilde{1}$	$\tilde{5}^{-1}$	$\tilde{7}^{-1}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	(0.0202, 0.0323, 0.0635)
SC_2	$\tilde{5}$	$\tilde{1}$	$\tilde{7}$	$\tilde{3}$	$\tilde{3}$	(0.1446, 0.3522, 0.7788)
SC_3	$\tilde{7}$	$\tilde{7}^{-1}$	$\tilde{1}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	(0.0841, 0.1583, 0.3134)
SC_4	$\tilde{5}$	$\tilde{3}^{-1}$	$\tilde{5}$	$\tilde{1}$	$\tilde{1}$	(0.1078, 0.2286, 0.5480)
SC_5	$\tilde{5}$	$\tilde{3}^{-1}$	$\tilde{5}$	$\tilde{1}^{-1}$	$\tilde{1}$	(0.0990, 0.2286, 0.4903)

Table 11 The pairwise comparison matrix of sub-criteria in relation to the customer satisfaction

	SC_1	SC_2	SC_3	SC_4	SC_5	Fuzzy weights x_{i_3}
SC_1	$\tilde{1}$	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	$\tilde{7}^{-1}$	(0.0295, 0.0450, 0.1395)
SC_2	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{7}^{-1}$	$\tilde{7}^{-1}$	$\tilde{7}^{-1}$	(0.0200, 0.0409, 0.0656)
SC_3	$\tilde{3}$	$\tilde{7}$	$\tilde{1}$	$\tilde{1}$	$\tilde{5}$	(0.1323, 0.2860, 0.6305)
SC_4	$\tilde{5}$	$\tilde{7}$	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	(0.1147, 0.2411, 0.4791)
SC_5	$\tilde{7}$	$\tilde{7}$	$\tilde{5}$	$\tilde{3}$	$\tilde{1}$	(0.1804, 0.3870, 0.7818)

Table 12 The pairwise comparison matrix of sub-criteria in relation to the environmental protection

	SC_1	SC_2	SC_3	SC_4	SC_5	Fuzzy weights x_{i_4}
SC_1	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	$\tilde{5}$	$\tilde{5}$	(0.1414, 0.4315, 1.1819)
SC_2	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	(0.0660, 0.2115, 0.7091)
SC_3	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	(0.0555, 0.2115, 0.6146)
SC_4	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{1}$	(0.0399, 0.0728, 0.2994)
SC_5	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$	$\tilde{1}$	(0.0295, 0.0728, 0.2049)

The final vector of fuzzy weights of the performance of the projects, according to Equation (5), Table 5, and Tables 7-12, is:

$$W_{sc} = X \otimes W_c = [x_{i_j}]_{5\times 4} \otimes [w_{c_j}]_{4\times 1} = [w_{sc_i}]_{5\times 1} = \begin{bmatrix} (0.0151, 0.0971, 0.6097) \\ (0.0283, 0.2082, 1.2576) \\ (0.0204, 0.1084, 0.6957) \\ (0.0537, 0.2862, 1.6527) \\ (0.0547, 0.3002, 1.6245) \end{bmatrix}. \quad (8)$$

At the end, three HEMS strategies (Project 1 [A1], Project 2 [A2], and Project 3 [A3]) are compared in relation to performance presented in Tables 3 and 4 as presented in Table 13.

Table 13 The pairwise comparison of alternatives in relation to performance

		A_1	A_2	A_3	Fuzzy weights y_{i_1}
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	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	(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_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	$\tilde{1}$	$\tilde{3}$	$\tilde{5}$	(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)
	A_1	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	(0.0567,0.0916,0.2225)
	A_2	$\tilde{3}$	$\tilde{1}$	$\tilde{5}$	(0.2113,0.5378,1.2398)
SC_5	A_3	$\tilde{5}$	$\tilde{5}^{-1}$	$\tilde{1}$	(0.1751,0.3705,0.7947)

The final vector of fuzzy weights for HEMS strategies, according to Equation (7) is:

$$W_a = Y \otimes W_{sc} = [y_{i_j}]_{3\times 5} \otimes [w_{sc_i}]_{5\times 1} = \begin{bmatrix} (0.0223, 0.2979, 3.7493) \\ (0.0231, 0.3655, 5.4684) \\ (0.0237, 0.3367, 4.7738) \end{bmatrix}. \quad (9)$$

After the defuzzification of final weights vectors of performance and projects, they are ranked. The ranking results are shown in Table 14.

Table 14 Ranking sub-criteria and HEMS strategies

	λ=0.5		λ=1.0	
	FWs	Rank	FWs	Rank
Sub-criteria (performances)				
CO_2 reduction (SC_1)	0.1022	5	0.1033	5
Energy losses (SC_2)	0.2125	3	0.2143	3
Social benefit (SC_3)	0.1164	4	0.1176	4
Number of IHD installed (SC_4)	0.2844	2	0.2835	1
Installation costs (SC_5)	0.2845	1	0.2814	2
HEMS strategy				
Project 1 (A_1)	0.2719	3	0.2700	3
Project 2 (A_2)	0.3874	1	0.3891	1
Project 3 (A_3)	0.3406	2	0.3409	2

Based on the calculations, it can be concluded that the method can give several evaluation frameworks. The first one is the main criteria ranking.

For this particular customer group, the most important criterion for the selection of energy management strategy is the improvement of the technology, followed by the costs, the customer satisfaction and the environmental protection. Technological advancements increase the efficiency and security of energy supply, at the same time increasing user satisfaction and protecting the environment. The second evaluation level is the ranking of sub-criteria, where reduced customer bills (SC_5) proved to be the dominant category. The final ranking of the alternatives indicates that the A_2 project was assigned the highest rank, A_3 project is the second; the lowest priority has the A_1 project. This indicates that strategy 2 for the implementation of the HEMS should be selected, with the most balanced number of installed devices (thermo-stats, in home displays, directly controlled devices). The alternative 2, gives however, advantage to the installation of smart appliances.

The authors came to the same conclusion if we analyse this problem using BWM. BWM technique uses pairwise comparison to obtain the weights of the criteria. After identifying all the criteria, an expert determines the best and the worst criterion, and then the comparison can be performed.

Table 15 shows the best and the worst criterion, in this case sub-criterion, and their comparison to other sub-criteria with a scale of 1-9. Obtained comparison values are presented in the Table 15.

Table 15 Pairwise comparison matrix of BWM

j	Criteria	Best SC_5 a_{B_j}	Worst SC_1 a_{jw}
j_1	SC_1	5	1
j_2	SC_2	3	3
j_3	SC_3	4	2
j_4	SC_4	2	4
j_5	SC_5	1	5

Using the linear BWM to solve this problem we get the weights for every sub-criterion given in the Table 16. The consistency ratio is $\xi = 0.057$.

Table 16 Criteria weights using BWM

j	Criteria	Weight
j_1	SC_1	0.072
j_2	SC_2	0.158
j_3	SC_3	0.118
j_4	SC_4	0.237
j_5	SC_5	0.416

The performance matrix based on which we came to the best decision is the following (10-point scale): $P = \begin{matrix} A_1 \\ A_2 \\ A_3 \end{matrix} \overset{\begin{matrix} SC_1 & SC_2 & SC_3 & SC_4 & SC_5 \end{matrix}}{\begin{pmatrix} 4 & 3 & 8 & 9 & 2 \\ 6 & 7 & 5 & 8 & 9 \\ 10 & 9 & 3 & 2 & 5 \end{pmatrix}}$. Using the function $V_i = \sum_{j=1}^{n} w_j p_{i_j}$ we obtained the overall values for each considered project ($V_1 = 4.671$, $V_2 = 7.768$, $V_3 = 5.05$). It can be concluded that the best solution is project A_2.

The results show that by applying different methods different results are obtained. In the case of applying the AHP method, for 2 different values of the interval λ (0.5 and 1), alternative 3 was chosen as the best, while in the case of applying the BWM method, the best solution is project 2. These results are shown in Figure 2. The reasons should be sought in to the fact that even the evaluation of criteria weights is different in certain methods. Figure 3 shows that in the case of the BWM method, more weight is given to criterion SC_5 (costs), while in the case of the AHP method, these criteria are fairly equal.

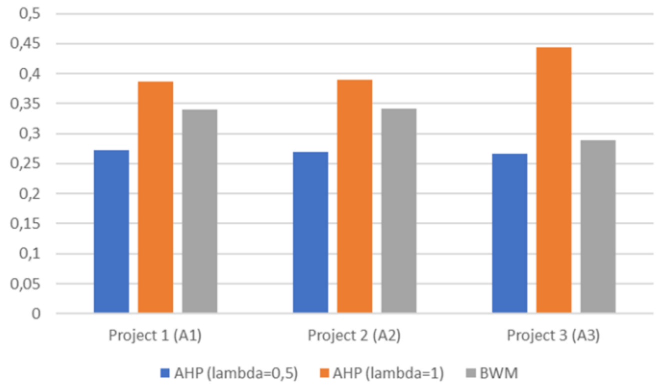

Fig. 2 Best solution comparison according to different methods

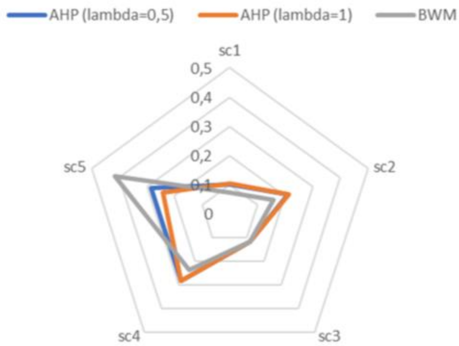

Fig. 3 Criteria weighting according different methods

Based on this analysis, it can be concluded that the evaluation of weighting factors has a decisive character in the choice of the final one of several alternative variants. Fuzzification of input values can also contribute to a more flexible view of the given problem and analysis of sensitivity to various input parameters.

In accordance with the nature of the proposed methods, the available resources, and the research objectives, the validation was done by a combination of simulation and modeling, comparative analysis, expert evaluation, and sensitivity analysis. Based on expert evaluations, a sensitivity analysis was performed, which includes varying input parameters and assessing how the method responds. Using computer simulations and modeling, the proposed method is validated. Also, comparative analysis, which enables the comparison of methods, contributes to the confirmation of the results obtained through the use of computer simulations and modeling.

5. CONCLUSION

An improved framework for assessing home energy management programs from the Smart Grid perspective is pro-posed and verified. This framework is based on the reduced performance indicator set obtained by the proper choice of qualitative and quantitative indicators. The integrated assessment approach is realized by defining appropriate metrics and key performances, establishing the strict hierarchical scheme of main criteria, sub-criteria, their quantitative and qualitative indicators and possible alternatives. This scheme avoids the ambiguities in the SG benefits evaluation. Using Fuzzy AHP method the uncertainties of indicator evaluation can be easily overcome. The method is tested on the case of evaluation of three HEMS strategy alternatives in the presence of heterogeneous criteria and uncertain environment. BWM technique generally proves to be easy to understand, as well as to apply in this context. With respect to the AHP, it requires fewer comparisons, less data and is more consistent and reliable.

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